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VOLUME 35 | ISSUE 1 | 2023

JERD | Journal of Esthetic and Restorative Dentistry

Special Annual Issue

Advances in Esthetic Dentistry 2023

Scientific evidence for CLINICIANS, clinical relevance for RESEARCHERS

Official Publication of the:
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American Academy of Esthetic Dentistry
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JOURNAL OF ESTHETIC AND RESTORATIVE DENTISTRY (ISSN: 1496-4155 [print]; ISSN: 1708-8240 [online]) is published eight times a year in January, March, April, June, July, September, October, and December by Wiley Periodicals LLC, 111 River St., Hoboken, NJ 07030-5774.

Periodical Postage Paid at Hoboken, NJ and additional offices.

Postmaster: Send all address changes to JOURNAL OF ESTHETIC AND RESTORATIVE DENTISTRY, Wiley Periodicals LLC, C/O The Sheridan Press, PO Box 465, Hanover, PA 17331 USA.

Back Issues: Single issues from current and prior year volumes are available at the current single issue price from cs-journals@wiley.com. Earlier issues may be obtained from Periodicals Service Company, 351 Fairview Avenue – Ste 300, Hudson, NY 12534, USA. Tel: +1 518 822-9300, Fax: +1 518 822-9305. Email: psc@periodicals.com

Information for Subscribers: *Journal of Esthetic and Restorative Dentistry* is published in eight issues per year. Institutional subscription prices for 2023 are: Print & Online: US$1320 (The Americas), US$1441 (Rest of World), €935 (Europe), £741 (UK). Prices are exclusive of tax. Asia-Pacific GST, Canadian GST and European VAT will be applied at the appropriate rates. For more information on current tax rates, please go to https://onlinelibrary.wiley.com/library-info/products/price-lists/payment. The price includes online access to the current and all online back files to January 1st 2018, where available. For other pricing options, including access information and terms and conditions, please visit https://onlinelibrary.wiley.com/library-info/products/price-lists. Terms of use can be found here: https://onlinelibrary.wiley.com/terms-and-conditions.

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Publisher: Journal of Esthetic and Restorative Dentistry is published by Wiley Periodicals LLC, 101 Station Landing, Suite 300, Medford MA 02155.
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Production Editor: Reeni Sunder (email: JERD@wiley.com).

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ISSN 1496-4155 (Print)
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DOI: 10.1111/jerd.13024

EDITORIAL

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Advances in Esthetic Dentistry 2023

Dear Colleagues,

We take great pleasure to present our annual special issue of *Advances in Esthetic Dentistry 2023* as part of the Journal of Esthetic and Restorative Dentistry (JERD). Since its inception in 2021, this special issue has become a true reference library of the top clinical/case reports, research, and review papers in esthetic dentistry. Articles featured in *Advances in Esthetic Dentistry* 2022 have been downloaded a stunning 52,000 times in the single year, exceeding 2160 downloads per paper, and 6140 for the most downloaded paper. Building on this past success, our goal for the current issue was to provide another inspiring update of contemporary esthetic dentistry while pushing the boundaries of interdisciplinary esthetic excellence in everyday clinical practice. In addition, we remain committed to bridging the gap that can exist between clinicians, researchers, and dental technicians, providing scientific evidence for clinical treatment.

The interest in esthetic dentistry remains at the forefront of dentistry. The fact that JERD content is comprehensive and inclusive of all specialties makes it the perfect medium for thorough update in the dynamic field of esthetic dentistry. The advantages and benefits for dental professionals are best illustrated by the variety of subjects in this issue. It contains a total of 27 articles including 11 clinical, 9 research, and 7 review articles with 298 pages and 581 images. Although the content to a large extent transcends beyond individual disciplines and topics, based on the predominant ones, it is divided into the following sections: restorative dentistry, prosthodontics, periodontics, implant dentistry, digital dentistry, and orthodontics.

The vastly illustrated clinical technique articles and case reports offer a wide variety of information on significant changes in interdisciplinary dental treatment as well as new technologies or practical approaches to recognized clinical challenges. The featured research and review papers provide much-needed scientific evidence on current and up-and-coming techniques and technologies in the field, providing valuable tools for treatment planning and clinical decision-making.

Authors for *Advances in Esthetic Dentistry* 2023 were invited based on their international reputation and prominence in esthetic dentistry. We also extend a special thank you to all co-authors for their valuable contributions. Each new issue of *Advances in Esthetic Dentistry* offers up-to-date, evidence-based information, pertinent to the integration of dental esthetics into oral health care, from general to highly specialized and interdisciplinary topics.

Another important factor that greatly contributed to the quality of this issue, is strong and timely support from the Wiley's editorial team. This includes but is not limited to Sindhu Varghese, Reeni Sunder, Zora Ma, Karen Harmon and Wiley's wonderful editors, Meg Crawford and Rosie Hutchinson.

We trust that you will find many 'pearls' in this issue that may help elevate your work in your office or laboratory to the next level. To continue the successful path of *Advances in Esthetic Dentistry*, we invite you to make this a collaborative effort. Please send your comments and suggestions, including topics of interest, to jerd_advances@wiley.com. We thank you for your great and continued support. Enjoy the 2023 issue of *Advances in Esthetic Dentistry!*

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Received: 20 December 2022 | Revised: 12 January 2023 | Accepted: 13 January 2023

DOI: 10.1111/jerd.13021

CLINICAL ARTICLE

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Nature-mimicking layering with composite resins through a bio-inspired analysis: 25 years of the polychromatic technique

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Abstract

Objectives: For decades, the dental community has discussed which materials would be the ideal substitutes for lost tooth structure. Initially, the biomimetic approach advocated that feldspathic ceramics would be the material of choice for enamel. However, given the complexity of obtaining excellent dental technicians and the financial cost, are composite resins a suitable replacement? The optical properties with opalescence and fluorescence effects, as well as this material's high fracture toughness, indicate it as a long-lasting restorative material. However, because this material depends on the operator's expertise, knowledge of layering techniques and the selection of each material for the different layers is required. Thus, knowledge of the polychromatic technique through a bioinspired approach is necessary to obtain results of life-like restorations. This article aims to review the polychromatic layering technique (PLT), considering the optical and mechanical properties of dentin and enamel and correlating these properties with current composite resins to guide clinicians in selecting the most suitable restoratives for their clinical challenges.

Clinical Considerations: The polychromatic layering technique is revisited, cross-referencing the properties of dentin and enamel with current composite resin restoratives and their biomimetic properties. The effectiveness and predictability of the PLT are corroborated in clinical cases of varying degrees of difficulty requiring different layering strategies.

Conclusion: After the bio-inspired analysis, using nature as a model to be understood and followed, it is possible to note how the polychromatic technique remains current and viable in mimicking nature, providing esthetic and natural results in the layering of composite resins.

Clinical Significance: Composite resins effectively replicate the optical and mechanical characteristics of natural dentin and enamel through the bioinspired approach presented by the polychromatic layering technique.

KEYWORDS
bioinspiration, biomimetic, composite layering, dental tissues, light propagation

1 | INTRODUCTION

Restorative dentistry, for decades, has been looking for materials and techniques to replace the tooth structure affected by injuries. In the research of developments for new products, countless alternatives are presented with the promise of being ideal substitutes. As a result, the industry has periodically introduced restoratives combining optimal mechanical and nature-mimicking properties. In addition, numerous in vitro and in vivo studies have scrutinized materials and methods to establish scientific and clinical grounds for consistently creating restorations that emulate dental tissues.[1–5]

Skilled ceramists use elaborate stacking techniques to artistically achieve high-quality results that mimic the living tissues (Figure 1). In the same way, composite layering techniques have been introduced with significant clinical acceptance and application, aiming at the quest for restorations that go unnoticed by the most attentive observer[6–8] (Figure 2A,B).

The clinician's critical challenge has consistently been producing restorations that mingle natural tissues' characteristics with synthetic restoratives according to biomimetic principles. Biomimetics is an interdisciplinary field in which principles from engineering, chemistry, and biology are applied to the synthesis of materials, synthetic systems, or machines that have functions that mimic biological processes.

In this scenario, ceramics are considered the materials closest to dental structures by the biomimetic dental school of thought—feldspathic porcelain, particularly—as they closely emulate dental enamel's mechanical and optical characteristics.[9] Because enamel is very similar to glass due to its high mineral content, the calcium phosphate crystals (hydroxyapatite) and other constituent minerals of this acellular layer give it an anisotropic behavior and a light dispersion like that found in porcelain[10] (Figure 3A–D). However, the definition of an ideal synthetic substitute can only be defended with deeper pondering. Porcelain is credited with being more abrasive to opposing enamel than composite resins. Additionally, its manufacturing technique also requires more invasive tooth preparations and a more complex and costly workflow due to the increased time and cost of the laboratory process.

Although immersing in materials science per se seems fascinating, the choice of a substitute synthetic material prompts reasoning that extends beyond mechanical and optical properties found in biomimetics to consider the overall scope of restorative dentistry as a field of health promotion.

Whether with resins or ceramics, the restorative process depends on the technical skill of the human being; in other words, it is operator-dependent.[11] However, ceramic works are more expensive and depend on an experienced ceramist who, in most cases, is not the dentist himself. Thus, the purpose of this article is to carry out a conceptual analysis not only through biomimetics but through the broader look of bioinspiration for the choice of materials and techniques that can be introduced more simply in the daily lives of clinicians. Furthermore, this article aims at understanding the natural tissues and the characteristics of currently available composite restoratives while scrutinizing and revisiting a logical pathway for their selection and application according to a widely accepted technique published by one of the authors in 1995—*the polychromatic layering technique*.[12]

FIGURE 1 Single unit ceramic crown on maxillary left central incisor.

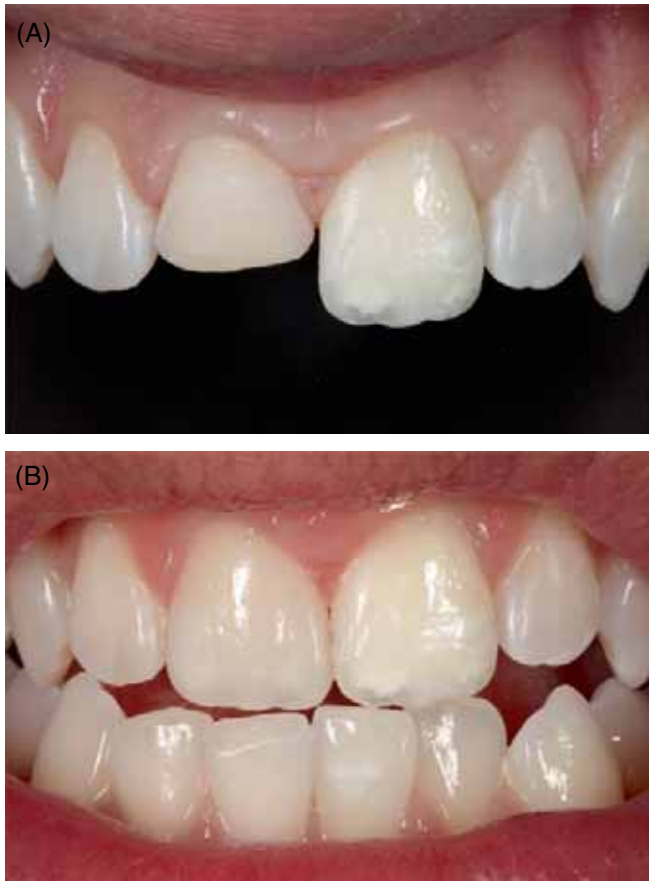

FIGURE 2 (A and B) Single unit composite restoration on maxillary right central incisor.

2 | THE CHOICE OF COMPOSITE RESIN AS A RESTORING MATERIAL

In many countries, academic discussions argue about the best restorative material when comparing composites versus ceramics. Often

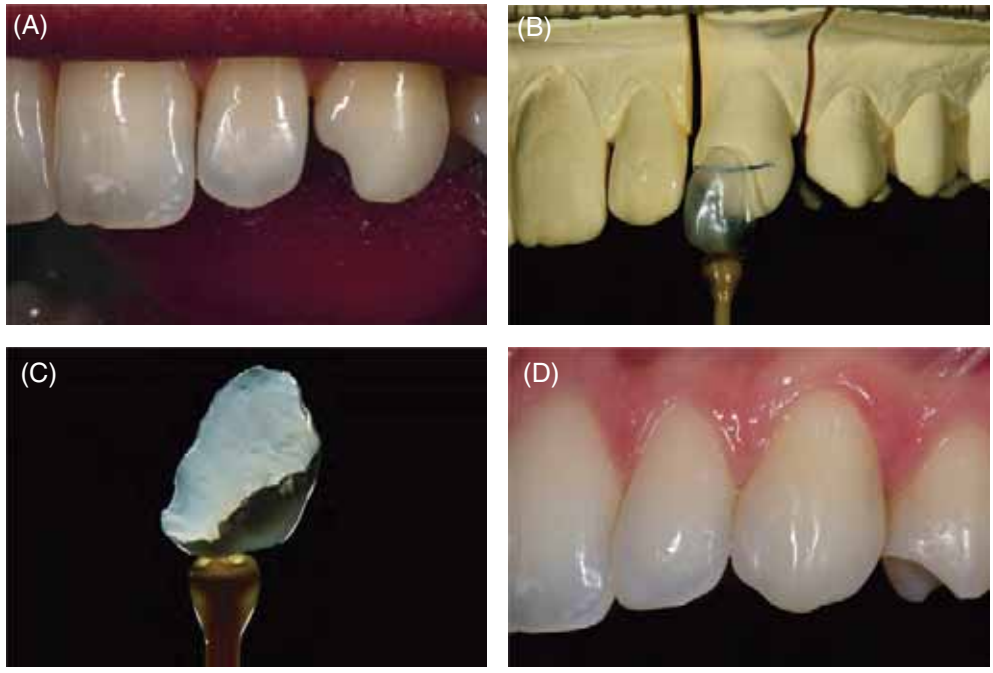

FIGURE 3 (A–D) Add-on feldspathic ceramic contact-lens type fragment.

defended even passionately, this analysis makes no sense when the focus is on the patient. Longevity studies demonstrate that both materials can be used successfully in dental restoration for decades, benefiting people in terms of esthetics and function.[11,13] Mechanically, the physical properties of composite resins have historically been optimized by the often ceramic filler particles of this composite (hybrid) material. With this, a perfect balance can be obtained in the proportion of the organic and inorganic components. In this way, even with simple layering techniques using a single shade and opacity, esthetic and functional results can be achieved with resins, unlike ceramics, which invariably depend on complex implementation techniques (Figure 4A–C).

Another favorable factor for using composite resins is their additive application technique. Because composite resins are directly applied in the mouth, creating a path of insertion, as in the case of indirect restorations, is unnecessary. This direct approach implies more significant preservation of healthy dental structures, keeping Contemporary Dentistry in an additive and not amputative era.[14]

Finally, the high operational cost of ceramic works and the need for an outsourced laboratory service—only sometimes readily available across different countries and their socioeconomic realities—make resins an attractive proposal that places the clinician as the protagonist of a successful esthetic/functional restoration.

3 | THE NATURAL TOOTH IN THE CONTEXT OF BIOINSPIRATION

Dental biomimetics is a concept that seeks to imitate the structure to be restored in the choice of replacement materials.[15] With this, the natural element is studied, and substitutes of similar characteristics are selected whenever eligible. However, when dealing with living beings, this may be a challenging task. Plain logic indicates that the best substitute for enamel should be tissue-engineered enamel itself. Without this possibility, a deep study of the element to be copied must be done, and the search for how to restore it can have a deeper meaning when nature is analyzed more broadly. Bioinspiration analyzes the target element and looks for other forms of intelligent design present in nature (Figure 5). For example, suppose the tooth presents a dentin/enamel junction with a stable and long-lasting chemical and micromechanical bond. Why can adhesives not be produced by studying glues synthesized by mussels that can attach them to the mineral content of rocks even when submerged in water?[16] Dental bioinspiration seeks answers in nature to restore nature itself when damaged. Thus, it does not focus only on the target element but analyzes beings from other specimens and classes to offer viable repair alternatives. However, like biomimetics, studies should always be initiated by the natural object, which is the focus of the copying process.

3.1 | The enamel

This acellular tissue is the hardest in the human body. Its formulation and formatting are intriguing. Its chemical base is mineral, consisting of approximately 95% calcium phosphate and 5% organic matter, which gives it high resistance to friction, demonstrated through tribology analysis.[17] However, it has little ability to withstand plastic deformation before fracture. So, this is a tissue of low fracture toughness. Toughness is the ability of a material to resist crack propagation. Despite the sigmoid prisms arrangement and the presence of proteins associated with a combination of diversely oriented prims in the interprismatic area, its fracture toughness is about four times lower than that of dentin[18] (Figure 6). Thus, the primary function of this outer layer that covers the tooth is to be a protective barrier to the

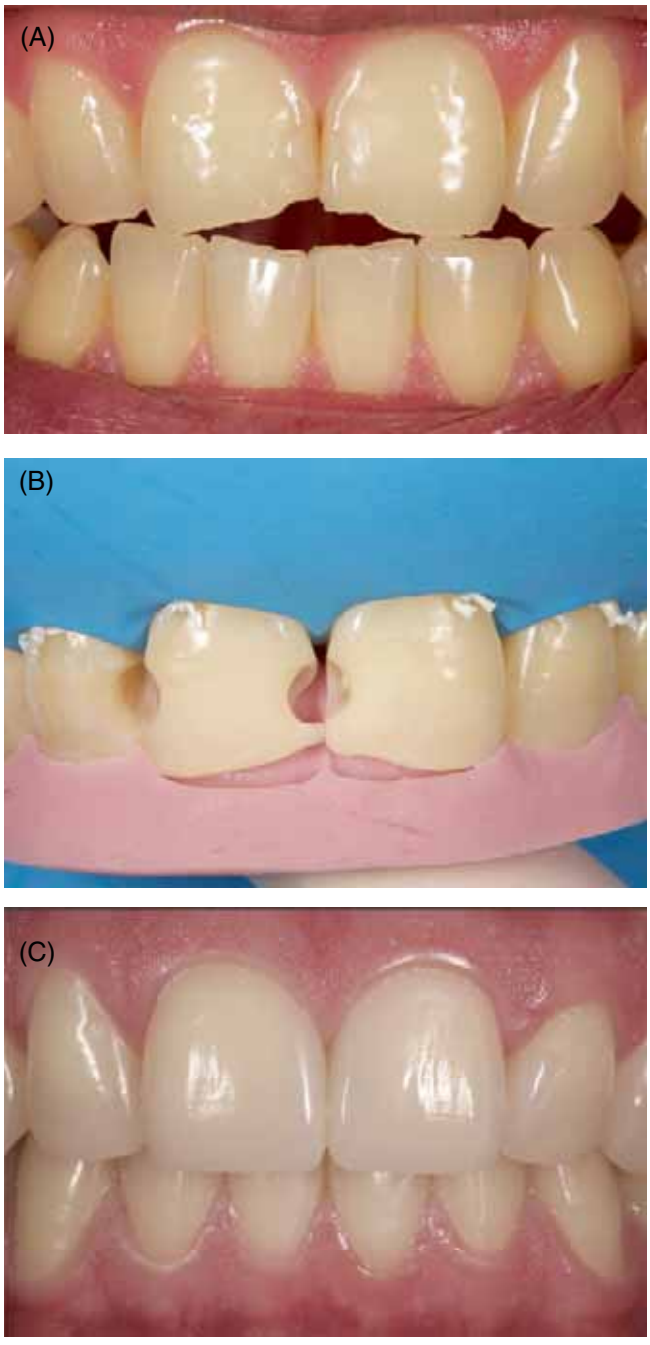

FIGURE 4 (A–C) Monochromatic composite resin restoration showing excellent esthetic results.

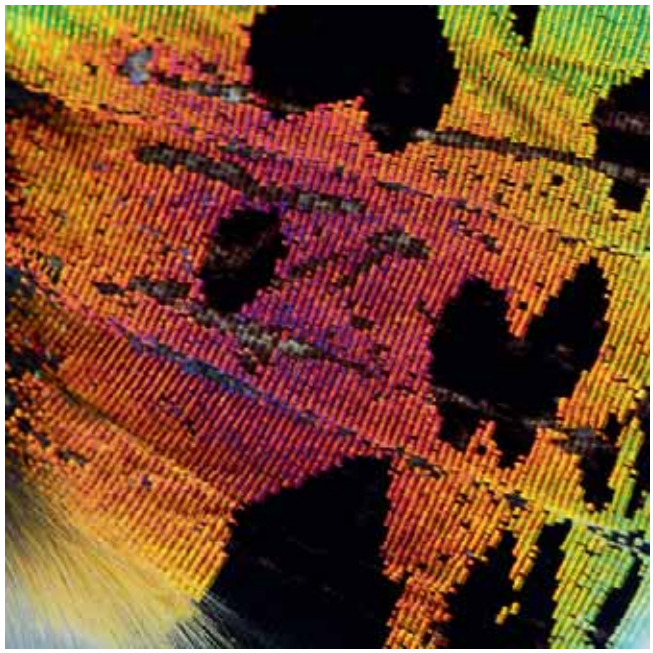

FIGURE 5 Bioinspiration example. Study of the wing of a butterfly to produce lenses and even cosmetics with an unrivaled light dispersion.

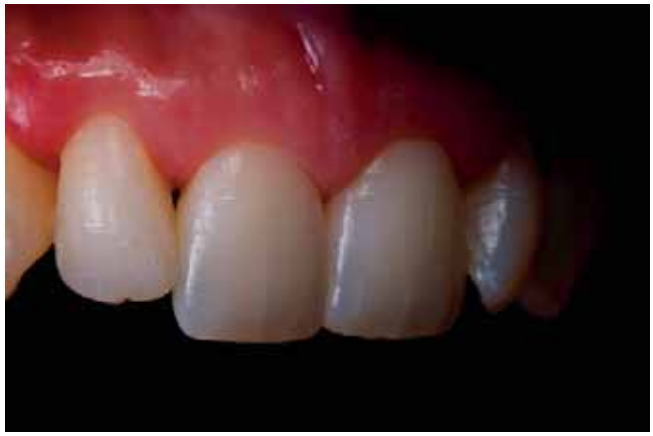

FIGURE 6 Enamel cracks demonstrating its low fracture toughness.

underlying cell layers, allowing masticatory efficiency due to coronal rigidity and protecting the dental organ from wear over a lifetime of occlusal service. The organized morphological aspect of this tissue grants it an anisotropy, not behaving equally depending on the direction of the applied load.

An essential aspect of the optical context of this layer is the molecular weight of hydroxyapatite, which is 502 g/mol with an approximate size of 20–70 nm. Despite being a birefringent structure, its average refractive index is 1.63.[19] The light scattering on this substrate will be of the Rayleigh type.[20] The small size of the mineral molecules that compose it will scatter the light with a wavelength of a bluish appearance. The wavelength of visible light is between 400 and 700 nm. If the size of the particles that make up an object is greater than the wavelength, the light does not decompose into its chromatic components. All wavelengths are equally dispersed, which is why it is seen as white when passing through a cloud. When the components are smaller, the light assumes a predominance of blue. For compositions greater than one-tenth of the wavelength, the scattering described as Mie will occur, where blue is no longer predominant, yellow and red becoming more evident. This physical phenomenon makes it possible to explain the opalescent effect in enamel. The

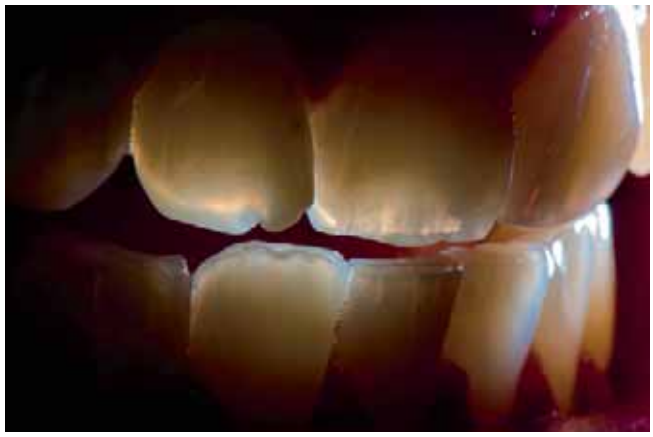

FIGURE 7 Opalescent effect.

FIGURE 9 Dentin yellow color.

incident light demonstrates the blue in this layer. On the other hand, the reflected light will present an orange tone since the blue scattering has already occurred during the passage of light inside the enamel (Figure 7).

3.2 | The dentin

Dentin is the tissue that presents a mixture of organic and inorganic components in a balanced way to promote fracture resistance. About

FIGURE 8 Enamel cracks barred in dentin.

70% of this tissue is of mineral origin (calcium phosphate), and 18% comprises collagen fibrils. This organic material has high resistance to plastic deformation, making dentin approximately 10× more resistant to bending than enamel. This behavior is due to an intriguing network formed by collagen types I, III, and V. Due to this more elastic characteristic, dentin offers high resistance to crack propagation (high fracture toughness).[18] As a result, the cracks formed in the enamel will lose energy as they pass through the junction and reach the dentin (Figure 8). The directional behavior of the load is complex in dentin. The peritubular region presents isotropic behavior, and the orientation of the tubules shows probable isotropy.[21]

The optics of this tissue is related to collagen molecular weight of approximately 300,000 g/mol and size between 180 and 280 nm; the intertwining of fibrils creates collagen networks with sizes in μm. The refractive index is 1.54. In this context, Mie-type scattering will occur, as previously mentioned. This higher molecular weight of the dentin components will not allow the sensation of the blue hue but the visualization of the reddish-yellow hue (brown), which explains the tones of group A of the Vita Classical shade guide as the most frequently found in dentin[22] (Figure 9). It should also be noted that this increased amount of protein creates an effect called fluorescence in this substrate, which is more intense in areas close to the dentin/enamel junction than close to the pulp. With age, the deposition of higher mineral content as secondary and tertiary dentin will decrease this effect[23] (Figures 10 and 11).

4 | BIOINSPIRED ANALYSIS

When the target element (the natural tooth) is studied, it becomes apparent that enamel and dentin are tissues with very different physical (mechanical and optical) behaviors. Despite the similarity in its primordial constitution, dentin resists fracture, presenting a greater optical density and a perception of warmer tones of the visible light spectrum. Enamel, on the other hand, has the function of resisting

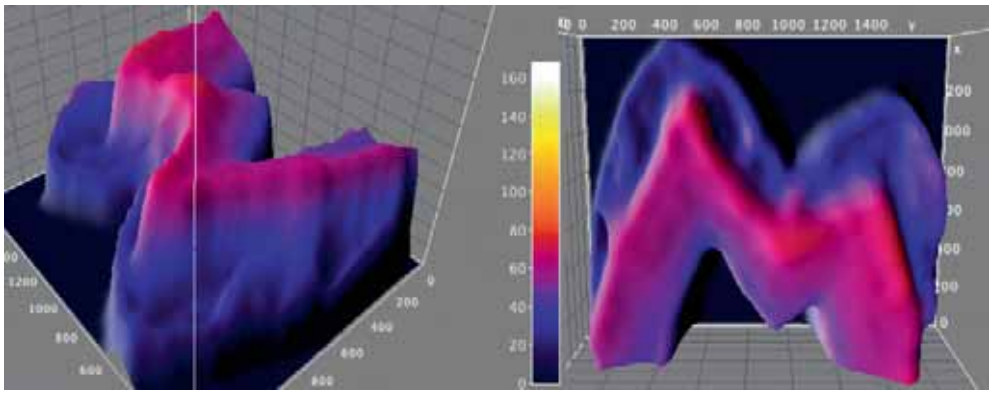

FIGURE 10 Tooth crown fluorescence 3D chart. Note how the effect is more intense from JED to the pulp.

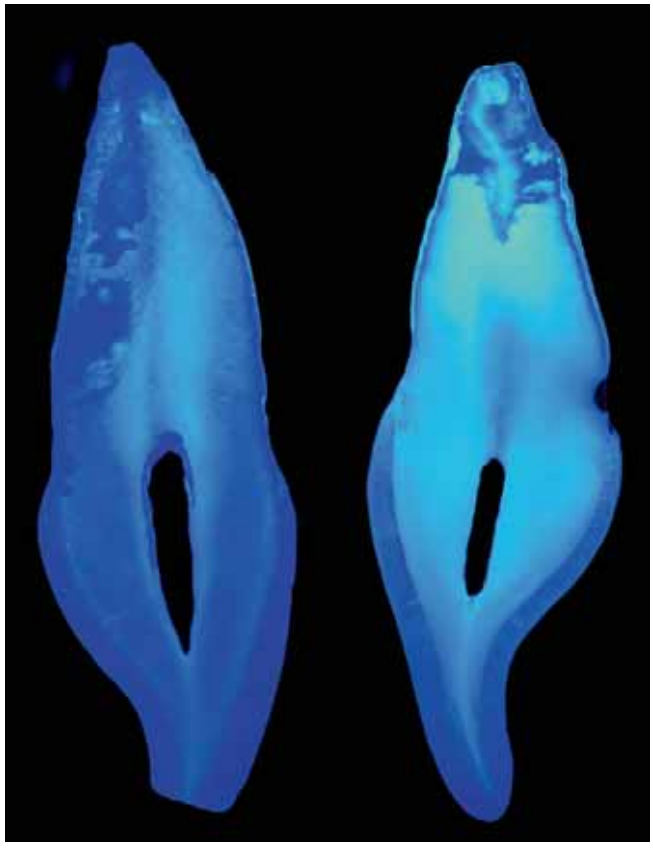

FIGURE 11 Comparison of fluorescence between old (left) and young (right) teeth.

attrition and increasing masticatory efficiency through coronal rigidity, scattering cooler shades of visible color. Within a biomimetic concept, considering the restorative materials currently present in dental practice, resins would be substitutes for dentin, while feldspathic ceramics would be substitutes for enamel. However, despite natural dentin having low wear resistance and natural enamel having low fracture resistance and low toughness, studies of hybrid systems help us to understand that in bioinspiration, an intermediate design model could supply the structural loss of these two materials with only a single restorative material. We have examples of natural bone composites, dentin, and even wood. The latter present specimens with hardness compared to metals depending on the direction and constitution of their fibers. They may also undergo industrial transformations creating materials of very high density and resistance.[24] In this scenario, when dental hybrid composites are processed to balance their organic and inorganic phases, materials can be produced with superior mechanical characteristics. An increase in density can be obtained by balancing different sizes and compositions of the inorganic phase and improving properties and bonds in the organic mesh. Historically, the first composite resins had low abrasive resistance. The modification in the size and composition of the loads provided materials with high resistance to fracture and wear. Studies show composite resins behave like enamel when annual wear rates are verified in vivo.[25]

Moreover, their flexural strength and elasticity bring them closer to the mechanical characteristics of natural dentin. With this, a composite resin can be categorized as a unique replacement for lost tooth structure, fulfilling the mechanical strength role of dentin and the abrasive strength role of enamel. On the other hand, their fragility lies in the potential of longitudinal chemical instability since these materials present a leaching process by hydrolytic degradation in water.[26] However, advances in light curing devices, especially formulations with industrial conversion (prefabricated CAD/CAM blocks), tend to improve the chemical stability of this material.

5 | THE CHOICE OF COMPOSITE RESIN AS A SINGLE SUBSTITUTION MATERIAL FOR LOST NATURAL TISSUE AND ITS MECHANICAL AND OPTICAL INTERACTIONS

5.1 | Mechanics

Even though composite resins have very similar base formulations, their mechanical behavior can vary dramatically depending on brand names due to the different uses of filler particles. This approach is so impactful that the current ranking factor for resins is particle size.[27] Two factors must be considered in this analysis. (1) Particles at the nanometer scale present an industrial deficiency in the silanization process, compromising the mechanical properties of these materials. For this reason, fillers smaller than 50 nm were grouped into clusters patented for a specific brand of resin (Figure 12) (Filtek Supreme

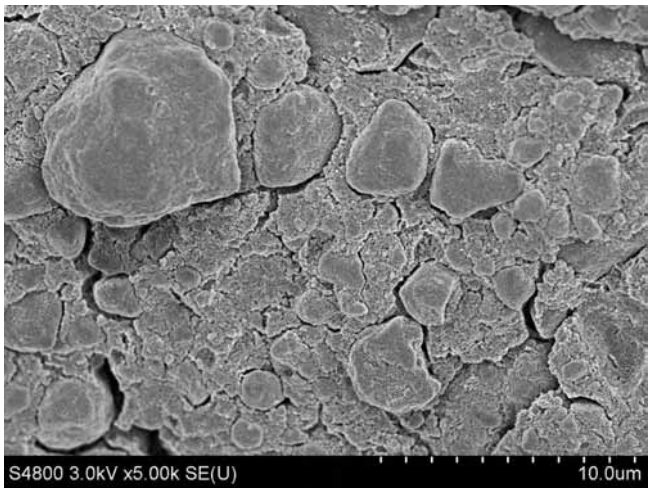

FIGURE 12 SEM of a nanofill clustered composite resin. Courtesy: Marcos Vargas.

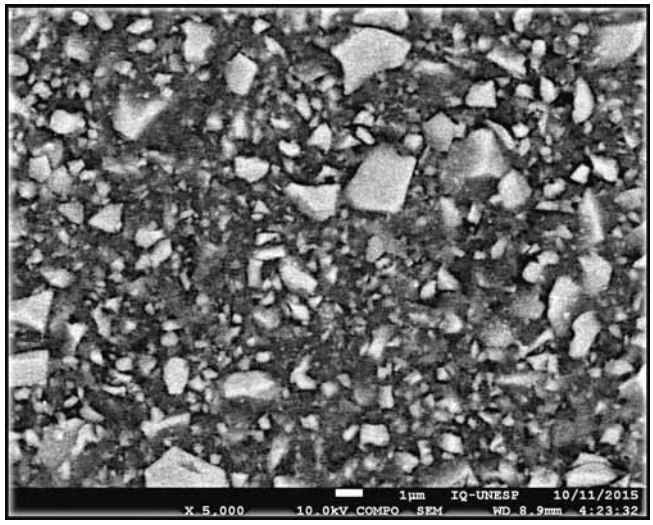

FIGURE 13 SEM of a nanohybrid composite resin.

Ultra, 3 M, Minnesota, USA). (2) Large particles considerably increase the fracture resistance but reduce the wear resistance, the polish, and, to a lesser degree, the flexural strength, which could be improved by increasing the small particle content of the organic phase.[28] Therefore, as the portion that will reconstitute dentin and enamel has different individual characteristics, it would be more logical to choose materials with different constitutions for each layer. The innermost portion of a resin buildup represents the structural reinforcement designated by natural dentin. In this constitutive layer of the restorative core, resins with high mechanical properties, especially fracture toughness, should be chosen. On the other hand, the outer layers need a smoothness provided by polishing, avoiding increased biofilm retention, improving chromatic stability, and high wear resistance.

5.2 | Optics

Following the principles of light scattering in natural teeth, the dentin layer has higher density and, therefore, Mie-type scattering, emphasizing reddish-yellow hues.[20] Thus, most studies analyzing the natural color of dentin indicate a high predominance of the hue of Group A on the Vita shade designation, as mentioned above. This phenomenon occurs when light is scattered in particles larger than 450 nm, increasing the chromatic effect of longer wavelength colors. However, particles with sizes within the visible light spectrum must be present for light decomposition in the material to occur. By this analysis, resins with characteristics suitable for dentin should contain particles ranging from nanometer to micrometer scale, with a predominance of medium-sized than micro or nanoparticles (Figure 13). This concentration will give the dentin layer a higher optical density, making it more opaque. This phenomenon happens in the natural model. However, it suffers variations according to a greater or lesser degree of dentin mineralization in the different areas of the crown and aging. Thus, the dentin will become more opaque from the cervical to the incisal third and from the outermost area to the area closest to the pulp (Figure 14A,B). With aging and increasing mineralization of the dentin structure,[29] fluorescence and opacity will decrease due to protein loss,

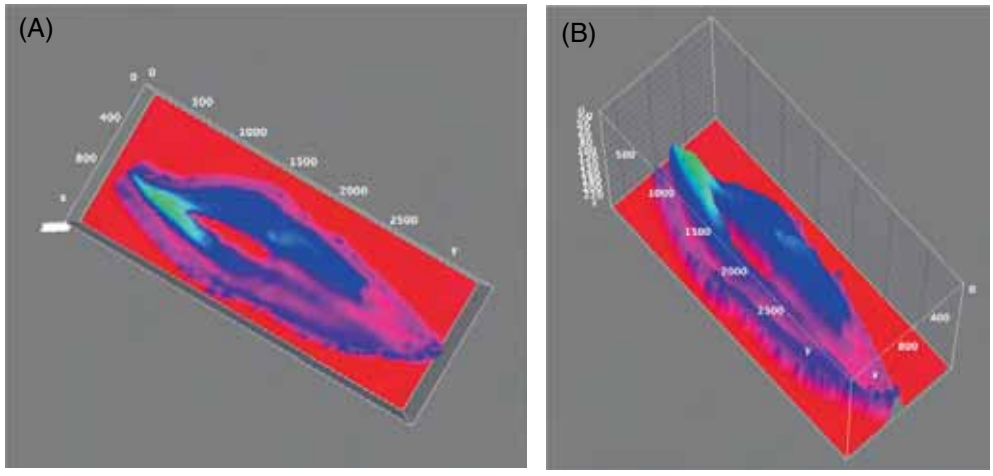

FIGURE 14 (A and B) Tooth crown opacity 3D chart. Green area is the most opaque part, follow by blue tones (medium opaque) and pink (transluscent area).

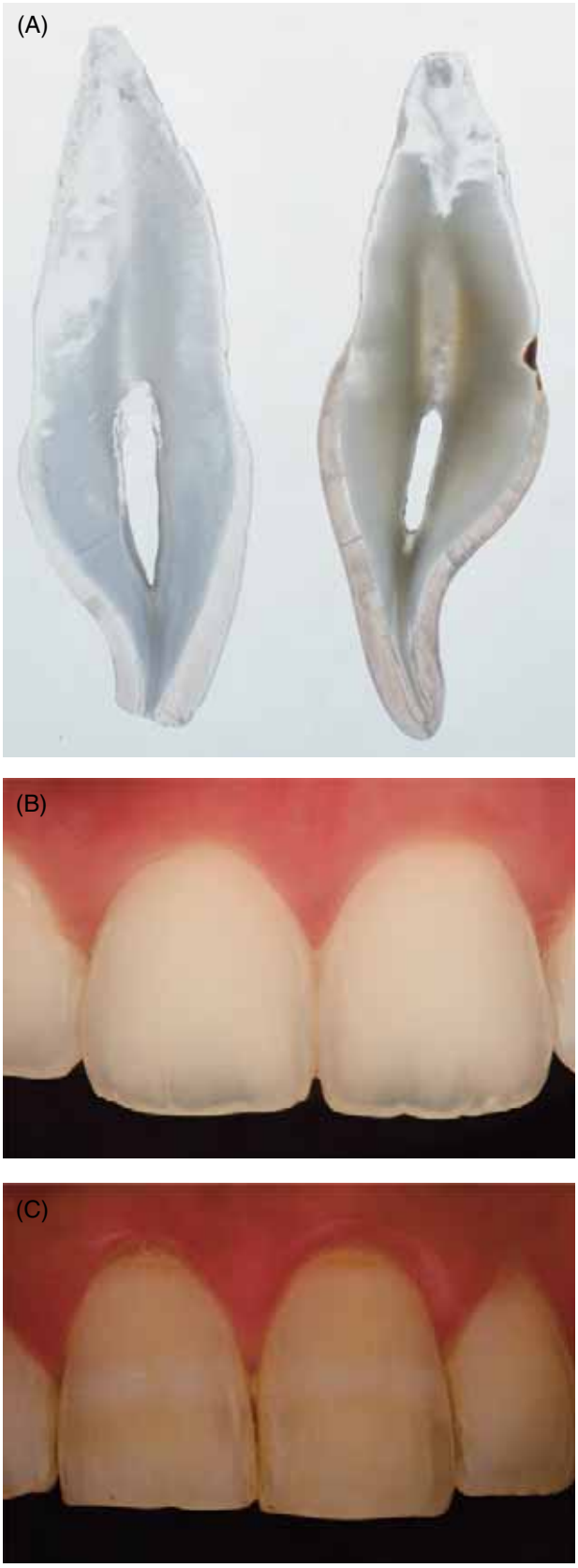

FIGURE 15 Comparison of opacity by age. (A) Extracted teeth (photographed with transmitted light) of older adult (left) and young (right). The older tooth is more translucent. Young and aged teeth show distinct opacity/translucency levels. (B) The young tooth is brighter. (C) The older tooth lost the luminosity.

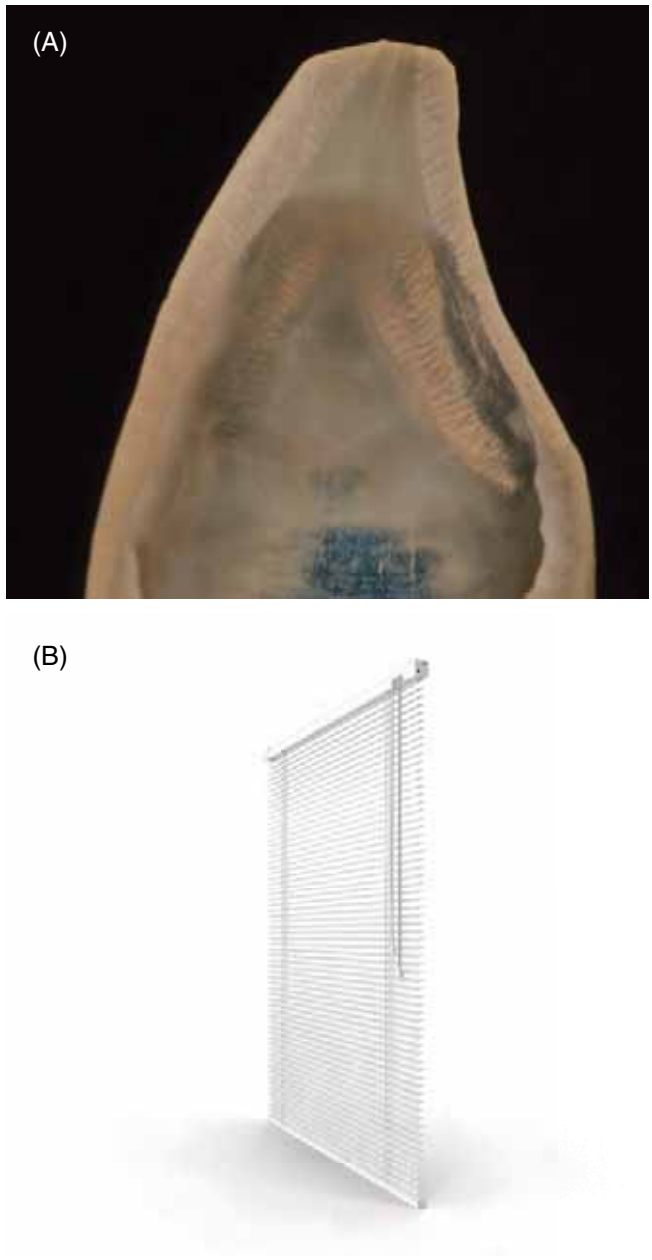

FIGURE 16 (A and B) Images demonstrating the translucent and opaque enamel lamellae and the blind analogy.

making the aged tooth more translucent in the dentin layer. It will also become less reflective of visible light, generating a grayish appearance of low luminosity (Figure 15A–C).

When the enamel is analyzed, a curious situation can be noticed. Enamel is not a translucent material as commonly advocated by clinicians. Instead, it presents an organized arrangement of opaque and highly translucent lamellae in horizontal layers to the crown—when viewed from a facial perspective—compared analogously to a partially open blind. Therefore, the enamel will function as an optical fiber in the hypermineralized prismatic lines capturing the color of the dentin underneath. In addition, the enamel will have a highly opaque behavior in the protein-rich interprismatic areas (Figure 16A,B). If this were not, the tooth would seem bluish even in the face of warmer dentin

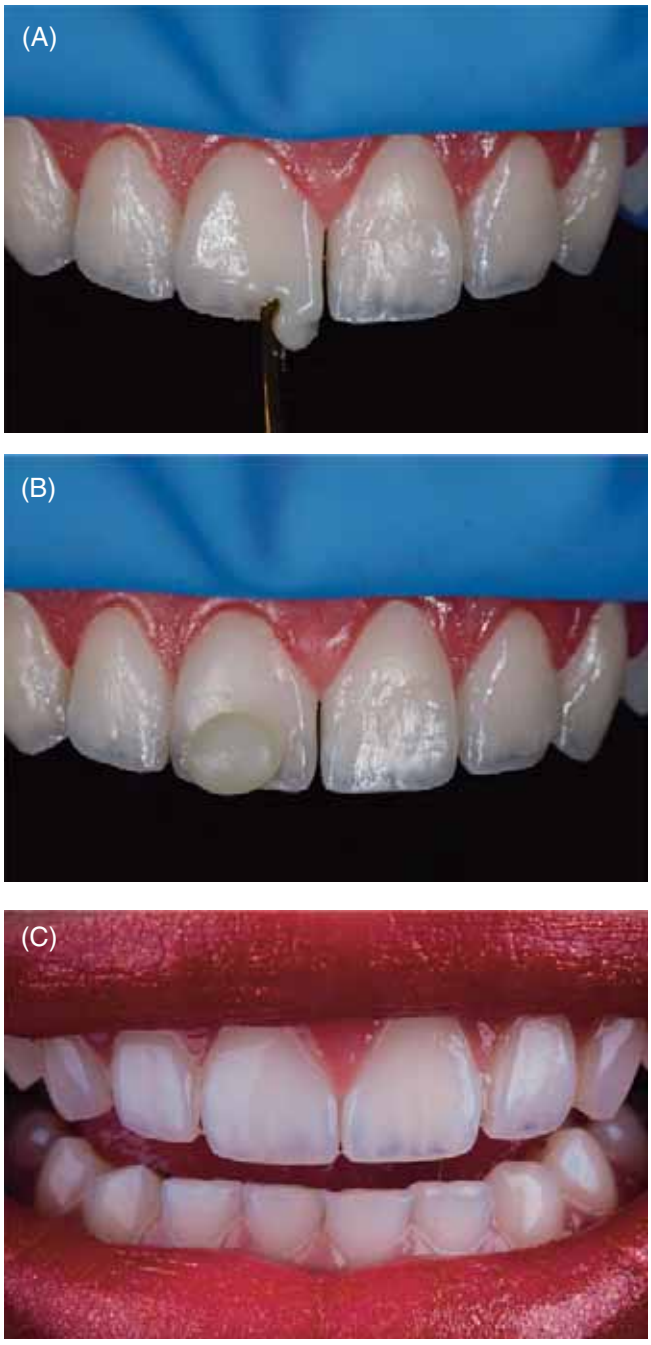

FIGURE 17 (A–C) Cutback being performed and a value-modifying achromatic composite resin layer applied. Post-operatory result.

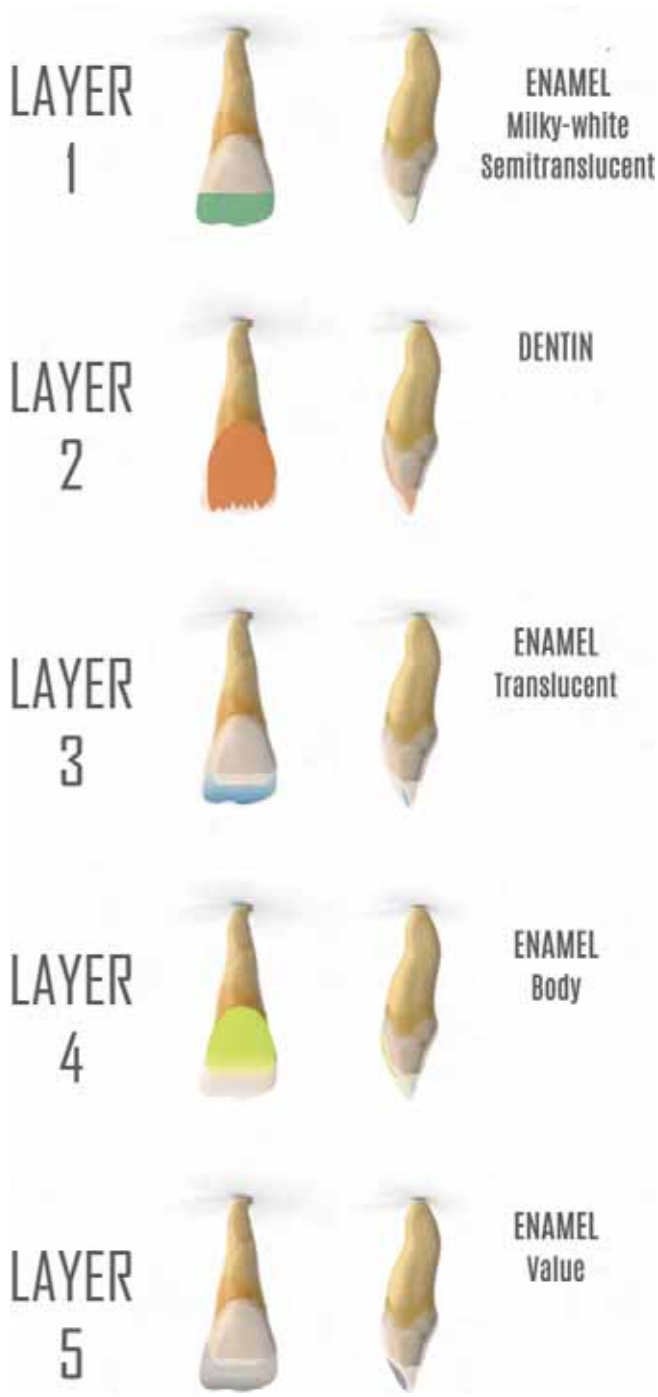

FIGURE 18 Layering diagram in the polychromatic layering technique.

colors. This constitution explains the enhanced light reflection in young patients due to the thicker layer of this tissue. Abrasion and attrition decrease this characteristic with age, making the enamel more translucent overall and exacerbating the teeth' low luminosity with aging. Another essential factor is that composite resins cannot perfectly reproduce this unique characteristic because the material does not present an organized distribution of phases. The latter is one of the factors that most corroborates the naturalness of the polychromatic technique compared to other techniques described in the literature. A single layer of enamel with only one opacity will only be able to reproduce some of the nuances of opacity and translucency visible along the crown. Therefore, enamel shades of higher opacity, that is, higher value, should be used in the middle third area, giving high luminosity to this region, especially in young patients. However, a cutback and the use of enamel shades that reproduce the optical aspect produced by the junction of the buccal and palatal translucent lamellae will provide adequate luminosity and a natural appearance to

the restoration (Figure 17A–C). For this purpose, inner opalescent and external resin masses of varying opacities are recommended.

6 | SELECTION OF COMPOSITE RESIN BRANDS FOR THE DIFFERENT AREAS OF THE POLYCHROMATIC TECHNIQUE

Initially described by one of the authors of this article, the polychromatic layering technique (PLT) is based on the rationally organized distribution of five layers that reproduce the optical characteristics of the natural tooth. The conceptual diagramming of the arrangement of the layers by the polychromatic technique is represented in Figure 18.

7 | LAYERS IN THE POLYCHROMATIC TECHNIQUE

Layer 1: In this palatal/lingual layer, the resin must elicit high abrasion/attrition resistance, as it is the path for anterior and canine guidance. High fracture toughness is also required, significantly increasing the resistance of this area to functional loads. As it is a region that challenges the reproduction of natural enamel, the material must have a milky-white semitranslucent characteristic. The milky-white halo along the incisal edge and the bluish opalescent halo internally to it can be achieved by adjusting the thickness of this milky-white semitranslucent layer to allow optical changes. The choice should fall on micro-hybrid and nano-hybrid materials whose particle size composition encompasses nanometric and micrometric scales. The significant filler size variation will allow the correct scattering of light and dispersion into blue wavelengths when these types of particles are present. Thus, variations between 20 and 180 nm (blue effect) and particles within the visible light spectrum will favor natural optics, high fracture toughness, and abrasive resistance.

Layer 2: This is the core layer, the most important for the fracture resistance of the tooth/restoration compound. Because it is an inner layer, fracture toughness is far more critical than wear resistance. This layer defines the primary hue and chroma of the tooth. One chroma more saturated than the desired final shade should be chosen for the cervical and middle third. The most prevalent hue for this dentin layer is A in the VITA Classical shade guide. The opacity should block the mouth's dark background and allow for proper mamelon design and morphology. In this zone, classic microhybrids and larger-particle nanohybrids, predominant in their composition, will generate a high resistance and a Mie-type dispersion, providing a reddish-yellow hue.

Layer 3: This layer fills the depressions in-between, around, and over the mamelons and has little influence on the final strength due to its small quantity. However, it significantly contributes to the occurrence of opalescence. The beauty of incisal layering depends on this layer. A correct opalescence allows a through-and-through transmission of light, like the natural enamel's translucent lamellae, accentuating the Rayleigh type's blue dispersion. For accentuated Rayleigh scattering, the material must have nanometric particles and particles that promote light scattering (between 180 and 700 nm). Its refraction in the organic matrix stands differently than in the inorganic phase. High translucency nanocluster and hybrid resins produce the best results for this area.

Layer 4: This layer must be resistant to abrasion due to the sliding of food during cutting and hygiene techniques through brushing. The area of the cervical and middle third primarily covered by this layer will define the final color of the tooth. In this zone, the sum of the dentin and the thickness of the enamel, with its opaque and translucent lamellae acting as an optical fiber bringing the dentin color, will generate the zone of higher light reflection in the crown. In order to achieve high wear resistance and

TABLE 1 List of commercially available composite resin brands categorized according to filler and colorimetric characteristics.

Layers	Composite classification	Color characteristics	Brands
1	Nanohybrids (medium and large fillers)	Achromatic, translucent, milky	Vita-l-escence PF; Estelite Posterior PCE; Forma Incisal or WE; Miris 2 NR; Inspiro Skin Neutral SN; Renamel Nano Incisal Light; Venus diamond I; Essentia LE; Gradia Direct NT or WT; Filtek Supreme WE
2	Microhybrids or Nanohybrids (large fillers)	O, Opaque, Dentin, D	GrandioSO O colors; Enamel HRI UD colors; Herculite XRV D colors; Vita-l-escence Vita colors; Empress Direct D colors; Inspiro I colors; Renamel Microhybrid Vita colors; Miris S colors.
3	Nanohybrids (micro fillers)	Colors with high translucency and effects	Filtek Supreme GT; Harmonize Incisal Blue; Essentia OM; Vita-l-escence IrB; HRi OBN
4	Nano, micro or nanohybrids (micro fillers)	Body colors or semi-opaque enamels	Renamel microfill Vita colors; Estelite Sigma O colors; Estelite Omega E colors; Harmonize E colors; Herculite Ultra E colors
5	Nano, micro or nanohybrids (micro fillers)	Achromatic (incisal)	Renamel microfill IM; Estelite Sigma CE; Harmonize Clear; Herculite Ultra Incisal; Filtek Supreme CT

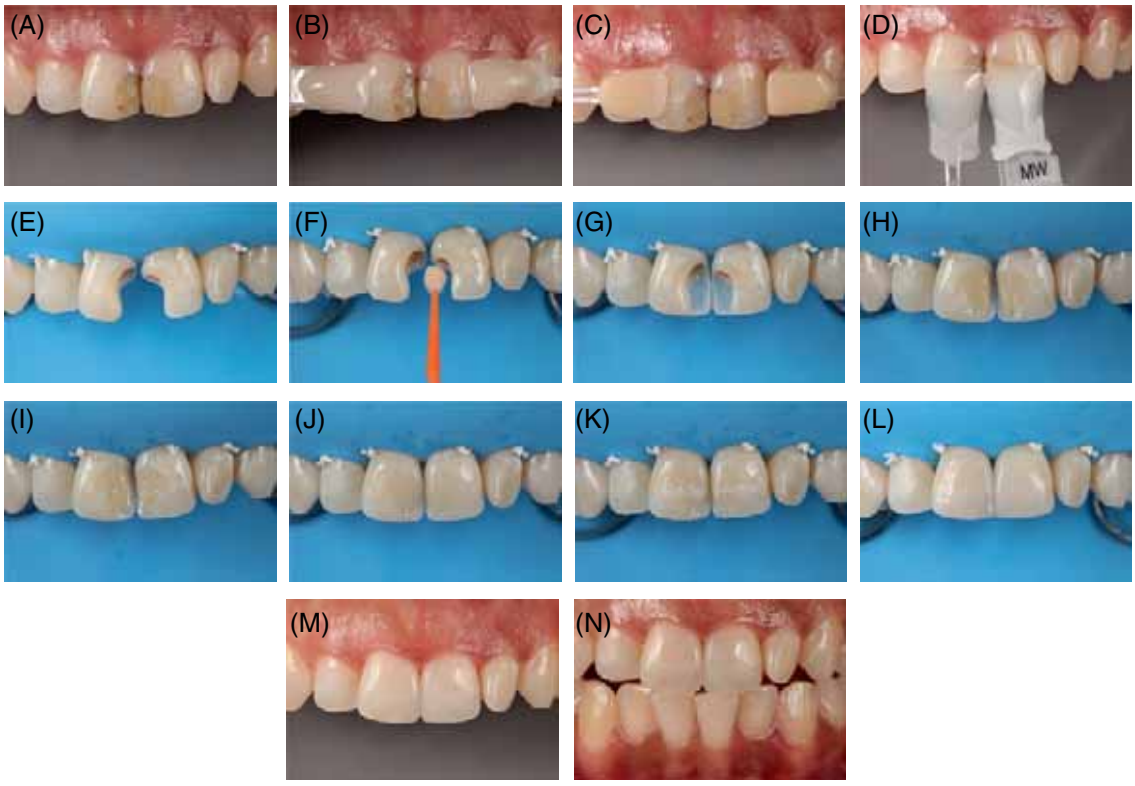

FIGURE 19 A step-by-step clinical case demonstrating the polychromatic layering technique for Class IV restorations. As part of a clinical trial, brands of similar properties were used for each layer on each central incisor. No differences can be perceived between the two restorations in the result. (A) Pre-operative condition. (B–D) Dentin and enamel shades are selected according to their distinct properties. (E) Bevel. (F) Adhesive protocol. (G) Palatal shell with a milky-white semitranslucent composite. (H) Dentin layer. (I) Translucent enamel (opalescent effect). (J) Body (chromatic) enamel. (K) White effect enamel. (L) Value (achromatic) enamel. (M and N) Follow-up after rehydration.

polishability, nanofilled and especially microfilled composites must be used. Nanohybrids with a predominance of nano and microparticles are also indicated. These materials must contain chromatic characteristics that will act synergistically with the opacity of the dentin. Thus, VITA-based resins of higher opacity designated by the manufacturer as "body" or natural translucency enamels will be essential allies in masking transition lines, especially in Class III and IV restorations.

Layer 5: This final layer aims to emphasize or modulate the effects obtained in the underlying layers. It must present high polishability and wear resistance like the previous layer. In addition, this resin must have a noticeable opalescent effect that increases significantly with thickness. Frequently, there is a decrease in luminosity compatible with the naturalness of the incisal third. In young teeth, the opposite may occur due to histological changes in the enamel. The same category of materials should be preferred as the previous layer (nanofills, microfills, or small particle nanohybrids) to avoid "islands" with different degrees of polishing in the final buccal layer. However, concerning translucency, they must be achromatic (non-VITA based) to only generate chromatic expressions by effect and not by pigments.

For the longevity of the restoration, the right choice of material in each of these five regions is paramount. To that effect, an analysis of the mechanical properties of the composite resins must be carried out to ensure a long-lasting functional behavior. Below is the indication of each brand according to the current literature and the authors' research and clinical experience regarding the characteristics of each material available on the market (Table 1).

The polychromatic technique predictably restores the anterior dentition seamlessly, provided the composite resins are selected according to their optimal mechanical and optical properties, and a methodical restorative protocol is followed. However, choosing the optimal shades for each layer from among the available brands may be challenging, especially when the clinician needs to gain hands-on familiarity with the vast array of commercial possibilities. Therefore, the authors recommend keeping a select combination of shades that clinicians can repeatedly master in their day-to-day challenges. Once the fundamental concepts of bioinspired protocols are fully mastered, combining different brands in a single case will no longer be a challenge and thus can provide esthetic results of high magnitude (Figure 19A–N).

8 | CONCLUSION

After the bio-inspired analysis, using nature as a model to be understood and followed, it is possible to note how the

polychromatic technique remains current and viable in mimicking nature, providing esthetic and natural results in the layering of composite resins.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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How to cite this article: Ricci WA, Fahl N Jr.. Nature-mimicking layering with composite resins through a bio-inspired analysis: 25 years of the polychromatic technique. *J Esthet Restor Dent*. 2023;35(1):7-18. doi:10.1111/jerd.13021

Received: 27 November 2022 | Revised: 27 December 2022 | Accepted: 28 December 2022

DOI: 10.1111/jerd.13019

CLINICAL ARTICLE

WILEY

A practical, predictable, and reliable method to select shades for direct resin composite restorations

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Abstract

Objective: This article describes a practical, predictable, and reliable method to select shades for direct composite restorations using custom shade guides made of resin composite at hand using a process of elimination

Clinical Considerations: Esthetics in direct resin composite restorations depends on the clinician's ability to reproduce the shape and shade of natural teeth, thus appropriate shade selection is a must. This method presented in this article simplifies the process of shade selection for direct resin composite restorations. The use of custom shades tabs made of commecially available resin composites, its arrangment and a process of elimination of tabs during shade selection allows the practitioner to obtain the best possible resin composite shade available for every case.

Conclusions: The use of custom shade guide tabs and an elimination protocol facilitates and expedites the process of shade selection for direct resin composites

Clinical Significance: The article presents a practical, predictable, and reliable method to select shades for direct resin composite restorations for daily practice.

KEYWORDS
dentin, enamel, resin composite, shade guide, shade selection

1 | INTRODUCTION

Direct resin composite restorations represent one of the most popular techniques for achieving functional and esthetic dental restorations.[1,2] Composite restorations are biocompatible, fully replace function and esthetics, while providing service for several years.[3,4] An esthetic direct resin composite is a restoration that replaces tooth structure, dentin and enamel, and blends into the surrounding tooth structure, making the restoration imperceptible.[5–7] This blending occurs through; adequate shade, contour, texture, and luster of the restoration.[2] However, several aspects of the restorative workflow including shade selection, material opacity selection, cavity preparation, layering technique, placement, contouring and polishing, influence the final outcome, of achievement of an imperceptible restoration.[2]

Tooth shade is the result of light interacting with dentin and enamel. Dentin is higher in opacity, chroma and value than enamel.[8] When light reaches the tooth, some light reflects on the tooth surface, while some light enters the tooth. Enamel and dentin will then either reflect, scatter, diffuse, and/or absorb light.[9]

Shade selection had been considered tedious, time consuming and unpredictable, frequently resulting in restoration mismatches, leaving both the dental professional and patient frustrated and dissatisfied.[10] Furthermore, when layering resin composites, replacing enamel with "enamel like" materials and dentin with "dentin like" materials, the procedure becomes highly challenging for the clinician.[10,11] Once the restoration is light cured, light dynamics plays an important role in assessing if the dentist was able to mimic the properties of natural teeth.[12] When light penetrates composite restorations, it can be reflected, absorbed, refracted, or diffused just like it does for natural tooth structure. Thus, the esthetic outcome is directly related to the optical interaction of light with the different layers of the resin composite restoration and tissues that compose the dental complex.[13]

The final esthetic integration will depend on the dentist's knowledge and ability to understand how to select the optimal shade and how to use the restorative material.[12]

In addition, because resin composite materials are not completely opaque and allow transmission of light, the authors recommend having a scalloped, infinite bevel over the facial surface to blend this "non-perfect" matched composite resin shade over the tooth structure, which will result in an imperceptible resin composite restoration.

In addition, different factors can affect the accuracy and precision of the shade selection method. Fatigue, aging, color blindness, emotional status of the clinician selecting the shade, the environment, the quality of the light, the method, the shade guide, the tooth to be restored, the restorative material, whether for direct or indirect restorations, have been cited to influence shade selection.[10,14]

Considering the need to achieve accuracy of shade selection, the purpose of this article is to describe a fast, practical, predictable, and reliable method to select shades for direct resin composites.

2 | SHADE SELECTION

Shade selection depends on the interaction of three factors that can influence the perception of color: light source, the dental structure, and the observer.[10,14–16]

Several terminologies have been used for the process of obtaining the shade to be used in the restorative procedure such as, shade selection, shade determination, and shade match. When using resin composite to restore teeth the process is known as shade selection.[7] Several shade selection methods and guides have been used to determine the shade for resin composites. In addition, intraoral electronic devices like Vita Easyshade (Vita Zahnfabrik, Bad Säckingen, Germany) or ShadeEye NCC Chroma Meter (Shofu Dental, Menlo Park, CA, USA); are available for shade determination, but they are applicable to shade measurement for monitoring whitening progress, for indirect restorations and laboratory communication. However, in the opinion of the authors these intraoral electronic devices are of minimal value for direct restorations.

3 | FACTORS AFFECTING SHADE SELECTION

In the process of shade selection, the following conditions need to be met to ensure the best possible outcome:

1. Environment control: This refers to the environment encountered in a dental office. It is recommended that the shade of the room has a neutral color, bright colors of patients' clothing should be covered and lipstick removed.[16]
2. Good quality light: The ideal light source for dental shade matching has a color temperature of 5500°K (Kelvin degrees).[10]
3. Good quantity of light: It refers to the amount of light in the dental shade match environment. Clinicians need to make sure there is enough amount of quality light in the room.[14]

FIGURE 1 Vita classical shade guide.

4. Clean teeth: Clinicians need to remove extrinsic stains, if present, from the tooth to be restored and adjacent teeth. The stains might interfere and/or modify the final shade outcome of the restoration.[17]
5. Dehydration prevention: The teeth need to be kept moist during the procedure, because dehydration sets in fairly fast which decreases translucency and chroma, and, increases value and opacity.[15]
6. Time: Cones are photoreceptors in the retina that are responsible for color vision as well as color sensitivity of the eye. These cells lose their ability to discern color rapidly if used for longer continuous period of time. Thus, clinicians are advised to be brief during shade matching and rest their eyes frequently to reinvigorate these cell to differentiate color.[14]

4 | SHADE GUIDES

Shades guides differ from brand, material, shape, fabrication type, and concept have been used over the years. In 1956, the first commercial dental shade guide was launched, named the VITA Lumin Vacuum (Vita Zahnfabrik, Bad Säckingen, Germany). This shade guide has evolved into the current Vitapan Classical shade guide (Vita Zahnfabrik, Germany), which is the most commonly shade guide used today for shade selection.[18–20]

It has been shown that although commercially available shade guides can be of great value for shade selection, these do not correlate well with either, the color of human teeth[21] or the shade of the resin composite.[22]

Most dental manufacturers of resin composite attempt to match the Vitapan Classical shade guide (Figure 1). Unfortunately, this guide is made of ceramic and each individual shade tab is an array of shades and opacities. This can be clearly noticed when covering the different parts of the shade guide (Figure 2). Based on this, it is easy to assume that resin composite manufacturers may try to imitate different areas of the shade guide, resulting in shade differences between resin composite brands[22,23] (Figure 3). Furthermore, it has been shown that there are differences between the same shade in different tabs[24–26] (Figure 4). Based on those limitations, the Vitapan

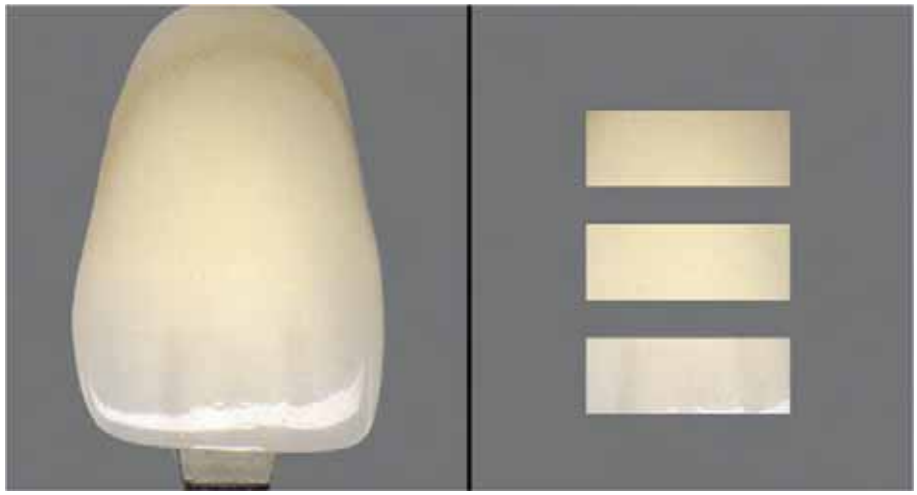

FIGURE 2 Vita classical shade tab showing an array of shades and opacities.

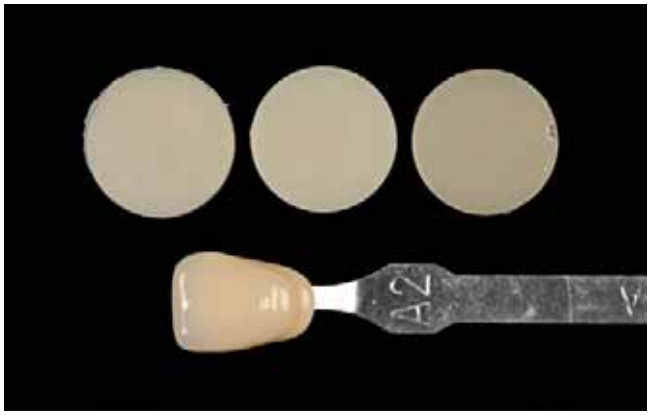

FIGURE 3 Shade A2 from several dental manufacturers showing different colors.

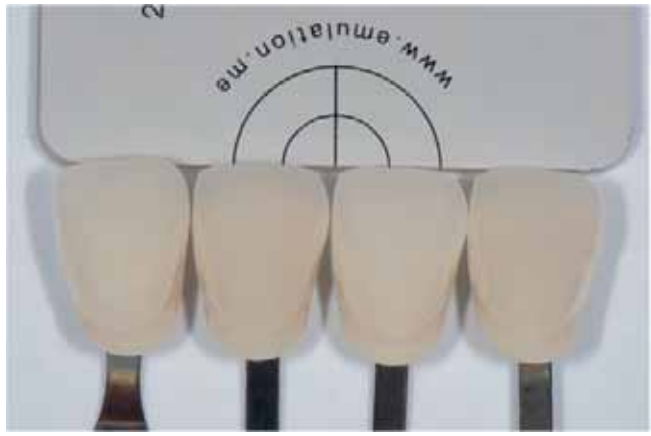

FIGURE 4 Several A1 Vitapan Classical shade guides showing different shades w polarizing light.

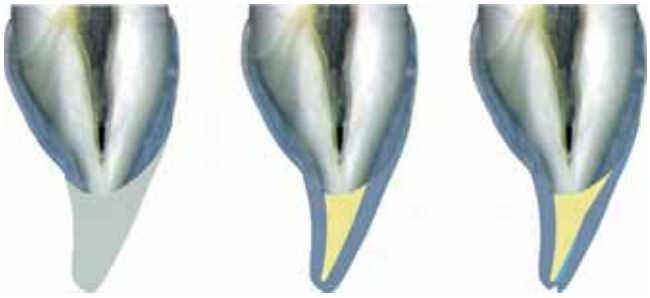

FIGURE 5 Different layering techniques according to the desired effect.

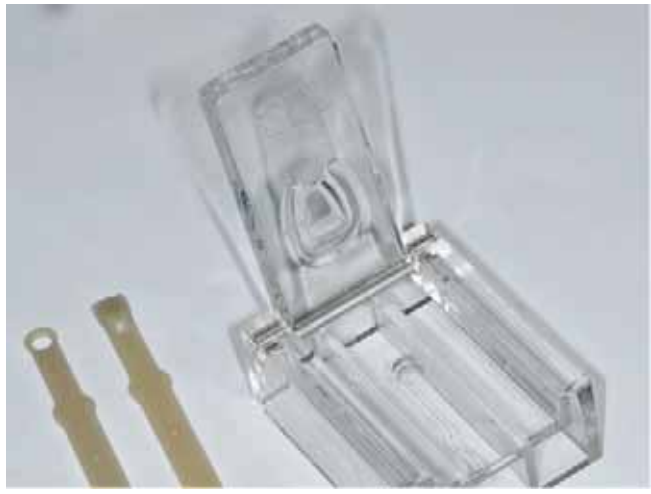

FIGURE 6 A jig can be used to fabricate shade guides, Shade Maker, 3M China.

Classical shade guide (Vita Zahnfabrik, Germany) cannot be used to accurately select the shade for resin composite restorations.

Some composite manufacturers also fabricate their own shade guides to closely resemble the shade of their materials. However, the majority are made up of plastic and not of resin composites.

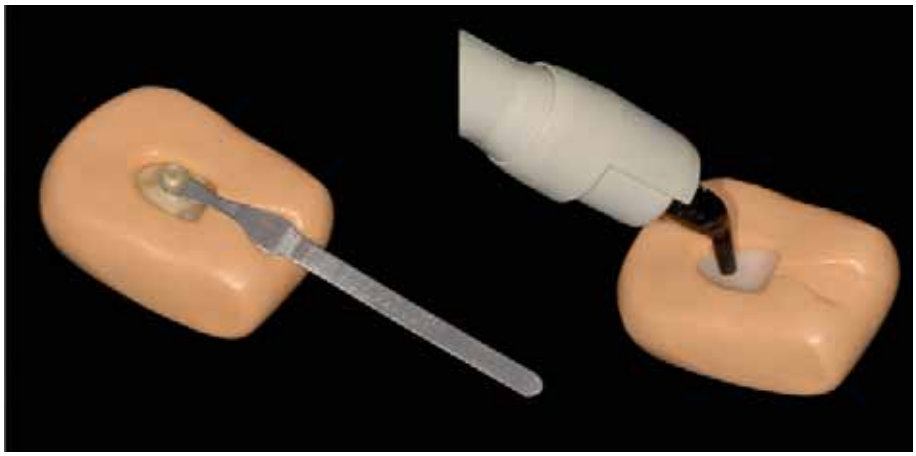

FIGURE 7 An impression of a shade tab is made and used to fabricate custom shade guides.

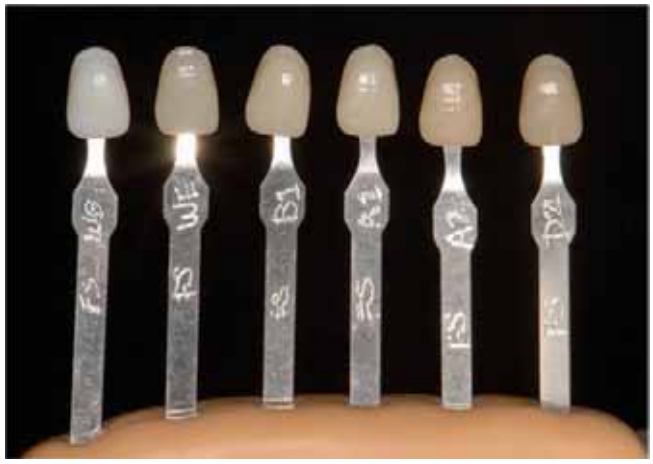

FIGURE 8 Custom shade tabs made of resin composite resin arrange from light to dark.

FIGURE 9 The Vitapan Classical shade guide arrange by perceived "Value."

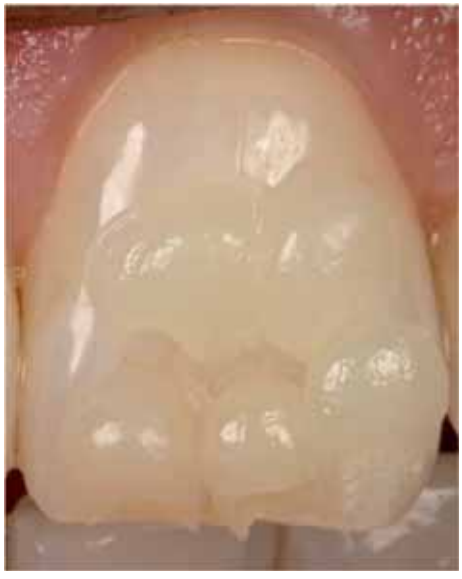

FIGURE 10 Small increments of various resin composite shades over the tooth.

Moreover, some manufacturers fabricate materials of various opacities to resemble enamel, dentin and more translucent materials for special effects, this creates a problem because the thickness of these shade tabs are not clinically relevant, making it almost impossible for the practitioner to use them for shade selection. A small group of manufacturers (i.e., Mosaic, Ultradent Products Inc, South Jordan, UT) provide or sell shade tab makers (i.e., Estelite Omega, Tokuyama Corporation, Yamaguchi, Japan) or molds that can be single shade or layered at clinically relevant thicknesses that makes shade selection easier.

The authors have been reliably using custom made shade guides fabricated from the resin composite they use. These can be made from single intermediate opacity materials for monochromatic restorations, that is, body, universal, or layered, that is, "enamel" over "dentin," with clinically relevant increment thicknesses to facilitate shade selection. Single monochromatic custom tabs are used when single opacity, single shade, materials are going to be used. Dual or layered tabs are used when the tooth requires a more elaborate layering technique to replicate esthetic nuances, like gradient of color, or halo and translucency effects. (Figure 5).

TABLE 1 Factors affecting shade selection

• Environment control: Remove lipstick and cover bright clothing.
• Good illumination: Enough amount of light (150–200 lighcandles).
• Quality of light: Illumination around 5500°K.
• Clean teeth: Plaque and biofilm free.
• Dehydration prevention.
• Being brief: Ability of the human eye to perceive color differences 3–5 s.

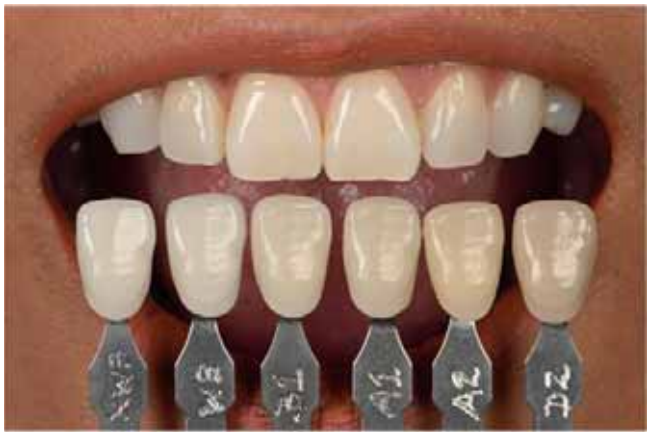

FIGURE 11 Initial pass of the custom shade guide.

FIGURE 13 Second elimination of tabs with the least close shades.

5 | FABRICATION OF A CUSTOM SHADE GUIDE

The process of fabricating custom shade tabs is relatively simple. A kit (i.e., 3M Shade Maker, 3M China Ltd., Shangai, China) can be bought to make custom shade guides (Figure 6), or an impression of a shade tab or a denture tooth is made in heavy body PVS material (Figure 7). After the PVS material sets, the shade tab is removed and filled with the resin composite material and polymerized

FIGURE 12 First elimination of tabs with the least close shades.

FIGURE 14 Third elimination of tabs with the least close shades.

according to manufacturer's instructions. The new made shade tab is then polished and glued to a metal or plastic tab. An old shade tab holder can also be used for this purpose. These custom shade tabs can then be labeled with the shade and brand of the resin composite used for identification purposes (Figure 8). The process of fabricating layered tabs requires the use of prefabricated molds (i.e., My Shade Guide, Smile Line, Switzerland) to be able to predictably have a consistent and clinically relevant layer of "enamel" over "dentin" materials.

These custom shades tabs should be arranged from perceived light to dark (Figure 8). An example of the Vitapan Classical shade guide arranged by perceived light to dark "value" can be seen in Figure 9. This facilitates the selection process because it places closest color shade tabs based on "Value" in close proximity of each other.

Another popular and effective method is to place small increments of various resin composite shades over the tooth to be restored to select the resin composite shade (Figure 10). This method can be time consuming because the thickness of the increments difficult to control, it does not represent layering, and the risk of dehydration setting in, as well as resulting in increased material cost. In the opinion of

FIGURE 15 Selection of the best match tab.

the authors this method is not fast, reliable, or efficient in day-to-day clinical practice.

6 | THE METHOD

Considering previously mentioned factors that affect shade selection (Table 1) and using a custom shade guide of the resin composite (Figure 8) we will proceed to select the most appropriate shade. The authors are not looking for a perfect match between the tooth color and the shade tab color, but for the closest possible match because in the authors experience it is very rare to find a perfect color match between resin composite and natural tooth.

The proposed method relies on a process of elimination, or the Roman principle of "divide to conquer." It methodically and systematically removes the shade tabs with most disagreement first. The shade tabs are compared with the middle third of the tooth to be restored. An initial pass of the custom shade guide next to the tooth to be restored is performed (Figure 11). Based on this pass, the clinician needs to eliminate the tabs with the least close shades (Figures 12 and 13). It is important to note that one is not selecting their impression of the best shade match, but rather eliminating the least likely matches. This process of elimination is repeated two or three times until one tab remains (Figure 14). Each pass of the shade guide should not exceed 4–5 s, to prevent possible error from eye fatigue. The remaining tab after the elimination process is the closest match. This will be the shade of resin composite to be used to restore the tooth.

Clinically, the shade guide is run at the same facio-lingually level and with the same inclination incisally to the tooth to be restored (Figure 11). The tooth to be restored and the shade tab need to be in the same vertical plane and should be evenly illuminated. It will probably not be a perfect match, but it is again the closest to the color of the tooth to be restored.

In certain situations, it is difficult to make a final decision between the two closest tabs, in these cases a digital photograph in black and white could help to select the closest tab (Figure 15). Doing so removes hue and chroma leaving only the value to assessed. Furthermore, if at this moment it is still unclear which tab to eliminate, choose to eliminate the tab with lower value, or darker shade.

7 | SUMMARY

Shade selection is a complex task that can be challenging for the dental clinician. While, several factors influence this process, it is ideal to have customized "shade selection" method for daily restorative workflows with resin composites. The authors in this article have described a technique to use custom shade guides made of resin composites at hand, along with a systematic approach to select the shade to make the entire process of shade selection practical, predictable and reliable for better esthetic outcomes.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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How to cite this article: Vargas M, Saisho H, Maharishi A, Margeas R. A practical, predictable, and reliable method to select shades for direct resin composite restorations. *J Esthet Restor Dent*. 2023;35(1):19-25. doi:10.1111/jerd.13019

Received: 13 November 2022 | Revised: 20 December 2022 | Accepted: 21 December 2022

DOI: 10.1111/jerd.13008

REVIEW ARTICLE

WILEY

Deep margin elevation—Present status and future directions

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Funding information
Freiwillige Akademische Gesellschaft Basel (FAG); Gottfried and Julia Bangerter-Rhyner Foundation

Abstract

Objective: Deep margin elevation (DME) is a treatment approach to relocate the cervical margin of teeth with subgingival defects to a supragingival position with a direct restoration to facilitate rubber dam isolation, impression taking, and bonding of indirect restorations. This article provides an overview of the current scientific evidence on DME and future directions for research.

Overview: The review included 38 studies on DME, most conducted *in vitro*. These studies indicate that DME has no detrimental effect on the fracture resistance of restored teeth. Evidence on the impact of DME on marginal quality is conflicting, but most *in vitro* studies observed no negative effect. Clinical studies, most comprising small patient cohorts, demonstrated favorable restorative outcomes and suggest that DME restorations made with scrupulous care are compatible with periodontal health. Bleeding on probing may occur more frequently at sites with DME, though evidence on this is not unequivocal.

Conclusions: Current evidence, based largely on laboratory studies and limited clinical data, supports DME as a viable approach to restore teeth with localized subgingival defects. However, further clinical studies with long-term follow-ups are required to provide corroborative evidence.

Clinical Significance: Current evidence suggests that DME is a viable approach to restore teeth with localized subgingival defects as a possible alternative to surgical crown lengthening. Proper working field isolation, meticulous care in the bonding and buildup procedure, and biofilm removal through patient-performed oral hygiene and professional maintenance care are crucial. As scant clinical trial-based evidence is available today, further research is needed to evaluate the long-term performance of DME restorations and their impact on periodontal health.

KEYWORDS
cervical margin relocation, composite resins, dental caries, dental restoration, proximal box elevation, subgingival margin

1 | INTRODUCTION

The management of teeth with subgingival defects often poses a challenge in clinical practice. Restoration of such teeth is complicated owing to difficult-to-achieve moisture and contamination control. To retain and restore teeth with subgingival defects, different treatment options are available.[1–4] As each of these present advantages and disadvantages, it is essential to choose the most favorable one on a case-by-case basis, taking into account all clinical factors as well as patients' expectations and needs.

Surgical extrusion, also referred to as intraalveolar transplantation, and intentional replantation are feasible treatment approaches for teeth with subgingival fractures, caries, and lesions caused by invasive cervical resorption that would otherwise be unrestorable.[1] However, they are

considered as treatment options of last resort because of their invasiveness, the risk of persistent periodontal ligament damage, and the necessity to perform root canal treatment in teeth with mature roots.[1] Orthodontic forced eruption, an alternative treatment for permanent teeth with subgingival defects in all age groups, allows for pulp preservation but is time-consuming and usually requires weekly or biweekly fiberotomy.[2,5]

Surgical crown lengthening, typically accomplished by either gingivectomy or apically positioned flap with or without osseous resection, is a reliable treatment approach to relocate the periodontal complex more apically and establish supragingival restoration margins that do not impinge on the supracrestal tissue attachment.[3] However, surgical crown lengthening is associated with longer treatment time, higher costs, patient discomfort, and in certain cases, compromised dental esthetics. Moreover, close proximity of neighboring teeth complicates interproximal tissue removal, and exposure of furcations should be avoided.

To reduce the duration and complexity of the treatment of teeth with subgingival defects, deep margin elevation (DME) has been suggested as a viable alternative in select cases.[4] DME, also known as proximal box elevation, cervical margin relocation, and coronal margin relocation, is a restorative approach that relies on a direct restoration to reposition the cervical margin to a supragingival position. With a direct restoration for DME in place, it is easier to isolate the working field with rubber dam, take a conventional or digital impression, bond an indirect restoration, and remove excess luting material.[6] In addition, DME facilitates the preservation of sound tooth substance as geometric requirements of indirect restorations can be disregarded in the areas that are restored directly.[7]

There has been a notable increase in reports on DME since 1998, when Dietschi and Spreafico published a seminal article on this treatment approach.[6] Given how research activity in the field of DME has increased over the past years and how often dental practitioners face the challenge of restoring teeth with subgingival defects, the purpose of this article was to provide an overview of the current scientific knowledge and treatment protocols for DME and outline future directions for research.

2 | MATERIALS AND METHODS

2.1 | Eligibility criteria

Published articles were selected according to the inclusion and exclusion criteria given below. No time or language restrictions were applied.

2.2 | Inclusion criteria

- *In vitro*, *in silico*, and clinical studies, healthcare survey studies, and review articles based on systematic literature searches
- Studies investigating DME
- Available full text

2.3 | Exclusion criteria

- Animal studies
- Case reports and case series with fewer than 10 patients
- Posters and abstract-only articles
- Summary articles containing no original data

2.4 | Search strategy

Six databases, Cochrane Library, Embase, OpenGrey through DANS, PubMed, Scopus, and Web of Science, were searched on 09/13/2022 using the following search string: "deep margin elevation" OR "proximal box elevation" OR "cervical margin relocation" OR "coronal margin relocation." The keywords and Boolean operators for the electronic search were identical in all six databases.

2.5 | Study selection, data collection, and data items

After removal of duplicates, the titles and abstracts of articles retrieved through the electronic search were screened against the eligibility criteria to select articles that were potentially pertinent to this review. The author names and journals were unblinded during the screening. After retrieving the full articles of potentially relevant articles, each report was assessed according to the eligibility criteria. Reasons for exclusion were recorded. Qualitative and quantitative data of included studies were extracted into pilot-tested, structured spreadsheets. No unpublished data were sought from authors or other sources. The data items extracted from the included articles are reported in Tables 1, 1, 2, 3, and 4.

2.6 | Risk of bias assessment

The risk of bias of each included study was assessed. The ROBFEAD, MINORS, RoBDEMAT, and AMSTAR tools were used for *in silico* studies, clinical studies, *in vitro* studies, and reviews respectively.[8–11] The CASP qualitative research checklist was used for healthcare survey studies.[12]

3 | RESULTS

3.1 | Included studies

Figure 1 shows the results of the study selection process, which led to the inclusion of seven review articles,[4,13–18] six reports of clinical investigations,[19–24] 24 reports of *in vitro/in silico* studies,[7,7,25–47] and one report of a dental healthcare survey.[48] Data extracted from these 38 articles are reported in detail in Tables 1, 2, 3, and 4.

TABLE 1 Overview of the included review articles

Study	Type of study	Included studies	Number of included articles	Quality of evidence	Main findings
Alghulikah et al. 2021	Systematic review	Clinical studies including case reports	6	Not reported	The systematic review advocates that DME is a reasonable, predictable, and reliable clinical procedure though more clinical studies with longer follow-ups are required.
Amesti-Garaizabal et al. 2019	Systematic review and meta-analysis	*In vitro*	13	Not reported	Meta-analysis of three studies showed no significant impact of DME on fracture resistance.
Juloski et al. 2018	Review	*In vitro* and clinical	12	Not reported	Currently there is no strong scientific evidence that could either support or discourage the use of DME.
Kielbassa et al. 2015	Systematic review	*In vitro* and clinical	19	Not reported	No significant difference in microleakage and marginal integrity between sites with DME and sites without. Unclear which material is best suited for DME. No clinical data on periodontal outcomes.
Mugri et al. 2021	Systematic review	Clinical studies excluding case reports	6	Of the six studies selected in this review, five showed a high risk of bias.	DME, in conjunction with indirect restorations, was found to have a better survival rate compared with teeth treated with crown lengthening surgery The review revealed a paucity of high-quality trials examining prognosis following the restoration of teeth with DME versus crown lengthening.
Saeralaathan et al. 2021	Systematic review	*In vitro*	9	Of the nine included studies, five and four studies were classified as having a medium and a high risk of bias, respectively. The overall level of evidence of the systematic review was considered moderate.	The marginal quality at the interface between root dentin and DME restorations appeared to be satisfactory in *in vitro* conditions. RBC of different viscosities seem to perform adequately as DME.
Samartzi et al. 2022	Review	*In vitro* and clinical	44	Not reported	Elevation material and adhesive system employed for luting seem to be significant factors concerning the marginal adaptation of the restoration. DME does not affect fatigue behavior, fracture resistance, failure pattern or repairability. DME and subgingival restorations are compatible with periodontal health, given that they are well-polished and refined. The available literature is limited mainly to *in vitro* studies.

Abbreviations: DME, deep margin elevation; RBC, resin-based composite.

3.2 | Risk of bias

Information on the risk of bias of included studies is presented in supplementary tables (Tables S1-S38 and Questionnaire SQ1), which are available in an open repository and as supporting information (Data S1).[50]

3.3 | Review articles

Of the seven review articles that included a systematic literature search, five articles were classified as systematic reviews[13,14,16–18] and one article included a meta-analysis.[14] The risk of bias of included

TABLE 2 Overview of the included clinical studies

Study	Study design	Follow-up	Sample size (patients/teeth)	Subjects	Teeth	Randomization	Blinding	Isolation	Matrix	Adhesive strategy/ adhesive	Restoration material for DME	Indirect restoration material	Indirect restoration design	Pretreatment of DME surface	Sequence of procedures	Main findings
Bertoldi et al. 2020	Cohort study	3 months	29 patients; 29 restorations	Periodontally healthy, full mouth bleeding score ≤ 15%; full mouth plaque score ≤ 15%; age range 24–70 years; mean age 45.3 years	Not reported; distance between cervical margin of defect and bone had to be at least 3 mm	N/A	Not reported	Rubber dam	Not reported	Not reported	Conventional RBC	N/A	N/A	N/A	3 months after DME surgical crown lengthening and histological assessment	Subgingival restorations compatible with gingival health, with inflammation levels similar to that of untreated root surfaces (very stringent eligibility criteria, in subjects with very good oral hygiene, cervical margin of DME at least 3 mm above the bone level, and weekly recall appointments between DME and surgical crown lengthening
Bresser et al. 2019	Cohort study	≤12 years; mean 4.8 years	120 patients, 197 restorations	Periodontally healthy, age range 30–106 years; mean age 61.6 years	Premolars, permanent molars	N/A	Not reported	Rubber dam	Circumferential or sectional metal matrix	E&R; 3-step E&R adhesive	Conventional RBC	LDS or indirect RBC	Partial indirect restoration	Tribochemical silica coating; prehydrolyzed silane-coupling agent, hydrophobic bonding	Not reported	Overall survival rate of teeth with DME 95.6% after 10 years of follow-up and longer. No periodontal outcome parameters reported.
Dietschi et al. 2019	Cohort study	≤21 years; mean 14.0 years	16 patients, 25 restorations, DME in 10 restorations	Part of a recall system, apart from the treated tooth/ teeth no severe, active carious or functional pathologies	Premolars, permanent molars	N/A	Not reported	Rubber dam	Not reported	Not reported/ multicomponent adhesive	Conventional RBC, flowable RBC	Indirect RBC	Inlay, onlay, overlay	Diamond bur finishing	Not reported	No fractures, secondary caries, or endodontic complications; DME restorations were rated as "ideal" or "satisfactory."
Ferrari et al. 2018	Controlled treatment trial	1 year	35 patients, 35 restorations	Periodontally healthy, age range 27–54 years; mean age 45.1 years	Permanent posterior teeth	Random allocation of proximal box to DME/no DME group	Not reported	Rubber dam	Metal matrix, no further details	Not reported; universal adhesive	Flowable RBC	LDS	Onlay	Not reported	Delivery of indirect restoration approximately 12 weeks after DME	No significant changes in plaque index and gingival index, significant more BoP after 1 year.
Ghezzi et al. 2019	Cohort study	≥1 year; mean	15 patients; 15 teeth	Age not reported; no systemic	Not reported	N/A	Not reported	Rubber dam	Metal matrix (single, or double	SEE; 2-step self-etch adhesive	Heated conventional RBC	Indirect RBC	Overlay	Grit blasting, silane coupling agent, 2-step	Delivery of indirect restoration	No complications in any patients over the

(Continues)

TABLE 2 (Continued)

Study	Study design	Follow-up	Sample size (patients/teeth)	Subjects	Teeth	Randomization	Blinding	Isolation	Matrix	Adhesive strategy/ adhesive	Restoration material for DME	Indirect restoration material	Indirect restoration design	Pretreatment of DME surface	Sequence of procedures	Main findings
		follow-up 5.7 years		disease, at least 2 recall visits per year					matrix technique)					self-etch adhesive	1 week after DME	follow-up period. 100% of restorations remained functional. No significant difference in probing depth and BoP in the three treatment groups (DME, open flap without ostectomy and DME, open flap with ostectomy and DME). Across groups, BoP, 100% at baseline, decreased to 40% at the 1-year follow-up. This suggests that DME does not negatively affect periodontal health when the connective compartment of the supracrestal tissue attachment is respected.
Muscholl et al. 2022	Cohort study	Mean follow-up period 2.7 years	63 patients; 63 restorations	>18 years old; in study cohort, 30% had periodontitis; 32 were smokers; 57% reported daily interdental brush use	Not reported	N/A	Not reported	Cotton rolls, suction, retraction cords, and astringent agents during DME; rubber dam after DME	None	E&R; 3-step E&R adhesive	Flowable RBC and conventional RBC (snowplow technique)	N/A	N/A	N/A	N/A	70% of restorations were given high quality ratings; no increased inflammation was found at sites with DME. Regular interdental brush use was associated with less gingival inflammation.

Abbreviations: BoP, bleeding on probing; DME, deep margin elevation; E&R, etch-and-rinse; LDS, lithium disilicate; N/A, not applicable; RBC, resin-based composite; SEE, selective enamel etching.

TABLE 3 Overview of the included *in vitro* and *in silico* studies

Study	Type of study	Teeth	Setup	Matrix	Adhesive strategy/ adhesive	Restoration material for DME	Indirect restoration material	Indirect restoration design	Pretreatment of DME surface	Sequence of restorative procedures	Load cycling/ artificial aging	Main findings
Alahmari et al. 2021	*In vitro*	Maxillary premolars	No neighboring teeth	Not reported	E&R, 4-step E&R adhesive	Conventional RBC; flowable RBC	LDS	Crown	Diamond bur finishing plus universal adhesive or 3-step E&R adhesive	No artificial aging of DME restoration before indirect restoration	2 weeks of water storage at 37°C	Specimens without DME had a higher fracture resistance than specimens with DME.
Baldi et al. 2022	*In silico*	Maxillary permanent molars	No neighboring teeth	Circumferential metal matrix	SEE, 2-step self-etch adhesive	Conventional RBC, incremental application; or a layer of highly filled flowable RCB (different layer thickness)	N/A	N/A	N/A	N/A	Simulated axial chewing load	RBC showed more homogeneous behavior in stress distribution than ceramic; flowable RBC liner reduced shear stresses and normal pressure on cavity floor and cervical margin area.
Bresser et al. 2020	*In vitro*	Mandibular molars	No neighboring teeth	Not reported	E&R, 3-step E&R A adhesive	thin layer of flowable RBC followed by conventional RBC	LDS	Inlays and onlays	Tribochemical silica coating; two-component silane-coupling agent, hydrophobic bonding	No artificial aging of DME restoration before indirect restoration	TML	DME did not statistical significantly affect the fracture strength, nor the fracture type or repairability of LDS restorations in molars.
Chen et al. 2021	*In silico*	Premolars	N/A	N/A	N/A	N/A	RBC, ceramic, LDS	Inlay	N/A	N/A	N/A	DME did not extensively affect the strength of the tooth structure.
Da Silva et al. 2021	*In vitro*	Third molars	No neighboring teeth	Not reported	E&R, 2-step E&R adhesive; SEE, 2-step self-etch adhesive	Conventional RBC	Indirect RBC	Inlay	Grit blasting	No artificial aging of DME restoration before indirect restoration	None	The 2-step self-etch adhesive showed higher sealing ability than the 2-step E&R adhesive when margins were located on dentin, regardless DME.
Frankenberger et al. 2013	*In vitro*	Third molars	No neighboring teeth	Not reported	Self-adhesive, self-adhesive resin-based luting material; not reported,	Conventional RBC; self-adhesive resin-based luting material	Leucite-reinforced glass ceramic	Inlay	Grit blasting and 4-step etch-and-rinse adhesive	1 week of water storage at 37°C between DME and delivery of	TML	Best marginal quality in group without DME (inlay bonded to dentin). DME made from

(Continues)

TABLE 3 (Continued)

Study	Type of study	Teeth	Setup	Matrix	Adhesive strategy/ adhesive	Restoration material for DME	Indirect restoration material	Indirect restoration design	Pretreatment of DME surface	Sequence of restorative procedures	Load cycling/ artificial aging	Main findings
					universal adhesive					indirect restoration		layered RBC superior to other DME groups. Self-adhesive resin-based luting material not suitable for DME.
Gonçalves et al. 2017	*In vitro*	Third molars	No neighboring teeth	Not reported	E&R, 2-step E&R adhesive	Conventional RBC, two 1-mm increments	Indirect RBC	Inlay	Grit blasting (in half of the specimens additionally application of a 2-step E&R adhesive)	No artificial aging of DME restoration before indirect restoration	1 week water storage of specimens before bond strength measurement	DME improved the bond strength of self-adhesive resin-based luting material.
Grassi et al. 2022	*In vitro/in silico*	Third molars	No neighboring teeth	Not reported	Self-etch, universal adhesive	Flowable bulk fill RBC	CAD-CAM RBC; leucite-reinforced glass ceramic	Inlay	Grit-blasting; universal adhesive	No artificial aging of DME restoration before indirect restoration	Stepwise stress mechanical fatigue test	DME was not negative for fatigue and biomechanical behaviors. RBC inlays were more resistant to the fatigue test but showed more non-repairable failures.
Grubbs et al. 2020	*In vitro*	Mandibular molars	No neighboring teeth	Circumferential metal matrix	SEE, universal adhesive	GIC; RMGIC; conventional RBC; bulk fill RBC	CAD-CAM RBC	Onlay	Diamond bur finishing and universal adhesive	No artificial aging of DME restoration before indirect restoration	TML	The material used for DME did not influence results in terms of margin quality and fracture resistance.
Ilgenstein et al. 2014	*In vitro*	Mandibular molars	No neighboring teeth	Not reported	E&R, 3-step E&R adhesive	Conventional RBC	Mark II CAD-CAM feldspar ceramic; CAD-CAM RBC	Onlay	Diamond bur finishing; universal adhesive	No artificial aging of DME restoration before indirect restoration	TML	DME had no impact on the marginal integrity and fracture behavior of root canal-treated mandibular molars restored with feldspathic ceramic onlays. RBC onlays were more favorable than ceramic onlays in terms of both marginal quality and fracture

TABLE 3 (Continued)

Study	Type of study	Teeth	Setup	Matrix	Adhesive strategy/ adhesive	Restoration material for DME	Indirect restoration material	Indirect restoration design	Pretreatment of DME surface	Sequence of restorative procedures	Load cycling/ artificial aging	Main findings
												resistance, particularly in specimens without DME.
Ismail et al. 2022	*In vitro*	Maxillary molars	No neighboring teeth	Circumferential metal matrix	SEE, universal adhesive	GIC; RMGIC; flowable bulk fill RBC; novel dual-curing RBC	N/A	N/A	Universal adhesive	N/A	Water storage in one group, thermocycling in another group	Flowable bulk fill RBC and the novel dual-curing RBC had better marginal integrity than GIC and RMGIC. All DME materials were adversely affected by aging.
Juloski et al. 2020	*In vitro*	Molars	No neighboring teeth	Circumferential metal matrix	E&R; 3-step E&R adhesive; SEE, universal adhesive	Flowable RBC; flowable bulk fill RBC	CAD-CAM RBC	Overlay	Diamond bur finishing plus universal adhesive or 3-step E&R adhesive	2 weeks of water storage at room temperature between DME and delivery of indirect restoration	None	DME provided an inferior seal of the margin than bonding the restoration directly to dentin without DME. The universal adhesive applied in self-etch mode showed a higher sealing ability of the marginal interface than the 3-step E&R adhesive.
Köken et al. 2018	*In vitro*	Molars	No neighboring teeth	Circumferential metal matrix	SEE; universal adhesive	Conventional RBC; flowable RBC	CAD-CAM RBC	Overlay	Universal adhesive	2 weeks of water storage at room temperature between DME and delivery of indirect restoration	None	No significant difference in interfacial leakage of DME made with flowable RBC or conventional RBC; higher leakage score at sites with DME than sites without.
Köken et al. 2019	*In vitro*	Third molars	No neighboring teeth	Circumferential metal matrix	E&R; 3-step E&R adhesive; SEE; universal adhesive	Flowable RBC	CAD-CAM RBC	Overlay	Diamond bur finishing	2 weeks of water storage at room temperature between DME and delivery of	None	The universal adhesive showed higher microleakage scores at sites with DME than at sites without DME. The

(Continues)

TABLE 3 (Continued)

Study	Type of study	Teeth	Setup	Matrix	Adhesive strategy/ adhesive	Restoration material for DME	Indirect restoration material	Indirect restoration design	Pretreatment of DME surface	Sequence of restorative procedures	Load cycling/ artificial aging	Main findings
										indirect restoration		3-step E&R adhesive showed no significant differences between sites with DME and sites without DME.
Magne 2021	*In vitro*	Typodonts	Typodont model	Sectional matrix within circumferential metal matrix	E&R; 3-step E&R adhesive	Conventional RBC	N/A	N/A	N/A	N/A	N/A	Novel matrix technique is advantageous for DME
Moon et al. 2021	*In vitro*	Mandibular molars	No neighboring teeth	Not reported	N/A	RMGIC	LDS	Inlay	Diamond bur finishing	No artificial aging of DME restoration before indirect restoration	TML	DME with RMGIC reduced the extent of the interfacial gap formation before and after simulated aging.
Müller et al. 2017	*In vitro*	Molars	No neighboring teeth	Not reported	E&R; universal adhesive	Conventional RBC	CAD-CAM RBC	Inlay	E&R (with a universal adhesive or a 4-step E&R adhesive) in two groups, none in one group	No artificial aging of DME restoration before indirect restoration	TML	No significant difference in the marginal quality at sites with and without DME; no significant difference between the different luting materials; detrimental impact of TML on marginal quality.
Pereira et al. 2022	*In vitro*	Maxillary molars	No neighboring teeth	Metal matrix	E&R; universal adhesive; self-etch; universal adhesive	GIC; conventional RBC; bulk fill RBC; flowable bulk fill RBC	CAD-CAM RBC	Inlay	Universal adhesive	24 h water storage between DME and delivery of indirect restoration	TML	The marginal integrity before and after aging was not significantly different. No significant differences were observed between margins relocated with different restorative materials in comparison to enamel margins.
Roggendorf et al. 2012	*In vitro*	Third molars	No neighboring teeth	Metal matrix bands	Not reported; universal	Conventional RBC; self-adhesive	Indirect RBC	Inlay		1 week of water storage at	TML	Bonding inlays directly to

TABLE 3 (Continued)

Study	Type of study	Teeth	Setup	Matrix	Adhesive strategy/ adhesive	Restoration material for DME	Indirect restoration material	Indirect restoration design	Pretreatment of DME surface	Sequence of restorative procedures	Load cycling/ artificial aging	Main findings
					adhesive; self-adhesive; self-adhesive resin-based luting material	resin-based luting material			Grit blasting and 4-step E&R adhesive	37° C between DME and delivery of indirect restoration		dentin showed similar amounts of gap-free margins compared with RBC applied in three layers as DME. The groups with self-adhesive resin-based luting material used for DME exhibited significantly more gaps in dentin.
Sandoval et al. 2015	*In vitro*	Third molars	No neighboring teeth	Not reported	E&R; 3-step E&R adhesive	Conventional RBC; flowable RBC	Leucite-reinforced glass ceramic	Inlay	Grist blasting or soft air-abrasion with sodium bicarbonate	No artificial aging of DME restoration before indirect restoration	Cycling mechanical loading	DME made with conventional or flowable RBC showed a favorable marginal quality, which was not different from restorations bonded directly on dentin. Soft air abrasion proved not to be different from grit blasting for treating DME restorations before adhesive luting.
Scotti et al. 2020	*In vitro*	Maxillary premolars	No neighboring teeth	Circumferential metal matrix	SEE; 2-step self-etch adhesive	Conventional RBC, flowable RBC, bulk-fill RBC	N/A	N/A	N/A	N/A	Cycling mechanical loading	Conventional and bulk-fill composites may be able to better maintain a marginal seal over time, because their use, in contrast to flowable RBC, was not associated with any significant alteration of the marginal seal after mechanical treatment.

(Continues)

TABLE 3 (Continued)

Study	Type of study	Teeth	Setup	Matrix	Adhesive strategy/ adhesive	Restoration material for DME	Indirect restoration material	Indirect restoration design	Pretreatment of DME surface	Sequence of restorative procedures	Load cycling/ artificial aging	Main findings
Spreafico et al. 2016	*In vitro*	Third molars	No neighboring teeth	Circumferential metal matrix	E&R; 3-step E&R adhesive	Flowable RBC; conventional RBC	CAD-CAM RBC; LDS	Crown	E&R (with a 3-step E&R adhesive)	No artificial aging of DME restoration before indirect restoration	TML	DME had no effect on the quality of cervical margins before and after TML.
Vertolli et al. 2020	*In vitro*	Third molars	No neighboring teeth	Not reported	N/A	GIC; RMGIC	Mark II CAD-CAM feldspar ceramic	Inlay	Not reported	No artificial aging of DME restoration before indirect restoration	TML	DME resulted in decreased ceramic fracture when preparation margins were located below the CEJ. No difference was found between DME with GIC or RMGIC. Increased heights of ceramic proximal box may lead to an increased probability of ceramic fracture.
Zhang et al. 2021	*In vitro*	Premolars	No neighboring teeth	Not reported	SEE; universal adhesive	Conventional RBC; flowable bulk-fill RBC	LDS	Endocrown	Tribochemical silica coating, silane-coupling agent, universal adhesive	No artificial aging of DME restoration before indirect restoration	Cycling mechanical loading	For endodontically treated maxillary premolars restored with ceramic endocrowns, DME increased fracture resistance but not microleakage.

Abbreviations: DME, deep margin elevation; E&R, etch-and-rinse; GIC, glass ionomer cement; LDS, lithium disilicate; N/A, not applicable; RBC, resin-based composite; RMGIC, resin-modified glass ionomer cement; SEE, selective enamel etching.

TABLE 4 Overview of the included dental healthcare survey study

Study	Study design	Subjects	Sample selection	Sample size	Response rate	Main findings
Binalrimal et al. 2021	Questionnaire-based study	Dental practitioners in Riyadh, Saudi Arabia; ≥1 of professional experience; command of English	Convenience sample	535 respondents	Not reported	Of the respondents, 66.9% reported to have heard of DME and 30.4% reported to use DME in clinical practice.

Abbreviation: DME, deep margin elevation.

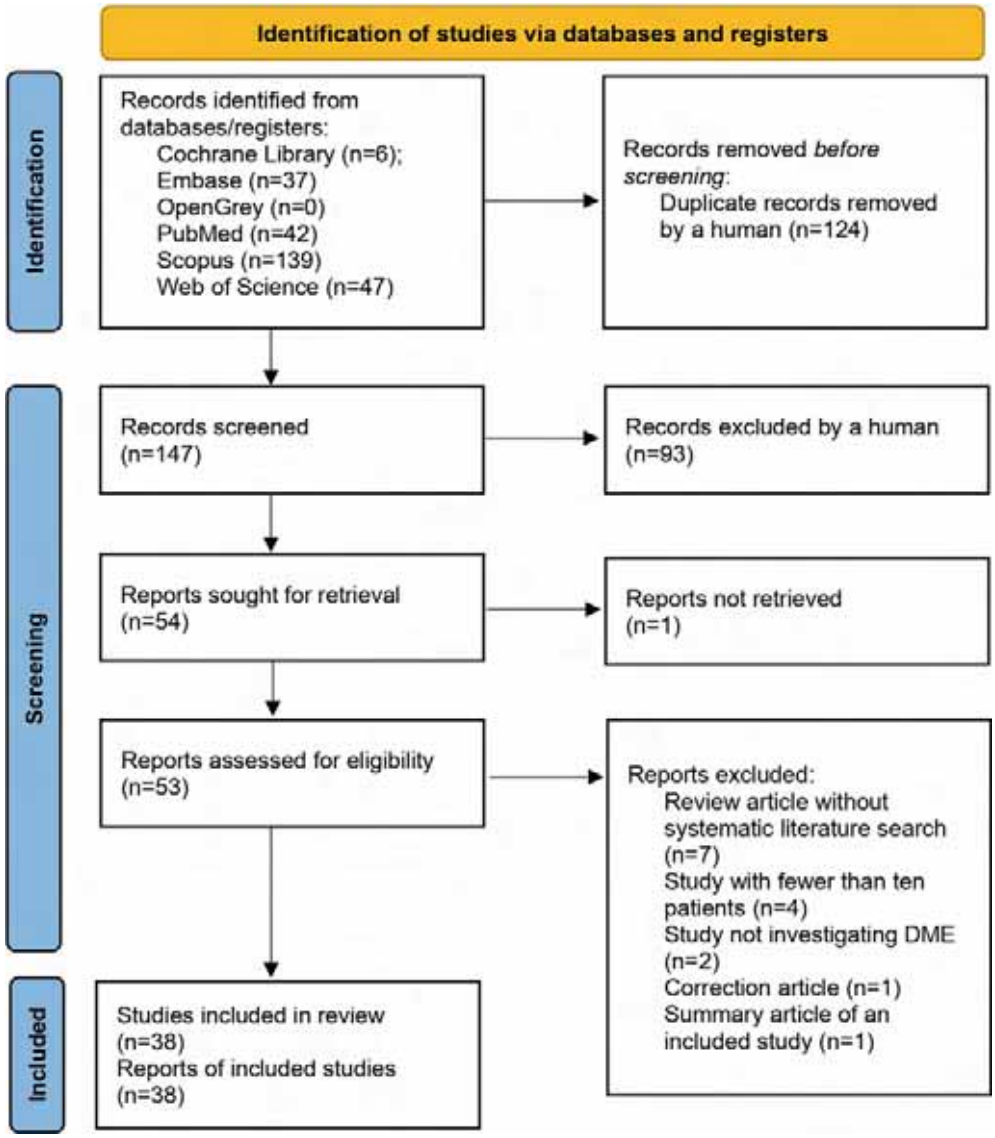

FIGURE 1 PRISMA 2020 flow diagram depicting the selection of records for this review[49]

studies was assessed in two review articles, which found a high risk of bias in five out of six included studies and four out of nine included studies, respectively.[17,18] According to one review article and a systematic review and meta-analysis, which included data on fracture resistance, the fracture resistance of teeth restored of teeth with DME is not significantly different from teeth restored without DME.[4,14] The body of available laboratory evidence suggests that the marginal quality at the interface between root dentin and DME restorations is satisfactory and similar to sites without DME.[4,16,18] Different adhesives and restoration materials used for DME were found to differ in their performance *in vitro* but unequivocal evidence in favor of certain materials is currently missing.[4,18] Resin-based composites (RBC) of different viscosities seem to perform adequately for DME.[4] According to the most recent review article, DME restorations that do

not infringe on the supracrestal connective tissue attachment are compatible with periodontal health if they are properly finished and well-polished.[4] One systematic review found teeth restored with DME and indirect restorations to have a better survival rate compared with teeth treated with surgical crown lengthening.[17] All reviews, highlighting the dearth of clinical studies, emphasized the need for further research.

3.4 | Clinical studies

Follow-up periods ranged from 3 months to 21 years.[19,21] Study population sizes ranged from 10 to 120 patients, with a total number of 278 patients and 349 restored teeth included in the six studies combined. In three studies, DME was performed in permanent posterior teeth.[20–22] Reporting of included teeth was incomplete in three articles.[19,23,24] One trial included a randomized allocation of mesial and distal boxes of mesial-occlusal-distal (MOD) cavities to two treatment arms.[22] No article reported blinding of patients, investigators making the assessments, and data interpreters. Two study reports provided information on the time point of the delivery of the indirect restoration, which in one study took place 1 week and in another 12 weeks after DME.[22,23]

3.5 | Clinical performance of teeth with DME and periodontal outcomes

Gingival inflammation levels at sites with DME were found to be similar to untreated sites in a study cohort comprising patients with very good oral hygiene.[19] The cervical margin of DME restorations were located at least 3 mm above the bone level, and patients in this cohort kept weekly recall appointments between the DME procedure and surgical crown lengthening, which was performed in all cases 3 months after DME.[19] In a study with 120 patients, an overall survival rate of teeth with DME of 95.6% was recorded after 10 years of follow-up.[20] No periodontal outcome parameters were reported.[20] A cohort study, providing data on 10 teeth with DME, reported no fractures, secondary caries, or endodontic complications, and DME restorations were rated as "ideal" or "satisfactory" after a mean follow-up of 14 years.[21] DME made either in the mesial or distal box of a MOD cavity revealed more frequent bleeding on probing but no significant changes in plaque and gingival indeces.[22] One study with 15 patients adjusted the treatment protocol depending on the ability to isolate the working field with rubber dam: if the working field could be isolated, DME was performed straightaway.[23] If it could not be isolated, a mucoperiosteal flap was raised.[23] When rubber dam isolation was possible after the flap was elevated, DME was performed without osseous resection.[23] Otherwise, osseous resection was made to allow rubber dam isolation.[23] No significant differences were found between these three treatment groups for probing depth and bleeding on probing. All restorations remained functional and no complications occurred over the 5.7-year follow-up.[23] An assessment of DME restorations made without rubber dam and matrix, sites with DME did not show increased signs of inflammation compared with other sites.[24] Regular interdental brush use was associated with less gingival inflammation, and 70% of the restorations were given high quality ratings after a mean follow-up period of 2.7 years.[24]

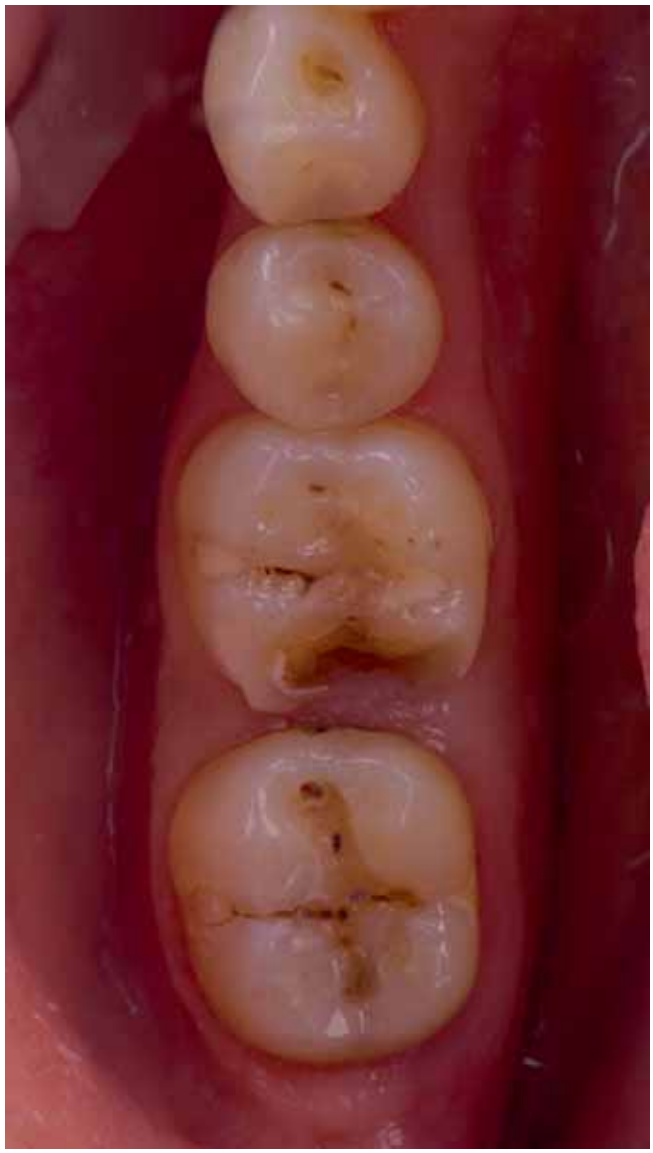

FIGURE 2 Preoperative occlusal view of a first molar with deep distal carious lesion. The second molar had failing restorations and recurrent caries.

3.6 | Isolation of the working field

Rubber dam was used to isolate the working field prior to DME in five of the six clinical studies included in this review.[19–23] Cotton rolls, suction, retraction cords, and astringent agents during the DME procedure and rubber dam isolation thereafter were used in one study.[24]

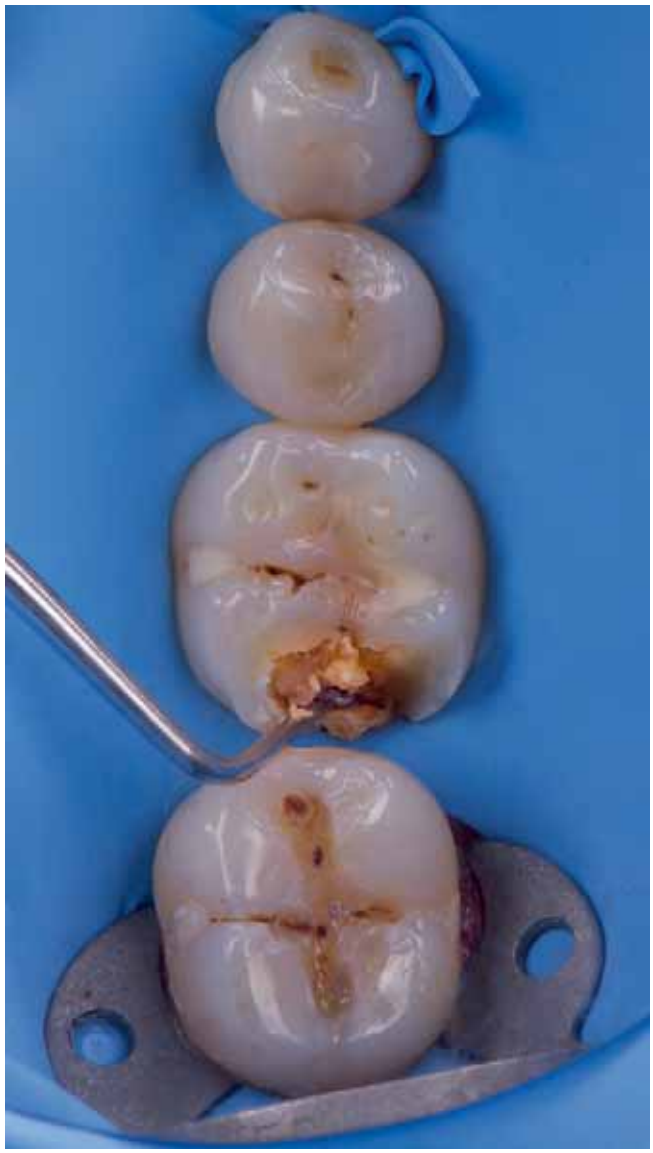

FIGURE 3 After rubber dam isolation, initial excavation with hand instrument

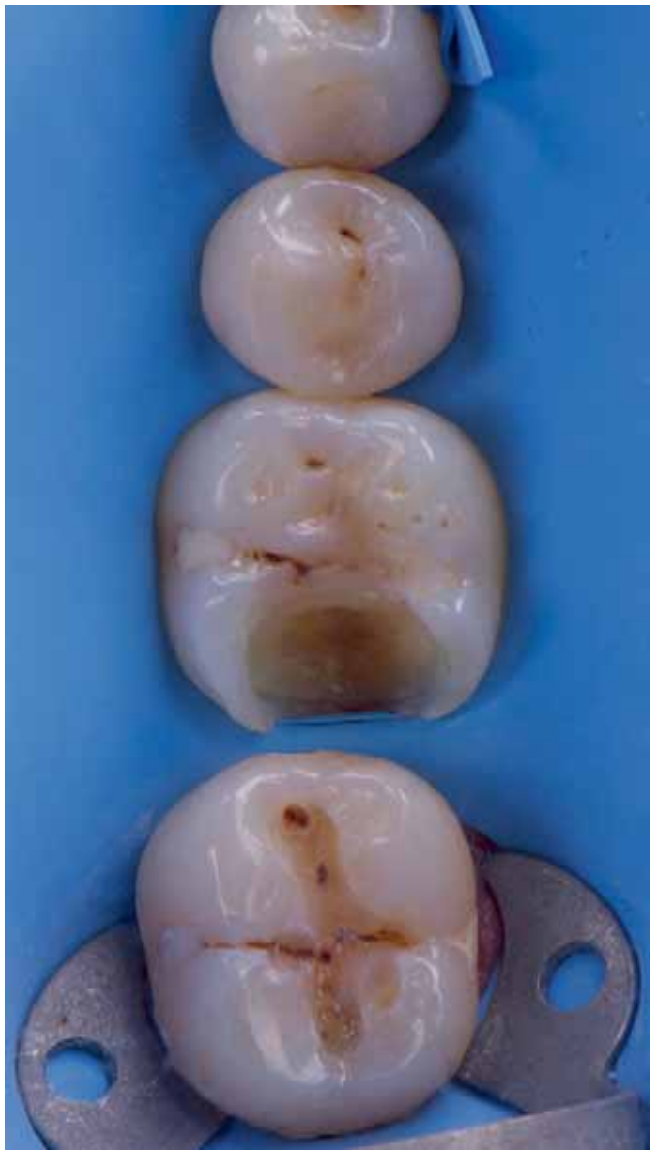

FIGURE 4 Situation after complete caries removal

3.7 | Teeth used in *in vitro/in silico* studies

Molars were selected as tooth specimens in 19 studies.[7,26,27,29–33,33,35–37,39–43,45,46] Nine study reports did not specify whether permanent molars, deciduous molars, or both were used.[27,32–36,39–41] Premolars were selected in four studies,[25,28,44,47] while one study used typodonts.[38] Except for the investigation that used typodonts, none of the included laboratory studies simulated physiological interproximal contacts.

3.8 | Matrix

Most clinical studies used metal matrices for DME.[20,22,23] Operators in one clinical study performed DME without a matrix.[24] Two reports of clinical investigations and 12 reports of *in vitro* studies furnished no information on matrix use.[7,19,21,25,27,29–31,33,39,40,43,46,47] Circumferential metal matrices were used in nine laboratory studies.[26,32,32,35–38,44,45] A laboratory study on typodonts demonstrated the advantage of packing Teflon (PTFE) tape behind a sectional metal matrix placed within a circumferential metal matrix to obtain a tight marginal seal in deep proximal cavities.[38]

3.9 | Adhesive strategies for DME

An etch-and-rinse approach, either with a conventional etch-and-rinse adhesive or a universal adhesive, was employed in two clinical investigations and 12 *in vitro* studies.[7,20,24,25,27,29,33,35,37,38,40,41,43,45] Selective enamel etching, either with a conventional self-etch adhesive or a universal adhesive, was chosen in one clinical investigation and nine

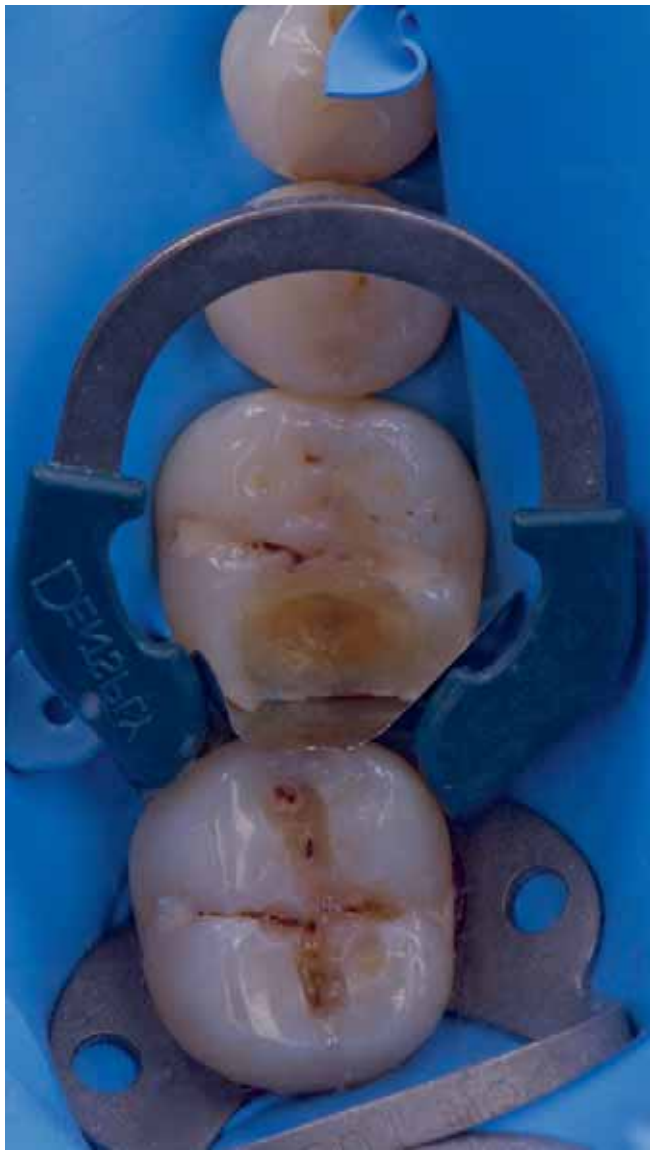

FIGURE 5 Sectional metal matrix to provide ideal marginal seal for the deep margin elevation (DME) material

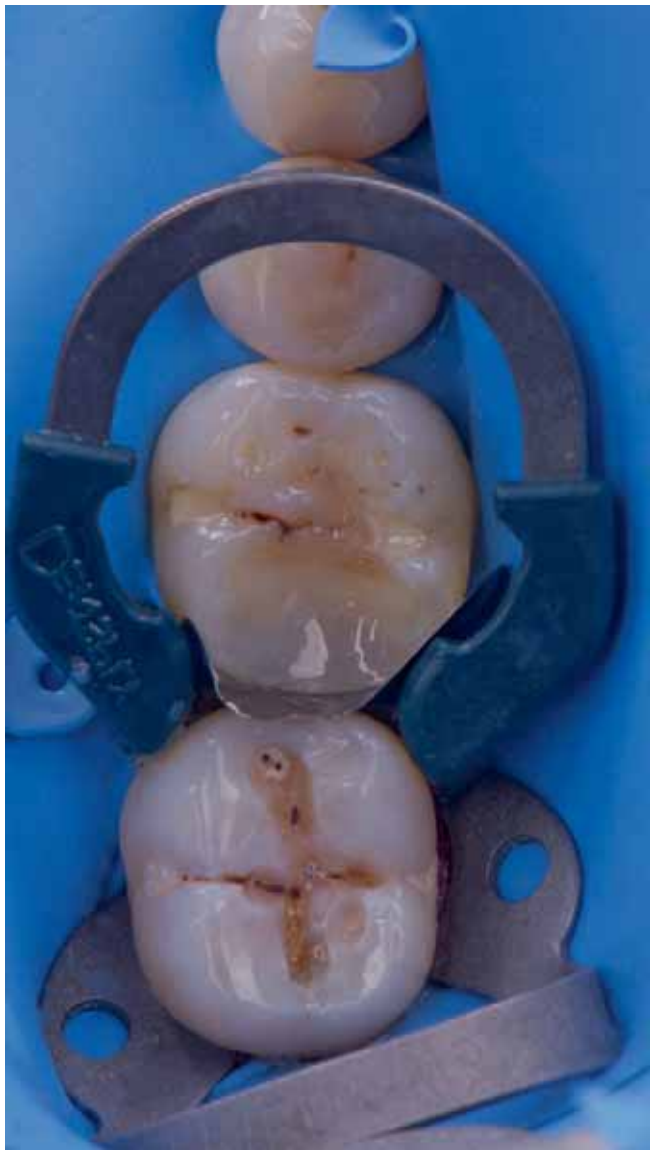

FIGURE 6 Selective etch technique and a self-etch adhesive were applied and a direct resin-based composite (RBC) restoration was placed and light cured

in vitro studies.[23,26,29,32,34–37,44,47] In two laboratory studies, a self-etch approach with a universal adhesive was used for DME.[31,41] Two laboratory studies used a self-adhesive resin-based luting material for DME without any phosphoric acid etching.[30,42] Five articles, reporting on three clinical investigations and two *in vitro* studies, included no or incomplete information on the adhesive strategy, adhesive, or both.[19,21,22]

3.10 | Restoration material for DME

In the included clinical studies, DME was made with conventional RBC, flowable RBC, or both. In the included *in vitro/in silico* studies, the materials used for DME included conventional RBC, flowable RBC, bulk-fill RBC, both high viscosity and flowable, conventional glass ionomer cement, resin-modified glass ionomer cement, and self-adhesive resin-based luting material. These *in vitro/in silico* studies did not show clear advantages of one group of material over another with the exception that self-adhesive resin-based luting materials were found to be unsuitable for DME.[30,42]

3.11 | Indirect restoration material and design

To restore teeth after DME, inlays and onlays/overlays made from CAD-CAM RBC blocks, lithium disilicate, or indirect RBC were most common in the included studies.[7,20–23,27–29,31–33,35–37,39–42] Of the included studies, only *in vitro* investigations used leucite-reinforced glass and feldspathic ceramics.[30,31,33,43,46] Evidence on

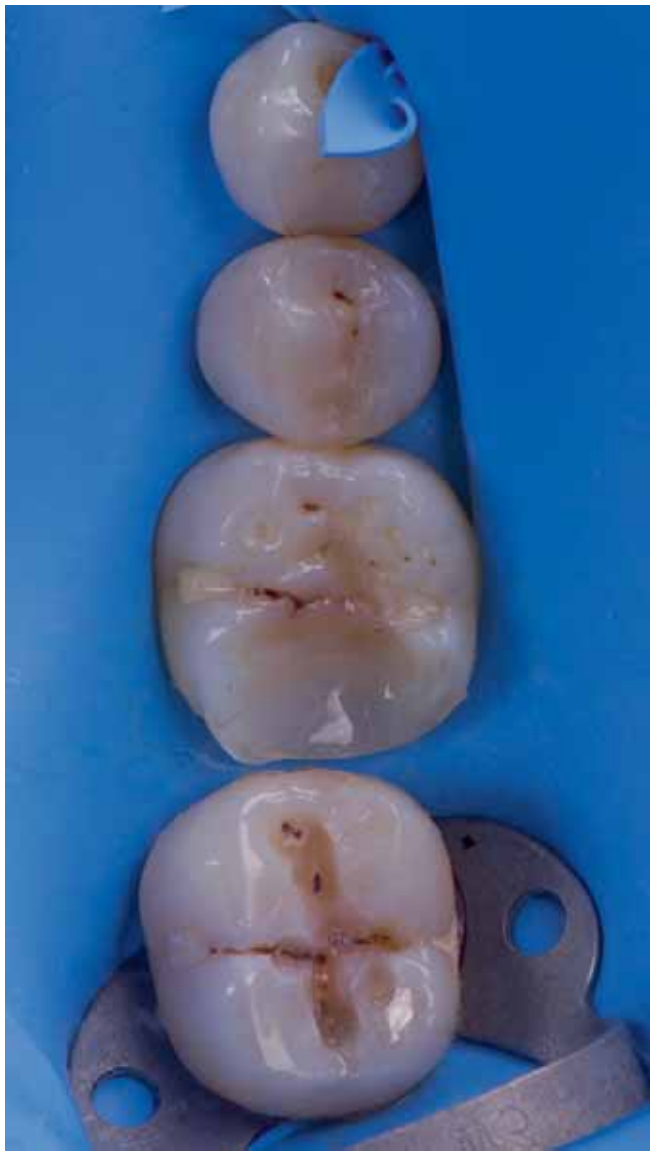

FIGURE 7 Deep margin elevation (DME) with resin-based composite (RBC) after matrix removal

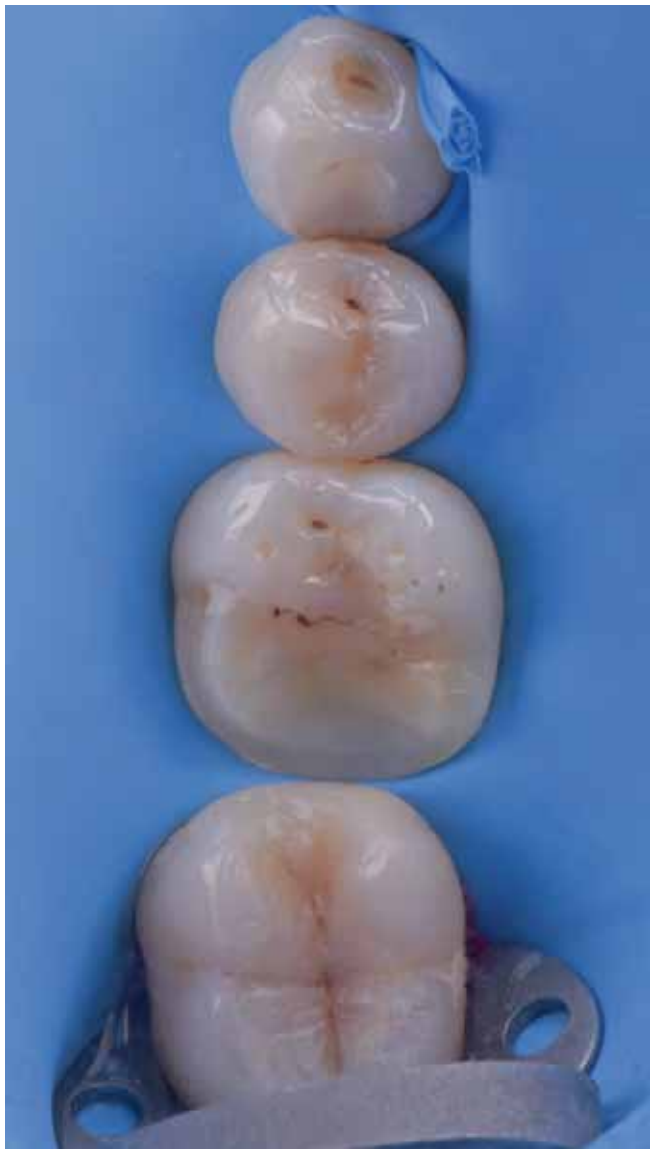

FIGURE 8 Preparation for indirect partial-coverage posterior ceramic onlay on the first molar and completed resin-based composite (RBC) restoration on the second molar

crowns and endocrowns placed on DME is limited to three *in vitro* investigations.[25,45,47]

3.12 | Pretreatment of DME surface prior to indirect restoration delivery

Procedures carried out as pretreatment of the DME surface before bonding an indirect restoration included grit blasting,[7,29,43] diamond bur finishing,[21,37,39] tribochemical silica coating, soft air-borne particle abrasion with sodium bicarbonate,[43] application of a silane coupling agent and/or adhesive,[34,36,40,41,45] and combinations of these methods.[7,20,23,25,27,30–33,35,42,47] The included studies provided scant evidence on the impact of different pretreatment protocols, with only one study, showing no differences between soft air abrasion and grit blasting, containing data on this.[43]

3.13 | Sequence of restorative procedures in *in vitro/in silico* studies

In most of the included studies, indirect restorations were made after DME without delay.[7,25,27,29,31–33,39,40,43,45–47] In six studies, the teeth with DME were stored in water before the indirect restoration was bonded, with reported water storage periods ranging from 24 h to a fortnight.[30,35–37,41,42]

FIGURE 9 Lateral view of prepared molar after removal of the provisional restoration. Air-borne particle abrasion was applied to the resin-based composite (RBC) to prepare the deep margin elevation (DME) surface for bonding of the onlay.

FIGURE 10 Total-etch technique with phosphoric acid

FIGURE 11 Bonding agent application

FIGURE 12 The ceramic onlay was etched with hydrofluoric acid

FIGURE 13 Silane coupling agent application

FIGURE 14 Ceramic onlay inserted with resin-based luting material

3.14 | Load cycling/artificial aging of restored teeth in *in vitro/in silico* studies

In most of the included studies, the restored teeth were subjected to thermomechanical load cycling or mechanical load cycling.[26,27,30–34,39–47] In four studies, the specimens were not exposed to any loading or artificial aging.[29,35–37]

3.15 | Dental healthcare survey data

In a questionnaire-based study, comprising a convenience sample of 535 dental practitioners in Riyadh, Saudi Arabia, 66.9% and 30.4% of the respondents reported to be familiar with DME and to use it in clinical practice, respectively.[48]

FIGURE 15 Removal of excess luting material before light curing

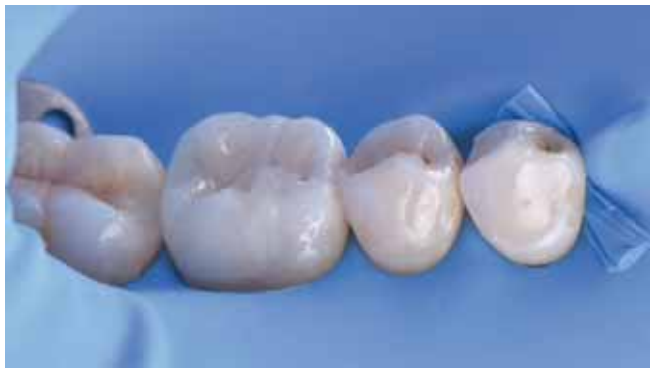

FIGURE 16 Finished and polished onlay restoration after deep margin elevation (DME)

4 | DISCUSSION

The assessment of published reports showed that evidence on DME is largely derived from laboratory studies and a small number of clinical investigations. This underscores the critical need for further clinical studies that include long-term follow-up periods and evaluate patient-centered outcomes in addition to restorative and periodontal parameters. Moreover, given the paucity of treatment trial-based evidence, conclusions for clinical practice can only be drawn cautiously and with reservation. The findings of laboratory studies suggest that DME has no detrimental effect on the fracture resistance of restored teeth. Though some *in vitro* studies found the marginal quality of DME restorations to be inferior to that of indirect restorations bonded directly to dentin,[30,33,36,37] studies reporting no such negative effect of DME currently prevail in number.[40,41,43–45] Clinical investigations, most conducted with stringent case selection and rather small patient cohorts, demonstrated favorable restorative outcomes, and they suggest that DME restorations made with meticulous care may be compatible with periodontal health. However, special cleaning devices such as interdental brushes are recommended in addition to regular toothbrushing to prevent gingival inflammation.[24] Bleeding on probing may occur more frequently at sites with DME, though evidence on this is ambiguous.[19,22–24]

It is crucial to consider the methodological limitations of this narrative review article, which is mainly descriptive. Even though this review was based on a systematic search of published literature, it did not pursue the same overriding objectives that systematic reviews try to fulfill. Rather, the goal of this article was to survey the available data on DME and to provide a general summary of current evidence. As such, it does not contain a critical appraisal and synthesis of studies that address a specific research question. Systematic reviews that are narrower in scope and conducted within an established methodological framework are much better suited for such purposes.

There is no consensus on which is the most suitable dental material for DME. However, more comprehensive data are available on RBC than glass ionomers cement and resin-modified glass ionomer cement as materials for DME. In addition, a recent systematic review of laboratory studies showed advantages of restoring proximal cavities that extend beyond the cementoenamel junction (CEJ) with RBC rather than glass ionomer cement or resin-modified glass ionomer cement.[51] DME restorations with adequate marginal adaptation and favorable behavior under cycling loading can be made with conventional RBC, flowable RBC, and bulk fill RBC of different viscosities, which is why dental practitioners may choose any of these RBC materials to restore deep proximal boxes.[51,52]

A clinical case in which the DME technique was used to treat a mandibular molar with a bonded ceramic onlay is shown in Figures 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16.

Self-adhesive resin-based luting materials are not suitable for DME. Consequently, they should not be used as alternatives to RBC to restore subgingival cavities.[30,42] However, self-adhesive RBC, a type of restorative material to which much research and development is dedicated today, may become a suitable material for DME in the future. This class of restorative material aims to combine the stability of conventional RBC with the ease of use of glass ionomer cement.[53]

Similarly, the development of novel antimicrobial biomaterials promises benefits for DME once the challenges of biocompatibility and controlled release of antimicrobial agents are overcome.[54,55] Furthermore, following case reports demonstrating favorable outcomes of a novel technique, a clinical trial is investigating the performance of RBC restorations placed on calcium-silicate cement applied in marginal defects extending to the alveolar crest.[56]

Currently available data do not provide conclusive evidence on which adhesive strategy is most appropriate for DME. A recent systematic review also found no clear effect of different bonding protocols and types of adhesives on marginal adaptation of RBC restorations in class II cavities extending beyond the CEJ.[51] This suggests that one may choose the adhesive strategy for DME according to one's personal preference. However, when an etch-and-rinse or selective enamel etch approach is applied, over-etching or inadvertent etching of dentin should be avoided.[4,35,57,58] Self-etch adhesives or universal adhesives, applied in self-etch or selective enamel etch mode, offer certain advantages for DME.[4]

A tight-fitting matrix facilitates the provision of direct restorations with excellent marginal adaptation. Circumferential metal matrices, the type of matrix most used in the studies included in this review,

were shown to have a positive influence on the marginal quality of deep class II RBC restorations.[59] Such matrices may therefore be regarded as the matrix system of choice for DME. However, it is often tricky to achieve a good marginal seal with a matrix in proximal defects extending beyond the CEJ. A recent laboratory study demonstrated the benefit of trimming circumferential matrices to increase their curvature and decrease their height, which allows for easier placement.[38] If residual gaps at the gingival margin persist – a common occurrence, especially in teeth with cervical concavities – placing a sectional metal matrix within the circumferential metal matrix and carefully packing a small piece of PTFE tape at the gingival level between the two may help to obtain an optimal seal.[38] PTFE tape, packed behind a matrix, can also be used when it is not possible to place a wedge.[20]

With the so-called R2 technique, operators placed DME restorations without a matrix in one clinical study in which favorable long-term outcomes were observed.[24,60] However, the authors of that study report emphasized the high degree of difficulty inherent in this approach. The R2 technique should therefore only be used by well-trained dental practitioners in cases where they deem excellent marginal adaptation of the RBC is feasible without a matrix.[24] In any case, to ensure good marginal quality, it is important to carefully remove excess adhesive and RBC.[38,61,62] It is also advisable that dental practitioners meticulously check DME restorations with a fine explorer and take a bitewing radiograph to assess the marginal adaptation before they proceed with the restorative treatment.

Dental practitioners or patients may sometimes defer the provision of an indirect restoration after DME. For example, deep marginal defects ought to be restored prior to endodontic treatment to establish restorability and allow rubber dam isolation.[63,64] However, for a variety of reasons, indirect restorations are occasionally made with delay after endodontic treatment. It is unclear under what circumstances an existing RBC restoration may be left in place as DME. No laboratory studies are currently available that exposed DME restorations to artificial aging before bonding of an indirect restoration. The maximum time between DME and final insertion of an indirect restoration in clinical studies was 12 weeks.[22] More research is therefore needed to evaluate whether intact, direct RBC restorations may be used as DME after prolonged clinical use. Likewise, given the paucity of data on the long-term stability of DME in teeth with root canal treatment, research on DME in endodontically treated teeth is needed.[63]

The adhesive interface between the DME and the indirect restoration is not viewed as a weak point.[4] Nevertheless, it is important to appropriately pretreat the occlusal DME surface to enhance the bonding performance of the restoration placed on top. The laboratory studies included in this review offer scant evidence on such surface pretreatments.[43] However, there is ample evidence on reliable protocols to repair direct RBC restorations and to bond indirect restorations after immediate dentin sealing.[65,66] Arguably, the same principles apply when bonding an indirect restoration after DME. Air-borne particle abrasion with aluminum oxide is the preferred surface treatment of RBC before conditioning the tooth substance and applying adhesive bonding agents. Further research is needed to assess whether the additional application of a two-component silane coupling agent, which improves the repair bond strength of direct RBC restorations,[65] provides benefits for the stability of the interface between the DME and the indirect restoration.

The restorative management of anterior teeth with secondary caries, root caries, and crown-root fractures frequently presents a challenge.[1,67] Yet, case reports aside, evidence on DME in anterior teeth is scarce.[68] Considering the advantages that DME may have over more invasive treatment methods such as surgical extrusion and crown lengthening, studies that investigate DME in anterior teeth are necessary. DME may also be considered in the case of fractured cusps, though this procedure is not supported by strong evidence at present.[69] This is because, with few exceptions, published data are derived from DME in proximal boxes of posterior teeth. It is questionable whether restorations in which DME constitutes a large portion of the restoration margin are compatible with periodontal health.

Restoration margins that infringe on the supracrestal connective tissue attachment are associated with inflammation and loss of periodontal supporting tissue.[19,70] However, the vertical dimension of the supracrestal tissue attachment shows considerable intra-individual and inter-individual variation, making it difficult to estimate whether or not a restoration will violate the supracrestal connective tissue based on mean values calculated in meta-analyses.[71] Periodontal and transgingival probing under local anesthesia helps determining the dimension of the supracrestal tissue attachment at a specific site. Regular follow-up and maintenance are necessary to monitor and maintain periodontal health after DME.[71] Though DME restorations had no adverse effect on periodontal parameters in most studies included in this review, bleeding on probing was found to occur more frequently at sites with DME in one investigation.[22] Thus, further studies with adequate sample sizes are needed to determine whether DME is compatible with periodontal health in the long term. Moreover, considering that localized restoration margins impinging on the supracrestal connective tissue attachment led to periodontal inflammation in some patients but not in others, additional investigations are required to identify the underlying causes for this.[24] Such insights should enable more personalized treatments in the future.

Teeth restored with DME place special demands on the oral hygiene performed by patients to prevent periodontal disease.[22,24] Given that interdental biofilm control is essential for periodontal health and prevention of secondary caries, more research is required to determine the means by which individuals with DME restorations achieve adequate biofilm removal and how to foster long-term adherence to oral hygiene recommendations. In addition, protocols for appropriate maintenance care, including professional debridement with instruments that reduce the risk of iatrogenic damage to dental restorations, need to be established.[72,73]

The most common reasons for DME in clinical practice include defective restorations and carious lesions detected at a stage when nonrestorative treatment is no longer an option. Novel diagnostic approaches, obtaining promising results *in vitro*, may soon facilitate early detection of proximal root caries lesions.[74] Moreover, machine learning applications are on the verge of causing a step change in

caries detection and diagnosis.[75] Improved detection of early lesions combined with refined measures for noninvasive caries control may thus open the avenue for treating more teeth without restorative intervention.[76]

5 | CONCLUSION

Current evidence, based largely on *in vitro* studies and a very small number of clinical investigations, supports DME as viable approach for restoring teeth with localized subgingival defects. Along with careful case selection, it is important to carry out the restorative procedure with painstaking care to minimize irritation of adjacent tissues and create conditions conducive to long-term success. Regular follow-up visits are necessary to monitor periodontal health, remove microbial deposits, and motivate patients to maintain or improve their oral hygiene. Further clinical studies with long-term follow-up are imperative to corroborate the findings available today and to determine which treatment modalities produce the most favorable outcomes.

ACKNOWLEDGMENTS AND DISCLOSURE

We thank the Gottfried and Julia Bangerter-Rhyner Foundation and the Freiwillige Akademische Gesellschaft Basel (FAG) for providing scholarships for Florin Eggmann during the conduct of this work. The authors declare that they do not have any financial interest in the companies whose materials are included in this article

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://zenodo.org/, reference number https://doi.org/10.5281/zenodo.7455366.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Eggmann F, Ayub JM, Conejo J, Blatz MB. Deep margin elevation—Present status and future directions. *J Esthet Restor Dent*. 2023;35(1):26-47. doi:10.1111/jerd.13008

Received: 24 September 2022 | Revised: 16 October 2022 | Accepted: 18 October 2022

DOI: 10.1111/jerd.12979

RESEARCH ARTICLE

WILEY

Clinical in-situ evaluation of the effect of rubber dam isolation on bond strength to enamel

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Abstract

Objective: To evaluate the effect of rubber dam isolation on shear bond strength of two different adhesive systems to enamel.

Materials and Methods: The mesial, distal, lingual, and vestibular enamel surfaces of thirty human third molars were prepared (total $n = 120$). A custom splint was made to fit a volunteer's maxilla, holding the specimens in place in the oral cavity. Four composite resin cylinders were bonded to each tooth with one of two bonding agents (OptiBond FL and Prime&Bond active) with or without rubber dam isolation. Shear bond strength was tested in a universal testing machine and failure modes were assessed. Significance level for statistical analyses was set at 5%.

Results: All pairwise comparisons revealed statistical differences ($p < 0.05$). The highest mean shear bond strength values were obtained in rubber dam experimental groups, regardless of the adhesive system. Group OptiBond FL with rubber dam presented the highest mean bond strength values. Fracture modes for specimens bonded without rubber dam isolation were adhesive and cohesive within enamel, while rubber dam experimental groups revealed only cohesive fractures.

Conclusions: Absolute isolation with rubber dam increases bond strength to enamel, independent of the adhesive system. The three-step total-etch system OptiBond FL provided significantly higher bond strength values than Prime&Bond active under both experimental conditions.

Clinical Significance: Rubber dam isolation has a significant effect on bond strengths to enamel, independent of the adhesive system. Its application is, therefore, advised whenever adhesive procedures are performed. A filled three-step etch-and-rinse adhesive performed superiorly, with or without rubber dam isolation, when bonding to enamel compared to an isopropanol-based universal adhesive.

KEYWORDS
absolute isolation, adhesion, adhesive system, enamel, humidity, rubber dam, shear bond strength

1 | INTRODUCTION

Today, the great majority of restorative procedures requires adhesive techniques.[1] The clinical success of these restorations is directly related to the bond strength and its durability to prevent marginal gap formation, bacterial leakage, postoperative sensitivity, recurrent caries, and loss of the restoration.[1,2]

In addition to adequate material selection, proper adhesive protocols and techniques must be followed meticulously to enhance clinical outcomes and ensure long-term success. Quality of the resin-adhesive-tooth interface is not only influenced by the chemical composition of the bonding agents and the applied polymerization protocols but also by the environment to which they are exposed, such as temperature and humidity.[3–7]

Proper moisture control is one of the most challenging steps in adhesive dentistry. Previous studies have shown that keeping a dry enamel surface by eliminating remnant moisture prior to adhesive application is crucial for long-term bond durability.[8,9] Bonding surfaces are exposed to saliva, blood, and crevicular fluid but also to water molecules present in exhaled air.[9,10]

The amount of water saturated in exhaled air is often ignored. However, it is reported to be about 27 mg/dm^3 and its possible detrimental effects on the bonding interface require thorough evaluation.[11] The average oral temperature and relative humidity are around 30°C and 80% respectively, with humidity ranging from 74% to 94%.[1,12] Factors that may influence relative humidity include tooth position within the dental arches, the patient's nose or mouth breathing, and use of protective devices such as rubber dam.[12]

The rubber dam isolation technique was first proposed in 1864.[13] It offers many advantages, such as reduced humidity, lower contamination of the operating field by saliva, blood or crevicular fluid, decreased risk of cross-infection, and enhanced safety by preventing injuries to the surrounding soft tissues as well as leakage or aspiration of dental materials.[5,10,14] In spite of the apparent benefits, the majority of dentists never or only rarely use rubber dam isolation during operative dentistry procedures. Whether absolute isolation with rubber dam or relative isolation, for example with cotton rolls and high-speed suction, have any effect on clinical outcomes is a common but largely unanswered question among clinicians.[15–17]

Adhesive systems can be divided into etch-and-rinse and self-etch adhesives.[18–20] The effectiveness of etch-and-rinse adhesive systems on enamel surfaces is well supported by the literature.[9] However, to simplify the clinical procedures, universal adhesives have been introduced. These all-in-one adhesives combine etching, priming, and bonding into a single bottle and application step, allowing the operator to select either an etch-and-rinse, self-etch or selective-enamel-etch adhesive strategy. Such universal adhesive systems are widely accepted but may not offer the same bond strength values and durability as their predecessors.[20–23]

There are only few scientific studies evaluating the effects of oral humidity on bond strength, and the ones that exist fail to provide valid experimental models.[24,25] In vitro studies can provide valuable information about physical and biomechanical properties of materials in a controlled and calibrated laboratory environment, purposely eliminating some hard-to-control influencing parameters. On the other hand, interoperative variations, individual patient factors, and the intraoral environment may well influence clinical outcomes and contribute to the differences in bond strength values found between in vivo and in vitro studies.[26,27] Most often, temperature and relative humidity are simulated in experimental chambers. However, these devices are not capable of fully replicating oral environment conditions. Testing adhesive restorations performed in a patient's oral cavity provides additional and more accurate information on the actual effects of relative humidity.[26]

This clinical study evaluated the effect of rubber dam isolation on shear bond strength of two different adhesive systems, OptiBond FL (Kerr Corporation, California, USA) and Prime&Bond active (Dentsply Sirona, Konstanz, Germany), to enamel.

The research hypotheses were:

1. Rubber dam isolation improves shear bond strength to enamel, independent of the adhesive system used.
2. Highly filled three-step etch-and-rinse adhesive provides higher bond strength values than an isopropanol-based universal adhesive.

2 | MATERIALS AND METHODS

2.1 | Specimen preparation

According to the notification CE-001/2013, the specimen collection and clinical part of this study were approved by the Ethics Committee of the Faculty of Medicine of the University of Coimbra. Thirty sound human third molars, clinically and radiographically free of caries, cracks, restorations, root canal treatment or other abnormal features were collected, immediately cleaned with periodontal scalers, and polished with pumice and water to remove adherent organic material or calculus. The teeth were stored in distilled water for a maximum of 3 months, followed by immersion in chloramine for 5 weeks at 4°C. Afterwards, they were placed in a cylindrical mold and embedded in auto-polymerizing acrylic resin (Schmidt Dental Solutions, Madrid, Spain; batch number 47975) up to the cementoenamel junction. Each tooth had the mesial, distal, lingual, and vestibular enamel surfaces carefully flattened with a conical diamond bur (105–120 μm grit) under water cooling, attached to a parallelometer. All preparations were kept in sound enamel. The surfaces were finished with coarse contouring and polishing discs (Sof-Lex, 3 M, California, USA). Bonding procedures were performed immediately after preparation of the enamel surfaces.

For the clinical part of the study, a 26-year-old female volunteer with no history of previous carious lesions and a plaque index lower than 10% was recruited. All procedures were conveniently explained without disclosing details regarding the study aims and explicit written consent was signed by the volunteer patient who agreed and approved the terms.

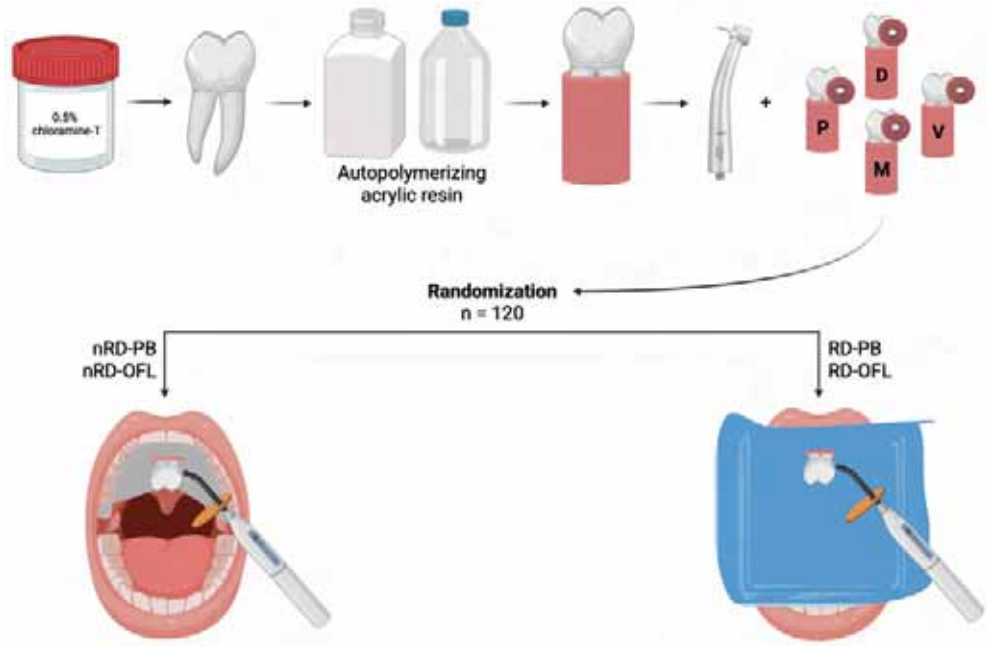

FIGURE 1 Schematic representation of the specimen preparation and intraoral set up during bonding procedures according to the experimental groups P (palatal or lingual), D (distal), V (vestibular), M (mesial), nRD (no rubber dam), RD (rubber dam), PB (Prime&Bond active), OFL (OptiBond FL). Created with BioRender.com.

2.2 | Oral device design

A custom splint was fabricated to fit a volunteer's maxillary arch. The custom splint was digitally designed (Zirkonzahn Software-Module CAD/CAM Bite Splints version 9071, Zirkonzahn, Gais, Italy) using an intraoral scan (Primescan, Dentsply Sirona, Bensheim, Germany) and 3D-printed in NexDent Model 2.0 white resin (Vertex-Dental B.V., Soesterberg, Netherlands) with a NextDent 5100 printer (3D SYSTEMS, Vertex-Dental B.V.). The oral splint featured a palatal cylindrical slot that fit the acrylic bases of the extracted teeth, exposing only the teeth's crowns while giving full access to all four tooth surfaces (mesial, distal, vestibular, lingual).

2.3 | Experimental groups

The experimental groups were:

- RD-OFL: OptiBond FL adhesive applied under rubber dam isolation
- nRD-OFL: OptiBond FL adhesive applied without rubber dam
- RD-PB: Prime&Bond active adhesive applied under rubber dam isolation
- nRD-PB: Prime&Bond active adhesive applied without rubber dam

Each one of the four prepared enamel surfaces was randomly assigned to one of the four experimental groups with a research randomizer (https://www.randomizer.org) for a total of 120 specimens. All four experimental groups were tested on the same tooth to allow direct comparisons in identical enamel conditions. Specimen preparation and experimental groups are illustrated in Figure 1.

2.4 | Bonding procedures

The teeth were attached one by one to the slot in the oral device, with the area to be restored facing the anterior region, thus simulating the normal positioning and angle of a central incisor being restored on the vestibular aspect. A thermo-hygroscope was used to record the dental office's environmental conditions. The room's relative humidity was kept at 46% and the temperature was kept at 22°C. One experienced operator performed all experimental procedures under 10x magnification (Leica M320, Leica Microsystems, Heerbrugg, Switzerland).

All procedures prior to the adhesive application were performed outside of the patient's mouth to avoid any cross-contamination between fluids that contacted the tooth samples and the patient's oral cavity. In all experimental groups, each prepared enamel surface was etched for 30 s with 37.5% phosphoric acid (Gel etchant, Kerr Corporation, California, USA) followed by a thorough rinse with an air-water stream for 30 additional seconds and air dried with a strong air flow until completely dry. Each sample was then placed inside the patient's mouth according to the specificities of the tested groups.

During the bonding procedure of experimental groups performed under relative isolation (nRB-OFL, nRB-PB), the patient was instructed to breathe through the nose and a suction cannula was placed to remove excess moisture. In both groups, the etched enamel surfaces were air-dried one more time to ensure total absence of water and left to rest for 30 s without the presence of any oral fluids to better mimic clinical conditions. One of the two bonding systems, total-etch (nRB-OFL) or universal (nRB-PB), was actively applied with a microbrush for 20 s, after which the surfaces were airdried with a mild air flow free of any oil or water residues for 10 s and light-cured for 20 s with a polywave LED curing light source with a measured intensity of 1200 mW/cm^2 (Bluephase Style 20i, Ivoclar Vivadent, Schaan, Liechtenstein).

For the bonding procedure of the experimental groups performed under absolute isolation (RB-OFL, RB-PB), a rubber dam sheet (Nic Tone, MDC Dental, Jalisco, Mexico) was punctured with a single hole, placed around the tooth's crown, and held in place by a clamp and a frame holder. Once the enamel surfaces were air dried with a strong air flow until completely dry, one of the two adhesive systems, total-etch (RB-OFL) or universal (RB-PB), was actively applied with a microbrush for 20 s, after which the surfaces were airdried with a mild air flow free of any oil or water residues for 10 s and light-cured for 20 s.

The dentin primer of the OptiBond FL system was not applied to any of the surfaces since all tested samples consisted exclusively of enamel. Once the application of the bonding systems was concluded, a composite resin (Ceram.X.Spectra ST Low Viscosity, Dentsply Sirona, Konstanz, Germany) was condensed into a soluble translucent cylindrical capsule with 4.39 mm height and a 2.54 mm internal diameter, positioned onto the prepared enamel surface, and polymerized from all sides with the LED light-curing unit for a total of 80 s. Materials, manufacturers, chemical composition, and lot numbers are listed in Table 1. After bonding procedure completion, each specimen was stored in distilled water at 37°C for 7 days.

2.5 | Shear bond strength testing

The testing sequence was randomly defined for both the teeth and the groups within each tooth. One blind-to-the-groups, calibrated and experienced operator performed the shear bond strength tests. All 120 specimens were placed in a universal testing machine (model AG-I, Shimadzu Corporation, Kyoto, Japan) and a shear load was applied at the bonding interface until failure with a crosshead speed of 0.5 mm/min. Failure load was recorded in Newtons (N) and calculated in Megapascals (MPa) by dividing the failure loads by the bonding area (N/mm^2).

2.6 | Failure mode analysis

The fracture surfaces were independently evaluated by two blinded-to-the-groups examiners with a dental operating microscope (Leica M320, Leica Microsystems, Heerbrugg, Switzerland) under 40x magnification. The failure modes were classified as:

(0) - adhesive failure. (1) - cohesive failure within enamel. (2) - cohesive failure within the composite resin. (3) - mixed failure within enamel. (4) - mixed failure within the composite resin.

2.7 | Statistical analysis

Statistical analysis was performed with IBM SPSS for Windows version 26.0 (SPSS, Chicago, Illinois, USA) and MS Excel (Microsoft Corporation, Redmond, Washington, USA). The significance level was set at 5% ($\alpha = 0.05$). The shear bond strength results were described using mean, standard deviation, minimum and maximum values. After verifying the normality of data distribution with the Shapiro–Wilk test, repeated measures ANOVA testing was carried out to detect statistically significant differences between the means across groups. Post-hoc multiple pairwise comparisons were performed with the Dunn–Šidák test.

TABLE 1 Materials specifics

Material (abbreviation)	Manufacturer	Type	Composition	Lot number
OptiBond FL (OFL)	Kerr Corporation, California, USA	Three-step total-etch adhesive	Primer: 2-hydroxyethyl methacrylate, ethanol, 2-[2(methacryloyloxy) ethoxycarbonyl] benzoic acid, glycerol phosphate dimethacrylate Bond: glass, oxide, chemicals, 2-hydroxyethyl methacrylate, Ytterbium trifluoride, 3-trimethoxysilylpropyl methacrylate, 2-hydroxy-1,3-propanediyl bismethacrylate, alkali fluorosilicates (Na)	7831887
Prime&Bond active (PB)	Dentsply Sirona, Konstanz, Germany	Universal adhesive	Bi- and multi-functional acrylate, phosphoric acid-modified acrylate resin, initiator, stabilizer, isopropanol, water	2011000070
Ceram.X.Spectra ST Low Viscosity	Dentsply Sirona, Konstanz, Germany	Composite resin	Ethoxylated bisphenol A dimethacrylate, urethane modified Bis-GMA dimethacrylate resin, 2,2-ethylenedioxydiethyl dimetharcylate, ytterbium trifluoride, 2,6-di-tert-butyl-p-cresol	2008000516
Gel etchant 37.5%	Kerr Corporation, California, USA	Etching gel	Phosphoric acid 35–40%, cobalt alumina blue spinel	7831887
Nic tone dental dam (thick)	MDC Dental, Jalisco, Mexico	Rubber dam	Latex	11068038

To evaluate the differences between failure modes, McNemar testing was used between all pairs of groups. The p-value was corrected by the Benjamini-Hochberg method (false discovery rate controlling procedure) for multiple comparisons (false positive rate of 0.05).

A power analysis was performed in G* Power 3.1.9.2 software and a repeated measures ANOVA test ($\alpha = 0.05$) was considered. The power achieved was 100%.

3 | RESULTS

3.1 | Shear bond strength

Statistically significant differences were observed between the experimental groups regarding shear bond strength ($p < 0.001$). Multiple pairwise comparisons revealed statistical differences between all study groups ($p < 0.001$), except for the comparison between nRD-PB and nRD-OFL ($p = 0.008$), as shown in Figure 2. The highest mean shear bond strength values were obtained in rubber dam experimental groups, regardless of the adhesive system (Table 2). OptiBond FL revealed greater mean shear bond strength values under both conditions (with and without rubber dam isolation).

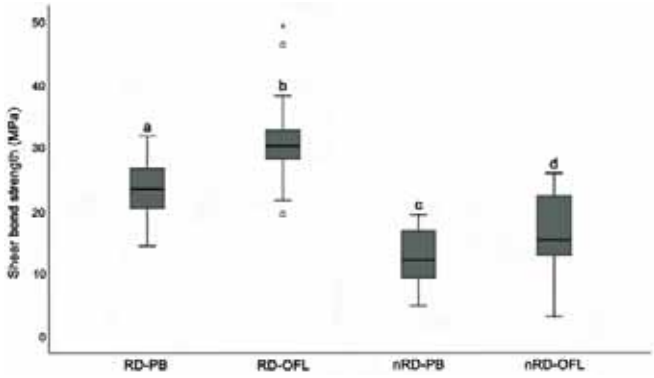

FIGURE 2 Box-plot of shear bond strength distribution within the study groups. Groups indicated by different letters present statistically significant differences ($p < 0.05$) according to the Dunn–Šidák post-hoc test.

3.2 | Failure mode analysis

Cohesive failures within enamel exclusively occurred in rubber dam experimental groups (Table 2). Failures were mostly adhesive in RD-PB and RD-OFL groups (56.7% and 66.7%, respectively). All specimens in the two no-rubber dam groups failed adhesively. No mixed or cohesive failures within the composite resin were observed.

Prime&Bond active and OptiBond FL showed no statistically significant differences regarding failure modes when tested under the same experimental conditions with or without rubber dam isolation ($p > 0.05$, Table 2). However, a statistically significant predominance of cohesive failures was observed in rubber dam compared to no-rubber dam groups, within the same and between both tested adhesive systems ($p < 0.05$).

4 | DISCUSSION

Our findings support the hypothesis that rubber dam placement minimizes the detrimental effects of intraoral humidity, ultimately improving shear bond strength of both tested adhesive systems, a three-step total-etch (OptiBond FL) and a universal adhesive (Prime&Bond active), to enamel under clinical conditions. In addition, OptiBond FL revealed higher enamel bond strength values than Prime&Bond active, independent of rubber dam isolation during the bonding procedures. Therefore, both research hypotheses were accepted.

Of the few bonding studies where relative humidity effects are considered, most opt to test the bond strength to dentin and overlook the importance of enamel bonding. While adhesion to dentin may even benefit from a moist environment, enamel bonding requires dry conditions without any water or moisture to attain peak bond strength. Failure to ensure optimal conditions for proper bonding to enamel will lead to poor marginal sealing and, ultimately, restorative failure.[8] Therefore, bond strength studies to enamel under clinically relevant conditions are critically important.

Statistically significant differences in bond strength values were detected among all groups, with higher mean shear bond strength values in experimental groups with rubber dam isolation. When properly placed, rubber dam serves as a shield to relative humidity in the oral cavity, which, as shown, has a negative effect on the adhesive interface. These findings are in accordance with previous reports that

TABLE 2 Study groups' mean bond strength values (MPa), percentage of failure mode and failure mode proportion comparison

Study group	Shear bond strength (MPa) Mean ± SD*	Failure mode		
		Adhesive	Cohesive in enamel	Proportion comparison*
RD-PB	23.16 ± 4.26[a]	17 (56.7%)	13 (43.3%)	a
RD-OFL	30.84 ± 6.31[b]	20 (66.7%)	10 (33.3%)	a
nRD-PB	12.57 ± 4.12[c]	30 (100%)	0 (0%)	b
nRD-OFL	16.33 ± 6.08[d]	30 (100%)	0 (0%)	b

Note: Different letters within each column indicate statistically significant differences between the study groups regarding shear bond strength and failure mode proportion ($p < 0.05$).

a dry working field cannot be established in the oral cavity without the correct application of a rubber dam.[12] Similarly, one in vitro study demonstrated that bond strength declines with increasing temperature and humidity in an environmental chamber. Significantly worse values were obtained for the group exposed to 37° C and 90% relative humidity, supporting the recommendation that composite resin restorations should be made under absolute isolation.[3] Authors who studied analogous hypotheses chose simulate the oral environment simulation in a controlled humidity chamber.[27] However, there are possible disadvantages to this method: the chamber's inability to replicate natural inhalation, down time, and exhalation cycles as they occur in clinical scenarios. In addition, the constant high humidity may impair water evaporation, directly promoting a bias towards an adverse outcome.[12,26]

In another study, the microshear bond strength of a resin composite to enamel was tested with three different adhesive systems applied at various humidity conditions.[27] However, contrary to what was observed in the present study, no significant influence of humidity on bond strength to enamel was found. The divergence of results might be explained by the differences in the experimental protocols and adhesive systems used. Despite that, this same study stated that total-etch and two-step self-etch adhesive systems exhibited significantly higher microshear bond strength values than that of one-step self-etch adhesives to enamel, for all humidity conditions.[27] In the present study, higher mean shear bond strength values were found with OptiBond FL when both adhesive systems are tested under the same isolation conditions. Moreover, when analyzing standard deviations, groups in which rubber dam was used exhibit standard deviations of about 20% of the mean shear bond strength value, whereas in the experimental groups where absolute isolation was not performed, higher standard deviations of approximately 33% for the universal system and 42% for the three-step total-etch system were found, suggesting less variation and greater predictability when rubber dam isolation is used.

Even though the three-step total-etch system showed higher mean values of shear bond strength in both experimental conditions, with and without absolute isolation (30.84 MPa and 16.33 MPa respectively), it was also the one with greater differences between maximum and minimum bond strength values (25.94 MPa and 3.00 MPa, respectively) in the group without rubber dam. These findings indicate that OptiBond FL can be highly susceptible to relative humidity and unpredictable without proper isolation, which may be due to its chemical composition. HEMA is a hydrophilic monomer found in OptiBond FL, absent from Prime&Bond active. If water absorption takes place before polymerization, it may lead to a reduction in the degree of polymerization conversion due to dilution of the adhesive system.[6,18,21] Increased content of HEMA in adhesives decreases the degree of conversion and may jeopardize the polymer mechanical properties.[7,19]

In this study, failure modes were either adhesive or cohesive in enamel. Out of the two, there was a higher proportion of overall adhesive fractures. However, it is worth mentioning that cohesive enamel fractures were exclusively registered in experimental groups where rubber dam was used. This suggests that the absence of absolute isolation compromises the bonding interface. When adequate absolute isolation techniques were used, either adhesive system tested could provide bond strength values that exceeded the cohesive strength of enamel itself. Furthermore, failure modes were similar among groups where the same experimental conditions were tested, meaning that no significant difference in fracture type between adhesive systems was found, independent of isolation. Besides bond strength values, failure patterns are important parameters that must be assessed when evaluating adhesion, since the cohesive strength of dental substrates sets the bar for the expected performance of adhesive systems.[27]

Although the present study was performed in situ, higher relative humidity values are expected to be found in clinical conditions when rubber dam is not used or is improperly placed.[26] The custom-designed oral device used in this experimental work may have led to improved relative isolation compared to the clinical environment since humidity from surrounding tissues was completely blocked (i.e., gingival crevicular fluid, saliva, or blood). In addition, the capsule used to apply the composite resin also shielded the restorative material from humidity immediately after being placed. It is also worth noting that restorative procedures in a clinical environment are more time-consuming and, therefore, increased exposure to humidity and consequent effects on adhesion are expected. In this study, the best-case scenario was simulated, meaning that the tooth slot was in a location equivalent to that of the vestibular surface of an anterior tooth. Other oral locations, such as mandibular teeth or even posterior upper teeth, are exposed to a higher degree of humidity and moisture and may, therefore, suffer from more pronounced effects. A previous study showed that significantly higher temperatures and relative humidity values are found at molar sites than those found in the incisor positions (incisor 26.2°C/84.8%RH vs. molar 27.3°C/90.7%RH).[26] In the present study, intraoral conditions were standardized by performing procedures in only one patient. However, differences between patients' oral environments should be considered in further studies. One study stated that during mouth breathing, temperatures are significantly higher, and the amount of exhaled water is higher than during to nose breathing. Thus, even though our volunteer was instructed to breathe through the nose, differences between patients' breathing patterns must be taken into consideration.[1,11,25] Although intraoral temperature and relative humidity values were not recorded in this study, a previous study showed that the placement of different isolation methods produces significant alterations in intraoral temperature and relative humidity.[5] The room's environmental conditions also influence these values.[5] Regarding the use of rubber dam, one study evaluated how different types, number of exposed teeth and air vents in the rubber dam sheet influence temperature and relative humidity. It was concluded that simple moisture exclusion with cotton rolls is insufficient (100% relative humidity) and that rubber dam isolation lowers relative humidity to levels equivalent to those of the room. However, the same cannot be said about temperature. Additionally, it was concluded that there is no difference in moisture exclusion when a single tooth or multiple teeth are exposed.[5]

The present study demonstrates that intraoral relative humidity has a significant effect on bond strength values to enamel. Without adequate rubber dam isolation, the performance of dental adhesives

is compromised, thus potentially compromising the longevity of restorations and with long-term consequences on our patient's oral health. Further clinical considering different intraoral sites and including multiple patients with different breathing patterns, followed by sample aging, are needed to evaluate long-term effects of rubber dam use. Ultimately, clinical studies should be implemented to correlate restoration survival with humidity levels during bonding procedures.

5 | CONCLUSIONS

Within the limitations of this clinical study, the following conclusions were drawn:

1. Absolute isolation with rubber dam increases bond strength to enamel, independent of the adhesive system.
2. The three-step total-etch system OptiBond FL provided significantly higher bond strength values than Prime&Bond active under both experimental conditions.

ACKNOWLEDGEMENT AND DISCLOSURE

The authors thank Professor Francisco Caramelo from the Coimbra Institute for Clinical and Biomedical Research (iCBR), Laboratory of Biostatistics and Medical Informatics (LBIM), Faculty of Medicine, University of Coimbra for promptly and carefully assisting with the statistical analysis. The authors also thank Dr. Raphaël Gameiro (Dental Technician) for modeling and manufacturing the custom-designed splint used to position samples intra-orally. The authors do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Falacho RI, Melo EA, Marques JA, Ramos JC, Guerra F, Blatz MB. Clinical in-situ evaluation of the effect of rubber dam isolation on bond strength to enamel. *J Esthet Restor Dent*. 2023;35(1):48-55. doi:10.1111/jerd.12979

Received: 14 November 2022 | Revised: 28 November 2022 | Accepted: 29 November 2022

DOI: 10.1111/jerd.12998

RESEARCH ARTICLE

WILEY

Shrinkage-induced cuspal deformation and strength of three different short fiber-reinforced composite resins

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Abstract

Objective: The aim of this study is to assess the shrinkage-induced cuspal deformation and strength of large MOD restorations using three different short fiber-reinforced composite resins (SFRC).

Materials and Methods: Twenty-seven typodont teeth #30 (Columbia) received a standardized slot-type preparation (5-mm by 5-mm depth and bucco-palatal width). Three types of SFRCs (everX Posterior, everX Flow, and a 50/50 mixture of both materials) were used with the Optibond FL bonding system. The intercuspal distance of each specimen ($n = 9$) was measured after preparation, immediately after restoration and at 3, 18, and 24 h. Each specimen was then subjected to simulated mastication (30° angulation with cyclic loading of buccal cusp at 5 Hz), starting at 100 N with 100 N increase every 100 cycles until fracture. Failure mode was determined as re-restorable versus nonrestorable failures. Cusp deformation data were analyzed by two-way repeated measures ANOVA and the fracture performance by Kaplan–Meier survival analysis.

Results: Shrinkage-induced cuspal deformation ranged from 27–34 microns (immediately) to 33–43 microns (24 h). The largest deformations were observed for everX Flow and the 50/50 mixture (up to 43 microns at 24 h), which also demonstrated the lowest average strength (1456 to 1511 N). everX Posterior demonstrated the least amount of shrinkage-induced cuspal deformation (27 microns, up 33 microns at 24 h) and the higher average strength (1744 N). everX Flow tended to demonstrate more repairable partial fractures while everX Posterior induced mainly catastrophic failures.

Conclusions: Large direct MOD restorations were most favorably restored with everX Posterior (less shrinkage, higher strength) at the expense of failure mode. everX Flow induced more friendly failure modes but more shrinkage-induced cuspal deformation.

Clinical Significance: When a low-cost restoration must be chosen, EverX Posterior will significantly improve the performance but not the failure mode of directly layered restorations. Because of its increased shrinkage values, everX Flow is best indicated as a limited liner to cover the IDS layer and improve geometry for semi-(in) direct restorations.

KEYWORDS
cusp deformation, fatigue resistance, short fibers, shrinkage stress

1 | INTRODUCTION

Large direct posterior restorations require mastering of shape, contours, occlusal anatomy, and function,[1,2] The dilemma of polymerization shrinkage,[3,4] and shrinkage stresses constitute additional daily challenges faced by dental professionals. When a successful adhesive protocol is used, the shrinkage can cause cuspal deformation and enamel cracks at the cusp base.[5,6] Hence, reduction of contraction stresses should be a priority in selecting the appropriate direct techniques.[7]

Various approaches have been proposed to manage shrinkage, such as elaborate layering techniques,[8] sandwich approaches using glass ionomer bases,[9] and fiber meshes,[10] in addition to delayed and slow-start light polymerization protocols.[11] It important to note, however, that most of the shrinkage stress develops during and after the vitrification stage and keeps progressing in the absence of light. Thus, the relaxation of the stress is limited when considering the time scales proposed for the soft polymerization protocols[12] and for the conversion rate to be clinically adequate. In other words, slow-start polymerization should be so slow that the resin would end up being unable to polymerize to an acceptable conversion rate.

The use of glass ionomer bases in the open and closed sandwich restorations can help minimize the shrinkage stress, and even more so with the use of the new "super-closed" technique, in which the volume of shrinking material is reduced significantly.[9] Layering techniques were also believed to help but do not necessarily have the ability to reduce shrinkage stresses[13,14] and might even yield worse results compared with bulk filling.[15] This is because of the V-factor of the restoration,[16] the amount of which can be related to the volume of the restoration and will increase with the distance between the most remote points of the cavity. Even when "stress-reducing" techniques are used (sophisticated layering, irradiation modes, and etc.), a large restoration will still generate major deformation. Factors influencing stress development are extremely complex (conversion rate, shrinkage, elastic modulus, shape, boundary conditions, and etc.) and the context that generates stresses should be always considered, including volume and size. Reducing the V-factor is a valid approach. It can be achieved by introducing nonshrinking components ("megafillers") such as conventional GIC in the sandwich technique, prepolymerized inserts, or using semi-(in)direct and indirect techniques (inlays). During the past decade, manufacturers have started to focus on simplifying direct techniques by proposing bulk filling materials. Among them, a short fiber-reinforced composite (SFRC) was introduced for high-stress bearing areas in 2013 (EverX Posterior, GC, Leuven, Belgium).[17] It offers a combination of flexural modulus and fracture toughness that is unique within the group of bulk-fill materials (12.6 GPa and 2.6 MPa $m^{1/2}$, respectively). It can be used in 4-mm deep increments, and can potentially match the toughness of dentin.[18,19] In a large MOD defect, it can possibly improve the performance of direct restoration to the same level as a CAD/CAM indirect restoration.[20] Due to the high viscosity (5%–15% content by weight of 0.017 by 0.8 mm e-glass fibers) and limited esthetics of everX Posterior, the manufacturer came up with a flowable version in 2019. The new product, called everX Flow[21] is designed to address the various challenges that face the users such as workability (low viscosity) and esthetics (dentin color). Due to the smaller size of its e-glass fibers (0.006 by 0.14 mm), the flow version has a higher content of fibers (25% by weight) than its predecessor. It was also presented with a better fracture toughness (2.8 MPa $m^{1/2}$) but lower flexural modulus (9.0 GPa) than everX Posterior. Yet, its shrinkage stress is still higher than its precursor.[22] In large MOD restorations, however, absolute control over the stresses can only be achieved through the use of indirect techniques,[8,23] thus significantly lowering the V-factor and limiting the shrinkage stress to the very thin layer of luting material. CAD/CAM materials are the main tenet of this approach due to their wear properties, color integration, fast processing, and millability in thin layers.[24,25,26,27,28]

The last decade, however, has been marked by challenging economy, inflation, and economic uncertainty. Hence there has been a rise in the demand and popularity of affordable restorations. Contemporary composites resins for direct restorations and the use of SFRC as dentin replacement material in large restorations have the potential of fulfilling this demand. Thus, this work assessed the cuspal deformation (shrinkage induced) and comparative strength of MOD direct SFRC of molars with three different types of formulations (everX Posterior, everX Flow, and 50/50 mixture). The null hypotheses were that (1) no significant differences would be found in cuspal deformation, and (2) there would be no significant difference in strength and failure mode between the three groups.

2 | MATERIALS AND METHODS

Twenty-seven identical plastic teeth (Typodont Tooth #30, Columbia, San Dimas, CA) received a standardized MOD preparation and were then restored in bulk with either (1) flowable fiber-reinforced composite resin (everX Flow; GC), (2) packable fiber-reinforced composite resin base (everX Posterior; GC), and (3) 50/50 mixed fiber-reinforced composite resin bases (everX Flow, everX Posterior, GC). The mixture was prepared in advance by combining equivalent amounts of everX Posterior and Flow, stacking them, pressing them flat and repeatedly folding and pressing them together using a vibrating spatula (Microvibes, Smileline, St. Imier, Switzerland) until a smooth paste was obtained.

The intercuspal distance was measured immediately after preparation, after restoration, as well as at 3, 18, and 24 h following the restoration. All specimens were then subjected to a cyclic load test.

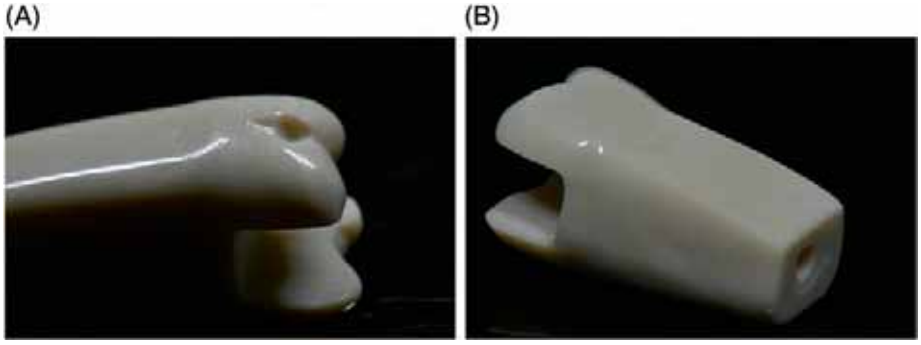

FIGURE 1 Standard MOD tooth preparation 5-mm in bucco-palatal width, 5-mm in depth, (A) buccal view with modified buccal fossa, (B) lingual view with flattened cusp and root.

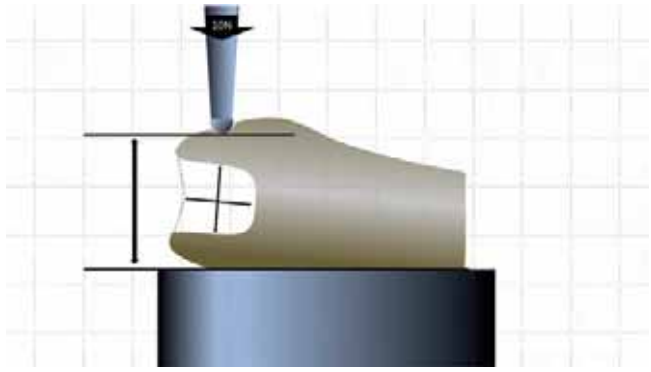

FIGURE 2 Schematic view of specimen laid flat for intercuspal distance measurement in Acumen 3 system (MTS).

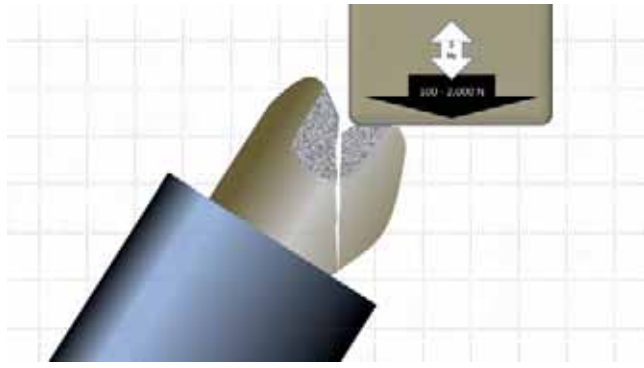

FIGURE 3 Schematic view of specimen positioned at 30° for cyclic loading in Acumen 3 system (MTS).

2.1 | Tooth preparation

A high-speed electric handpiece and tapered diamond bur (ref 6856–027, Brasseler, Savannah, GA) were utilized to prepare a standard MOD slot-type defect with a 5-mm bucco-palatal width and 5-mm occlusal depth under a microscope (Leica MZ 125, Leica Microsystems, Wetzlar, Germany). A round diamond bur (801–010, Brasseler) was used to prep 1 mm-deep fossa on the buccal cusp, centered on the buccal developmental groove (Figure 1A). A model trimmer (Ray Foster 10'' Model Trimmer, USA) was used to flatten the lingual surface of the crown and root (Figure 1B) in order to facilitate intercuspal distance measurements.

2.2 | Initial intercuspal measurement

Each prepared specimen was placed on a flat stainless-steel base on their flattened lingual surface inside the test system (Acumen 3, MTS Eden Praire MN). The contour of the root was drawn on the surface of the base with a pen to guide and repeat the precise positioning at each measurement. A 10 N load was applied to the buccal fossa (at roughly 90° angle from the tooth axis) through a spherical stainless-steel tip (1.5-mm curvature radius) (Figure 2). A total of three measurements were recorded and averaged to determine the exact intercuspal distance before restoration.

2.3 | Restoration

The prepared MOD surface of each specimen was carefully air-abraded (RONDOflex plus 360; KaVo Dental, Charlotte, NC, USA) using 30-μm silica-modified aluminum oxide (Rocatec Soft; 3M-ESPE, St. Paul, MN, USA) for 15 s at a distance of 10 mm with a pressure of 30 psi, followed by the application of 1 coat of adhesive resin (Optibond FL, bottle 2; Kerr, Orange CA). EverX restorative material was then used to bulk-fill the entire defect and was polymerized for a total of 60 s (3×20 s) at 1,000 mW/cm^2 (VALO Curing Light, Ultradent Products, Inc., South Jordan, UT, USA). The margins were mechanically polished (Diacomp Featherlite, Brasseler). Occlusal anatomy was modified by creating a 1 mm-deep mesio-distal groove at 90° angle to the occlusal surface (round fine diamond 801–010 bur) for all three groups to induce failure at a predictable location (Figure 3).

2.4 | Repeated intercuspal measurements

Restored specimens were kept at ambient temperature and the intercuspal distance was measured again immediately after restoration, and at 3, 18, and 24 h. Each measurement was repeated three times. The difference between the baseline position (initial measurement after preparation) and subsequent measurement at 3/18/24 h was calculated.

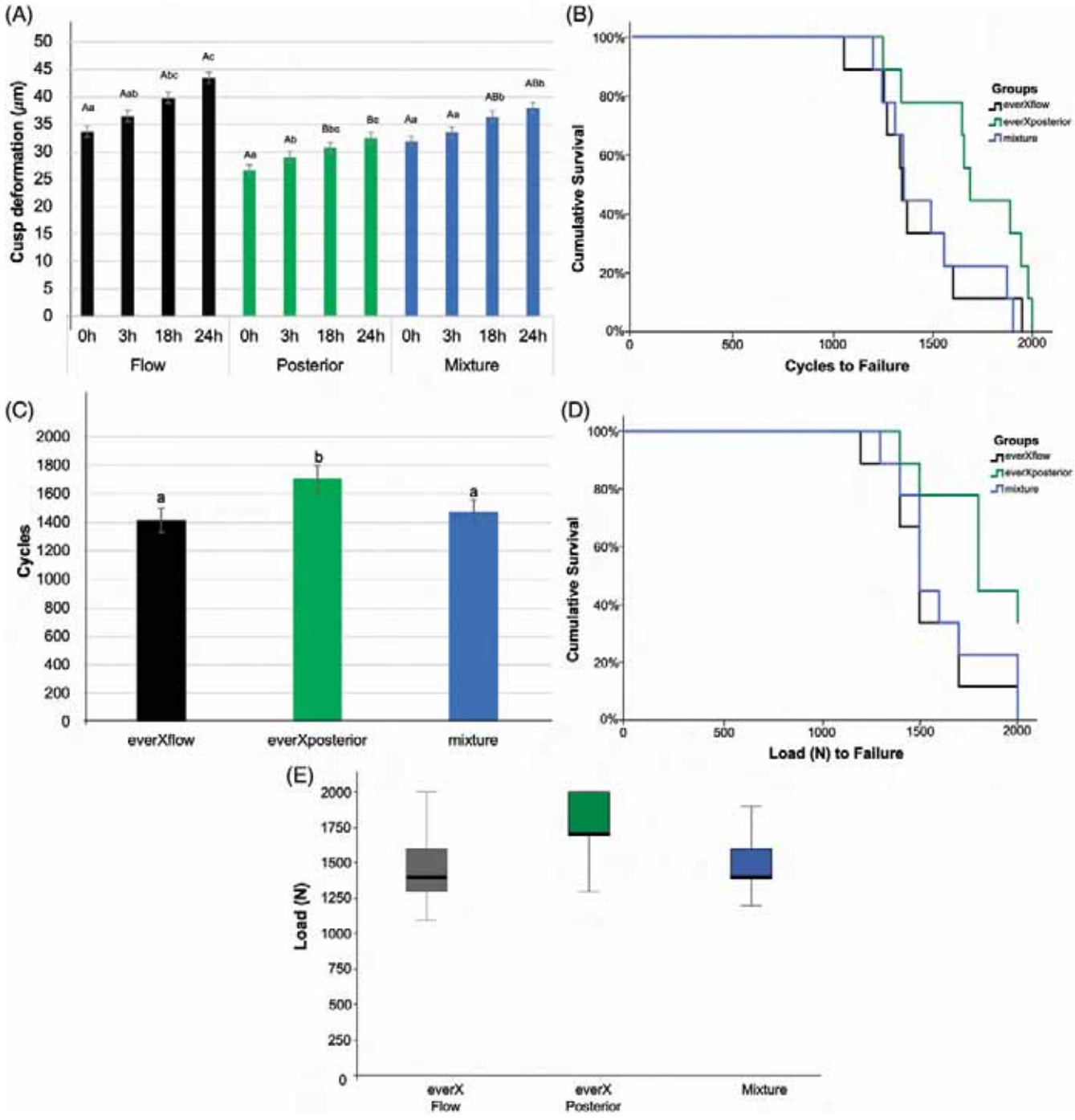

FIGURE 4 (A) Mean cusp deformation (µm ± SE) of the three experimental groups for the four different times. Different capital or small letter indicates statistically significant difference within the same time and within the same composite, respectively. (B) Kaplan–Meier fatigue resistance survival curves for cycles of all three groups. (C) Mean survived cycles and standard errors of cycles to failure. Kaplan–Meier and Log Rank post hoc test ($p < 0.05$) with different letters indicating significant differences. (D) Life table survival curves for load of all groups. (E) Box-and-whisker diagram of load at failure (in Newtons) presenting median (bold black horizontal line), minimum and maximum values (whiskers), total number of specimens ($N = 27$, $n = 9$), and interquartile range (box).

2.5 | Accelerated fatigue test

Once intercuspal assessments completed, specimens were mounted in a stainless-steel positioning jig 3 mm below the simulated cementoenamel junction using acrylic resin (Palapress vario; Heraeus Kulzer, Armonk, NY, USA). The test was carried in an artificial masticatory machine using a closed-loop electrodynamic system (Acumen 3). The masticatory test was simulated through a flat composite resin CAD/CAM antagonist (Lava Ultimate; 3M-ESPE-CEREC) contacting the whole buccal cusp slope (30° angle to the tooth axis). The cusp

TABLE 1 Mean cusp deformation (μm ± SE) for the three experimental groups at the four different times

	Time			
Material	0 h	3 h	18 h	24 h
everX Flow	33.7 ± 2.3^{Aa}	36.5 ± 2.9^{Aab}	39.8 ± 2.8^{Abc}	43.4 ± 2.5^{Ac}
everX Posterior	26.6 ± 1.1^{Aa}	29.0 ± 1.2^{Ab}	30.7 ± 1.5^{Bbc}	32.5 ± 1.5^{Bc}
50/50 mixture	31.9 ± 2.3^{Aa}	33.5 ± 1.9^{Aa}	36.4 ± 2.4^{ABb}	38.0 ± 2.4^{ABb}

Note: Two-way repeated measures ANOVA followed by Bonferroni adjustment for multiple pairwise comparison. Different superscript capital or small letter indicates statistically significant difference in the columns and rows, respectively.

slope was finished perfectly flat using sandpaper (1500-grit) while gently loading with the antagonist. Isometric contraction forces (load control) were applied. The cyclic load was applied at a frequency of 5 Hz, starting with a load of 100 N, which increased by 100 N every 100 cycles until 2,000 N. All load tests were uninterruptedly recorded and monitored using a macro video camera (Canon Vixia HF S100, Canon USA, Melville, NY). Samples were cyclically loaded until fracture and the number of endured cycles and failure modes of each specimen was recorded. After the test, each sample was photographed and evaluated (two-examiner agreement).

2.6 | Statistical analysis

The Shapiro–Wilk test was used to assess the normal distribution of the data ($p > 0.05$) and a visual inspection of their histogram, normal Q–Q plots, and box plots showed that the data were approximately normally distributed. Levene's test showed homogeneity of variance ($p = 0.115$). As the cusp deformation data (μm) presented sphericity (Mauchly's test, $p > 0.05$). Groups were compared using two-way repeated measures ANOVA followed by Bonferroni adjustment for multiple pairwise comparisons as a post hoc test ($p < 0.05$).

The Kaplan–Meier test was applied to compare the fatigue resistance of the groups regarding the cycles (continuous variable). The effect of the type of fiber-reinforced composite material was assessed by the post hoc log-rank test. Life table analysis was applied to compare the fracture load step at which the specimen failed (ordinal variable), followed by the Wilcoxon test for pairwise comparison. For all statistical analyses, the level of significance was set at 95%. The data were analyzed with statistical software (SPSS 23, SPSS Inc, Chicago, IL).

3 | RESULTS

3.1 | Cusp deformation

Two-way repeated measures ANOVA showed the effect of resin [$F(1.59\ 12.75) = 5.45$; $p = 0.025$] as well as the effect of the time [$F(2.08\ 16.65) = 32.614$; $p < 0.001$], but the effect of the combination of resin and time was not found [$F(2.26\ 18.07) = 0.873$; $p = 0.447$].

TABLE 2 Pairwise post hoc comparison for cycles and load

	everX Flow	everX Posterior	50/50 mixture
everXflow	–	*0.039	0.990
everXposterior	*0.035*	–	*0.047
mixture	*0.651*	*0.067*	–

Note: Nonitalic cells = Kaplan–Meier followed by post hoc Log Rank tests for cycles; Italic cells = Life table followed by post hoc Wilcoxon–Gehan test for load.
*indicates statistically significant difference between groups ($p < 0.05$).

The means and standard errors of all groups are presented in Figure 4 and Table 1.

At 0 and 3 h, no differences were found among the three composite resins. For 18 h, everX Posterior presented the smallest cusp deformation (30.7 ± 1.5 SE μm) compared with everX Flow (39.8 ± 2.8 SE μm) ($p = 0.029$) but not different from the 50/50 mixture (36.4 ± 2.4 SE μm, $p = 0.199$). Similarly, for 24 h, everX Posterior presented the smallest cusp deformation (32.5 ± 1.5 SE μm) compared with everX Flow (43.4 ± 2.5 SE μm) ($p = 0.029$) but not different from the 50/50 mixture (38.0 ± 2.4 SE μm, $p = 0.173$). Within the same composite resin, 0 h presented smaller cusp deformation than 18 and 24 h for all three composite resins ($p < 0.05$).

3.2 | Fatigue resistance

All specimens failed before the end of the test, hence the mean cycles and median load at failure could be calculated. The fatigue resistance survival curves are presented for all 27 specimens considering cycles (Figure 4B,C) and load (Figure 4D,E). The Kaplan–Meier and post hoc log-rank test for the number of cycles to failure revealed significantly higher mean ± standard error survival for the group everX Posterior (1,707.8 ± 90.6) than group Mixture (1,475 ± 85.7, $p = 0.047$) and then group everX Flow (1,414.4 ± 85.3, $p = 0.039$). No difference was found between everX Flow and the mixture group for either cycles or load (Table 2). The life table followed by the post hoc Wilcoxon test for the mean load at failure revealed significantly higher loads for everX Posterior (1,783 N) than for everX Flow (1,450 N) ($p = 0.035$). The load descriptive statistics of the data are shown in a box and whisker diagram in Figure 4E. Group everX Posterior

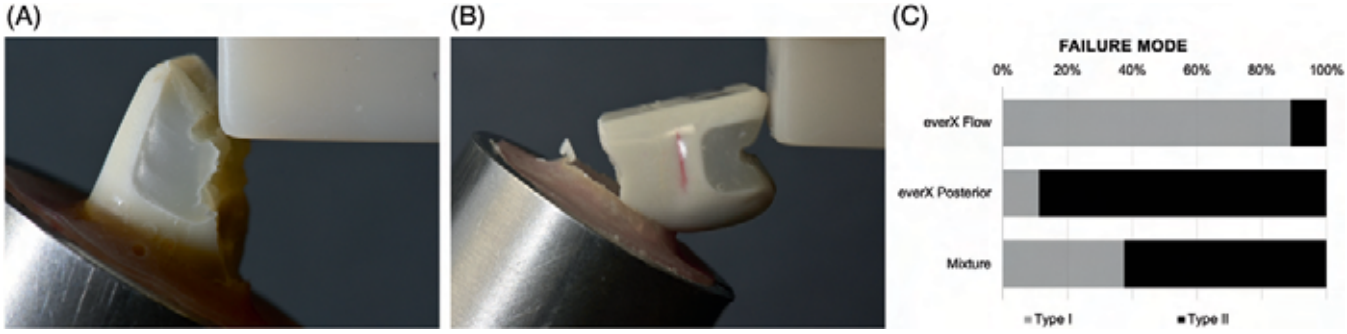

FIGURE 5 Failure modes (A, type I restorable, B, type II non restorable) and distribution for each group (C).

TABLE 3 Failure types, numbers, and percentages after the fatigue-to-failure test

Group	Type I	Type II
EverX Flow ($n = 9$)	8 (89%)	1 (11%)
EverX Posterior ($n = 9$)	1 (11%)	8 (89%)
Mixture 50/50 ($n = 9$)	4 (44%)	5 (56%)

Abbreviations: Type I, partial cusp fracture, cusp only, re-restorable; Type II, total crown fracture, root, nonrestorable.

presented more type II failure and everX Flow presented more type I failure, as shown in Figure 5.

The failure mode was evaluated to classify the fracture as restorable, or nonrestorable. Nonrestorable failure meaning total crown fracture (below the acrylic resin base limit) affected 89% of everX Posterior group, 56% the 50/50 mixture, and 11% of everX Flow SFRC (Table 3).

4 | DISCUSSION

This research assessed the strength and shrinkage-induced cuspal deformation of MOD direct restoration of molars using three different SFRC resins. The null hypotheses are rejected because (1) a significant difference in mechanical performance and failure mode among the three materials was found, and (2) cusp deformation (induced by shrinkage stress) was not the same across groups.

The goal of this in vitro study was to obtain the highest level of standardization for all procedures by controlling the nature and the dimension of substrate, preparation dimensions and restorative steps, as well as loading configuration and occlusal morphology. While using natural teeth would at first seems more realistic, plastic teeth were chosen instead to focus on the behavior of the restorative material itself. Unlike natural teeth, plastic teeth come from a single industrial mold and have identical, morphology and cuspal deformation properties.

The standardization level achieved here would never be possible in a clinical study due to the number of confounding variables, such as the patients' dietary habits, caries susceptibility, masticatory factors, tooth morphology, variability in hard tissue properties and dimensions, and so forth.

One of the most challenging factors in conducting a true fatigue test is the complexity of the process, testing at low load/high cycles is time-consuming as it involves performing over 1,000,000 cycles before a failure can be observed. The accelerated fatigue test introduced by Fennis et al.,[29] which is performed in a relatively short time, is the most relevant assessment method. The Acumen 3 (MTS) electrodynamic system used in this study features a rigid load frame, micron-accurate displacement sensors and an automatic linear motor that can provide highly precise motion and load control.

The angle of force was modified to 30° and applied to the supporting cusp using a composite resin CAD/CAM block (Lava Ultimate; 3M-ESPE-CEREC) as an antagonistic cusp. This measure escalated the stress to the restoration and replicate an extreme load scenario (nonworking contact). The specimens were subjected to extremely high loads, which were used far beyond the physiological limits of masticatory forces, all specimens survived the first half of the experiment (>1,000 N), demonstrating outstanding survival rates. Due to standardization, fracture modes were consistent (type I or type II).

everX Posterior (GC) is a unique bulk-fill dentin-replacement hybrid composite resin containing E-glass fibers of 1–2 mm length. Other FRC materials (Alert by Generic Pentron and Restolux by Lee Pharmaceuticals) preceded everX by more than a decade and were offered as condensable composite resins with increased fracture toughness. The glass fibers, however, were chopped to a very short size (60–120 microns length) and mechanical properties were only slightly better than those of most conventional composites with traditional fillers. Fiber fillers require a critical fiber length (in the millimeter scale) in order to significantly influence overall mechanical properties. This was the goal of everX Posterior, which is recommended for high stress-bearing areas. It presents a high fracture toughness (2.6 MPa $m^{1/2}$) and flexural modulus within the family of bulk-fill materials but can be used easily in 4-mm deep increments and can potentially match the toughness of dentin. Alike most FRC materials, it cannot be polished well and can only be used as an internal build-up or base to be covered with a regular composite resin (microhybrid or nanohybrid). In the present study, however, it was decided not to introduce this confounding variable and use only the SFRC, which in turn allowed to reveal the discrepancy between the different formulations. everX Posterior proved to be worth of consideration when restoring large defects that would normally require a semi-direct or indirect approach, but for which a direct technique is the only

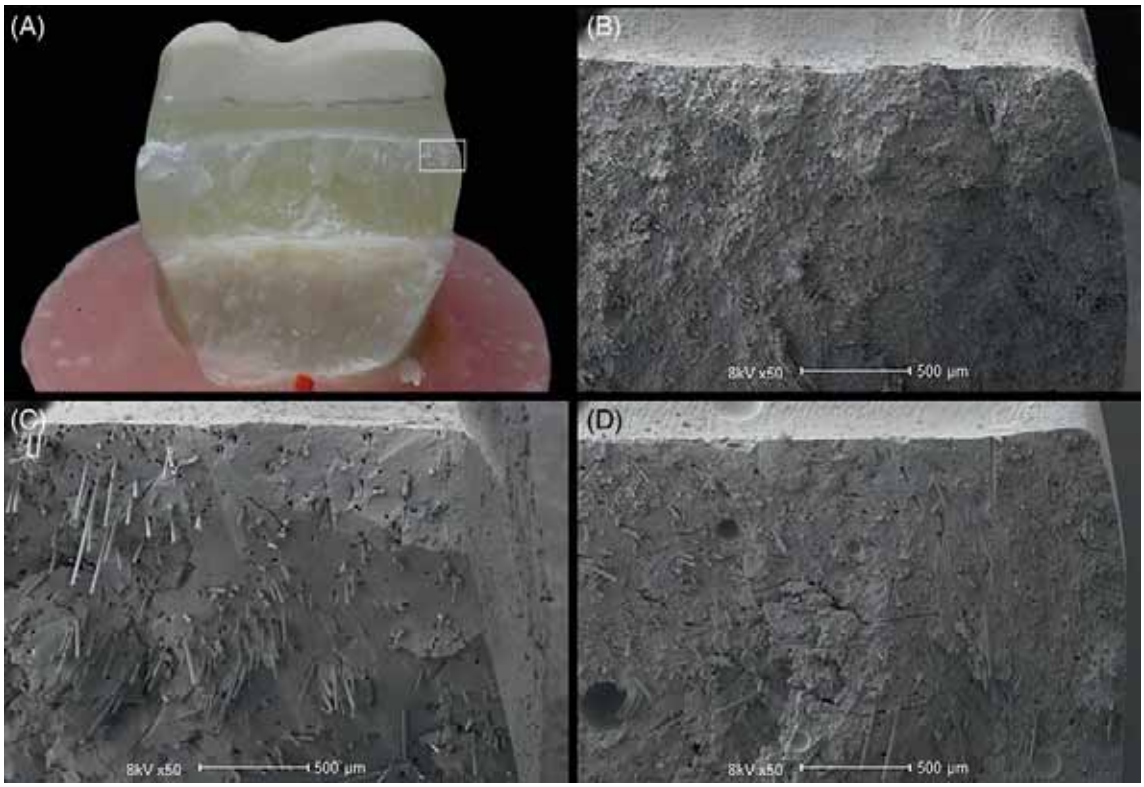

FIGURE 6 Fractured specimens of the three groups. (A) Macrophotography of a sample, showing the area (white rectangle) used for the scanning electron microscopy images (SEM) of the groups. (B) SEM of everX Flow sample presenting a higher density of smaller fibers. (C) SEM of everX Posterior sample presenting lesser density of fibers with greater dimensions. (D) SEM of 50/50 mixture sample presenting both types of fibers (hybrid composition) and voids incorporated during the mixture process.

option due to financial and patient limitations. As such, it was able to match the performance of CAD/CAM semidirect composite resin inlays.[20] everX Posterior could be regarded as a possible substitute of the GIC in the sandwich approach, provided that it is covered with a sufficiently bright material to compensate for its excessive translucency. The present study does align with existing data about the shrinkage difference between the two SFRC.[22] The flowable SFRC was obtained by reducing the barium glass filler content and modifying the resin matrix, in addition to decreasing the critical fiber length. It seems that the resulting increase in fiber content (Figure 6) was not enough to make up for the lost volume, possibly explaining the increased shrinkage rate in EverX Flow. The present results, however, does not support the existing data about the superior fracture toughness of everX Flow[21,22] because everX posterior had superior fracture resistance. The lower flexural modulus (9.0 GPa) of everX Flow along with the reduced fiber length (below the critical level) might explain this difference.

In view of the above and considering clinical feasibility, it seems advisable that everX Posterior be recommended in large direct restorations (easy to apply in large bulk) while everX Flow can be used rather as a liner (small volume) on top of immediate dentin sealing to smoothen the geometry and protect the dentin bond when doing semi-(in)direct CAD/CAM restorations.

Alike the mixture of microfiller and macrofiller in hybrid composite resins, the 50/50 mixture presented with the potential to generate synergetical properties. However, the mixture only revealed intermediate performances between the Flow and Posterior versions of the material for both cuspal deformation and strength. This absence of synergy might have been caused by the significant number of voids incorporated during the mixing process (Figure 6D).

Increased cuspal deformation will logically increase the risk of cracking in enamel. Totally avoiding this problem is only possible with inlays. In direct techniques, the very limited incidence of cracks speaks for EverX Posterior performance in another study.[20]

It is the essence of Biomimetic Restorative Dentistry (BRD) to mimic tooth structure and as such, SFRCs constitute the most biomimetic dentin replacements because of their superior fracture toughness. Natural dentin is reinforced by collagen fibers that can stop and deflect cracks initiated from enamel. A significant outcome of this experiment is the combination of lesser cuspal deformation induced by shrinkage and higher strength for the direct restorations with everX Posterior SFRC base. These outstanding properties, however, made the crown so strong that failure was directed toward the root. Large MOD defects have proven best to be restored using CAD/CAM inlays with an SFRC as a base for optimal strength with lower shrinkage-induced cracks, and most friendly failure modes.[20] When a low-cost restoration must be chosen instead, the SFRC alone will significantly improve the performance of direct restorations.

5 | CONCLUSIONS

This study assessed the shrinkage-induced cuspal deformation and strength of large MOD restorations using three different SFRC resins (everX Posterior, everX Flow, and mixture 50/50). Restorations with everX Posterior SFRC yielded excellent mechanical performance with the least amount of shrinkage-induced cuspal deformation and the higher average strength. everX Flow tended to demonstrate more repairable partial fractures while the extreme strength of EverX Posterior induced mainly catastrophic failures.

ACKNOWLEDGMENTS AND DISCLOSURE

The authors wish to express their gratitude to GC (Lueven, Belgium) for providing everX Flow material and Dr Mehrdad Razaghy (Beverly Hills Dental Labs) for everX Posterior. The authors do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Magne P, Carvalho MA, Milani T. Shrinkage-induced cuspal deformation and strength of three different short fiber-reinforced composite resins. *J Esthet Restor Dent*. 2023;35(1):56-63. doi:10.1111/jerd.12998

Received: 9 December 2022 | Revised: 12 December 2022 | Accepted: 13 December 2022

DOI: 10.1111/jerd.13001

CLINICAL ARTICLE

WILEY

Single-retainer all-ceramic resin-bonded fixed dental prostheses: Long-term outcomes in the esthetic zone

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Abstract

Objectives: To present an update on the concept of cantilevered single-retainer all-ceramic resin-bonded fixed dental prostheses (RBFDPs) first presented 25 years ago in the Journal of Esthetic Dentistry.

Overview: The initially presented case of the concept was followed clinically over 26 years and is presented along with two additional clinical long-term cases using varying methods to obtain an esthetic and hygienic ovate pontic design. Veneered alumina and zirconia ceramic (3 mol% yttria–tetragonal zirconia polycrystalline ceramic; 3Y-TZP) was used and bonded with a phosphate monomer containing luting resin after 50 μm alumina particle air-abrasion at 0.25 MPa pressure. The restorations replacing incisors did not debond and soft tissues in the pontic area were maintained over 26 years.

Conclusions: Cantilevered single-retainer all-ceramic RBFDPs today made from veneered 3Y-TZP zirconia ceramic can be considered a standard of care for the replacement of single incisors and provide an excellent esthetic outcome with a long-term preservation of soft tissues in the pontic area.

Clinical Significance: Bonding nonretentive oxides ceramics such as alumina and zirconia ceramic with phosphate monomer containing luting resins after alumina particle air-abrasion is durable over decades. This proves that bonding to zirconia ceramic is not of any problem when adequate methods are used. Single-retainer zirconia ceramic RBFDPs maintain soft tissues in the edentulous area of single missing incisors and often deem implants unessential for this indication.

KEYWORDS

durable zirconia ceramic bonding, long-term clinical outcome, ovate pontic design, single-retainer RBFDPs, single tooth replacement, soft tissue preservation

1 | INTRODUCTION

In the early nineties two-retainer all-ceramic resin-bonded fixed dental prostheses (RBFDPs) made from alumina ceramic were introduced into restorative dentistry to overcome the esthetic problems of metal-ceramic RBFDPs,[1] which most significantly were the grayish shine-through of the metal retainer wings and often partially visible parts of the metal framework. However, one quarter of alumina RBFDPs fractured within the first year of clinical service.[2] In most instances, framework fracture occurred only at one connector between the

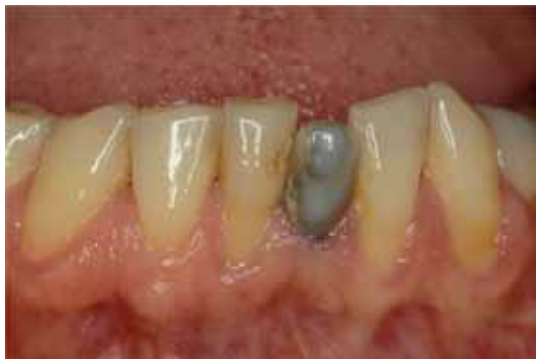

FIGURE 1 Labial view of the mandibular teeth of a 55-year-old male patient. The endodontically treated and discolored left lower central incisor needed to be replaced because of an external root resorption.

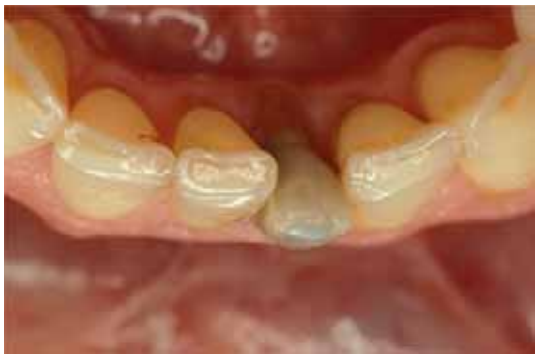

FIGURE 2 Preoperative occlusal view. The tiny composite resin filling at the disto-lingual surface was fully included into the tooth preparation.

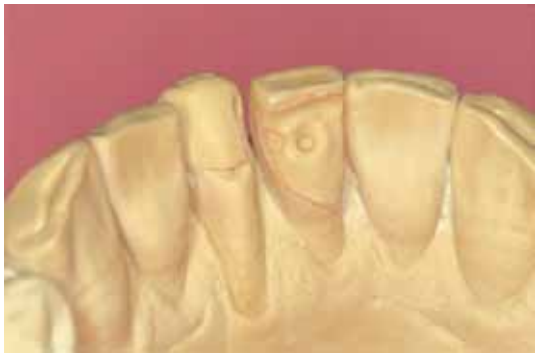

FIGURE 3 View of the master cast demonstrating preparation features including a minimal lingual veneer, a groove on the cingulum and a shallow proximal box preparation. The left central incisor was removed from the master cast with a laboratory bur since the tooth would be extracted directly prior to the insertion of the restoration (immediate pontic technique).

pontic and retainer wing of one abutment tooth leaving the pontic attached as cantilever to the other abutment tooth, which continued to function over the next 10 years.[3]

Based on this experience, in 1997 the authors first presented cantilevered alumina ceramic RBFDPs with a single retainer as a minimally invasive and highly esthetic treatment method in the Journal of Esthetic Dentistry.[4] Advantages of the single-retainer design included improved esthetics due to the avoidance of a second connector, preserved physiologic tooth mobility[5] due to the avoidance of splinting and the avoidance of the risk of undetected retention loss a retainer in a multiple-retainer design with the subsequent high risk of caries. In addition, flossing is easier with the single-retainer design, thus facilitating oral hygiene, as floss can be passed through the proximal contact of the cantilevered pontic to the adjacent tooth, in contrast to the splinted two-retainer design, where floss must be inserted under one of the pontic connections.

Only a few years later, bonding to densely sintered zirconia ceramic was shown to be equally effective as to alumina ceramic.[6,7] That provided the basis for today's standard of care when replacing single missing incisors with single-retainer zirconia RBFDPs (3Y-TZP) which showed long-term survival over 10 years which surpasses that of implant-retained single crowns.[8,9]

Today, more than 25 years after the introduction of the concept of single-retainer all-ceramic RBFDPs, the clinical outcome of the case presented initially is shown as an example of the excellent long-term clinical outcome of cantilevered all-ceramic RBFDPs together with two other long-term cases. All three patients agreed to their clinical documentation of the treatment and to the publication of the long-term outcome.

The RBFDPs had been fabricated with a minimum retainer wing thickness of 0.7 mm, a minimum connector height of 3 mm, and a minimum connector width of 2 mm. The presented cases exemplarily show that the concept of cantilevered RBFDPs does not only functions very well long-term but also does not result in clinically relevant loss of hard and soft tissues in the areas of the missing teeth as it is often claimed.[10,11] It also does not bear the risk of frequent long-term complications seen with implant-retained crowns such as periimplantitis, crown infraposition, and missing proximal contact points,[12,13] which might compromise esthetics and restoration function for the patient considerably.

2 | CLINICAL FOLLOW-UP CASE 1 OVER 26 YEARS

In a 55 years old male, the esthetic replacement of a discolored left lower central incisor was made using a single-retainer alumina ceramic RBFDP in the immediate pontic technique in 1996 (Figures 1 and 2).[4] The preparation of the abutment tooth was minimally invasive and limited to enamel, including a minimal lingual veneer preparation, a cingulum groove, and a shallow proximal box preparation at the connector to the pontic (Figure 3). The single retainer alumina ceramic RBFDP was fabricated with a copy-milling technique, that is, a resin analog of the framework was modeled with light-cured resin and then milled from presintered alumina blocks using the Celay copy-milling machine (Mikrona, Speitenbach, Switzerland).[4] The pontic of the finished framework was veneered with feldspathic ceramic. Following tooth extraction, the length of the pontic was adjusted so that the pontic base supported the soft tissues around the extraction socket (Figure 4). The restoration was inserted with a phosphate monomer luting resin (Panavia 21 TC, Kuraray, Japan) under rubberdam isolation (Figure 5).[14] The esthetic

FIGURE 4 After tooth extraction, the length of the pontic was adjusted to the extraction socket so that the pontic base supported the gingival margin circumferentially.

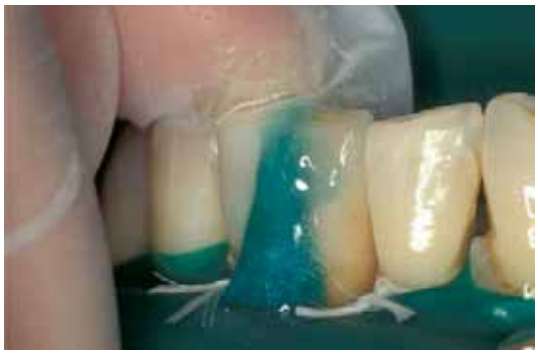

FIGURE 5 The all-ceramic RBFDP was held in place with finger pressure until the luting composite resin had set.

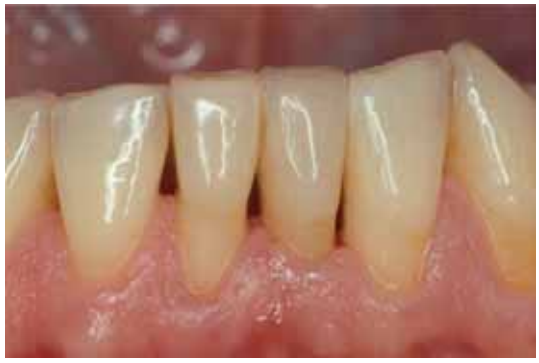

FIGURE 6 Frontal view of the single-retainer all-ceramic RBFDP. Note the initial collapse of the papilla.

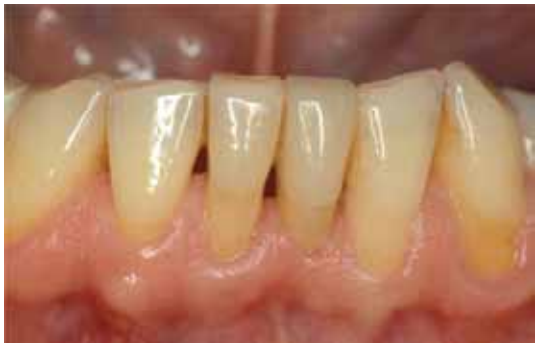

FIGURE 7 Frontal view of the restoration at a 9 month recall visit. Note the nearly complete recovery of the papilla.

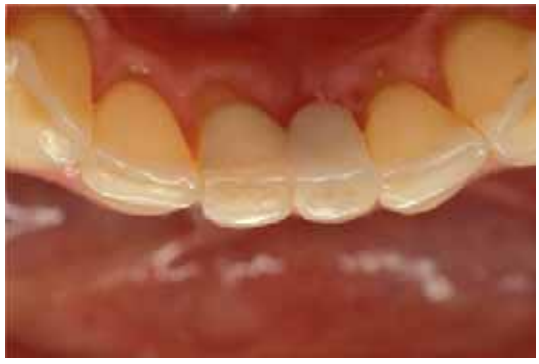

FIGURE 8 Occlusal view of the single-retainer all-ceramic RBFDP.

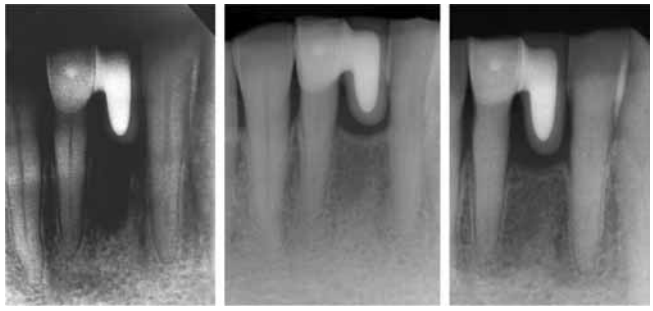

FIGURE 9 (A) Initial radiological control after insertion of the RBFDP. (left) (B) Radiological control 6 years after insertion of the RBFDP. The extraction socket shows a good ossification. (right) (C) Radiological control 23 years after insertion of the RBFDP.

result of the all-ceramic RBFDP is shown after 1 week (Figure 6) and 9 months (Figures 7 and 8) of insertion. After 9 months both papilla at the extraction side had nearly completely remodeled. The radiographs show the extraction socket and the adjacent teeth after 1 week, after 6 years, and after 23 years (Figure 9). Initially the patient flossed regularly under the ovate pontic. However, the patient was then in recall at his home dentist over the following years and stopped flossing under the pontic at some point. In September 2022 the now 81-year-old patient was visited at his home in Freiburg (South Germany) and the restoration was inspected. The patient is still fully satisfied with the esthetics and function of the RBFDP 26 years after insertion (Figures 10–12). Despite some deficits in the patient's oral hygiene, the lower anterior teeth and the soft tissues around the pontic are healthy and there has been no clinically relevant loss of soft tissue. The RBFDP has never lost retention and no tooth migration or rotation of the pontic has occurred after this time.

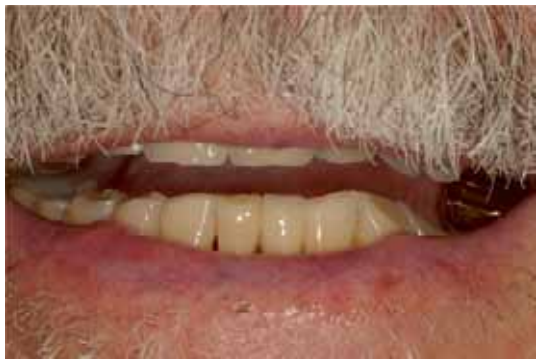

FIGURE 10 Labial view of the now 81-years old patient.

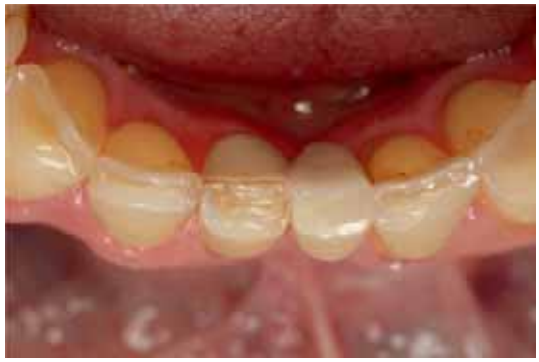

FIGURE 12 Occlusal view of the RBFDP after 26 years.

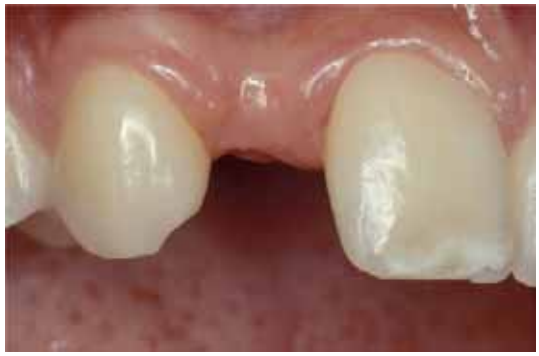

FIGURE 14 The edentulous space showed slight soft tissue excess in vertical direction but a moderate ridge defect in horizontal direction.

3 | CLINICAL FOLLOW-UP CASE 2 OVER 26 YEARS

A 15-year-old female patient presented with a congenitally missing maxillary right lateral incisor (Figure 13). The edentulous space showed slight soft tissue excess in vertical direction but a moderate ridge defect in horizontal direction (Figure 14). After minimally invasive preparation of the abutment tooth within the enamel and impression taking (Figure 15), the single-retainer alumina ceramic RBFDP was fabricated with a copy-milling technique and labially

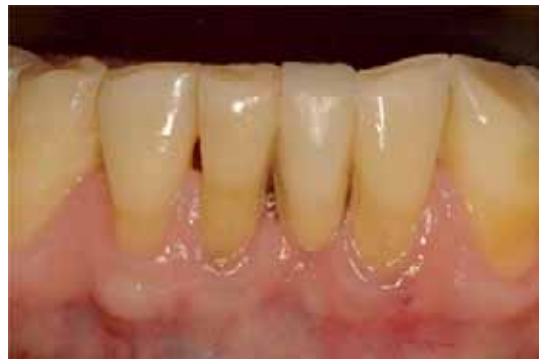

FIGURE 11 Frontal view of the RBFDP 26 years after insertion. Note the clinically not relevant loss of hard and soft tissue caused by physiological aging.

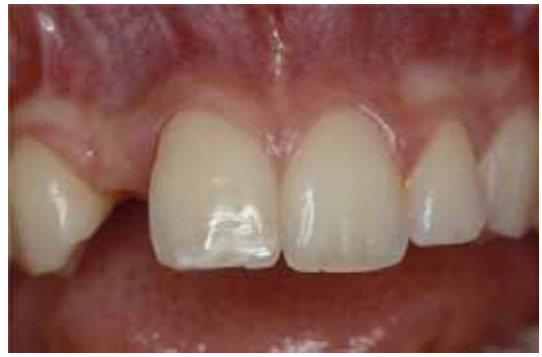

FIGURE 13 Labial view of a 15-year-old female patient with unilaterally congenitally missing maxillary right lateral incisor.

FIGURE 15 View of the master cast demonstrating preparation features. The edentulous area of the cast was reshaped to achieve an ovoid support of the pontic.

veneered with feldspathic ceramic. The edentulous area of the cast was reshaped to achieve a concave rest area for an ovate pontic. Due to the ovoid pontic, the soft tissue became ischemic when the RBFDP was tried on clinically (Figure 16). To avoid hyperpressure of the ovate pontic,[15] the soft tissue was reshaped using an electrotome sling as an electrical cutting instrument to fit the ovate pontic leaving more than 2 mm of soft tissue between the pontic and the supporting alveolar bone (Figure 17). A minimum tissue thickness of 2 mm between the pontic and the alveolar bone

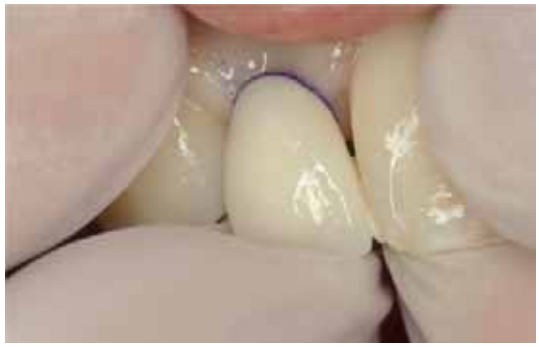

FIGURE 16 Due to the ovoid pontic the soft tissue became ischemic when the RBFDP was tried on.

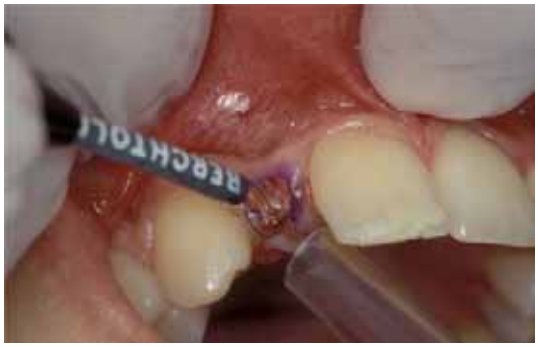

FIGURE 17 After local anesthesia, the soft tissue was reshaped using an electrotome sling for adaptation to the ovate pontic.

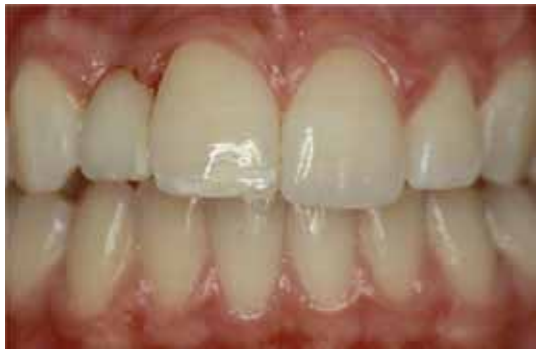

FIGURE 18 Labial view at the day of insertion of the RBFDP

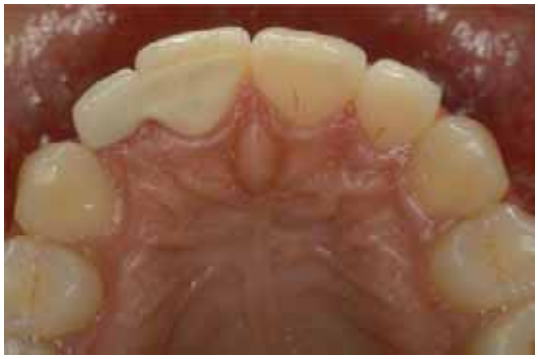

FIGURE 19 Occlusal view at the first recall visit

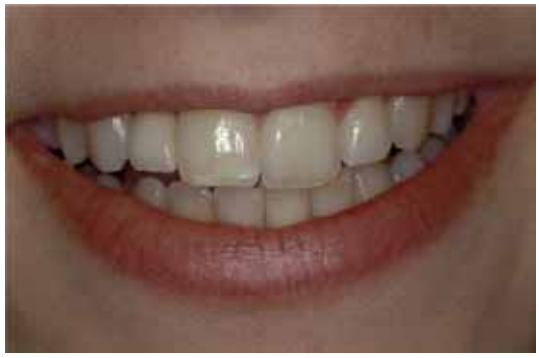

FIGURE 20 Smiling 15-year-old patient.

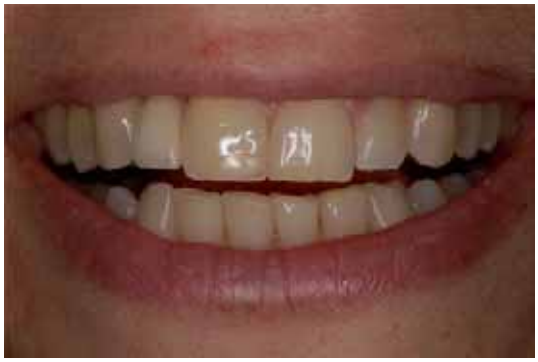

FIGURE 21 Smiling 41-year-old patient 26 years later.

respects the biological width by leaving enough space for the periosteum, connective tissue, and epithelium.[16] Then, the restoration was inserted with a phosphate monomer luting resin (Panavia 21 TC, Kuraray, Japan) under rubberdam isolation. The soft tissue wound healed against the ovate pontic (Figure 18). At the following recall visit the tissues had healed and the patient was satisfied (Figures 19 and 20). In October 2022 the now 41-year-old patient was met at a café in Cologne (West Germany) and the restoration was inspected (Figures 21 and 22). The soft tissues around the pontic looked healthy and no clinically relevant loss of soft tissue was detected. The RBFDP has never lost retention and no tooth migration or rotation of the pontic has occurred. However, the patient's natural teeth had become somewhat darker over the years due to natural aging, so that the pontic now appeared considerably lighter than the natural dentition. The patient was advised either to bleach the natural teeth or to replace the veneer of the pontic with a veneer of a better matching color.[17]

4 | TODAY'S STANDARD TREATMENT USING VENEERED ZIRCONIA—FOLLOW UP OVER 18 YEARS

After the availability of densely sintered zirconia ceramics for the fabrication of dental restorations in the early 2000s and the

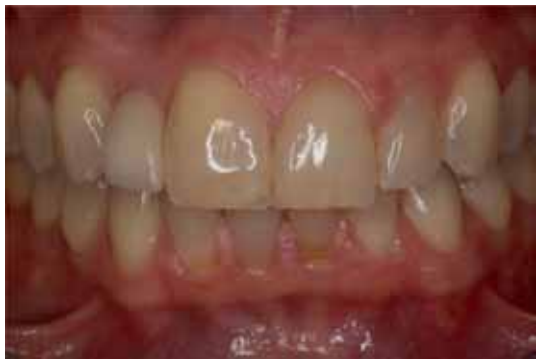

FIGURE 22 Labial view of the RBFDP 26 years after insertion. Note the considerable color difference between the pontic and the natural dentition.

FIGURE 23 Extraoral view of a 20-year-old female patient with congenitally missing maxillary lateral incisors.

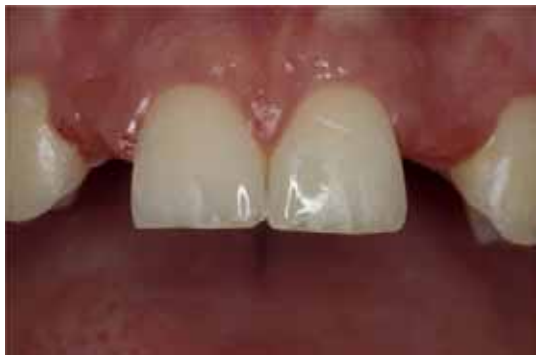

FIGURE 24 The labial view reveals tissue excess in vertical dimension.

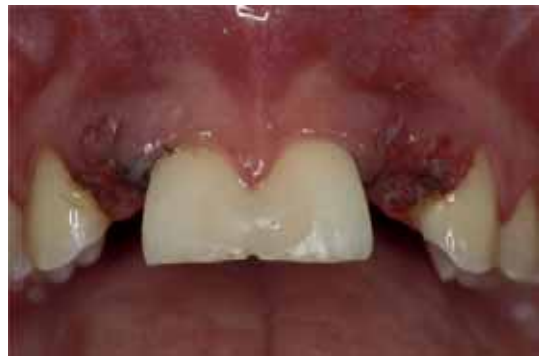

FIGURE 25 Labial view after roll flap surgery to broaden the ridge in horizontal direction and to create a concave depression in the soft tissue for the ovate pontic.

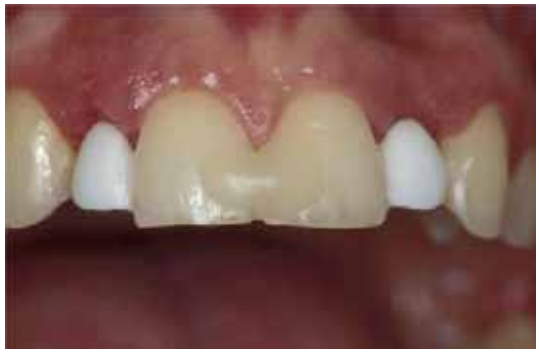

FIGURE 26 Labial view of the try-in of the 3Y-TZP zirconia ceramic framework to be veneered with feldspathic ceramic.

demonstration that bonding to zirconia works in the long term if adequate methods with phosphate monomer containing luting resins were chosen,[7] quickly zirconia ceramic replaced alumina ceramic as framework material for RBFDPs with even better results.[9] The following case illustrates the positive outcome using veneered zirconia ceramic.

A 20-year-old female patient with congenitally maxillary lateral incisors presented herself in 2004 after completion of her orthodontic therapy (Figure 23). The patient had soft tissue excess in the edentulous area (Figure 24). Due to the inappropriate axes of the teeth adjacent to the gaps the originally intended implant therapy was not possible. The desired ovate pontic design was achieved after horizontal ridge augmentation with the roll-flap technique simultaneously removing the tissue excess in vertical direction (Figure 25).[18,19] Using the rolling flap surgery, a connective tissue pedicle was formed from the palatal side and the alveolar ridge through incisions and then deflected into a labial pocket created between the mucosa and the periosteum. Hereby, the ridge was broadened in horizontal direction and a concave depression was created in the soft tissue for the ovate pontic. The intraoral try-in of the 3Y-TZP zirconia ceramic framework revealed that the minimum vertical connector height of 3 mm was considerably exceeded (Figure 26).

The zirconia ceramic framework was fabricated with two splinted retainer wings to provide long-term retention after orthodontic closure of a large diastema medial on request of the orthodontist and the patient. Splinting the two retainer wings on the adjacent central incisors has been shown not to create the problems seen with two-retainer RBFDPs splinting a central incisor and a canine because the splinted central incisors move in a similar direction during functional loading while canines moved in a different direction especially during laterotrusion.[20] The canines had not been selected as abutment teeth

FIGURE 27 The fit checking silicone at the final try-in of the finished RBFDP indicated a broad ovate pontic contact area.

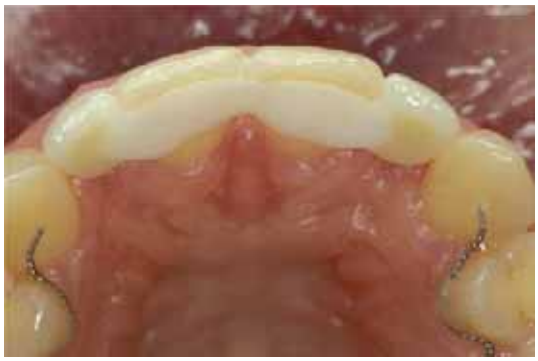

FIGURE 28 Occlusal of the inserted RBFDP.

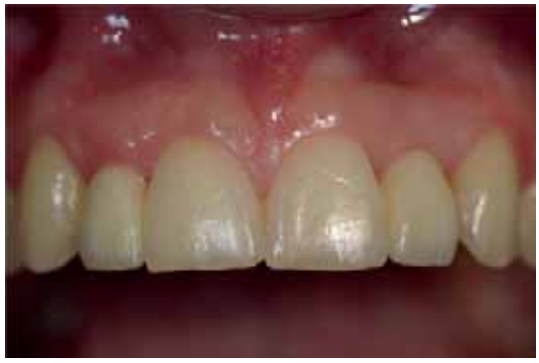

FIGURE 29 Labial view of the inserted RBFDP.

FIGURE 30 Postoperative smile of the patient.

FIGURE 31 The patient and treating team directly at the day of insertion of the RBFDP in May 2004. Author MK, patient, author RG, assistant (from left to right).

FIGURE 32 Labial view 1 year after insertion.

in order to avoid inference of the retainer wings with the existing canine guidance in a deep bite situation where the incisors allowed insertion of the retainer wings due to the existing overjet. The framework was veneered with feldspathic ceramic and the pontics were designed to provide an ovate pontic with an extensive soft tissue contact as revealed by a fit checking silicone (Figure 27). The finished RBFDP was inserted under rubberdam isolation with a phosphate monomer containing luting resin (Panavia 21 TC, Kuraray) after air-abrasion of the bonding surfaces with 50 µm alumina particles at 0.25 MPa pressure. The alumina particle abrasion cleaned, roughened and activated the zirconia ceramic bonding surfaces.[21] Then the labial composite resin splinting of the incisors was removed (Figures 28 and 29). The patient and the treatment team were satisfied with the esthetic outcome achieved in 2004 (Figures 30 and 31). At the recall 1 year later, the soft tissues had been maturated and the pontic emerged naturally from the gingiva (Figures 32 and 33). The patient was at regular recall at her home dentist in the city of Lübeck in Northern Germany in the following years and only showed up only in 2019 after chipping of the incisal edge of the left pontic after 15.5 years when multiple repair attempts of her home dentist were unsuccessful. The intraoral repair was successfully made after

FIGURE 33 Smile of the patient 1 year after insertion.

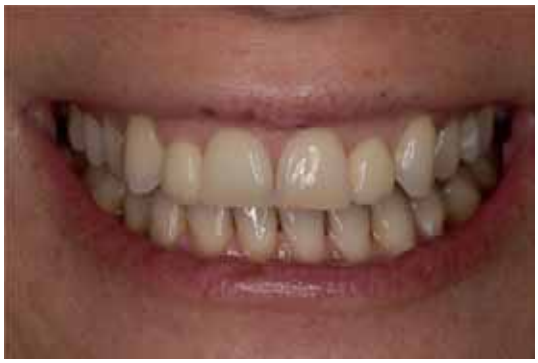

FIGURE 34 Smile of the patient more than 18 years after insertion.

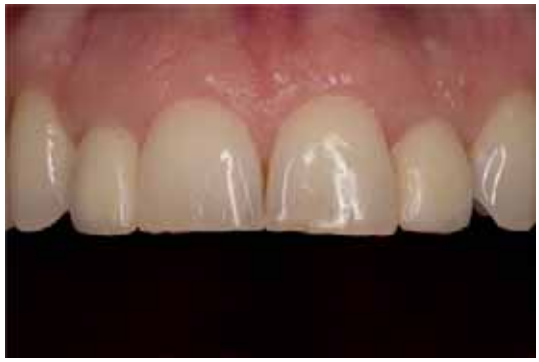

FIGURE 35 Labial view more than 18 years after insertion.

FIGURE 36 The patient and author MK more than 18 years after insertion of the RBFDP in October 2022.

intraoral hydrofluoric acid etching and silanating the chipped veneering ceramic with composite resin.[22] At a recall visit at the patient's home in Lübeck in September 2022, that is, more than 18 years after insertion of the RBFDP (Figures 34–36), the esthetics and restoration function were without problems and no clinically relevant loss of soft and hard tissues was visible except loss of the incisal edges of the central incisors due to protrusive parafunctions of the patient who had not worn a splint as a night guard over many years.

5 | DISCUSSION

The concept of single-retainer all-ceramic RBFDPs evolved from the good clinical survival rates unexpectedly achieved with unilaterally fractured all-ceramic RBFDPs.[2] All-ceramic RBFDPs offer significant esthetic advantages over metal-based restorations in the esthetic zone.[1,20] Using only one retainer wing with a minimal preparation of the enamel is minimally invasive and provides long-term survival and success rates which exceeded those obtained with implant-retained crowns.[8,9,23,24] In these studies the clinical results with maxillary and mandibular RBFDPs did not differ significantly. A systematic review of the survival and complication rates of RBFDPs after a mean observation period of at least 5 years, confirmed the superior survival of cantilevered single-retainer all-ceramic RBFDPs.[25] In addition, cantilevered metal-ceramic RBFDPs with a metal framework showed a better clinical outcome compared with conventional two-retainer RBFDPs.[26,27] It was suggested that shear peel forces, resulting from differential movements of the two abutment teeth in the conventional two-retainer RBFDP design, are reduced in the cantilevered single-retainer design.[26]

It is assumed that the cantilevered single-retainer design in all-ceramic RBFDPs also reduces tensile stresses developing in the bonding interphase when using a two-retainer design due to the differential tooth mobility of splinted abutments during functional loading. This might be especially important when lateral incisors are to be replaced because of the differential movements of the central incisor and the canine during protrusion and laterotrusion. In addition, the cantilevered pontic might act as leverage for functional loads resulting in an increased tactile sensitivity of the abutment tooth compared with the abutments in the two-retainer design.[28] It can be hypothesized that the higher tactile sensitivity leads to patients perceiving possible unfavorable stresses at an early stage and then unconsciously avoiding them, which might be one reason for their better survival and success rates.

Risks and complications associated with implant-retained crowns such as periimplantitis,[12] crown infraposition and missing proximal contact points,[12,13] do not exist when replacing missing teeth with RBFDPs. The already cited systematic review of the complication rates of RBFDPs after a mean observation period of at least 5 years,

reported no such complications.[25] Instead, the most common complications were debonding (loss of retention) and chipping of the veneering material, both of which are easy and predictable to eliminate. In addition, when a RBFDP fails due to trauma or other reasons neither the hard and soft tissues are harmed as usually the RBFDP just debonds or fractures.[3,8,9] By contrast, when an implant fails, often considerable soft and hard tissue defects might occur after implant removal.[29,30]

Three different methods were used in the presented cases to achieve an ovoid pontic rest, that were the intermediate pontic technique,[4] shaping the concave gingiva contact area with an electrotome sling, and the roll-flap technique.[18] Regardless of the technique used, the hard and soft tissue conditions around the pontics were stable 18 to 26 years after the RBFDPs were incorporated. This is in concert with clinical studies evaluating the ridge stability in the edentulous pontic area with and without ridge augmentation procedures, revealing only clinically not relevant minimal soft tissue changes over 10 years.[31,32] Therefore, the often made claims that hard and soft tissues in edentulous areas will be lost when using tooth supported fixed dental prostheses and that implants are required for prevention of tissue loss[10,11] are neither supported by the presented clinical long-term cases nor by actual scientific data.[31,32]

Recently published clinical data for single-retainer 3Y-TZP zirconia ceramic RBFDPs replacing canines, premolars and even molars suggest, that the presented single-retainer concept might not only work for missing incisors but also for all other areas of single missing teeth.[33,34] For posterior abutment teeth, the retainer design includes an occlusal rest or partial coverage of the occlusal surface. It must be also emphasized that all published clinical studies used a strong 3Y-TZP zirconia ceramic and that no clinical evidence has yet been published on long-term results with RBFDPs made from more translucent, but weaker 4Y- and 5Y-TZP zirconia.

6 | CONCLUSIONS

Cantilevered single-retainer all-ceramic RBFDPs today made from veneered zirconia ceramic can be considered a standard treatment for the replacement of incisors and provide an excellent esthetic outcome with a long-term preservation of soft tissues in the pontic area.

ACKNOWLEDGMENTS AND DISCLOSURE

The authors thanks their patients for agreeing to conduct the long-term follow-up visits in a private environment and to publish the results. Matthias Kern has published a textbook on the topic related to this article for which he receives an honorarium. In addition, he lectures worldwide on this topic for various dental organizations including dental manufacturers such as Ivoclar Vivadent and Kuraray Noritake. Open Access funding enabled and organized by Projekt DEAL. The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data sharing point does not fit this manuscript type.

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How to cite this article: Kern M, Gläser R. Single-retainer all-ceramic resin-bonded fixed dental prostheses: Long-term outcomes in the esthetic zone. *J Esthet Restor Dent*. 2023; 35(1):64-73. doi:10.1111/jerd.13001

Received: 4 November 2021 | Revised: 16 March 2022 | Accepted: 17 March 2022

DOI: 10.1111/jerd.12909

CLINICAL ARTICLE

WILEY

Randomized controlled pilot study assessing efficacy, efficiency, and patient-reported outcomes measures of chairside and labside single-tooth restorations

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Funding information
Dentsply Sirona

[Correction added on 10 May, after first online publication: CSAL funding statement has been added.]

Abstract

Objectives: To test whether or not a chairside workflow (CHAIR) is similar to a labside workflow (LAB) in terms of efficacy (primary outcome) and efficiency (secondary outcome).

Material and methods: Eighteen subjects in need of a single-tooth restoration in the posterior region of the maxilla or mandible were consecutively recruited and randomly assigned to the CHAIR or LAB workflow. Patient-reported outcome measures (PROMs; efficacy) were assessed using a questionnaire with visual analog scale. The white Æsthetic score (WES) was applied to evaluate the Æsthetic outcome objectively. The clinical and laboratory time (efficiency) were recorded. Nonparametric methods were applied for the group comparisons.

Results: The overall median Æsthetic evaluation after treatment was 10 (interquartile range = IQR: 9.5–10) in group CHAIR and 10 (IQR: 9.5–10) in-group LAB (Mann–Whitney [MW] test $p = 1.000$). The WES amounted to 4 (IQR: 3–5) (CHAIR) and to 8 (IQR: 7–9) (LAB) (MW test $p < 0.0001$). The median total working time for the clinician in-group CHAIR was 49.9 min. (IQR: 40.9–63.7) and 41.4 min. (IQR: 37.2–58.2) in-group LAB (MW test $p = 0.387$).

Conclusions: Subjective PROMs of single-tooth supported restorations fabricated in a CHAIR or LAB workflow led to similar scores of patients' satisfaction and a moderate negative correlation for the objective evaluation of the clinician in the LAB workflow.

Clinical significance: PROMs can be considered a key element in the decision-making process for restoring single-tooth restorations. The patients' perception of Æsthetics was similar for the CHAIR or LAB workflows. The additional efforts undertaken with the LAB workflow did not result in a patient benefit when compared to a CHAIR workflow.

KEYWORDS
chairside, digital workflow, labside, patient-reported outcomes, single-tooth restorations

1 | INTRODUCTION

Fully digital workflows in restorative dentistry are based on computer-aided design and computer-aided manufacturing (CAD/CAM) processes. These technologies thereby offer a wide range of benefits for patients and clinicians. This is based on data reporting the fully digital workflow to be more efficient, since time-consuming manual steps can be reduced compared to conventional impression and fabrication techniques.[1,2] Consequently, the digital approach has been considered an alternative to conventional restorative approaches for fixed dental prostheses (FDPs).[3]

Two options exist to treat patients in need of a single-tooth restoration applying a digital workflow: in office systems (chairside fabrication of the restoration by the dentist) and lab-based systems (labside fabrication of the restoration by a dental technician/milling center).[1]

In the LAB workflow, the digital impression is sent to a dental laboratory. The dental technician uses a CAD software to design the reconstruction. The restoration is then milled with a CAM system in the dental laboratory or by a centralized milling center. During the second appointment in the dental practice, the restoration will be usually inserted.[3] The LAB process is well-documented and demonstrated to result in favorable long-term outcomes of the restorations.[4]

In the CHAIR workflow, an indirect restoration is designed and fabricated in the dental practice and delivered in one single appointment.[5–7] The CHAIR workflow has a long history in restorative dentistry with initial indications ranging from inlays to onlays. Later on, the extent of the restoration (veneers, full crowns, implant-borne crowns) as well as the number of restorations being fabricated simultaneously increased. Reported data on the CHAIR workflow demonstrate favorable clinical outcomes with survival rates ranging between 94.6% and 96.3% after 4 years[6,8] and 83.5% and 95% after 10 years.[7,9]

Critical parameters in the decision-making process for either one of the two workflows include scientific clinical data, costs, efficacy and efficiency.

Both digital workflows have been extensively described in the literature with a focus on objective criteria (e.g., survival rates, accuracy of the restorations). From a patient's perspective, comparative data on patient-reported outcome measures (efficacy and efficiency) are considered to be a key element in the decision-making process for either one of the two workflows.

Consequently, the aim of the present pilot randomized controlled clinical trial was to test whether or not a CHAIR workflow is similar to a LAB workflow in terms of efficacy (primary outcome) and efficiency (secondary outcome).

2 | MATERIAL AND METHODS

2.1 | Study design and population

The present study was designed as randomized controlled pilot study, comparing a chairside to a labside workflow for the fabrication of single-tooth restorations in the molar region based on questionnaires and clinical examinations. The clinical trial was performed based on the guidelines of the Helsinki declaration and approved by the local ethics committee of the Canton of Zurich, Switzerland (ref. KEK-ZH_Nr. 2019-02016).

Eighteen subjects in need of a single tooth-borne restoration in the posterior region of the maxilla or mandible were consecutively recruited at the Clinic of Reconstructive Dentistry, Center of Dental Medicine, University of Zurich, Switzerland. All participants hat to fulfill the following inclusion criteria:

- ≥ 18 years of age
- Need for a single tooth-borne crown in the premolar and molar zone of the maxilla or mandible (without third molars).
- At least one interproximal contact had to present.
- Presence of antagonists

Patients were excluded from the study in case of the following exclusions criteria:

- Active periodontal disease
- Poor oral hygiene after hygienic phase (Plaque Index > 20%)
- Self-declared pregnancy or breast feeding at the date of inclusion
- Known or suspected non-compliance, drug or alcohol abuse
- Inability to follow the procedures of the study, for example, due to language problems, psychological disorders, dementia, etc. of the participant
- Smoking more than 15 cigarettes a day
- Bruxism

All subjects received all necessary information related to the study protocol and interventions and provided their informed consent prior to the start of the investigation.

2.2 | Clinical and laboratory procedures

The clinicians were similar experienced with both workflows. Before the study initiation, the clinicians attended a training session to review the study protocol, to standardize the clinical procedure and to calibrate the assessments techniques. This meeting was organized by the study monitoring team of the clinic.

2.2.1 | Screening

The eligibility of the patient for the clinical trial was assessed during a screening visit based on the inclusion criteria. Once included, the patients' preferences for both workflows were assessed with a questionnaire. After the initial examination (screening visit) the patient has been randomly allocated to the two treatment groups, so that an equal distribution (1:1) of patients resulted to both treatment groups. The randomization sequence was generated by using a computer-generated list and sealed envelopes. An independent person, not

belonging to the study team, has generated these allocation sequences. Whenever a clinician enrolled a patient for the study, a subject number was assigned to the patient.

2.2.2 | Preparation/impression

The study abutment teeth were prepared following the manufacturer's guidelines for all-ceramic restorations with at least 1.5 millimeters of occlusal reduction. In both digital workflows, an intraoral scanner (Primescan, Software version 5.1.3, DentsplySirona, Bensheim, Germany) was used to record a partial-arch (study site) scan and an occlusal registration (buccal scan) following the manufacturer guidelines. Depending on the randomization the scan was transferred to the dental laboratory via internet (LAB) or the clinician continued with the design of the restoration using a CAD Software (CHAIR).

CHAIR workflow

After virtual designing the restorations in the CAD software (CEREC, Software version 5.1.3, DentsplySirona, Bensheim, Germany) the digital file was sent to an in-house milling machine (CEREC MCXL, DentsplySirona, Bensheim, Germany). The restorations were milled out of a zirconia-reinforced lithium silicate glass–ceramic block (Celtra Duo, DentsplySirona, Bensheim, Germany). After machining, the fixation of the sprue from all the restorations was removed. Subsequently, the restorations were tried in and selective chairside adjustments were performed. When a correct fit was achieved, the restorations were cemented by using a 3-step etch-and-rinse adhesive system and dual-curing resin cement. After removal of excess cement and polishing the restorations were delivered in the same appointment.

LAB workflow

In the labside workflow, one single dental technician performed all the laboratory steps for the fabrication of the monolithic full-contour single-tooth restorations (Celtra Duo, DentsplySirona, Bensheim, Germany). After designing and milling the restorations (inLab SW 19.1; MCX5, DentsplySirona, Bensheim, Germany) were adjusted and prepared for the try-in appointment. At the try-in appointment the clinicians evaluated all the clinical parameters (e.g., contact points, occlusion, color, shape, marginal adaptation, color of the crowns). Subsequently, the restorations were, if necessary, adjusted, then finalized by an individualization and glazing step.

In both workflows the final restorations were adhesively cemented with a 3-step etch-and-rinse adhesive system and dual-curing resin cement and the time for chairside finishing (polishing, removal of cement) was recorded.

The adhesive pretreatment of the dentin was applied following the manufacturer's instructions, using a self-etching primer, adhesive and a bonding agent (Syntact classic and Heliobond; Ivoclar Vivadent, Schaan, Liechtenstein).

For the adhesive placement the restorations were cleaned with a cleaning paste (Ivoclean, Ivoclar, Vivadent, Schaan, Liechtenstein) and a 5% hydrofluoric acid etching gel (IPS ceramic etching gel, Vivadent, Schaan, Liechtenstein) was applied and immediately after the dried and etched internal parts were silanated (MonoBond Plus, Vivadent, Schaan, Liechtenstein) for the adhesive cementing. The restorations were adhesively placed with a dual-curing resin cement (Variolink Aesthetic DC, Vivadent, Schaan, Liechtenstein). After initial light activation, all the excess luting materials was removed and thereafter light-polymerization was applied from the palatal, buccal, occlusal and interproximal side. The occlusal contacts were checked and if needed adjusted. The removal of excess luting materials was completed using different fine-grit bur sizes and polishing paste according the manufacturer's instructions.

The subjects were scheduled 1–2 weeks after cementation for the final examination and patients-reported and clinical outcomes were assessed.

2.3 | Outcome measures

2.3.1 | Patient-reported outcome measures

PROMs were assessed using questionnaires consisting of a visual analog scale (VAS) with anchor terms 0 (low) to 10 (high).

The questionnaire provided prior to the treatment included four questions evaluation the subjective patient's expectations for the treatment. This included the following questions:

(1) How high is your expectation in terms of Æsthetics of the crown?

(2) What is your expectation in terms of the shape of the crown?

(3) What is your expectation in terms of the color of the crown?

(4) What is your expectation in terms of the chewing comfort of the crown?

An additional question assessed the importance of costs relative to Æsthetics on a VAS with anchor terms – 5 (high for costs), 0 (costs and Æsthetics equally important) and 5 (high for Æsthetics):

(5) What is more important to you: the costs or Æsthetics of the crown?

At the final visit, four questions assessed whether or not the patient's expectation had been fulfilled in terms of the same parameters as described above.

1. Were your expectations in terms of Æsthetics of the crown fulfilled?
2. Where your expectations in terms of the shape of the crown fulfilled?
3. Where your expectations in terms of the color of the crown fulfilled?
4. Where your expectations in terms of the chewing comfort of the crown fulfilled?

2.3.2 | Æsthetic outcomes (WES)

The clinician's perspective of the restoration Æsthetic was assessed with the white Æsthetic score index WES[10] evaluating the Æsthetic appearance. After delivery of the restorations one clinician who was

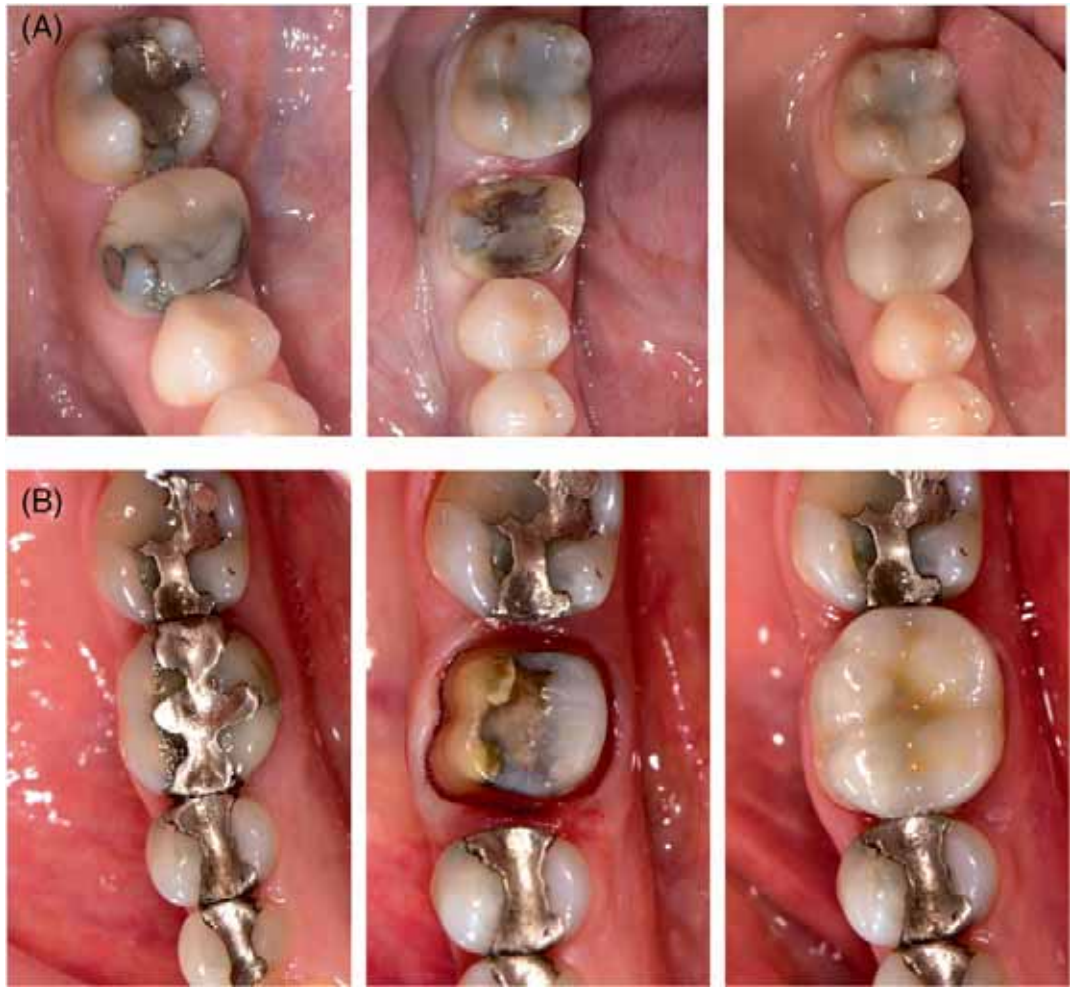

FIGURE 1 (A) Single-tooth crown 46 restored in the CHAIR workflow. (B) Single-tooth crown 46 restored in the LAB workflow

not involved in the treatment of the patients, was asked to assess the Æsthetic of the restorations. The occlusal and side view of each restoration was shown on the computer (Keynote, Version 11.0, Apple Inc., Cupertino, California U.S.). A clinician, not involved in the study was asked to rate the Æsthetic appearance using the WES index. The evaluation comprised 5 subgroups: tooth form, tooth volume, color, surface textures and translucency. The highest WES score in each subgroup was 10, which indicates closest match of the clinical single-tooth restorations with the neighboring teeth. For the correlation between the subjective patient-reported outcome measures (VAS Æsthetic scores after treatment) for the CHAIR and LAB and clinician's Æsthetic satisfaction (WES total scores) was calculated.

2.3.3 | Clinical and laboratory time recording

The following manufacturing and clinical steps were recorded in both workflows (in min): Impression taking, CAD of the restoration, chairside adjustment time, chairside finishing time.

In the CHAIR workflow the time for the clinician to design the restoration with the CAD software, the chairside adjustment time and finishing time were recorded.

And in the LAB workflow the time needed to design the restoration with the CAD software as well as adjustments of the restorations in the laboratory was documented. Thereafter, the chairside adjustment time, if necessary, as well as the finishing time after cementation were recorded.

2.3.4 | Technical outcomes

For the final restoration examination two independent evaluators performed all outcome measures by using the modified United States Public Health Service (USPHS,[11]) criteria. In the event of disagreement in the assessment of a criterion, the evaluators reached agreement in discussing the discrepancy. Alfa was given when there was an ideal clinical situation presented and no need of adjustments was necessary. Bravo (B) was rated when minor mismatches in color, shade, anatomical form and increased

TABLE 1 Patient-reported outcome measures (PROMs) for Æsthetics, shape, color, chewing comfort and the relationship between costs and Æsthetics (VAS, %) prior to (P) and after the prosthodontic treatment (D)

	CHAIR (P)	LAB (P)	*p-value HL CL*	CHAIR (D)	LAB (D)	*p-value HL CL*
Æsthetics						
n	9	9	*1.000*	9	9	*1.000*
Median VAS	8	8	*0*	10	10	*0*
IQR: Q1-Q3	3.5–9.5	6–9	*(−4, 2)*	9.5–10	9.5–10	*(0,0)*
Shape						
n	9	9	*0.941*	9	9	*0.735*
Median VAS	9	9	*0*	10	10	*0*
IQR: Q1-Q3	3.5–9.5	6.5–9	*(−4, 2)*	9.5–10	10–10	*(0, 0)*
Color						
n	9	9	*0.559*	9	9	*0.359*
Median VAS	8	8	*0*	10	10	*0*
IQR: Q1-Q3	3.5–9	7–9.5	*(−4, 1)*	7–10	9.5–10	*(−3, 0)*
Chewing function						
n	9	9	*0.620*	9	9	*0.471*
Median VAS	10	10	*0*	10	10	*0*
IQR: Q1-Q3	9–10	9.5–10	*(−1, 1)*	9.5–10	10–10	*(0, 0)*
Relation cost-Æsthetics						
n	9	9	*0.050*			
Median VAS	0	0	*0*			
IQR: Q1-Q3	−3.5–0	0–3	*(−5, 0)*			

Note: HL, Hodges-Lehmann estimate for the group difference with its 95% confidence interval (CL).

occlusal contacts occurred. These mismatches were, however, still clinical acceptable and needed no further treatment. Charlie (C) or Delta (D) respectively when the restorations had to be redone because they clinically unacceptable.

2.4 | Statistical analysis

Descriptive statistics were computed for all the variables with software SAS 9.4 (SAS Institute Inc., Cary, North Carolina, U.S.). Results are presented as medians and interquartile ranges (Q1-Q3) for continuous variables and as frequency tables for qualitative variables. Group comparisons were based on the nonparametric Wilcoxon-Mann-Whitey (MW) test for continuous variables (because of the small samples and the ordinal variables) and the Chi-squares test for categorical ones. Nonparametric Hodges-Lehmann (HL) estimates for the group differences together with its 95% confidence interval are derived for the continuous variable. Pearson or Spearman correlation coefficients were used for association between continuous variables. Results were considered significant at the 5% level (two-sided $p < 0.05$). No correction for the multiple testing of several variables is applied.

3 | RESULTS

Eighteen patients (10 women and 8 men) with a total of 18 posterior single-tooth CAD/CAM restorations participated in the present study. This included two maxillary molars, 12 mandibular molars and four mandibular premolars. All patients were assigned at random to the CHAIR group and the LAB group (Figure 1).

3.1 | Patient-reported outcome measures

All results for PROMs according to Æsthetics, shape, color, chewing comfort and the relationship between costs and Æsthetics prior to and after the prosthodontic treatment are displayed in detail in Table 1 and Figure 2. Hodges-Lehmann estimate with the 95% confidence intervals are given in the tables.

Related to patients' perceptions the median VAS score for Æsthetics was 8 (IQR: 3.5–9.5) prior to and 10 (IQR: 9.5–10) after treatment for the CHAIR group as well as 8 (IQR: 6–9) and 10 (IQR: 9.5–10) for the LAB group (intergroup [MW test] $p = 1.000/1.000$).

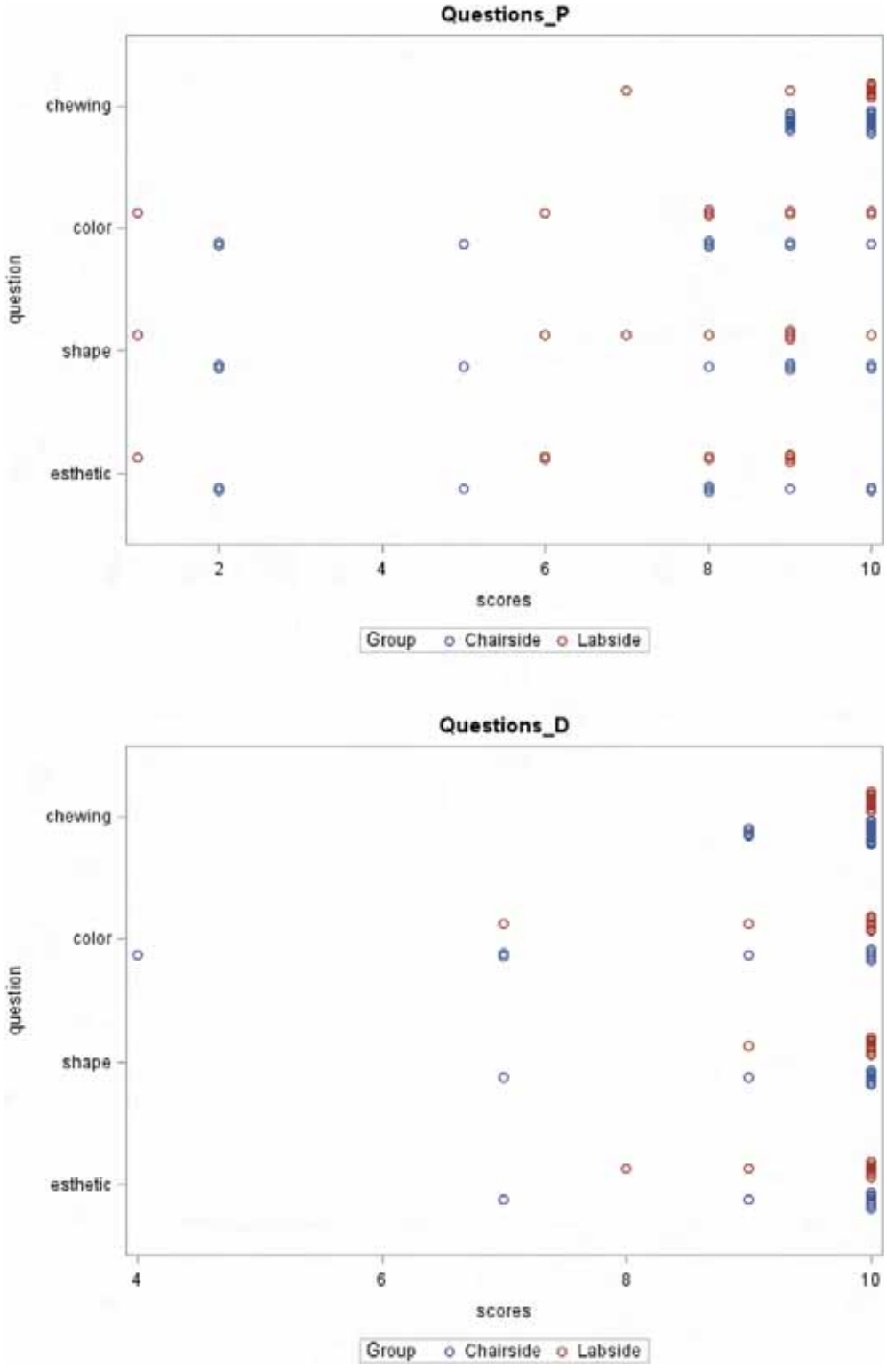

FIGURE 2 Scatterplots for patient-reported outcome measures (VAS) according to Æsthetic, shape, color, chewing function for both groups (CHAIR, LAB) prior treatment (P) and after treatment (D)

The respective median VAS score for anatomical shape of the tooth amounted to 9 (IQR: 3.5–9.5) (prior to treatment) and to 10 (IQR: 9.5–10) (post treatment) for the CHAIR group as well as to 9 (IQR: 6.5–9) and to 10 (IQR: 10–10) for the LAB group (intergroup $p = 0.941/0.735$).

The median VAS score for color match was 8 (IQR: 3.5–9) prior to and 10 (IQR: 7–10) after treatment for the CHAIR group as well as 8 (IQR: 7–9.5) and 10 (IQR: 9.5–10) for the LAB group (intergroup $p = 0.559/0.359$).

TABLE 2 WES scores of the clinicians' Æsthetic satisfaction

Group	Tooth form	Tooth volume/outline	Color	Surface texture	Transluvency	Total score Æsthetic
CHAIR	1	2	0	1	0	**5**
CHAIR	2	1	1	0	0	**4**
CHAIR	1	1	1	0	0	**3**
CHAIR	1	2	1	1	0	**5**
CHAIR	2	2	1	0	0	**5**
CHAIR	1	1	0	1	0	**3**
CHAIR	1	1	1	0	0	**3**
CHAIR	2	1	0	0	0	**3**
CHAIR	1	2	1	1	0	**5**
LAB	2	2	1	2	2	**9**
LAB	1	2	1	2	2	**7**
LAB	2	2	1	2	2	**9**
LAB	1	2	1	1	2	**7**
LAB	1	2	1	2	2	**8**
LAB	1	2	1	2	2	**8**
LAB	2	2	1	2	1	**8**
LAB	1	2	1	2	1	**7**
LAB	2	1	2	2	2	**9**

TABLE 3 Time measurement (in minutes) for CHAIR and LAB group

	Design (min.)	Chairside adjustments (min.)	Finishing/Polishing (min.)	Total time (min.)
CHAIR	5.12 (3.04/7.96)	7.3 (5.74/7.37)	16.52 (8.85/21.44)	49.89 (40.56/63.74)
LAB	13 (10.5/14.5)	0 (0/2.5)	7 (3.5/12.53)	41.42 (33.29/58.17)
p values	<0.001	0.003	0.018	0.387
HL/CL	−6.91 (−9.91, −4.42)	6.63 (3.75, 7.33)	8 (1.12, 15.52)	8.47 (−4.34, 23.4)

Note: HL, Hodges-Lehmann estimate for the group difference with its 95% confidence interval (CL).

The median VAS score for chewing comfort was 10 (IQR: 9–10) prior to and 10 (IQR: 9.5–10) after treatment for the CHAIR group as well as 10 (IQR: 9.5–10) and 10 (IQR: 10–10) for the LAB group (intergroup $p = 0.620/0.471$).

The median VAS score for the importance of costs relative to Æsthetics revealed no significance (intergroup $p = 0.050$) between the two groups 0 (IQR: −3.5-0) for the CHAIR group; 0 (IQR: 0–3) for the LAB group).

VAS scores for Æsthetics, tooth shape, color match and chewing comfort showed an improvement within both groups (CHAIR and LAB) without reaching a statistical significance. The scores pre- and post-treatment for the ratio Æsthetics-cost reached no statistical significance (Figure 2).

The VAS scores for Æsthetics, tooth shape, color match and chewing comfort between CHAIR and LAB compared to baseline, showed statistically significant changes for Æsthetics ($p = 0.023$ for CHAIR and $p = 0.031$ for LAB group) and for tooth shape ($p = 0.031$ for CHAIR and $p = 0.016$ for LAB group).

3.2 | Æsthetic outcome (WES)

The clinicians' objective Æsthetic assessment according the WES index after delivery of the restorations is shown in Table 2. The median WES scores for Æsthetics rated by the clinician for the was 4 (IQR: 3–5) for the CHAIR group and for 8 (IQR: 7–9) (intergroup $p < 0.001$ for the LAB group.

The Spearman test revealed a moderate negative (−0.73) and significant ($p = 0.025$) correlation between the clinicians' and patients' satisfaction in the CHAIR group. In the LAB group, a trend towards a positive non-significant correlation (0.43) between the clinicians' and patients' Æsthetic satisfaction was found ($p = 0.244$).

3.3 | Treatment time

All results for the time measurement are displayed in Table 3. The median time for the virtual design of the restorations ranged from

TABLE 4 The modified US Public Health Service (USPHS) criteria for assessing single-teeth restorations

Category/rating	Alfa A (%)	Bravo B (%)	Charlie C (%)	Delta D (%)
Fracture	CHAIR 9 (100%) LAB 9 (100%)			-
Occlusal wear	CHAIR 8 (88.8%) LAB 9 (100%)	CHAIR 1 (11.1%)		-
Marginal adaptation	CHAIR 6 (%) LAB 8 (88.8%)	CHAIR 3 (%) LAB (1 (11.1%)		-
Anatomic form	CHAIR 9 (100%) LAB 8 (88.8%)	LAB (1 (11.1%)		-
Radiograph	CHAIR 9 (100%) LAB 9 (100%)			-
Patient satisfaction	CHAIR 9 (100%) LAB 9 (100%)			

5.1 min (IQR: 3.0–8.0) in the CHAIR workflow to 13.0 min (IQR: 10.5–14.5) for the LAB workflow (intergroup $p = 0.000$).

When the restorations were delivered, the time needed for chairside adjustments ranged between 7.3 min (IQR: 5.7–7.4) in the CHAIR workflow and 0.0 min (IQR: 0–2.5) in the LAB workflow. The chairside adjustment time was statistically significant in favor of the labside group (intergroup $p = 0.003$).

The time to finish/polish the restorations after cementation ranged between 16.5 min (IQR: 8.9–21.4) for the CHAIR workflow and 7.0 min (IQR: 3.5–12.5) for LAB workflow. The clinicians invested significantly less time for the finish and polish the labside restorations compared to the chairside restorations (intergroup $p = 0.018$).

The overall treatment time, meaning taking every manufacturing step of both workflows into account, the total active working time for the clinician in the clinical ranged between 49.89 min (IQR: 40.6–63.7) (CHAIR) and 41.42 min (IQR: 37.3–58.2) (LAB) (intergroup $p = 0.387$).

3.4 | Clinical examination (USPHS)

All data recorded according to USPHS criteria are displayed in Table 4. All restorations were rated alfa for all parameters, except for two labside restorations being rated bravo (one restoration for anatomic form, one restoration marginal adaptation).

4 | DISCUSSION

The present RCT assessing efficacy (patient-reported outcome measures), time efficiency and clinical outcomes of single-tooth restorations fabricated in a CHAIR or LAB workflow predominantly revealed: (i) the subjective patients' assessment of Æsthetics post treatment to be independent of the applied workflow; (ii) that the additional efforts undertaken in the labside workflow did not result in higher PROMs compared to a chairside workflow; (iii) a similar overall chairside time for both workflows and, (iv) similar clinical outcomes according to modified USPHS criteria for both workflows.

Indirect restorations in the posterior zone are indicated to maintain and/or improve chewing function and Æsthetics. Functional aspects and technical outcomes of posterior single-tooth restorations are well-documented and can objectively be assessed applying a plethora of outcomes measures.[10,12,13] Whereas clinical studies focused in the past on objective criteria and indices to evaluate Æsthetics of single-tooth restorations,[14] data on subjective parameters (e.g., PROMs) are scarce.[15] Moreover, it has been recommended to include PROMs as a routine method of assessment in clinical studies.[14,16–19] The outcomes of the present study with a primary focus on PROMs demonstrated similar Æsthetic outcomes for the two applied workflows. Specifically, the patient's perception of Æsthetics evaluated after treatment amounted to a score of 10 on the VAS in both workflows. These findings are in line with a study comparing the Æsthetic outcome of posterior single-implant restorations using two different workflows.[3] In that study patients evaluated Æsthetics of posterior restorations with or without additional veneering. The respective median VAS score was 8.2 versus 9.0. In addition, the overall satisfaction in terms of Æsthetic outcomes was high in both groups and the extra effort of veneering did not result in higher PROMs.

Several possibilities exist to fabricate single-tooth restorations in the posterior zone. In general, the LAB workflow is considered the gold standard for posterior single-tooth restorations. It traditionally involves impression taking, design and laboratory manual steps. In order to improve the fabrication process, more modern concepts applying digital technologies aim at reducing for example the chairside and laboratory time, the number of clinical appointments and costs (fabrication of monolithic restoration instead of veneered restauration) for the benefit of the patient ([1,2,5]). In the present study, the number of appointments needed differed between the two workflows (CHAIR: 1; LAB 3).

The additional efforts undertaken in the LAB workflow did not result in more favorable PROMs. This to some extent, might come as a surprise, having included a highly skilled dental technician. It does, however, confirm data of previous studies, demonstrating that the patient's perception of Æsthetics is lower and the patient's acceptance higher than the ones of professionals and dental technicians ([17,20,21]). In contrary, professionals and dental technician perceive

color differences to a higher extent. In the present study the restorations were professionally assessed applying objective (WES) and subjective criteria (VAS). It was demonstrated that the Æsthetic outcomes differed within both workflows in favor of group LAB. Clinicians were more critical though than patients, when assessing the Æsthetic outcome. This resulted in in a moderate correlation with a statistical significance in the CHAIR group. The negative association can be explained by the fact that clinicians deal with Æsthetic assessments on a daily basis and are trained to apply standardized parameters, whereas patients evaluate the Æsthetic appearance with their own subjective parameters. In contrast, the LAB group demonstrated a positive trend reaching a statistical significance. The clinicians' Æsthetic satisfaction was therefore similar to the patients' satisfaction. Two further appointment (for the LAB group) did not offer more favorable Æsthetics compared to the CHAIR workflow from a patient's perspective.

Other parameters might therefore be considered in the decision-making for a specific treatment option. This includes financial aspects as well as chairside time. The CHAIR workflow is associated with higher investment costs (e.g., milling machine) for the professional, but lower treatment costs for the patient. In the LAB workflow, these investments are made by the dental laboratory and can therefore be outsourced from the clinic.

The LAB workflow required three times the number of appointments compared to the CHAIR workflow. Interestingly, when calculating the active chairside time, the differences between the two workflows were negligible (CHAIR: 49.9 min.; LAB: 41.4 min.). This included, in the group CHAIR, the design and milling of the restoration as well as some time needed for adjustments (i.e. occlusion, contact points). In the LAB workflow, the active chairside time was lower since the entire fabrication process of the restoration was outsourced and the time for adjustments was substantially lower.

The outcomes of the present clinical study and its generalization are to some extent limited by (i) the study design being a pilot investigation with a rather low sample size due to the lack of previous clinical data and, (ii) the lack of split-mouth design that did not allow intergroup comparisons within the same patient.

5 | CONCLUSIONS

The present study demonstrated similar and high PROMs when single teeth were restored by a chairside or a labside workflow. The additional efforts undertaken in the labside workflow did not result in more favorable PROMs, but in less chairside time for the clinicians and a higher WES score.

ACKNOWLEDGMENTS AND DISCLOSURE

The present study was mainly funded by the Clinic for Reconstructive Dentistry and the Department of Computerized Restorative Dentistry, University of Zurich, Zurich, Switzerland. In addition, the study was supported with restorative materials from Dentsply Sirona. The authors gratefully acknowledge Gisela Müller (Clinic of Reconstructive Dentistry, University of Zurich) for assistance in the study process. A.M. is the inventor and the developer of the AI biogeneric restoration and articulation software used in this study both in the Chairside and Labside process. A.M. holds an endowed professorship, which is partly financed by Dentsply Sirona. The other authors do not have any financial interest in the companies whose materials are included in this article and report no conflicts of interest related to the outcomes of the study. Open access funding provided by Universitat Zurich.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Zuercher AN, Ioannidis A, Hüsler J, Mehl A, Hämmerle CHF, Thoma DS. Randomized controlled pilot study assessing efficacy, efficiency, and patient-reported outcomes measures of chairside and labside single-tooth restorations. *J Esthet Restor Dent*. 2023;35(1):74-83. doi:10.1111/jerd.12909

Received: 28 November 2022 | Revised: 3 January 2023 | Accepted: 4 January 2023

DOI: 10.1111/jerd.13016

REVIEW ARTICLE

WILEY

Indirect restorative systems—A narrative review

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Funding information
Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP); Young Investigators Award, Grant/Award Numbers: BEPE 2021/08018-2, 2019/06893-1, EMU 2016/18818-8, 2021/06730-7, 2012/19078-7; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Grant/Award Number: 307255/2021-2; CAPES, Grant/Award Number: 001

Abstract

Objective: The background and clinical understanding of the properties of currently available indirect restorative systems and fabrication methods is, along with manufacturer and evidence-based literature, an important starting point to guide the clinical selection of materials for tooth and/or implant supported reconstructions. Therefore, this review explores most indirect restorative systems available in the market, especially all-ceramic, along with aspects of manufacturing process, clinical survival rates, and esthetic outcomes.

Overview: Progressive incorporation of new technologies in the dental field and advancements in materials science have enabled the development/improvement of indirect restorative systems and treatment concepts in oral rehabilitation, resulting in reliable and predictable workflows and successful esthetic and functional outcomes. Indirect restorative systems have evolved from metal ceramics and polymers to glass ceramics, polycrystalline ceramics, and resin-matrix ceramics, aiming to improve not only biological and mechanical properties, but especially the optical properties and esthetic quality of the reconstructions, in attempt to mimic natural teeth.

Conclusions: Based on several clinical research, materials, and patient-related parameters, a decision tree for the selection of indirect restorative materials was suggested to guide clinicians in the rehabilitation process.

Clinical Significance: The pace of materials development is faster than that of clinical research aimed to support their use. Since no single material provides an ideal solution to every case, professionals must continuously seek information from well designed, long-term clinical trials in order to incorporate or not new materials and technological advancements.

KEYWORDS
ceramics, dental implants, dental materials, dental prosthesis

1 | INTRODUCTION

Prosthodontists have treated more than 1 million patients per year in the United States, with conventional and implant-supported fixed dental prostheses (FDP) comprising approximately 50% of all treatments performed in dental offices.[1] Such prosthodontic procedures have a projection to increase due to the potential rise in the population, especially of elderly individuals.[2] However, oral rehabilitation is a complex and meticulous specialty that encompasses the treatment of defective/missing single or multiple teeth through tooth or implant supported reconstructions, requiring a comprehensive knowledge of oral biology and physiology, biomaterials and biomechanics, as well as training of dentists, laboratory technicians, and related staff.[3]

The rapid advance in computer-aided design/ computer-aided manufacturing (CAD/CAM) by either subtractive or additive (3D printing) technologies have revolutionized oral rehabilitation field not only by providing a time-efficient fabrication process but also by resulting in high accuracy and adaptation of protheses and/or prosthetic components relative to conventional hand-layering techniques, which are prone to a greater number of interferences as a result of many laboratory steps and reliance on manual skills.[4,5] Moreover, the combination of digital tools and virtual reality has facilitated the communication between dentists, laboratories, and patients by using virtual models of the treatment plan, which can be machined or 3D-printed using different types of materials, eventually improving clinical outcomes and productivity.[6–8]

Technology has also encouraged the increased use of indirect restorative systems which, stimulated by the population aging and rising prevalence of dental care needs, is projected to reach a market size of approximately 8 billion dollars by 2027. There are currently several new indirect restorative materials on the market with different chemical, physical, and mechanical properties that directly affect clinical survival and success rates, as well as esthetic results and costs, all of which must be considered in materials selection for each clinical scenario.[9] Most of the restorative materials include a CAD/CAM block or disk version, including metals, polymers, and ceramic systems; while 3D-printing is currently being extensively used for the production of dental models, CAD-designed treatment plan prototypes and surgical guides, as well as temporary polymeric restorations prostheses.[10–12] Extensive research in the biomaterials science has been focusing on the development of 3D-printed indirect restorative systems, with a potential to significantly innovate the future of restorative dental care; however, the development of dental materials is very complex and involves many fields of knowledge, including the understanding of the influence of the harsh oral environment and oral function on the clinical performance of restorative materials.[13]

Among restorative materials, dental ceramics have played an important role in the restoration of implants tooth-supported reconstructions. The large scale use of ceramic systems is chiefly a result of their biocompatibility, esthetics, chemical inertness, favorable strength and fracture toughness, hardness, and wear resistance.[13,14] Therefore, the possibility of providing a favorable balance between strength and translucency combined with wear resistance and intraoral stability, make them suitable for numerous clinical applications.[15–24] However, due to the high number of products available and the speed at which new products are being introduced on the dental market, clinicians frequently face a complex decision-making process to choose an indirect restorative system.[25] More often, the selection is based on criteria such as material strength and translucency, manufacturing techniques, core or abutment shade/translucency, available space for the restoration, position in the arch (anterior/posterior), type of support (tooth or implant) stability and span of edentulous space, experience of dentist/technician, and patients desire.[9,15] This manuscript aims to revisit currently available indirect restorative systems, especially all-ceramic systems, regarding the mechanical and physical properties, manufacturing techniques, applicability in different clinical scenarios, and clinical data together with future trends.

2 | INDIRECT RESTORATIVE SYSTEMS

The search for a strong and esthetic indirect restorative system in dentistry increased after the introduction of the feldspathic ceramics crown in 1903 by Land, and with the introduction of reinforced ceramics first by the addition of aluminum oxide to feldspathic porcelain in 1965 by McLean.[14] Thereafter, a remarkable variety of ceramic and polymeric systems has been launched on the dental market, stimulated by technological advancements throughout the 2000s and improvements in adhesive cement systems.[15,16,26] Considering dental materials development, an ideal system should first be biocompatible and mimic the optical properties of natural teeth in terms of anatomy, shade, translucency, opalescence, and fluorescence. Additionally, mechanical properties must be guaranteed to resist the harsh oral environment and to withstand cyclic loading. Moreover, the material processing should be relatively time and cost effective, as well as provide a small misfit on the margins, a durable bond to the tooth/core/implant structure, cause minimal wear on the antagonist, and be easy to polish and repair, resulting in predictable long-term results in a variety of clinical applications.[27] Unfortunately, up to the present moment, there is no indirect restorative all-ceramic system that provides the very best of all these characteristics.

Metal ceramics, introduced in the 1960s, were the first modality of indirect restoration used in a large scale in the clinical practice to restore extensively damaged teeth.[14,16] Given the inherent brittleness and low strength and fracture toughness of feldspathic ceramics, the development of compatible metal alloys and use of reinforcing frameworks were critical to improve the strength and toughness of the assembly and, consequently, increase the range of clinical applications.[14,16] Such indirect restorative modality has been well documented in the literature, suggesting excellent survival rates in a variety of clinical scenarios.[18,19,21–23,28] Up to the present moment, metal ceramics are still considered the most appropriate restorative option for partial and full arch FDPs, in which all-ceramic systems do not present a satisfactory performance, especially when high occlusal load is involved and/or support system is not biomechanically favorable, such as implant-supported reconstructions.[23,25,29]

The metal alloys currently used for framework fabrication are high noble, noble, or predominantly base metal, which can be manufactured by conventional lost wax casting, and more recently by subtractive CAD/CAM manufacturing and 3D-printing additive manufacturing.[14,30–32] The opaque metal framework is veneered with feldspathic ceramics using conventional powder-liquid condensation technique or by heat pressing and CAD/CAM technologies, PRESS-on and CAD-on techniques.[14,33] Conventional feldspathic ceramics are fabricated through a vitrification process in high temperature, creating a silica glass matrix with a dispersed crystalline content.[14,34] The main composition of feldspathic ceramics is of potash feldspar ($K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$) and a silica ($SiO_2$) network, containing a variety of oxides, such as SiO_2, Al_2O_3, K_2O, Na_2O, and additives including B_2O_3, CeO_2, Li_2O, TiO_2, and Y_2O_3.[14,34] For bilayered restorations, the amount of leucite crystals formed by feldspar not only increase the intrinsic strength but also make the material suitable for veneering metallic frameworks by providing a coefficient of thermal expansion (CTE) approximately or less below that of the

framework, favoring mechanical interlocking and reducing the presence of residual tensile stress at the interface.[14,15] The application of feldspathic ceramics is made by the incorporation of fine particles with polymeric binders in an aqueous medium to form a slurry, which can be applied directly on a plaster die (i.e., for veneers fabrication) or on a metal alloy or another high-strength ceramic framework, such as zirconia. For each layer, the feldspathic ceramic is heated slowly to evaporate the binder and to coalesce the particle to densify and then cooled slowly to prevent cracking.[14,35]

Metal ceramics have been advocated in several studies as the standard of care for tooth and implant supported reconstructions, especially for long-span prostheses.[18,19,21–23,28] Some recent findings support such a perspective through the presentation of high survival rates, 94%–98%, for both tooth and implant supported metal ceramics fabricated using the conventional lost wax casting technique after an observation period of 5 years.[18,19,21–23,28] The most frequently reported biological complications have been associated with secondary caries (2.7%) and periodontal/peri-implant inflammatory diseases (3%–5%), while technical complications mainly comprised the fracture of the veneering ceramic (2.6% and 8.6% for tooth supported single crowns and FDPs; and 2.8% and 11.6% for implant supported single crowns and FDPs, respectively).[18,19,21–23,28] For implant supported reconstructions, screw loosening has also been frequently reported as a recurrent technical complication (approximately 4% after a mean follow-up period of 5 years).[23,28] Similarly, full-arch implant supported metal ceramics FDPs have also demonstrated high survival rate, 98.8% after a follow-up of 5 years, with few biological and mechanical-technical complications.[36] Regarding framework fabrication method, tooth supported metal ceramic crowns fabricated with Co–Cr or noble alloy frameworks by CAD/CAM machining have presented a cumulative survival rate of 81% after a mean observation time of 10 years, with a predominance of biological complications (13.5% secondary caries, 6.5% loss of vitality, and 6.1% periodontitis) over technical complications (4.7% fracture of veneering ceramic and 1.8% loss of retention)[37]; likewise, CAD/CAM titanium frameworks for tooth-supported FDPs presented a survival rate of 88% up to 6 years of follow-up,[38] supporting CAD/CAM manufactured metal ceramics as a viable alternative to the conventional lost wax casting processing method. Further clinical studies are warranted to investigate the clinical performance of metal ceramic rehabilitations with frameworks fabricated by 3D-printing techniques.

Given that the most common technical complication reported for metal ceramics is the fracture of the veneering feldspathic ceramic, the success of metal ceramics depends on a durable bond between the porcelain and the metal framework. In fact, three main factors control metal-ceramic bonding, including mechanical interlocking at the interface between porcelain and the metal framework, interatomic bonding across the oxide-porcelain interface along with the type and magnitude of residual stress present in the veneering ceramic, which might be reduced by using feldspathic ceramics with a compatible CTE.[14] Several other factors can be associated with veneering ceramic susceptibility to fracture, including feldspathic ceramic layer thickness, framework material and processing method, low strength and toughness of the porcelain, inadequate ceramic firing, and defects caused during the fabrication process and adjustments.[14,32,39]

The metallic framework manufacturing method can significantly affect metal-ceramic interface bond, which might also influence technical complication rates, with the conventional lost wax casting and selective laser melting (SLM) 3D-printing methods outperforming CAD/CAM method for Co–Cr frameworks[30–32]; Such new technologies for metal framework fabrication seem to provide acceptable clinical levels of marginal misfit for tooth and implant supported single crowns and FDPs, comparable to conventional casting (all lower than clinically acceptable levels, 120 μm), although CAD/CAM method has shown inferior marginal adaptation relative to other methods.[31,40,41]

Irrespective of metal alloy type and processing method, metal frameworks prevent light transmission and make it a challenge to achieve an acceptable optical effect, especially for tooth supported anterior reconstructions. Therefore, esthetic concerns have driven the development of all-ceramic systems.

3 | ALL-CERAMIC SYSTEMS

It has been well-defined that dental ceramics are nonmetallic inorganic structures containing oxygen compounds with one or more metallic or semi-metallic elements, with the most common systems being composed of a crystalline phase surrounded by a silica glass matrix.[13,14] Several classification systems have been previously proposed for indirect restorative systems, especially all-ceramic systems, with different specifications of categories, such as by composition, etching ability, processing method, microstructure, physical and mechanical properties, among others, making it virtually impossible to include all available systems in a single classification scheme.[15] A recent approach to classify indirect restorative materials used in dentistry has been based on their formulation and specific clinical attributes that resulted in a wide-ranging classification with a remarkable clinical relevance.[15] In this classification, the all-ceramic (i and ii) and ceramic-like systems (iii) have been arranged as: (i) glass-matrix ceramics, nonmetallic inorganic ceramic materials that contain a glass phase and are subdivided in feldspathic ceramics, synthetic ceramics, and glass-infiltrated ceramics; (ii) polycrystalline ceramics, nonmetallic inorganic ceramic materials that do not contain any glass phase and are subdivided in alumina, zirconia, and alumina-zirconia composites; and (iii) resin-matrix ceramics, polymer matrices containing predominantly inorganic refractory compounds that may include feldspathic ceramic and glass ceramics.[15] It is evident that, from a materials science perspective, the resin-matrix ceramics group could never be included in a restorative all-ceramic classification system as a ceramic material given that such CAD/CAM blocks are comprised also of organic compounds; for this reason the term "ceramic-like" has been suggested in the past, although likely due to insurance and refund purposes, it has been coined as a porcelain/ceramic by the American Dental Association Glossary of Dental Clinical Terms.[42] Another class of material that will be a topic of discussion is the fiber-reinforced composites (FRC) produced for CAD/CAM machining, which is gaining increased interest due to its high long-term survival rates especially in partial FDP[43] to full-arch implant-supported reconstructions.[44]

3.1 | Glass-matrix ceramics

Feldspathic ceramics (FEL) were the first materials used in dentistry, in which the vitrification processing at high temperature generate various crystalline nucleus surrounded by a silica glass matrix.[14,34] Feldspathic ceramics consist primarily of a variety of oxides, such as SiO_2, Al_2O_3, K_2O, Na_2O, and additives including B_2O_3, CeO_2, Li_2O, TiO_2, and Y_2O_3.[14,34] Pigments can be used to mimic the shade and optical phenomena of natural tooth.[14,34] Given that chipping and delamination of the veneering porcelain are the main causes of failure for bilayered restorations, an alternative approach has been proposed through the use of full-contour/monolithic ceramic restorations, designed and fabricated usually by CAD/CAD machining and/or heat pressing technologies.[16,17,45–47] Monolithic FEL ceramic systems can mimic the shade, translucency, opalescence, and fluorescence of natural tooth; however, this type of ceramic is very brittle and present low strength and toughness, which makes them more prone to fracture and limits its application for veneers, inlays, onlays, and single tooth anterior crowns.[48–50] FEL ceramics can most frequently be found to be manufactured by powder-liquid condensation technique or CAD/CAM machining techniques in different shades and translucencies.

Owing to the low mechanical properties of FEL ceramics, the restorations are usually limited to conventional preparation thickness, about 1.5–2.0 mm incisal/occlusal reduction, proportionally reducing according to enamel thickness and anatomical considerations of the other areas of the tooth for each restorative modality.[51] Feldspathic ceramic veneers have exhibited a survival rate of 87% after a mean follow-up period of up to 8 years, with debonding (2%), fracture/chipping (4%), and secondary caries (1%) representing the main complications associated with this type of rehabilitation.[49] Similarly, a high 5-year survival rate, approximately 95%, have been reported for inlays/onlays and crowns made by FEL ceramics, with secondary caries and endodontic complications as the main biological complications (11.3%–19.9%) and ceramic chipping/fracture the most common technical complication (11.5%–52.3%), followed by loss of retention (17%).[50] Moreover, FEL ceramic laminate veneers and single crowns have demonstrated a marginal gap that is within clinically acceptable levels, an average of 114 μm and 100 μm, respectively[52,53]; with a significant influence of the fabrication method of the restoration.

To become less dependent on natural raw materials and to improve the mechanical properties of glass ceramics, industry has begun to produce synthetic materials, which despite similar main composition among different manufacturers, present key differences that affect their final properties and clinical use.[15] An important system introduced on the dental market was the leucite glass ceramics (LEU) in the late 1980s. LEU is a potassium aluminum silicate (K_2O–Al_2O_3–SiO_2), as the conventional feldspathic ceramic, however with a greater content of K_2O (12%) that results in the formation of 35%–45% volume fraction of tetragonal leucite with morphology of 1–5 μm lamina-like crystals.[14,54] Leucite crystals reinforce the glass phase by controlling propagation of cracks due to the formation of compressive stress around particles during cooling due to either phase transformation from cubic to tetragonal that causes a contraction along the axis or glass-leucite CTE difference.[55] LEU systems present a notable improvement in the mechanical properties (σ: 160 MPa, K_{ic}: 1.3 MPa $m^{1/2}$, hardness-*H*: 6.2 GPa) relative to traditional feldspathic ceramics,[16] however, despite the improvement, their indication is also limited to laminate veneers, inlays, onlays, anterior and posterior crowns, usually following conventional preparation design.[21,22,56,57] LEU can be commercially found to be manufactured by heat pressing or CAD/CAM machining techniques in different shades and translucencies.[45,52]

LEU-based veneers and crowns have demonstrated high survival rates in the long term, 96%–100% after approximately 5 and 10 years,[21,22,56,57] with the main causes for failures being periodontal problems (4%) and unacceptable chipping and restoration fracture (5%).[57] Marginal fit of LEU restorations was below 90 μm, which is also clinically acceptable (<120 μm).[58] Similarly, LEU restorations fabricated by heat pressing and CAD/CAM have provided clinically acceptable levels of marginal misfit, below 60 μm, with also comparable fracture load, indicating the suitability of LEU systems for both processing methods.[52]

Lithium disilicate (LDS), introduced in the dental market in the 1990s, is currently the most used glass ceramic in the daily practice.[15] The constituents of LDS ceramics are approximately 70% volume fraction of lithium disilicate ($Li_2Si_2O_5$) crystals having either a classic small needle-shaped structure (2.0 to 3.0 μm size) or different morphologies in newly developed system, embedded in a glass matrix containing SiO_2, Li_2O, Al_2O_3, K_2O, P_2O_5 and other oxide substitutes.[59] LDS presents a favorable balance between mechanical properties and esthetic performance, with almost fourfold the strength of feldspathic ceramics (σ: 360 MPa, K_{ic}: 2.7 MPa $m^{1/2}$, hardness-*H*: 5.8 GPa).[16] The favorable mechanical properties of LDS systems may lie in two major factors, first with their elongated lithium disilicate crystals that form an interlocking crystalline pattern that limits crack propagation, and second with the divergence between the LDS-glass CET that induces compressive stresses around the crystals, as previously explained by LEU systems.[55] Therefore, LDS can be used in different applications, such as anterior and posterior veneers, inlays, onlays, overlays, and crowns, as well as 3-unit FDPs up to the premolar region, and implant-supported single crowns.[20,21,24,60–62] Moreover, tooth-supported LDS monolithic restoration has shown high predictability under minimally invasive preparation, incisal/occlusal reduction lower than 1.0 mm.[61] LDS can be manufactured by heat pressing or CAD/CAM machining techniques in different shades and translucencies to meet esthetic needs.[62]

LDS veneers have shown a high survival rate, 97.4% after 10 years, with a small rate of complications, 1.64% (0.55% and 1.09%, ceramic fractures and debonding, respectively).[60] Full veneer restorations, which is known as minimally invasive crown preparations with approximately 0.3 mm and 0.8 mm incisal tooth removal in the anterior dentition, have also presented a survival rate, 100% after 8 years, and a low rate of complications, 12.5% due to minor reparable chippings.[61] In a 5-year survival rate estimation, single crowns made by glass ceramics, including LDS (96%), have demonstrated similar survival percentage to those reported for metal ceramics (95%), both in

the anterior and posterior regions, with ceramic fracture the most frequently reported technical complication (2.3%).[21] Regarding implant supported single crowns restored with LDS, a 91% survival rate has been estimated after 5 years in function, with ceramic chipping being the most frequent complication (6%).[20] The 10-year survival rate for single crowns has been approximately 86%, with 20% repairable technical incidents, such as debonding and small chippings, and 5.7% biological complications that included endodontic and periodontal problems; and, for implant-supported single crowns were 94%, with 12% minor chippings and 18% biological complications that mainly included peri-implant problems.[24] In the case of FDPs, the survival rates have exhibited a significant decrease, 52%, with 44% technical failures and 11% biological failures.[24] Although promising clinical survival rates were reported in a 10-year follow-up for monolithic LDS tooth-supported FPD, the 15-year follow-up reported a substantial decrease in survival rate to only 48.6%, likely as a result of fatigue and crack propagation due to clinical aging of LDS in function.[63] Similarly, marginal misfit of LDS glass ceramic restorations was not different for restorations fabricated with either heat pressing or CAD/CAM techniques, all below 60 μm that is within the limits of clinical acceptance (<120 μm).[62] Considering implant-supported restorations, marginal misfit of single crowns made by LDS was also within the gap range required for clinical applications.[64] Since the patent expiration of the first LDS marketed in dentistry, several LDS systems have been launched. Most of them present with a different crystal configuration as well as glass matrix composition. The increased understanding of such novel LDS microstructures are of major importance as they affect the technician and the dentist handling, including the adhesive procedures.[65]

Lastly, a new class of promising glass ceramics was introduced in the dental market, zirconia reinforced lithium silicate ceramics (ZLS). ZLS encompasses a complex microstructure, which is composed of lithium metasilicate (Li_2SiO_3), lithium disilicate ($Li_2Si_2O_5$), and lithium orthophosphate (Li_3PO_4) crystals embedded in a glass matrix containing predominantly SiO_2, Li_2O, Al_2O_3, K_2O, P_2O_5, Z_2O and other coloring oxides.[59,66,67] The very fine rod-like crystal size exhibited in the ZLS system (0.5 to 1.0 μm), which is approximately 4 to 6 times smaller than LDS crystals, provides a higher percentage of glass content (50%) than LDS (30%),[59,68] improving the translucency of ZLS systems while maintaining similar mechanical properties to LDS (σ: ~300 MPa, K_{ic}: ~2.0 MPa $m^{1/2}$, hardness-*H*: ~6.0 GPa).[68–70] Manufacturers claim that the homogeneous dispersion of zirconia crystals into the glassy matrix improve the mechanical properties of the ceramic structure by toughening mechanisms; however, previous data have indicated that the zirconium oxide is potentially dissolved in the glass phase instead of acting as a reinforcing particle,[59] requiring further investigations. ZLS can also be used in different clinical applications, such as anterior and posterior veneers, inlays, onlays, overlays, and crowns.[71,72] Similar to the previous glass ceramics, ZLS can be commercially found in different shades and translucencies to be manufactured by heat pressing or CAD/CAM machining techniques.

Up to the present moment, data regarding clinical performances of ZLS are limited, with a short term evaluation of full and partial coverage indirect restorations indicating a promising survival rate, 99% survival after 1[71] and 3 years[72] in function. ZLS restorations have also exhibited clinically acceptable marginal gaps, all <100 μm for tooth and implant supported restorations.[73–75] More clinical studies are required to confirm the long-term performance of ZLS restorations as well as to investigated clinical complications.

The high esthetic results of glass ceramics are achieved by mimicking the color, translucency, opalescence of natural tooth, depending on the intended clinical use. The translucency of dental ceramics has shown to be affected by restoration thickness, number of firings, luting agent, core/abutment color, and texture.[76–78] Within a standard thickness and shade, LDS presented the lowest translucency (translucency parameter—TP: 26–33), followed by LEU (TP: 35–39) and felspathic ceramics (TP: 40–46). Additionally, fabrication method has shown to influence translucency parameter of LDS (higher translucency for CAD/CAM, TP: 33, relative to heat-pressing, TP: 26), LEU (higher translucency for heat-pressing, TP: 39, relative to CAD/CAM, TP: 35), and feldspathic ceramics (higher translucency for conventional method, TP: 40–46, relative to CAD/CAM, TP: 33).[76] Altogether, the data reveals the tradeoff between crystalline content and optical properties, which might also influence the clinical selection of indirect restorative systems.

Surface finishing of glass ceramics usually consists of polishing and/or glazing.[79–82] After finishing, the surface becomes smoother, which might result in some clinical benefits, such improved esthetics of the restoration and decreased antagonist wear.[83] Both techniques, polishing and glazing, have been the focus of research comparing the surface properties and color stability of glass ceramics before and after different finishing procedures; however, there is not a consensus in the literature concerning the ideal protocol. Most of the studies have indicated that polished surfaces (depending on protocol) results in smoother surfaces than glazed surfaces[79–82]; however, glazing might also have a potential improved effect on color stability and flexural strength of glass ceramics.[80] Besides finishing procedures, staining of ceramic restorations might be a useful procedure to improve the mimicking of nuances and shade of natural teeth, especially for monolithic restorations that usually do not meet the high esthetic demands without staining. Nonetheless, an increased number of firing procedures might be required for extrinsically staining glass ceramic restorations, which has been associated with alterations in the color, translucency, and mechanical properties.[84] It is noteworthy that ceramic thickness has also dictated the effect of multiple firings in glass ceramics translucency, with no significant change for glass ceramics with at least 1-mm thickness.[78] Moreover, an important clinical concern lies in the time-lasting of glass ceramic stains and glaze after installation. While a previous study has shown no clinically perceptible color alteration of stained and glazed glass ceramics after toothbrushing simulations up to 15 years,[85] other study exhibited a gloss and color change beyond clinically perceptible levels in a period that would be equivalent to 3 years of toothbrushing.[86] Such results raise a red flag on the need for more clinical investigations concerning the duration of such finishing procedures after clinical installation and use.

Literature findings have indicated that glass ceramics with a smoother contact area, polished group, presented a low wear rate on

the antagonist relative to the glazed group.[83] Also, glass ceramic type has shown a significant influence on the antagonist wear performance, with LDS samples producing the least wear loss, followed by LEU and FEL ceramics. Moreover, LDS ceramics exhibited similar wear loss as LEU, both higher than FEL ceramics.[87]

Small chippings are the most frequently reported technical complication for glass ceramics, which might need clinical repair. The adhesion strength of glass ceramics to resin composites followed by different surface treatment has been investigated, including hydrofluoric acid etching (HF) and airborne particle abrasion with alumina particles or silica-coated alumina particles. The bond strength with conventional adhesive systems to resin composite after HF conditioning was significantly higher than all other surface treatments for FEL ceramics and LDS systems.[88,89] On the other hand, application of micromechanical and chemical surface preparation methods (diamond bur abrasion, alumina or silica-coated alumina particles abrasion) might enhance bond strength of the composite to the substrate material for LEU and also for LDS glass ceramics.[88]

Conventional methods of producing ceramic restorations, such as powder-liquid condensation and heat pressing present major drawbacks, such as the reliance on a manual production. With CAD/CAM and intraoral scanning technologies, an automized production process has been introduced in oral rehabilitation through a fully or partial digital workflow that allows for the production of a customized treatment with reduced production costs and improved time-efficiency, approximately 50% reduction in the mean work time relative to the conventional workflow.[6–8] However, despite the high efficiency of such systems, the CAM manufacturing process still presents some limitations concerning equipment costs and the dimension of the tools associated with the equipment that might affect the designing of complex geometries,[90] such as milling thin walls and small dimension components. Moreover, even with an optimal use of a block/disc capacity, the material consumption is high since non-milled parts might result in up to 80% waste.[91,92]

To overcome problems associated with CAM processing, additive manufacturing technologies (AMs) have been currently introduced for the manufacture of indirect restorations. The layer-by-layer approach not only reduces the overall material waste but allows the construction of highly complex structures.[90,93,94] Different AM procedures have been investigated regarding their suitability for manufacturing of ceramics components, such as selective laser sintering (SLS), fused deposition modelling (FDM), direct ink writing (robocasting), and stereolithography (SLA).[90,93–95] For glass ceramics, SLA AM techniques have proven to be a feasible method to 3D-print slurries formulations containing high solid loading.[93] It is well known that the development of processable slurries for glass ceramics is challenging due to the morphology of the glass ceramics powder, which has also a great impact on the achievable printing and post-processing parameters, including layer thickness and sintering behavior.[90,95] A recent study proposed the use of SLA to reproducibly print dense and reliable LDS glass ceramic samples that meet the high requirements for dental restorations regarding mechanical properties and aesthetics (approximately 400 MPa),[93] and high precision to print ceramic components, such as crowns.[94] Future studies are required to provide an extensive laboratory characterization of AM glass ceramic systems along with clinical studies to support clinical applicability of such production process.

3.2 | Polycrystalline ceramics

The characteristic of the ceramic systems classified in the polycrystalline group is a dense glass-free fine-grain crystalline structure formed by a sintering process that provide favorable strength and toughness, mostly with limited translucency due to the absence of glass phase.[15] Alumina, or aluminum oxide (Al_2O_3), was the first representative of polycrystalline ceramics, introduced in the 1970s due to its favorable biocompatibility and satisfactory mechanical properties and wear resistance.[16] Alumina-based ceramics have been continuously improved, resulting in a pure material that fulfilled clinical requirements in the 1990s with the Procera (Nobel Biocare) system (σ: 695 MPa, K_{ic}: 3.2 MPa $m^{1/2}$, hardness-*H*: 17 GPa).[16] Alumina has been extensively used in prosthodontics for the fabrication of crown frameworks.[15,21,22,96] The clinical application of Procera system have resulted in high survival rates for single crowns, approximately 96% after a follow-up of 5 years, with fracture of the veneering ceramic being the most common reason for failure.[21,22,96] However, the inherently brittle nature of alumina systems limits their range of application as well as the significant progress made in high-strength polycrystalline zirconia systems have driven the clinical use to the latter.[15]

Zirconia, or zirconium dioxide (ZrO_2), systems introduced in the 1990s to dentistry, have been considered one of the most promising indirect restorative materials used in oral rehabilitation. This material presents three crystallographic configurations depending on the temperature, each with different properties: (i) the cubic phase (*c*, stable from 2370°C to the melting point) with moderate mechanical properties, (ii) the tetragonal phase (*t*, stable from 1170°C to 2370°C) with the highest mechanical properties, and (iii) the monoclinic phase (*m*, stable from 1170°C to the room temperature) with the lowest mechanical properties.[97–103] The rationale for zirconia use as a dental restorative material has been based on the use of tetragonal (*t*) phase properties and the associated tetragonal-to-monoclinic (*t*–*m*) transformation toughening mechanism.[100] Therefore, conventional zirconia ceramics are composed of a crystalline tetragonal matrix stabilized at room temperature with the addition of yttrium oxide (Y_2O_3), named as yttria-stabilized tetragonal zirconia polycrystals (Y-TZP).[16,47,98,102,104,105] When subjected to tensile stresses, Y-TZP grains undergo a martensitic *t*-*m* transformation that is accompanied by a volumetric expansion of ~5% and ~7% shear, which give rise to compressive stresses in the vicinity and potentially close an advancing crack, thus increasing the fracture toughness of the material.[100,102,103] As a result, 3Y-TZP systems present the highest mechanical properties among all-ceramic systems currently used in the dental market (σ: 900–1200 MPa, K_{ic}: 5–9 MPa $m^{1/2}$, hardness-*H*: 11 GPa),[16] which have led to a wide spectrum of indication in oral rehabilitation, including the manufacturing of frameworks (that is subsequently veneered with translucent feldspathic ceramics to meet esthetic requirements) for tooth and implant supported single crowns to FDPs and implant components.[19,20,22,23,28,29]

For tooth supported porcelain veneered Y-TZP single crowns, systematic reviews have shown high survival rate, which was similar to metal ceramics, higher than 94% after 5 years.[21,22] FDPs made by Y-TZP systems have also demonstrated high survival rates, 90% after 5 years, however, significantly higher levels of technical complications were described relative to metal ceramics, up to 20% chipping and 2% framework fracture.[18,19] Similarly, a long-term evaluation of Y-TZP FDPs has shown higher rates of framework fractures relative to conventional metal ceramics.[106] For implant supported Y-TZP crowns, systematic reviews have also shown similar survival rates to metal ceramics, 92%–97% after 5 years.[20,28] Porcelain-fused to zirconia FDPs made with Y-TZP systems have also demonstrated high survival rates, 93%–98%, however, significantly high level of technical complications, especially veneering ceramic fracture (34.8%–50% chipping and 4% framework fracture after 5 years) was described.[17,20,23,28,29] The high rate of technical complications has led the last consensus of the European Academy for Osseointegration not to consider zirconia veneered system as a first option material for implant supported partial or full-arch FDPs restorations.[25]

Despite pragmatic investigations of the reasons for the high fracture rates of the veneering porcelain over zirconia frameworks, this event still represents the most commonly reported technical complication for Y-TZP-based restorations, especially for long span tooth supported FDPs and implant supported restorations.[16,23,25,29,107] In this context, the fabrication of anatomically contoured monolithic restorations, where the lower fracture toughness veneering ceramic is removed completely or just from functional occlusal areas, seems to be an alternative with Y-TZP systems to enhance clinical success.[16,17,108–112] Nonetheless, the limited translucency is the major drawback of conventional Y-TZP systems for full-contour rehabilitation,[113] which has driven innovations in the biomaterial science towards the development of translucent zirconia systems.[47]

The high opacity of polycrystalline ceramic systems is usually a consequence of the anisotropic crystal structure (chiefly noncubic crystals), in which there is a discontinuity of the refractive index at the grain boundaries, leading to a reduction in the light transmittance and light scattering.[114,115] The presence of pores and secondary crystal content has also shown a profound effect on light scattering.[47,115,116] Hence, the first improvement in the optical properties of Y-TZP systems, second generation of zirconia systems, has been achieved by changing the composition and processing method.[47] Such modifications involved a drastic reduction of the alumina additive concentration and an increase in the yttria content to stabilize more cubic crystals, and the use of sintering protocols with higher temperatures to increase the density and eliminate residual porosity, thereby decreasing light scattering.[47] Despite a modest improvement in translucency (translucency parameter—TP first generation: ~7; TP second generation: ~10),[117] these Y-TZP systems can achieve reasonable biomimetic characterization with the addition of coloring liquids before sintering and superficial extrinsic staining, while maintaining high mechanical properties.[47,108,118,119] Still, due to the metastability of 3Y-TZP, the second generation zirconia has clinically shown 100% loss of glaze at the occlusal surfaces at 1 year and phase transformation characterized also by increased roughness and grain pull-out at the occlusal surfaces in a similar pattern observed in the past for retrieved orthopedic hip prostheses.[120]

The limited light transmission of second generation Y-TZPs have led to the development of a third generation dental zirconia, ultra-translucent zirconia.[121] This material is characterized by the predominant presence of optically isotropic cubic crystals by increasing yttria content (4–5 mol%), yttria partially stabilized zirconia (Y-PSZ). Nonetheless, the prevalence of the cubic phase, more than 50% cubic crystals, reduces the stress-induced transformation toughening effect of tetragonal-based systems, resulting in a decrease in the strength and fracture toughness, which affect the range of clinical indication.[47] According to the manufacturers, third generation Y-PSZs are indicated for full-contour crowns, which may improve the survival rates of esthetic restorations in the long term relative to bilayered zirconia-based reconstructions, requiring further clinical investigations.

Sequentially, a fourth generation of zirconia has been proposed through the development of multilayered systems.[122,123] The multilayered zirconia aims to mimic the natural teeth properties that present a gradual change along the structure, in which the incisal area of a crown is the most translucent, growing in chroma and opacity towards the gingival region. In fact, multilayered blocks/disks contain different compositions and crystalline structures, ranging from tetragonal to cubic phases from the respective areas of high opacity (cervical) to high translucency (incisal).[122] Previous studies have shown consistent optical properties in the areas of higher opacity (TP: 20–30, depending on the thickness 1–0.4 mm, respectively), presenting the least yttria content (first and second generation Y-TZP, predominantly tetragonal phase and smaller grain size), relative to areas of higher translucency (TP: 30–40, depending on the thickness 1–0.4 mm, respectively) presenting the most yttria content (third generation Y-PSZ, predominantly cubic and higher grain size).[122,123] Nonetheless, the production process of multi-layered zirconia blocks/disks through incremental powder pressing has resulted in a reduction of approximately 30% in the strength relative to the bulk counterpart, where fracture origin was usually located at the interface and originated from interfacial defects,[124] requiring further improvements. According to the manufacturers, multilayer zirconia systems have a similar clinical indication to conventional Y-TZP, which also demands further clinical investigations to support clinical use.

Given the evolution of zirconia systems, it is difficult for the clinician to choose the most suitable material for each specific clinical case. When it comes to the third and multilayered generations, the scientific data evaluating them is scarce, mainly because the multilayer system is the latest release on the market. For predominantly second generation Y-TZP restorations, a recent systematic review has indicated that tooth and implant supported monolithic single crowns presented 96%–100%, and FDPs, 99.6% 3–5 years survival rates,[17,125] with small chippings being the most frequent complication (0.39%).[17] Moreover, monolithic zirconia has also shown to be a feasible alternative to the conventional metal framework for full arch implant-supported prosthesis, achieving 100% survival and success rates after short-term 2 years of follow-up.[126]

Full-contour restorations allows for a reduction of the restorations thickness, especially when high strength ceramic systems are used, such as second and fourth generation zirconia.[16,108–112] Implant-supported posterior zirconia crowns have been able to withstand physiologic occlusal forces even with a thickness as low as 0.5 mm when resin cement is used.[127] Nonetheless, a previous study reported that the flexural strength of monolithic zirconia between 0.8 mm and 1.3 mm in thickness can exceed typical masticatory forces,[128] suggesting that 1.0 mm is the optimal thickness for monolithic zirconia restorations. Moreover, thickness has shown to affect the color accuracy of different high translucency monolithic systems, with 1.0 mm being considered the optimal thickness in terms of shade/translucency accuracy, which could be used as a reference for the selection and preparation of abutments in clinical applications.[127] Clinical studies are also warranted to investigate the performance of reduced thickness monolithic zirconia restorations.

Adaptation is another key criterion that potentially affects the long-term clinical performance of FDPs. For zirconia systems, the marginal discrepancy of single crowns was below clinically acceptable levels for tooth and implant supported restorations, most of them lower than 120 μm.[129,130] Similarly, marginal discrepancy values below 120 μm have been reported for tooth and implant supported restorations FDPs, with a tendency for higher gaps for longer spans and FDPs subjected to a higher number of firings during veneering process.[131–133] Such results indicate the potential influence of processing parameters on the clinical parameters of ceramic restorations.

Surface treatment methods, such as polishing, glazing, and staining maximize the mimicking of natural tooth characteristics of all-ceramic systems.[134] Similar to glass ceramics, polishing is a more effective finishing procedure to improve the physical properties of the material relative to glazing, creating a smoother surface without affecting the mechanical properties.[134–138] Besides, staining might require an increased number of firing procedures, which for zirconia systems has resulted in alterations in the translucency; however, it is noteworthy that ceramic thickness and block initial translucency has also dictated the effect of multiple firings on the properties of zirconia ceramics.[139,140] Also, extrinsic staining can be damaged or removed by in-office or external trauma, such as occlusal adjustments, oral function, and toothbrushing.[85,141,142] Previous findings have indicated that toothbrushing extrinsically stained zirconia restorations led to a significant alteration in the translucency and shade in up to 15-year simulations.[85,86,142] Moreover, glass ceramics have shown to retain stains longer than zirconia ceramics, which may lie in the similar glass content present in both materials.[86,143]

Wear is a complex process affected by many factors, such as material properties, surface characteristics, oral environment, and function.[144–146] A recent systematic review has indicated that polishing can reduce the wear of zirconia restorations on natural teeth more than glazed or porcelain veneered restorations.[147] Furthermore, the glaze layer can deteriorate with time in function, resulting in zirconia exposure to the harsh oral environment.[148] Another study has compared the antagonist wear for both zirconia and LDS systems, with zirconia samples experiencing less wear and LDS equivalent wear relative to natural enamel.[149] Such results indicate that, despite the high hardness of zirconia systems, they potentially cause a very smooth wear behavior to the antagonist.

There is a relevant debate regarding the susceptibility to *t-m* phase transformation triggered by water presence at low temperatures, a phenomenon known as low temperature degradation (LTD) specifically in first and second generation and multilayered Y-TZP systems.[101,150] The two main clinical concerns regarding the effect of LTD on zirconia restorations are: firstly, the high level of technical complications reported for bilayered Y-TZP reconstructions; and secondly, the Y-TZP surface direct exposure to the adverse oral environment for monolithic Y-TZP reconstructions that might potentially influence their optical and mechanical properties.[108,151,152] In fact, both effects, transformation toughening and LTD, arise from the *t-m* transformation; however, spontaneous and progressive transformation by the exposure of Y-TZP systems to hydrothermal environments may eventually result in the elimination of any toughening effect.[117,153–155] LTD has shown to occur likely due to the accumulation of tensile stresses in the tetragonal grains, triggering *t–m* transformation.[101,150,156] A cascade of *t–m* transformation might occur from the surface into the bulk of the material by an initial corrosion stress mechanism and nucleation-and-growth process, which has shown to lead to surface roughening, eventually grain pull-out and microcracking, while deteriorating the density, mechanical properties and wear resistance of the Y-TZP.[101,117,119,154–156] Literature findings have indicated a wide variation in the *t-m* susceptibility and detrimental effects among different Y-TZP systems, which has been associated with differences in the composition, microstructure, grain size, manufacturing and processing methods, residual stress along with aging protocol.[101,117,119,152,154–159] For bilayered restorations, LTD effects have been detected at the veneer/Y-TZP interface of dental prostheses, where the presence of moisture during the sintering process triggers phase transformation that may induce higher levels of tensile stresses and increased delamination rates.[160] Finally, a progressive *t-m* phase transformation has also been associated with an increase in the Y-TZP translucency, which may alter esthetic results of monolithic rehabilitations in the short-term.[117,119,161]

In an attempt to improve zirconia stability, ceramic composites have been proposed, such as zirconia-toughened alumina (ZTA) and alumina-toughened zirconia (ATZ) composites.[15,117,119,162–164] Such combinations have revealed an increase in the fracture toughness for pure alumina systems and more stability for pure Y-TZP zirconia systems through different mechanisms, including stress-induced phase transformation and compressive stress resulting from the thermal expansion mismatch of the two crystalline phases for the former,[165,166] as well as limited zirconia grains interconnectivity decreasing the LTD phenomena for the latter.[105,167] ZTA (15%, 20%, and 30% Y-TZP) and ATZ (20% alumina) composites have been successfully produced by our research team and the physical and mechanical characterization (ZTAσ: ∼950 MPa, ∼860 MPa, and 915 MPa, respectively, and ATZσ: ∼800 MPa) showed that both compositions were not only hydrothermally stable, compared to their Y-TZP isolated counterparts, but also presented adequate resistance

and both lead us to an innovative material, suitable for use as frameworks up to 3-unit FDPs.[117,119,163,164,168] ATZ systems have currently been available in the dental market for the fabrication of implants and prosthetic components, such as abutments.[169–171] Particularly, ATZ abutments have exhibited excellent survival rates in clinical use, 95% after 5 years,[169–171] with 19% and 4% complication rates for single and FDPs, respectively.[170] More studies are necessary for the development of an ideal polycrystalline composite system for dental prosthesis fabrication as well as compatible veneering ceramics for acceptable esthetics.

Regarding intraoral repairing procedures in polycrystalline ceramics, especially for zirconia-based restorations, various surface treatments have been proposed, including airborne particle abrasion with alumina particles or silica-coated alumina particles, primers, grinding with diamond burs, and laser application (yttrium aluminum garnet (Er:YAG), carbon dioxide (CO_2), neodymium-doped yttrium garnet (ND:YAG), and erbium chromium:yttrium scandium gallium garnet (Er,Cr:YSGG) lasers).[141,172–174] Despite recent publications of novel repair techniques, the overall results indicated that solely the mechanical treatment with airborne particle abrasion and bur grinding were efficient to increase the bond strength.[172,175] Additionally, simultaneous use of chemical etching, including 10-methacryloyloxydecyl dihydrogen phosphate (MDP) monomer in a primer and/or adhesive system, has increased bond strength to zirconia systems.[176,177]

At present, the polycrystalline ceramic systems, zirconia and zirconia-alumina composites, used in dental restorations are mainly fabricated by uniaxial and isostatic pressing ceramic powders in the form of blocks to be CAD/CAM machined and sintered at high temperatures for long periods to reach high densification; however, some defects can be generated after sintering such as porosities affecting microstructure, optical and mechanical properties of the restorations.[178,179] In this context, exploiting new methods of manufacturing polycrystalline ceramics, such as AM techniques has currently been the focus of several biomaterials research groups. Similar to glass ceramics, different AM procedures have been investigated regarding their suitability to fabricate polycrystalline ceramics components, with direct ink writing, FDM and SLA the most common methods.[90,180] SLA additively manufactured Y-TZP and ATZ systems, with printing orientation of 0° and 90°, have been compared to milled Y-TZP, where the results showed that the phase composition, residual porosity, and strength of the AM Y-TZP and ATZ ceramics were slightly lower or comparable to that of milled Y-TZP,[181,182] as well as the technique produced highly accurate components.[183] Similarly, direct ink printing is a promising AM technology for polycrystalline ceramics, with post-processed Y-TZP samples reaching a final density of 96.9% and high flexural strength (763–843 MPa), all similar to values reported for milled Y-TZP samples.[184,185] Irrespective of AM method, to create a ceramic suspension with a high solid loading, low viscosity, and homogeneous dispersion which favor additional post-processing steps, such as sintering, to create a dense structure is critical, and still requires extensive investigations to support its broad clinical use.[90,183]

3.3 | Glass-infiltrated polycrystalline ceramics

As briefly presented above as a glass-matrix ceramics, the first glass infiltrated material was represented by In-ceram systems (VITA Zahnfabrik), including In-ceram alumina, In-ceram spinell (magnesium aluminate—$MgAL_2O_4$), and In-ceram zirconia. These glass-matrix ceramic systems were introduced in dentistry in the early 1990s using the slip-casting technique, where a slurry of densely packed polycrystalline ceramic would be sintered and, after the formation of a porous skeleton of polycrystalline ceramic particles, infiltration with lanthanum-based glass could be performed to infiltrate the porosity and increase the strength (σ: 500 MPa, K_{ic}: 3.5 MPa $m^{1/2}$, hardness-*H*: 20 GPa).[15] Given the limited range of application of In-ceram systems and the upsurge of reinforced glass ceramics and polycrystalline zirconia systems, the use of conventional glass infiltrated In-ceram system has decreased and they are no longer in the market.

A new method of glass infiltration in polycrystalline ceramics by capillary pressure during sintering has been currently proposed.[186–189] For zirconia and alumina systems, such a technique has shown to produce a layer of glass, which is developed with a similar CTE to the matrix material (predominantly aluminosilicate glass, as described in the glass ceramic section), on the surface of approximately 15-μm thickness, followed by a graded layer of glass/zirconia of approximately 100 μm, creating a gradual variation in the elastic modulus from the surface to the graded layer and bulk polycrystalline matrix (i.e., elastic modulus increase of 68 GPa, 137 GPa, and 240 GPa, respectively, for glass infiltrated Y-TZP).[189–191] Biomechanically, a gradation in the composition/properties across the thickness of a polycrystalline ceramic has decreased the magnitude of tensile stresses on the surface (reduction of 10%–15% and 15%–20% for alumina and Y-TZP systems, respectively) and improved stress dissipation into the material bulk (60–70 and 30–100 μm for alumina and Y-TZP systems, respectively), increasing the flexural strength and fatigue resistance of such materials.[189,191–196] In addition, glass infiltration into the bulk of polycrystalline ceramics has shown to reduce porosities and defect population, as well as to induce the presence of residual compressive stresses which along with the elastic gradient may hinder crack formation and propagation.[189] For high translucency systems, the strength of a graded third generation zirconia (graded Y-PSZ—582 MPa), was over 70% higher than that of their non-graded counterpart (non-graded Y-PSZ—324 MPa).[195]

In addition, a stepwise properties transition in ceramic materials has provided a low mismatch of properties for bilayered graded reconstructions, where the interfacial energy for fracture of veneering feldspathic ceramics, with similar properties to the glass layer, was about fourfold higher compared with conventional bilayered rehabilitations.[187,197] Nonetheless, despite increasing the mechanical properties, the glass-infiltration method can modify the optical properties of the material, where the glass decreased the translucency of the zirconia systems.[198] Therefore, this technique would require the application of a thicker layer of feldspathic ceramic to meet esthetic requirements of shade and translucency of natural teeth, which is also a subject for future research.

The wear performance of glass-infiltrated polycrystalline systems have already been investigated in some studies, where a functionally graded glass/Y-TZP presented excellent wear behavior resulting in a restoration resistance to wear damage as well as a mild wear to the antagonist, capable of preserving enamel structure, similarly to polished Y-TZP.[148,199] Therefore, the benefits of glass infiltration in polycrystalline ceramics that were highlighted in this section all indicate that this technique might be a promising option for dental prostheses and implant components, and a key strategy to reduce the high chipping rates associated with feldspathic ceramic veneered restorations due to the gradual change in the properties at the interface, requiring further investigations to support future clinical application.

Particularly, glass-infiltrated polycrystalline systems have been promising to be processed by AM 3D-printing methods since glass infiltration would be an important strategy to seal defects produced during the ceramic processing.[200] Further studies are also warranted. Currently, these graded systems are not commercially available.

3.4 | Polymeric matrix indirect systems (PMI)

3.4.1 | Resin-matrix ceramics

The rapid advances in CAD/CAM technologies have renewed restorative systems with a polymer matrix through the conformation of preprocessed disks and/or blocks with innovations in the materials composition through a reinforcement with a high inorganic content (>60% by weight).[46,201–203] In fact, resin-matrix ceramic systems belong to a class of materials composed of methacrylate polymer matrices containing predominantly ceramic inorganic particles, which have been currently coded as porcelain/ceramics by the American Dental Association.[15,46,203,204] There are several types of resin matrix-ceramics where the chemical composition and filler type/content varies significantly among different companies.

Overall, CAD/CAM resin-matrix systems advantages include a homogeneous, dense, and reliable microstructure due to block/disk fabrication under an industrial environment of high temperature and pressure,[109,205] as well as high milling damage tolerance that may be linked to the polymeric content that provides an excellent machinability and small marginal gap, no need for post-milling firing, easy adjustment and polishing, and repairability.[202,203] The mechanical properties of different resin-matrix ceramic systems are dictated by their composition and microstructure, presenting a range of 150–270 MPa in the flexural strength and 10–30 GPa in the elastic modulus,[202,203,206,207] which support their indications for inlays, onlays, overlays, and tooth and implant supported crowns.[208–210]

The favorable biomechanical behavior of resin-matrix ceramics is determined by their polymeric content and low elastic modulus, which provides a favorable resilience and allegedly improves occlusal forces dampening and damage tolerance.[211–216] For tooth supported reconstructions, resin-matrix ceramics reconstructions potentially improve the biomechanical performance due to similar elastic modulus to dentin.[202,203,206,207] Partial coverage restorations and single crowns made by resin-matrix ceramics have shown a high survival rate in the mid-term, higher than 90% after 3 to 5 years, with a significant increase in the marginal discoloration and surface roughness as the most frequently clinical complication over time,[208] along with chipping/fracture of the material and debonding.[208–210] As implant-supported crowns, one resin-matrix ceramic material has shown very poor survival in the short term.[217] Longer clinical follow-up periods are needed to evaluate the mid- and long-term performance of resin-matrix ceramic restorations.

For implant supported reconstructions, particularly, resin-matrix ceramics rehabilitations have also been associated with a potential reduction in the stress distribution to the peri-implant tissues due to occlusal forces dampening, which may also decrease biological complication rates.[211,212] Despite favorable biomechanics, a recent systematic review and meta-analysis comparing the clinical performance of implant-supported single crowns has exhibited a high fracture rate for one resin-matrix ceramic system (33% after 5 years), statistically higher relative to conventional ceramic systems, lithium disilicate and zirconia (both ~9% after 5 years).[20]

Given the improved milling damage tolerance and excellent machinability, small marginal gaps are expected for resin-matrix ceramics relative to glass ceramics and polycrystalline ceramics.[202,203] A previous study has investigated the marginal misfit of partial coverage restorations made by polymer-infiltrated ceramic network (Enamic, VITA) and feldspathic ceramic, in which lower gaps were observed for the former relative to the latter.[218] Resin-matrix ceramic crowns fabricated with resin nanoceramic and polymer-infiltrated feldspathic ceramic systems (Lava Ultimate and Vita Enamic, respectively) have shown a mean marginal gap of approximately 60–90 μm,[219–221] which was similar when compared to LDS and ZLS crowns[220]; all within clinically acceptable levels.

Moreover, for resin-matrix ceramics, it has also been suggested that polishing instead of staining/glazing might provide better physical properties to the restoration.[222] Previous studies have shown that staining/glazing might be removed after a short period of clinical use.[223] Then, maintaining shade and translucency as well as surface roughness in esthetic restorations is an important factor for the success of the treatment; however, physical properties stability is always at risk when in contact with the oral environment, with resin-matrix ceramics properties stability being inferior to glass-matrix and polycrystalline ceramics.[56,224,225] The higher degree of physical properties alteration for resin-matrix ceramics has shown to be greatly influenced by the hydrophilicity of the polymer matrix and, consequently, by water and pigments absorption.[226] Further studies correlating composition and microstructural features with physical properties stability of the different resin-matrix ceramics are necessary to improve the understanding of the clinical performance of such restorations.

Similarly, abrasion can influence the esthetics and longevity of resin-matrix restorations, which can be replicated in laboratory through toothbrushing or chewing simulation, among other methods.[224,227,228] Toothbrushing the surface of resin-matrix ceramics after a simulation of 6 and 10 years has deteriorated the surface gloss and increased the surface roughness, which was

significantly higher when compared to LEU glass ceramics and also within clinically unacceptable levels for some resin nanoceramic systems, requiring surface repolishing.[224,227,228] This finding reveals the importance of periodic clinical maintenance of indirect restorations.

Resin-matrix ceramics seems to present a friendly wear behavior on the antagonist. Some studies have indicated a volume loss due to wear on the antagonist teeth considerably greater for glass ceramics, LDS and ZLS, followed by polymer-infiltrated feldspathic ceramic (Enamic, VITA), resin nanoceramic, monolithic zirconia, and natural tooth enamel, respectively; with the amount of wear in monolithic zirconia significantly lower than glass ceramics and resin matrix ceramics.[225,229,230] The favorable wear behavior of resin-matrix ceramic systems on the antagonist might also lie in the low elastic modulus and resilience of polymer-ceramic restorations.[211–216]

CAD/CAM resin-matrix ceramics bond strength to resin composite might be adversely affected by the high degree of polymer matrix polymerization that occurs due to the industrial manufacturing process, indicating that intraoral repair procedure should be preceded by surface pretreatments, such as bur grinding, hydrofluoric acid etching, airborne particle abrasion with alumina particles or silica coated alumina particles, and/or primers, followed by the placement of a direct resin composite.[214,231] A previous study has compared the effect of such surface pretreatments on the bond strength improvement, with airborne particle abrasion with alumina or silica coated alumina particles producing successful bond strength results for resin nanoceramics, and hydrofluoric acid etching improving polymer-infiltrated feldspathic ceramic repair bond strength; also, the application of a universal adhesive system after surface treatments is recommended to increase bond strength.[232,233]

Nowadays, resin-matrix ceramics are usually manufactured for blocks production and CAD/CAM machining, which allows for the incorporation of a high content of inorganic particles, as mentioned above. The rapid development of AM methods in dentistry has also boosted the availability of 3D-printed polymeric materials, however, up to the present moment, focusing mainly on the fabrication of temporary prostheses.[10,11] Stereolithography (SLA) AM technologies are also the most common 3D-printing methods used for resin-based systems reconstructions,[10,11] with the disadvantage of the presence of a low filler content in the available materials, which compromise the mechanical properties and range of clinical indication.[10] 3D-printing parameters, including layer thickness and printing orientation, have shown to play a critical role on the physical and mechanical (s = 90–150 MPa) properties of the currently available 3D-printed polymeric materials, all still requiring extensive research.[10,234,235] Additionally, future studies should investigate different AM technologies along with preprocessing, printing, and postprocessing parameters to obtain a reinforced resin-matrix ceramic system for AM manufacturing.

3.5 | Fiber-reinforced composites

From the aerospace and aeronautical industrial fields, fiber-reinforced composites (FRC) have emerged as promising systems to advanced biomedical application due to their high strength and stiffness to weight ratios.[236–239] Recently, CAD/CAM technology have revolutionized dental FRC systems, improving their range of clinical application.[205,240] Dental CAD/CAM FRCs are generally composed of a high-volume fraction of reinforcement compounds, carbon or glass fibers, along with inorganic ceramic particles bonded to a methacrylate or epoxy based polymeric matrix.[236,241,242] FRC blocks/disks are industrially fabricated under controlled conditions of temperature and pressure, which decreased defect population and increased the material reliability, as well as such fabrication method favors the inclusion of a higher amount of fibers with improved interfacial adhesion and alignment in different directions in the blocks/discs.[205,240,243–245] Hence, the properties of CAD/CAM FRC composites are directly dependent on the fiber type and composition, fiber geometry and orientation, fiber volume fraction, inorganic particles type and content, polymer matrix type, and quality of the fiber-matrix interface (σ: 540–740 MPa, K_{ic}: 9 MPa $m^{1/2}$).[236,241,242]

Despite such systems cannot be considered a ceramic-like material, they have been introduced as an indirect restorative system that can replace metal and Y-TZP frameworks in both tooth and implant supported reconstructions with more similar properties to the restoration components and surrounding tissues. In fact, FRC rehabilitations may offer significant clinical advantages over metal/Y-TZP rehabilitations due to their lower elastic modulus and increased resilience, favoring chewing forces absorption and stress distribution and, consequently, improving the biomechanical performance of the restorations.[211,212,238,246] It is worthy to mention that the clinical performance of FRC restorations depends on the framework dimension, design, and three-dimensional position due to the anisotropic or orthotropic properties of such systems; ideally, FRC frameworks should be anatomically planned in a parallel alignment with the maximum principal stress direction to obtain the maximum biomechanical performance of the restoration.[236,238,239,241,246]

Despite several laboratory studies have shown a favorable biomechanical performance for CAD/CAM FRC restorations,[238,247,248] the literature is still scarce in addressing their clinical performance. Clinical studies have demonstrated a high survival rate for CAD/CAM FRC (e.g. TRINIA, Bicon LLC, Boston, MA) partial and full-arch FDPs installed over short/extra-short implants placed in severely atrophic mandibles, 94% and 100%, respectively, over a period of up to 10 years.[43,44,249,250] These data encourage the use of CAD/CAM FRC FDPs as a substitute for metal and Y-TZP frameworks, especially in biomechanically unfavorable clinical scenarios; however, long-term prospective studies are still required.

Usually, CAD/CAM FRC frameworks are veneered with acrylic or with indirect resin composite systems, which are more prone to fracture due to their low strength and fracture toughness and represent one of the most frequent technical complications associated with such reconstructions.[44,249,250] In this context, the novel resin-matrix ceramics systems developed for CAD/CAM use, discussed in the previous section, may further improve the biomechanical and esthetic behavior of FRC-based reconstructions through the CAD-on technique, reducing clinical complication rates; however, studies are

TABLE 1 Main clinical aspects and indications of indirect restorative systems currently available for tooth and implant-supported reconstructions

Indirect restorative system	FEL	LEU	LDS	MCE	ZIR	PMI
Indications	Veneers; anterior crowns; *inlays* and *onlays* up to premolars	Veneers; anterior crowns; *Inlays* and *Onlays* up to premolars	Veneers; anterior and posterior crowns; *inlays*; *onlays*; 3-unit FDP up to premolars	Anterior and posterior crowns; partial and full arch FDP	Anterior and posterior crowns; partial and full arch FDP	Anterior and posterior crowns; partial and full arch FDP
Method of fabrication	Powder-liquid; CAD/CAM	Heat pressing; CAD/CAM	Heat pressing; CAD/CAM	Powder-liquid feldspathic ceramic; and heat-pressing, CAD/CAM or 3D-printing metal alloy	Powder-liquid feldspathic ceramic; CAD/CAM framework; CAD/CAM monolithic	CAD/CAM for resin-matrix ceramics; indirect resin veneer and CAD/CAM framework for FRC systems
Space required for the restoration	1.5–2.0 mm	1.5–2.0 mm	1.0–2.0 mm	1.5–2.0 mm	0.5–2.0 mm	1.5–2.0 mm
Advantages	+++ Esthetics	+++ Esthetics	++ Esthetics ++ Flexural strength	+ Esthetics +++ Flexural strength	++ Esthetics +++ Flexural strength −++ Fracture toughness	+ Esthetics +++ Intraoral adjustment
Disadvantages	− Flexural strength − Fracture toughness	− Flexural strength − Fracture toughness	− Fracture toughness	− Chipping rates	−−− Chipping rates for bilayered restorations	− Esthetics − Flexural strength − Fracture toughness
Cementation general guidelines	*Adhesive cementation* (hydrofluoric acid; silane; photo or dual cure resin cement)	*Adhesive cementation* (hydrofluoric acid; silane; photo or dual cure resin cement)	*Adhesive cementation* (hydrofluoric acid; silane; photo or dual cure resin cement)	*Adhesive cementation* (sandblasting; primer coating; chemical or dual cure resin cement); *conventional cementation* (modified glass ionomer cement)	*Adhesive cementation* (sandblasting; primer coating; dual cure resin cement); *conventional cementation* (modified glass ionomer cement)	*Adhesive cementation* (sandblasting or hydrofluoric acid; silane; photo or dual cure resin cement)
Technical comments	High esthetic results will depend on the knowledge/ experience of the dentist/ dental technician	High esthetic results will depend on the knowledge/ experience of the dentist/ dental technician	High esthetic results will depend on the knowledge/ experience of the dentist/ dental technician	Tooth and implant supported crowns and partial and full arch FDPs. High esthetic results will depend on the experience of the dentist/ dental technician	First generation: Tooth and implant supported frameworks; second and fourth generation: Tooth and implant supported monolithic crowns, partial and full arch FDPs; third generation: Crowns	Resin-matrix ceramics: Inlays, onlays, tooth and implant supported crowns; Stain might be lost after a short period. FRC: Tooth and implant supported frameworks: crowns and partial and full arch FDPs

Abbreviations: FEL, feldspathic ceramic; LDS, lithium disilicate reinforced ceramic; LEU, leucite reinforced ceramic; MCE, metal ceramic; PMI, polymeric matrix indirect systems (resin-matrix ceramics and fiber-reinforced composites); ZIR, zirconia; +, favorable; −, unfavorable.

required to investigate the clinical performance of such a restorative modality. Moreover, the possibility of clinical repair through conventional chairside restorative procedures might also be an advantage of such FRC rehabilitations using the methods previously described for resin-matrix ceramics.[236,238,251] Finally, finishing procedures and wear performance will depend on the veneering material, which potentially

is also similar to those reported for resin-matrix ceramics in the previous section.

FRC systems with improved mechanical properties are currently available for AM manufacturing.[205,240] Several studies have been performed to investigate the use of AM approaches, particularly fused deposition modeling (FDM), to fabricate prosthetic or implant components made by FRC systems, especially poly-ether-ether-ketone (PEEK) based components[252–254]; however, such systems present the same drawback of the limited filler content that restricts their mechanical properties, even under optimized printing parameters ($\sigma = 170$ MPa; elastic modulus $= 3$ GPa).[255] Future studies should investigate different AM technologies along with slurries preparation with different polymer matrices and fibers composition/size/distribution and processing parameters to obtain a FRC system for AM manufacturing with compatible properties to be used in oral rehabilitation.

4 | INDIRECT RESTORATIVE SYSTEM SELECTION

It is highly recommended that each clinical case needs to be systematically evaluated by means of a decision tree in order to allow the selection of the most appropriate indirect restorative system, as depicted in the Table 1. The rationale for the selection of a system for a single restoration and partial or full arch FDP is based on some main aspects, including: physical and mechanical properties of the system along with the shade and translucency of the neighboring/abutment teeth, the available space for the restoration, clinical data, patient and dentist expectations, and experience of the dentist and dental technician.[9]

It is highly recommended that the choice of the restorative system is conducted early during the rehabilitation process due to the impact on the clinical procedures, such as the amount of preparation and design for tooth supported restorations or the abutment selection for implant supported reconstructions. The selection is basically managed by the dentist in association with the dental technician and patient trying to fulfill biological, structural, functional, and esthetic requirements of the area to be restored. A clinical assessment needs to be performed considering esthetic and functional requirements, where anterior rehabilitations usually demand the selection of systems that might favor esthetics over strength, while posterior rehabilitations and implant supported restorations demand a special care for functional/mechanical aspects, requiring the selection of systems that might present high strength over esthetics (Table 1).

The purpose of selecting an indirect restorative system in oral rehabilitation is to ensure the best biomechanical behavior and esthetic results for a specific tooth or implant supported prothesis. From a biological point of view, clinicians should always select dental materials that allow for minimally invasive restorations, especially for tooth supported reconstructions, opting for partial coverage of the tooth structure and/or supragingival margins of the preparations when possible.[256] In this context, for tooth-supported restorations, it is crucial to assess the presence, amount, and location of dental enamel due to its influence on the resistance of the dental element, supporting minimally invasive preparations and providing high stability to bonding procedures, which might also favor the indication of highly translucent glass ceramics.[257,258] The histological characteristics and properties of dentin make its behavior as a substrate not as predictable as enamel; however, there is no contraindication of the use of any indirect restorative system as long as all procedures recommended by the manufacturers are strictly followed.[259,260] In this context, pulp vitality and presence of endodontic treatment are also important parameters for the success of tooth supported reconstructions and choice of the indirect restorative system, along with the presence and height of the ferrule and the type of intra-radicular reconstruction for the latter condition (i.e., post material that might significantly influence the biomechanical behavior of endodontically-treated teeth).[261] In addition, the interocclusal space should be included in the clinical assessment for both tooth and implant supported restorations as it will influence the thickness of the restoration, choice of the implant component, among other aspects that are crucial to determine the best indirect restorative option for each clinical scenario, in which the esthetic-strength trade-off dictates the final clinical selection.

Another important aspect that affects the final esthetic results and indirect restorative system selection is the shade and translucency of the neighboring/abutment teeth. Substrates with markedly altered coloration or having metallic components need enough space to be restored with restorative systems with adequate masking ability (i.e., with a higher degree of opacity, which often required subgingival cervical tooth preparation and veneering with feldspathic ceramics to achieve better esthetic results).[256] Each indirect restorative system requires a minimum thickness to compensate for the shade of the substrate, which will be dependent on either the intrinsic physical properties of the material (such as opacity and strength) and the available space for the restoration, as well as the knowledge and experience of the dentist and dental technician with the specific material and fabrication method. Also, veneered restorations are frequently indicated for darkened substrates since monolithic restorations would require a greater amount of tooth preparation or interocclusal space along with great expertise of the dental technician to carry out the staining and a satisfactory esthetic result.

Finally, considering the main aspects that dictate clinical selection of indirect restorative systems and the evidence-based long-term outcomes, the experience and expertise of dentists and dental technicians with a certain material and fabrication technique might also have a significant influence on the final choice due to the increased possibility to fabricate restorations with more predictable esthetic outcomes and high accuracy, which potentially influence the clinical performance in the long-term.

5 | CONCLUDING REMARKS

This review presented the last developments for indirect restorative systems, including all-ceramics, ceramic-like and fiber-reinforced

composite systems, with recent data, including main properties, advantages, and limitations that still need to be overcome along with their main clinical applications. The current indirect systems provide a favorable balance between mechanical properties and aesthetic, mimicking the aspect of natural teeth. However, most of the recent indirect restorative systems still require further clinical investigations to provide a predictable long-term data and support clinical use in diverse scenarios.

Clinicians have shifted their attention to the use of monolithic all-ceramic systems lately to avoid the most common technical complications associated with bilayered all ceramic reconstructions, which is veneering material delamination or fracture. In combination with novel methods of fabrication, monolithic restorations seem to be reliable clinical options, however developments in the systems composition to improve optical and mechanical properties along with studies to validate clinical use are still required, especially for the newly developed indirect restorative systems, such as third and fourth generation zirconia systems and resin-matrix ceramics.

In addition, subtractive CAD/CAM and additive 3D-printing technologies have revolutionized the oral rehabilitation workflow, increasing time-efficiency and accuracy of the restorations. CAD/CAM indirect restorative systems have been widely used in dentistry and renewed all-ceramic materials available for clinical use, that is, with the introduction of reinforced glass ceramics, polycrystalline ceramics, and polymeric-based systems. Nowadays, 3D-printing technology have been particularly used for the fabrication of dental models, surgical and treatment plan prototypes, and polymeric temporary prostheses, however, extensive research is being performed focusing on the development of new reinforced all-ceramic and polymeric systems to be used for AM. Initial data have indicated promising results, with similar physical and mechanical properties to CAD/CAM systems; however, improvements in the ceramic powders obtained, inks or slurries, pre- and post-processing parameters, and comparisons between different AM techniques are still required before clinical application.

Finally, there is not a single material and probably there will not be a single material that meets the requirements for all clinical cases. Clinicians should be constantly seeking for knowledge to help with the choice of the most predictable restorative systems for each clinical condition based on the comprehension of each system properties and clinical data available.

ACKNOWLEDGEMENTS AND DISCLOSURE

This research was funded by Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP): Young Investigators Award grants 2012/19078-7 and 2021/06730-7, EMU 2016/18818-8, and scholarships 2019/08693-1 and BEPE 2021/08018-2; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) grant # 307255/2021-2/; CAPES financial code 001. The authors would like to thank the invaluable contribution of multiple collaborators and studens that were part of the research cited in the manuscript. The authors do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Research data not shared.

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How to cite this article: Bonfante EA, Calamita M, Bergamo ETP. Indirect restorative systems—A narrative review. *J Esthet Restor Dent*. 2023;35(1):84-104. doi:10.1111/jerd.13016

Received: 12 December 2022 | Revised: 13 December 2022 | Accepted: 13 December 2022

DOI: 10.1111/jerd.13007

RESEARCH ARTICLE

WILEY

Using artificial intelligence to predict the final color of leucite-reinforced ceramic restorations

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Funding information
University of Florida Seed, Grant/Award Number: 00129566

Abstract

Objectives: The aim of this study was to evaluate the accuracy of machine learning regression models in predicting the final color of leucite-reinforced glass CAD/CAM ceramic veneer restorations based on substrate shade, ceramic shade, thickness and translucency.

Methods: Leucite-reinforced glass ceramics in four different shades were sectioned in thicknesses of 0.3, 0.5, 0.7, and 1.2 mm. The CIELab coordinates of each specimen were obtained over four different backgrounds (black, white, A1, and A3) interposed with an experimental translucent resin cement using a calibrated spectrophotometer. The color change (CIEDE2000) values, as well as all the CIELab values for each one of the experimental groups, were submitted to 28 different regression models. Each regression model was adjusted according to the weights of each dependent variable to achieve the best-fitting model.

Results: Different substrates, ceramic shades, and thicknesses influenced the *L*, *a*, and *b* of the final restoration. Of all variables, the substrate influenced the final ceramic shade most, followed by the ceramic thickness and the *L*, *a*, and *b* of the ceramic. The decision tree regression model had the lowest mean absolute error and highest accuracy to predict the shade of the ceramic restoration according to the substrate shade, ceramic shade and thickness.

Clinical Significance: The machine learning regression model developed in the study can help clinicians predict the final color of the ceramic veneers made with leucite-reinforced glass CAD/CAM ceramic HT and LT when cemented with translucent cements, based on the color of the substrate and ceramic thicknesses.

KEYWORDS
artificial intelligence, CIEDE2000, CIELab, color science, dental ceramics, spectrophotometer

1 | INTRODUCTION

Dental ceramics are constantly developing and are essential materials for restorative dental treatments.[1] For conventional feldspathic ceramics, the dental technician constructs a ceramic restoration by condensing and sintering layers of ceramic powder with different shades and opacities to mimic the natural tooth structure. However, this approach is becoming rare since computer-aid design and computer-aid manufacturing (CAD/CAM) can produce monolithic ceramic restorations with similar optical properties but higher mechanical properties.[2–4]

IPS Empress CAD (Ivoclar Vivadent, Schaan, Liechtenstein) is a leucite-reinforced ceramic that presents a higher leucite volume as its crystalline phase, resulting in improved mechanical properties.[5] The material is processed using the hot-pressing or CAD/CAM techniques.

The mechanical strength and excellent optical properties make leucite-reinforced ceramics suitable for veneers and anterior crowns.[6]

The chairside CAD/CAM dentistry is an extraordinary achievement that allows the dentist to select and handle ceramic materials. Consequently, the final results depend on the dentist's skills with these materials.[7–17] Considerable research has been devoted to color-matching CAD/CAM ceramic materials. However, most laboratory studies are hard to translate due to the vast number of clinical variables.[18–38]

Visual shade selection is the traditional and most common method used for shade evaluation in dentistry, but it still presents many limitations.[35,39–43] Instrumental color measurement has increased in popularity over the years.[44,45] Different spectrophotometers, colorimeters, and imaging systems have been used in dentistry for shade evaluation.[46,47] Instrumental measurement provides objective and quantitative data, reducing the visual method's subjectivity. However, there is no method to combine the CIELab coordinates (*L*, *a*, and *b*)[30,48] obtained from the tooth substrate and ceramic to predict the best ceramic type, shade, and thickness.

Artificial intelligence (AI) can optimize and accelerate the translation of in-vitro studies. The use of AI in materials science has significantly advanced in recent years, spurred by the desire to accelerate the creation of new materials.[49–51] Conventional methods for exploring potential product designs and material formulations are inefficient, requiring either fractional factorial designs that do not adequately model the interactions of design factors or requiring too much time. However, AI excels at modeling interactions without an exhaustive full-factorial study. In a previous study,[52] the authors were able to predict the depth of cure (DOC) of resin-based composites based on spectrophotometric parameters of the light curing units. Using AI, it was possible to show that the composite and light-curing unit radiant exposure are the most critical factors in determining the composites' depth of cure. This model can predict if the composite and curing light will pass the ISO 4049 standard tests, saving time and resources in materials research and development. Likewise, understanding the variables that influence the CIELab of ceramic restorations would extend the use of spectrophotometers in dentistry, and it can lead to the development of AI models for creating software-assisted shade selection.[53,54]

Thus, the specific aims of the study were to: 1—Evaluate the *L*, *a*, and *b* of monolithic ceramics with different thicknesses, shades, and translucencies, cemented on white, black, A1, and A3 substrates with a translucent resin cement. 2—Explore machine learning regression models to assist in the shade selection of ceramic restorations based on the color coordinate parameters (*L*, *a*, and *b*). The hypotheses tested in this study are: H_1—There will be significant differences in the *L*, *a*, and *b* color coordinates of monolithic ceramics with different thicknesses, shades, and translucencies cemented on white, black, A1, and A3 substrates with translucent resin cement. H_2—The regression model created using the color coordinate parameters (*L*, *a*, and *b*) from the substrate and ceramic and the thickness of the ceramic will predict the final color of the ceramic restoration.

2 | MATERIALS AND METHODS

Leucite-reinforced glass–ceramics blocks (IPS Empress CAD, C14, Ivoclar Vivadent, Schaan Liechtenstein) (Figure 1) in four different shades (HT—A1, A3; LT—A1, A3) were used in this study. The blocks were bonded to dressing sticks (Buehler, Lake Bluff, IL) to allow precise cuts without chipping the specimens during the section. The assembly was mounted in a precision diamond saw machine (Isomet, Buehler, Lake Bluff, IL with the Buehler's Isomet diamond blade 15 LC, dimensions: four inches (102 mm), thickness: 0.012 in (0.3 mm) Buehler, Lake Bluff, IL) and the blocks were sectioned under water cooling at 400 rpm. Specimens ($n = 5$) perpendicular to the long axis of the blocks were obtained with thicknesses of 0.3, 0.5, 0.7, and 1.2 mm. The accuracy of the final thickness was determined with a digital caliper (Mitutoyo Corp, Kawasaki, Japan) with an accuracy of ±0.05 mm. The glaze was not applied to avoid high reflection luster that could affect shade measurement. A pilot study showed that samples prepared following this protocol present similar superficial rugosity to the samples milled in the CEREC MC XL milling machine (according to the ISO 25178—Geometric Product Specifications—Surface texture, Sa = 18.56 ± 1.7 μm for the Isomet 15LC Diamond Saw and Sa = 17.57 ± 1.8 μm for the CEREC MCXL milling machine, $p = 0.832$).

An experimental translucent resin-based cement with a refractive index of 1.5229 (Table 1) was produced without photoinitiators to simulate the cementation of the ceramic veneer on the substrate without bonding the specimens together. This simulation mimicked the refractive index changes and the light propagation through ceramic, cement, and substrate interfaces.

Four different substrates were used: white background; black background; IPS Empress LT A1 CAD/CAM block; IPS Empress LT A3 CAD/CAM block. For reference, the CIELab coordinates of backgrounds were black ($L = 22.06$, $a = 0.33$, $b = 0.30$), white ($L = 97.29$, $a = -0.06$, $b = 2.39$), IPS Empress LT A1 ($L = 71.29$, $a = 0.99$, $b = 10.87$), and IPS Empress LT A3 ($L = 64.30$, $a = 2.13$, $b = 14.82$).

The color parameters of each specimen were obtained with a D65 illuminant over the different backgrounds interposed with the translucent resin cement using a calibrated spectrophotometer (CM-700d, Konica Minolta, Tokyo, Japan) with a target mask with a sensor-opening diameter of 3 mm (SAV). The CIE 1931 2° Standard Colorimetric Observer was used to calculate color coordinate values for each specimen. The sensor opening of the spectrophotometer was placed in the center of each specimen, and three measurements were collected in both SCI (specular component included) and SCE (specular component excluded) modes. The CIELab coordinates (*L*, *a*, and *b*) from the specimens were used to evaluate color change (ΔE_{00}) from the substrate to the surface of the veneer according to the CIEDE2000 formula: $\Delta E_{00} = [(\Delta L/K_L\ S_L)^2 + (\Delta C/K_C\ S_C)^2 + (\Delta H/K_H\ S_H)^2 + R_T\ (\Delta C/K_C\ S_C)\ (\Delta H/K_H\ S_H)]^{0.5}$, where ΔL, ΔC, and ΔH are the differences in lightness, chroma and hue, and Rt is a function (the so-called rotation function) that accounts for the interaction between chroma and hue differences in the blue region. Weighting functions, S_L, S_C, and S_H adjust the total color difference for variation in the location of the color difference pair in *L*, *a*, and *b* coordinates, and the

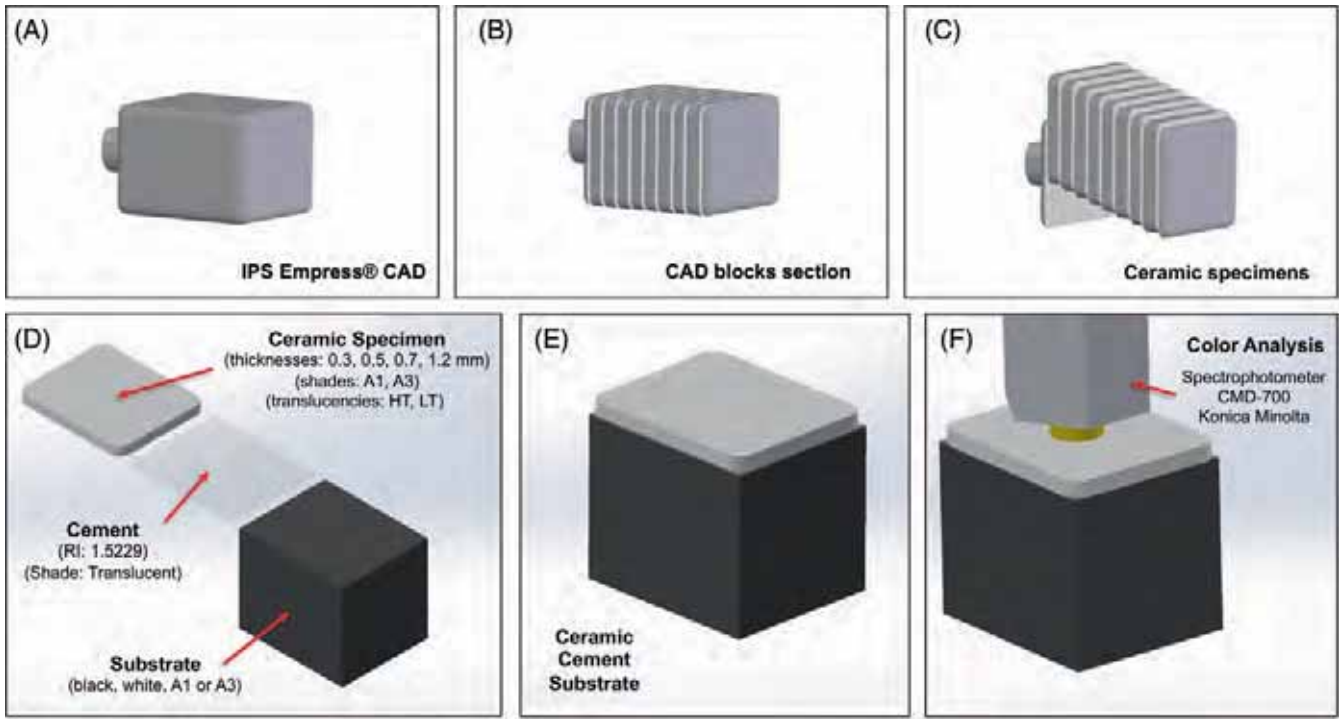

FIGURE 1 Experimental setup. (A) IPS Empress CAD block, (B) sectioning of the blocks, (C) ceramic specimens, (D, E) specimen assembly and evaluation according to different thicknesses, shades, and translucencies interposed by a translucent cement over different backgrounds and (F) spectrophotometric analysis using the CMD-700 Konica Minolta

TABLE 1 Chemical products used in experimental resin cement composition

Material	Chemical	Refractive Index	Concentration (wt%)	Manufacturer
Monomer	Bis-GMA[a]	1.540	26.0	Sigma Aldrich, St. Louis, MO, USA.
Monomer	Bis-EMA 10[a]	1.5112	23.4	Esstech Inc., Essington, PA, USA.
Monomer	TEGDMA[a]	1.459	2.6	Esstech Inc., Essington, PA, USA.
Filler Particle	16 nm fumed silica	1.535	2.0	Evonik Industries AG, Essen, Germany.
Filler Particle	7.5 μm $BaBSiO_2$[b]	1.553	50.0	Esstech Inc., Essington, PA, USA.

[a]Bisphenol A diglycidyldimethacrylate (Bis-GMA); Ethoxylated bisphenol A diglycidyldimethacrylate (Bis-EMA 10); Triethylene glycol dimethacrylate (TEGDMA);
[b]Barium Borosilicate ($BaBSiO_2$).

parametric factors K_L, K_C, and K_H are correction terms for the experimental conditions, which were set to 1. Differences in each inherent color parameter were also determined as ΔL, Δa, and Δb by subtracting each specimen from the substrate color coordinate parameter value ($+a$ = red, $-a$ = green; $+b$ = yellow, $-b$ = blue; $+L$ = white, $-L$ = black).

Data were entered into statistical analysis software (Stata/MP 17, StataCorp, College Station, TX, USA) and was checked for normality using Shapiro–Wilk's test and for variance homoscedasticity using Levene's test. Statistical analyses were performed according to the different experimental designs with a level of significance of $\alpha = 0.05$. A power analysis was conducted to determine the sample size for each experiment to provide a power of at least 0.8 at a significance level of 0.5 ($\beta = 0.2$). A three-way analysis of variance (ANOVA) was performed to detect differences in the color coordinates L, a, and b and where the independent variables were the substrates (Black, LT A3, LT A1, and White), the ceramic shades (IPS Empress LT A3, IPS Empress HT A3, IPS Empress LT A1, and IPS Empress HT A1) and the ceramic thicknesses (0.3, 0.5, 0.7, and 1.2 mm). A pairwise comparison was performed using Tukey's test. The descriptive statistical analysis was plotted using Origin Pro (OriginLab Co, Northampton, MA, USA).

The dataset containing all variables was organized into a Jupyter Notebook (www.jupyter.org). The dataset was split into train and test datasets using a 70/30 ratio. Twenty-eight supervised learning regression models were imported from the scikit-learn API (www.scikit-learn.org). All models' mean absolute error (MAE) and the accuracy (R^2 score) were calculated. The regression models with the lowest MAE and higher R^2 score were pre-selected for hyperparameter tuning using exhaustive grid search cross-validation (GridSearchCV, Scikit-learn). Also, the best model feature importance was used to calculate the coefficient of the importance of each one of the variables. The ΔL, Δa, Δb, and ΔE_{00} were calculated by comparing the test dataset to

compute for the error between the real data and the machine learning data.

3 | RESULTS

Figure 2 shows the CIELab values for the substrates and ceramics blocks used in this study. For the *L* value, it can be noticed that the Black background had the lowest *L* value as the White background had the higher *L* value. The A1 shade had higher *L* values than the A3 shade for the ceramic blocks, regardless of the translucency (LT or HT). For the same shade color (A1 or A3), the LT ceramics had higher *L* values than the HT ceramics.

For the *a* values, it was noted that the ceramic block IPS Empress HT A1 presented a negative *a* value, which makes it have a greenish aspect. The White background also presented a negative *a* value, but very close to 0. The black background presented a positive *a* value, which makes it have a reddish aspect. The ceramic IPS Empress LT A3 presented the highest *a* value followed by IPS Empress HT A3 and IPS Empress LT A1, respectively.

For the *b* values, all substrates presented a positive *b* value. The White background has a higher *b* value than the black background. The A3 ceramic A3 has a higher *b* value than the A1 ceramic. The LT ceramics have a higher *b* value than the HT ceramics.

Table 2 shows the ΔE_{00}, *L*, *a*, and *b*, and values of the different ceramic restorations with different thicknesses cemented on the different substrates. For the *L* values, significant differences were found among all variables (substrate vs. ceramic type vs. thickness, $df = 27$, $F = 54.87$, $p < 0.001$). According to the pairwise comparison, for the same ceramic type and thickness, the differences were found for all substrate shades ($df = 3$, $F = 5.1 \times 10^5$, $p < 0.001$), where the *L* final of the restoration follows white > A1 > A3 > black for the different backgrounds.

Within the same background, the influence of the different ceramic shades and thicknesses are statistically significant ($df = 9$, $F = 208.19$, $p < 0.001$). However, when the pairwise comparison was performed, the color of the background and the color of the ceramic dictated if the *L* of the final restorations was going to be higher or lower than the background. For the white background, when using different ceramics, the thinner the ceramic the higher the *L* of the final restoration. The inverse is true for the black background, the thinner the ceramic, the lower the *L* of the final restoration. For the A1 and A3 backgrounds, the influence of the thickness on the *L* of the final restoration depends on the differences on *L* values of the ceramic restoration and the background. Hence the higher the difference between *L* of the ceramic and *L* of the substrate the higher is the influence of the thickness on the final *L*. For A1 and A3 backgrounds restored with IPS Empress LT A1 and IPS Empress LT A3, respectively, no differences were found in the *L* of the final restoration among all different thicknesses. The same pattern was found for the *a* and *b* values. However, it is important to notice that the *L*, *a*, and *b* values will influence the final color independently, but an alteration of the axis (*L*, *a*, or *b*) can significantly influence the ΔE_{00} and, subsequently, the final color of the restoration.

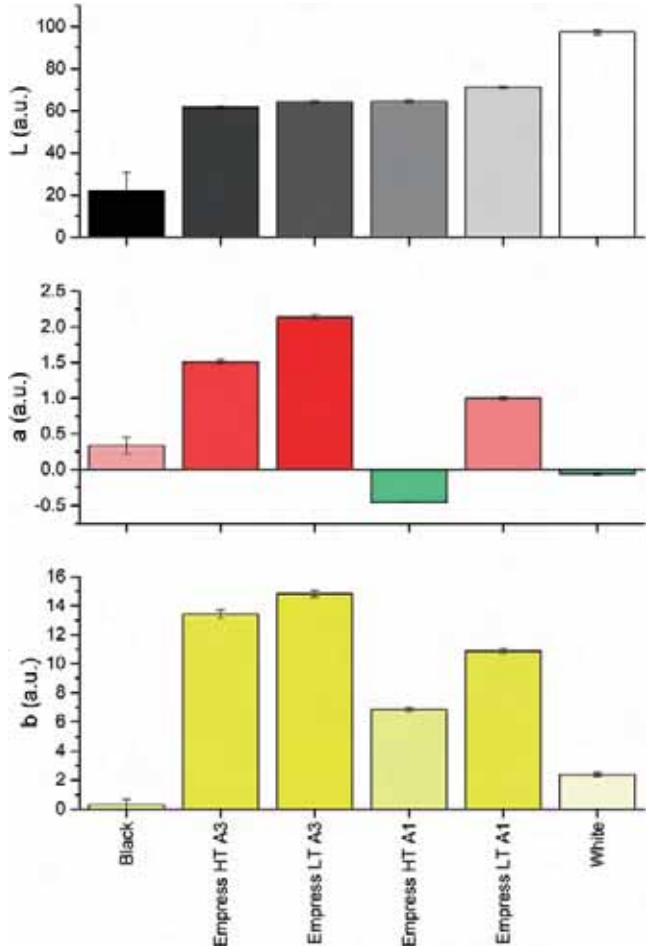

FIGURE 2 CIE *L*, *a*, and *b* color coordinates for the substrates (Black, Empress LT A3, Empress LT A1, and White) and ceramic blocks (Empress HT A3, Empress LT A3, Empress HT A1, and Empress LT A1) used to fabricate the specimens in this study

The decision tree regressor was the best model of all regression models with the lowest mean absolute error (0.226 ± 0.012) and the highest R^2 score (0.997 ± 0.001). All models' results and the best model hyperparameters tuning can be found in the GitHub repository. Figure 3A shows the feature importance of each one of the variables in predicting the final color of the ceramic restoration. The *L* of the substrate (L_{sub}) ranks as the most important feature influencing 60.39 ± 1.37% on the final color of the restoration. The thickness of the restoration is the second most important feature influencing 16.06 ± 0.56%, followed by the *a* of the substrate (a_{sub}). All other features combined account for 10.20 ± 0.45% of the final color of the restoration. Figure 3B shows the error in the ΔL, Δa, Δb, and ΔE_{00} when comparing the real-world data and the predicted data using the decision tree regression model. The machine learning regression model had an average ΔE_{00} error of 0.382 ± 0.316. However, it is important to notice that there are two outlier points above the 1.77 threshold, which suggests that from 634 entries on the testing data set, the regression model regression model could not predict the shade

TABLE 2 ΔE_{00}, *L*, *a*, and *b* values for the ceramic specimens (Empress HT A1, Empress LT A1, Empress HT A3, and Empress LT A3) with different thicknesses (0.3, 0.5, 0.7, and 1.2 mm) cemented over different substrates (Black, A3, A1, and White) used in this study

Substrate	Ceramic	Thickness	ΔE_{00}	*L*	*a*	*b*
Black	Empress HT A1	0.3	18.94 ± 0.75 Bd	37.93 ± 0.86 Bd	−0.46 ± 0.02 Aa	−5.15 ± 0.52 Cc
		0.5	24.6 ± 1.09 Bc	44.51 ± 1.22 Bc	−0.89 ± 0.05 Ab	−5.61 ± 0.43 Dd
		0.7	26.23 ± 0.41 Cb	46.57 ± 0.45 Bb	−1.06 ± 0.04 Ac	−4.32 ± 0.39 Db
		1.2	32.41 ± 0.82 Ca	53.24 ± 0.82 Ca	−1.33 ± 0.04 Ad	−2.5 ± 0.17 Da
	Empress LT A1	0.3	22.95 ± 0.57 Ad	42.83 ± 0.7 Ad	−0.79 ± 0.04 Ca	−4.63 ± 0.38 Bd
		0.5	28.22 ± 0.59 Ac	48.78 ± 0.67 Ac	−1.06 ± 0.03 Bb	−3.91 ± 0.48 Cc
		0.7	33.73 ± 0.74 Ab	54.59 ± 0.72 Ab	−1.18 ± 0.01 Bc	−2.09 ± 0.08 Cb
		1.2	40.82 ± 0.81 Aa	61.33 ± 0.72 Aa	−1.19 ± 0.02 Bc	1.14 ± 0.09 Ca
	Empress HT A3	0.3	18.03 ± 0.88 Dd	37.02 ± 1.09 Cd	−0.64 ± 0.09 Ba	−4.22 ± 0.62 Ad
		0.5	23.42 ± 0.68 Cc	43.61 ± 0.74 Cc	−0.88 ± 0.04 Ab	−3.19 ± 0.28 Bc
		0.7	26.35 ± 0.57 Cb	46.92 ± 0.62 Bb	−1.19 ± 0.05 Bc	−2.56 ± 0.25 Bb
		1.2	32.54 ± 0.86 Ca	53.52 ± 0.86 Ca	−1.2 ± 0.04 Bc	0.63 ± 0.3 Ba
	Empress LT A3	0.3	18.45 ± 0.62 Cd	37.62 ± 0.76 Bd	−0.58 ± 0.07 Ba	−3.96 ± 0.24 Ad
		0.5	22.69 ± 0.39 Dc	42.97 ± 0.43 Dc	−0.93 ± 0.04 Ab	−1.76 ± 0.23 Ac
		0.7	28.33 ± 0.64 Bb	49.21 ± 0.67 Cb	−0.99 ± 0.03 Ab	−0.21 ± 0.19 Ab
		1.2	36.18 ± 0.32 Ba	56.96 ± 0.31 Ba	−1.08 ± 0.05 Bc	3.92 ± 0.24 Aa
A3	Empress HT A1	0.3	2.76 ± 0.17 Bc	65.35 ± 0.28 Ba	1.78 ± 0.03 Ba	10.73 ± 0.25 Ca
		0.5	4.38 ± 0.53 Aab	65.93 ± 0.55 Ba	1.5 ± 0.06 Bb	8.51 ± 0.58 Db
		0.7	4.16 ± 0.25 Bb	65.1 ± 0.29 Ba	1.31 ± 0.03 Cc	8.62 ± 0.36 Cb[a]
		1.2	4.67 ± 0.32 Ba	65.13 ± 0.56 Ba	0.99 ± 0.05 Cd[a]	8.03 ± 0.36 Dc
	Empress LT A1	0.3	4.67 ± 0.41 Ac	67.48 ± 0.4 Ac	1.38 ± 0.07 Ca	8.91 ± 0.4 Da[a]
		0.5	4.65 ± 0.29 Ac	67.62 ± 0.37 Ac	1.34 ± 0.05 Ca	9.08 ± 0.3 Ca[a]
		0.7	5.21 ± 0.23 Ab	68.33 ± 0.27 Ab	1.17 ± 0.06 Db	8.73 ± 0.17 Ca
		1.2	6.06 ± 0.26 Aa	69.84 ± 0.34 Aa	0.84 ± 0.05 Dc	8.8 ± 0.17 Ca
	Empress HT A3	0.3	2.11 ± 0.31 Ca	65.11 ± 0.39 Ba	1.87 ± 0.04 Aa	11.66 ± 0.36 Bc[a]
		0.5	1.83 ± 0.38 Bab	64.71 ± 0.65 Cab	1.84 ± 0.06 Aa	12.07 ± 0.55 Bb[a]
		0.7	1.69 ± 0.36 Cab	64.26 ± 0.53 Cbc	1.73 ± 0.08 Bb	12.27 ± 0.63 Bab[a]
		1.2	1.58 ± 0.27 Cb	63.8 ± 0.48 Cc	1.73 ± 0.07 Bb	12.57 ± 0.66 Ba
	Empress LT A3	0.3	1.54 ± 0.23 Da	65.05 ± 0.3 Ba	1.86 ± 0.05 Ab	12.58 ± 0.36 Ab[a]
		0.5	1.3 ± 0.26 Ca	64.81 ± 0.38 Ca	1.81 ± 0.07 Ab	12.91 ± 0.32 Ab[a]
		0.7	0.83 ± 0.12 Db	64.8 ± 0.3 Bca	1.94 ± 0.04 Aa	13.72 ± 0.17 Aa[a]
		1.2	0.66 ± 0.19 Db	64.74 ± 0.32 Ba	1.88 ± 0.05 Aa	14.08 ± 0.16 Aa
A1	Empress HT A1	0.3	1.55 ± 0.25 Ac	71.08 ± 0.2 Ba	0.84 ± 0.05 Ba	8.68 ± 0.37 Da
		0.5	2.01 ± 0.2 Abc	70.91 ± 0.29 Ba	0.78 ± 0.05 Ba	8.08 ± 0.32 Db
		0.7	2.13 ± 0.17 Bb	69.37 ± 0.35 Bb	0.71 ± 0.07 Cb	8.77 ± 0.33 Da[a]
		1.2	3.03 ± 0.23 Ba	67.88 ± 0.35 Bc	0.65 ± 0.02 Cb	8.85 ± 0.15 Da
	Empress LT A1	0.3	1.46 ± 0.16 Aa	72.16 ± 0.24 Aa	0.71 ± 0.02 Ca	9.04 ± 0.14 Cb[a]
		0.5	1.34 ± 0.16 Ca	71.93 ± 0.26 Aa	0.71 ± 0.09 Ca	9.15 ± 0.22 Cb[a]
		0.7	1.24 ± 0.18 Ca	71.81 ± 0.11 Aa	0.72 ± 0.04 Ca	9.22 ± 0.24 Cb
		1.2	1.04 ± 0.24 Ca	72.1 ± 0.34 Aa	0.7 ± 0.07 Ca	9.79 ± 0.21 Ca
	Empress HT A3	0.3	1.64 ± 0.38 Ac	69.41 ± 0.5 Da	0.93 ± 0.06 Ad	10.38 ± 0.99 Bd
		0.5	1.48 ± 0.72 BCc	69.59 ± 0.82 Ca	1.14 ± 0.13 Ac	11.85 ± 0.53 Bc[a]
		0.7	2.22 ± 0.37 Bb	68.73 ± 0.44 Cb	1.25 ± 0.02 Bb	12.35 ± 0.26 Bb[a]
		1.2	4.06 ± 0.41 Aa	66.71 ± 0.43 Cc	1.53 ± 0.11 Ba	13.68 ± 0.47 Ba
	Empress LT A3	0.3	0.92 ± 0.36 Bd	70.19 ± 0.43 Ca	0.98 ± 0.1 Ad	11.3 ± 0.34 Ad
		0.5	1.91 ± 0.25 ABc	69.42 ± 0.29 Cb	1.13 ± 0.1 Ac	12.77 ± 0.2 Ac[a]

(Continues)

TABLE 2 (Continued)

Substrate	Ceramic	Thickness	ΔE_{00}	*L*	*a*	*b*
		0.7	2.93 ± 0.15 Ab	68.59 ± 0.17 Cc	1.35 ± 0.1 Ab	14.05 ± 0.2 Ab[a]
		1.2	4.03 ± 0.52 Aa	67.25 ± 0.49 Cd	1.75 ± 0.06 Aa	14.63 ± 0.64 Aa
White	Empress HT A1	0.3	4.05 ± 0.2 Cd	94.77 ± 0.38 Aa	−0.01 ± 0.02 Bd	6.95 ± 0.17 Dd
		0.5	6.6 ± 0.08 Dc	91.57 ± 0.22 Ab	0.24 ± 0.02 Dc	9.52 ± 0.08 Dc
		0.7	8.72 ± 0.4 Db	88.54 ± 0.83 Ac	0.43 ± 0.03 Db	11.38 ± 0.2 Db
		1.2	12.25 ± 0.27 Da	83.57 ± 0.5 Bd	1.02 ± 0.04 Da[a]	14.35 ± 0.21 Da
	Empress LT A1	0.3	5.82 ± 0.12 Bd	94.25 ± 0.16 Aa	0.01 ± 0.05 Bd	9.39 ± 0.18 Cd
		0.5	7.93 ± 0.13 Cc	91.86 ± 0.16 Ab	0.51 ± 0.03 Cc	11.91 ± 0.19 Cc
		0.7	10.1 ± 0.15 Cb	88.93 ± 0.49 Ac	0.98 ± 0.02 Cb	14.29 ± 0.12 Cb
		1.2	12.95 ± 0.15 Ca	84.69 ± 0.18 Ad	2 ± 0.05 Ca	16.91 ± 0.25 Ca
	Empress HT A3	0.3	7.44 ± 0.38 Ad	93.04 ± 0.35 Ba	0.34 ± 0.04 Ad	11.56 ± 0.52 Bd[a]
		0.5	10.09 ± 0.2 Bc	90.57 ± 0.31 Bb	0.94 ± 0.08 Bc	15.21 ± 0.26 Bc
		0.7	12.41 ± 0.24 Bb	87.14 ± 0.36 Bc	1.64 ± 0.09 Bb	17.82 ± 0.29 Bb
		1.2	16.85 ± 0.41 Ba	80.07 ± 0.59 Cd	3.11 ± 0.1 Ba	21.68 ± 0.68 Ba
	Empress LT A3	0.3	7.89 ± 0.33 Ad	92.79 ± 0.39 Ba	0.37 ± 0.05 Ad	12.23 ± 0.43 Ad[a]
		0.5	11.42 ± 0.19 Ac	88.72 ± 0.4 Cb	1.25 ± 0.03 Ac	16.81 ± 0.18 Ac
		0.7	13.8 ± 0.15 Ab	85.87 ± 0.25 Cc	2.01 ± 0.05 Ab	19.99 ± 0.19 Ab
		1.2	18.37 ± 0.24 Aa	78.22 ± 0.45 Dd	3.77 ± 0.14 Aa	23.51 ± 0.26 Aa

Note: Upper case letters shows difference between Ceramic according to the same susbtrate and thickness. Lower case shows differences between Thickness according to the same substrate and ceramic.
[a]No statistical differences were found between Substrates according to the same Ceramic and Thickness.

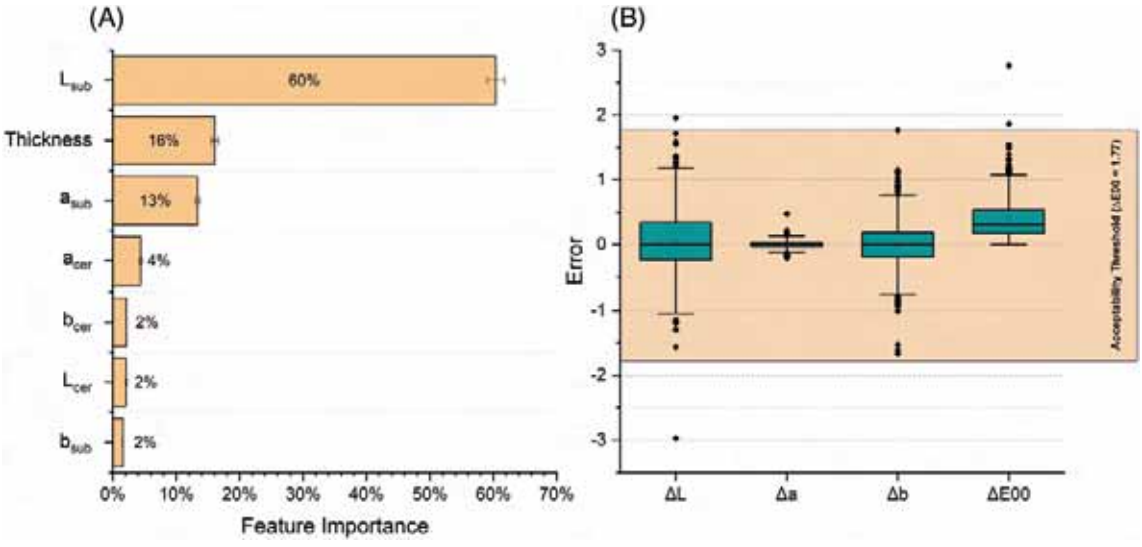

FIGURE 3 Summary of the Decision Tree Regressor results. (A) The relative importance of each independent variable to predict the final color of the ceramic restoration. (B) The measuring error to the predicted target value. The ΔL, Δa, Δb, and ΔE_{00} is obtained by the difference between the predicted result and the real measured data. The orange area represents the limit boundaries within the ΔE_{00} acceptability threshold (1.77)

within the acceptability threshold on two occasions. The complete model regression coding and deployment can be found in the GitHub repository (https://github.com/drmateusrocha/Predict-Color-Ceramic-Restorations).

4 | DISCUSSION

This study confirmed that the color of the substrate and the ceramic restorative material shade and thickness significantly influence the

final color of the restoration.[18,20,24,25] Thus, the first research hypothesis was accepted. From all variables, the substrate influences the final color of the restoration the most, followed by the ceramic thickness and the *L*, *a*, and *b* of the ceramic.

In a previous study,[17] the authors evaluated leucite-based 0.6 mm ceramic veneers cemented using seven different resin cement shades on dies of nine different substrate shades. None of the 63 combinations of cement and substrate shade resulted in an acceptable match with the target shade. Interestingly, they observed no color difference between veneers cemented with a translucent cement or cemented with a high chroma cement on the same substrate color. They considered that the substrate color was the dominant factor when cementing thin veneers, and an opaque ceramic should be incorporated to improve shade matching.

Also, another study[37] demonstrated no difference in the color matching of IPS Empress CAD veneers milled from different blocks (multichromatic and high or low translucency) with the same thicknesses (axial reduction of 0.8 mm) cemented over a discolored substrate (A4). Different cement opacities or different ceramic translucencies could not mask a discolored substrate. In the present study, the final *L* of the ceramic is affected by the ceramic material's translucency. When substrate A3 was considered, IPS Empress LT A1 significantly increased the *L* value of the final ceramic compared to the other ceramics. Interestingly, when the regression model developed in this study was applied to a similar scenario (substrate A4, IPS Empress CAD, and target final shade A1), a low translucency ceramic veneer would need a minimum thickness of 1.1 mm to achieve a final restoration shade below the acceptability threshold (1.77). Besides that, the regression model predicted that a 0.8 mm low translucency ceramic veneer would not mask a discolored substrate A4. Thus, the second research hypothesis was accepted.

In this study, for A1 and A3 backgrounds restored with IPS Empress LT A1 and IPS Empress LT A3, respectively, no differences were found in the *L* of the final restoration among all different thicknesses. However, the ceramic thickness influenced the final color when higher color differences between the substrate and the final ceramic were present. The interesting finding is that the difference between the ceramic shade and the dental substrate does not assume a linear correlation. While exploring the different regression models, it was found that the difference between the substrate and the ceramic shade assumes a sigmoid function. This means that the smaller the color differences between the substrate and the ceramic shades, the lower is the influence of the ceramic thickness on the restoration final color. Thus, when the ceramic shade is properly selected, minor discrepancies in the ceramic thickness will not be visually perceptible. However, when clinicians aim to use a whiter ceramic to mask dark substrates, the minimum ceramic thickness is fundamental to achieve an acceptable outcome.

The masking ability of 0.5 and 1 mm IPS Empress CAD restorations cemented with four different cement shades on a discolored resin substrate (A3.5) has been reported.[20] Their results agree with the present study's result as they found a significant difference in the *L* value between the different thicknesses evaluated. Considering a similar scenario (substrate A3.5, IPS Empress CAD, translucent cement, and final shade A1), the application of the regression model developed in this study indicated that a low translucency A1 IPS Empress CAD ceramic with a minimum thickness of 1.1 mm would be needed to produce a final restoration below of the acceptability threshold. The predicted final shade agreed with their results. It is important to notice that this study only tested the thicknesses of 0.5 and 1 mm. The IPS Empress CAD low translucency ceramic resulted in a color difference above the acceptability threshold in both thicknesses evaluated. A natural and satisfactory result is quite challenging when restoring a tooth presenting a discolored substrate with monolithic restorations.[25] An increased ceramic opacity can reduce the light transmission and improve the ceramic's ability to mask a dark substrate. This approach usually results in an unnatural appearance and the loss of the optical blend of the ceramic veneer with the substrate.[11]

One of the main advantages of a monolithic restoration fabricated by a CAD/CAM system is the time efficiency, as the restoration can be delivered in one clinical session. Another advantage is the higher chipping fracture resistance of monolithic restorations compared to porcelain-veneered restorations.[4] Monolithic CAD/CAM restorations are highly influenced by the substrate shade and the thickness and type of ceramic. The influence of the thickness on the restoration's final appearance depends on the type of CAD/CAM ceramic material.[36] Due to the vast number of available CAD/CAM materials, the generalizability of these results is limited.

Digital dentistry has been successful when determining the restorations' shape and position.[27] Nevertheless, the selection of the restoration's shade still relies on the dentist and dental technician's experience and ability. Color matching was a problem in the past, and despite the advances achieved by dentistry, it is still a major issue today.[40] The color of teeth is determined by a visual method, using shade guides comparisons, or by instrumental measurement.[41,47] Several researchers have addressed this field, seeking results that would allow more shade predictability while selecting the CAD/CAM material. Shade guides do not match natural teeth and other shade guides. The visual method is considerably affected by the type of shade guide,[15] the light conditions,[9] and the operator variables.[13,43] Finally, the reproducibility of the selected shade is impaired as the ceramic systems may not match the dentist's shade guide.[10]

Recent studies have investigated intraoral scanner applicability for shade selection.[16] The intraoral scanners' accuracy for color matching is inferior compared to a reference spectrophotometer.[44] However, color measurement is a recent feature added to intraoral scanners and surely will receive further improvement. Ideally, the development of software using a regression model to assist the dentist with shade matching integrated into the intraoral scanner software could provide immediate feedback during the tooth preparation resulting in more conservative and precise tooth preparations.

Since 1931, the International Commission on Illumination (CIE), has published recommendations on the specification of basic colorimetry standards.[22,23] The CIE system uses three coordinates to

determine a particular color in a color space. Over the years, different color formulas have been used in the industry: CIE 76 (ΔE_{ab}), CIE 94 (ΔE_{94}), CMC (ΔE_{CMC}) and CIEDE2000 (ΔE_{00}).[21] For color measurement in dentistry, two formulae are recommended for calculating ΔE: CIE 76 (ΔE_{ab}) and CIEDE2000 (ΔE_{00}).[48]

The CIEDE2000 is more complex than the anterior formulas and includes a rotation function and weighting functions to reduce discrepancies and errors that occur due to the nonuniformity of the CIELab color space for small color differences under reference conditions.[35,47] Recent research seems to agree that the CIEDE2000 is superior to its predecessors when representing color differences as human eyes see them.[30,42,43] Ideally, the color difference formula should correspond to the visual judgment of an average observer. Better color difference formulae provide better indicators of clinically and visually perceptible and unacceptable color differences between tooth colors.[42]

The objective data obtained from the instrumental color measurement are not practically and clinically meaningful without establishing thresholds for perceptibility and acceptability.[29] These thresholds are essential to guide the selection of esthetic dental materials and interpreting clinical research and laboratory research.[35] Perceptibility is the color difference between two objects that can be identified by 50% of observers under controlled conditions, with the other 50% of observers noticing no difference. A color difference at or below the 50:50% perceptibility threshold is considered a nearly perfect color match. Acceptability is the difference in color considered acceptable by 50% of observers, while the other 50% considering it unacceptable. If a color difference is above the 50:50% acceptability threshold, the color match is considered unacceptable. In dentistry, an unacceptable dental esthetics outcome results in replacement or correction of the restoration.

Acceptability and perceptibility values vary among color difference formulas. Recent literature has focused on establishing the CIEDE2000 formula thresholds for dental materials.[19,28,35,39] A relevant multi-center study[35] determined that the CIEDE2000 perceptibility threshold and the acceptability threshold values were 0.81 (0.34–1.28) and 1.77 (1.23–2.37), respectively. Although the present study used this reference as the threshold, the results should be interpreted with caution since the geometric configuration of the spectrophotometer used in this study was d:8° while these reference threshold values were obtained using a 0°/45° spectrophotometer.

The color measurement geometry defines the geometric conditions under which the object is illuminated and viewed. The geometry of the light source relative to the object is defined by the angular size, which varies with the distance between the light source and the object.[12] Nevertheless, it could be argued that the use of a spectrophotometer with d:8° illuminant/observer angle is unusual for clinical dentistry or even color research in dentistry, and most perceptibility and acceptability studies used a recommended illuminant/observer of 0° or 0°/45° (CIE) spectrophotometer. While there is some debate about what the best measurement geometry uses for clinical application, the existing instrument geometries are somewhat extreme; for example, a direct geometry such as 0°/45° emulates a real-world viewing environment where the object is viewed with a black or dark surround with an overhead light at 0° and is viewed at 45° by an observer. The color we see (or measure) under these conditions is specific to this measurement geometry. This type of illumination and viewing is rarely experienced in the real world, where, in most environments, the illumination usually comes from multiple directions, either directly or indirectly (diffuse).[26]

Thus, the reference perceptibility and acceptability threshold in this study would be unfeasible, restricting visual and instrumental comparisons. However, this is only true for gonioapparent colors (pertaining to a change in appearance with illumination angle or viewing angle).[26] The color we see (or measure) under these conditions is specific to this measurement geometry. For most diffuse objects (i.e., enamel and dentin after preparation), instrument geometry does not play a large role in altering the measured color. In fact, to rule out influences of the substrate surface on the final color, measure the true color of the substrate and generate a clean dataset for real color regression model application, the use of a d:8° spectrophotometer is essential.

A d:8°spectrophotometer uses an integrating sphere with a powdery white coating that reflects nearly 100% of the light energy.[45] A calibrated light source illuminates the inside of the sphere, which diffusely illuminates the sample (placed on the outside port of the sphere) from all directions, and the detector views the sample from a near-normal angle of 8°. This geometry correlates best with colors seen in diffuse viewing environments, and it has advantages over direct geometry in that it is less sensitive to variations in the sample surface. It is also much less sensitive to other appearance attributes such as visual texture, the directionality of the surface, and nonuniformity in surface color, which, depending on what is being measured, can be either an advantage or disadvantage.

Clinically, after the tooth preparation, the tooth surface can affect the clinician's ability to determine the true substrate color due to roughness produced by the prepping burs. The use of a 0°/45° spectrophotometer will be too sensitive to the prep roughness. Perhaps the most serious disadvantage of the 0°/45° spectrophotometer is that the substrate surface roughness is eliminated when the resin cement infiltrates the substrate during the bonding procedure. Thus, all potential differences in the substrate roughness during the substrate shade measurement can generate co-founder during the machine learning training.

There will always be some interaction between the surface morphology of a specimen and the efflux optics of an instrument. CAD/CAM restorations usually are polished using different polishing systems or glazed by applying a glaze paste or spray. Previous studies have compared the effect of polishing, glazing, the combination of both techniques, and their application in different phases of manufacturing ceramic restorations.[32,33] Different surface-finishing protocols result in different surface roughness and, consequently, other optical properties. Surface texture influences the light reflection, affecting the translucency and shade of ceramic restorations, the rougher the ceramic surface, the lower the ceramic material's translucency.[8] In the present study, the samples' superficial rugosity was similar to the restorations' rugosity of samples obtained from the CEREC MC XL milling machine in a pilot study. Thus, this regression model is to assist with the true color values of ceramic restoration. Further

investigation is needed to account for the variations in the surface roughness and gloss of different materials on the perceptibility and acceptability thresholds.

The shades from Vita Classic "A" group were selected in to train the machine learning as this group represents the most frequently selected shades for ceramic restorations.[14] Although the regression model can extrapolate to predict the shades on the B, C and D vita color groups, further studies need to be conducted to validate the regression model in different clinical scenarios. Also, the increase of database and software development can tune the regression model using machine learning.

Ideally, the use of translucent cements should be preferred as the influence of the cement on the final color of the restoration may be unpredictable. Many studies have investigated the coupling medium's effect on the ceramic restorations' final color.[50–52] The cement characteristics influence high translucent ceramics' shade more than low translucent ceramics' shade.[50] Also, cement shade has a higher effect on the final appearance of thinner ceramics.[52] Color and translucency of ceramic discs of 1.0 mm in thickness over white and black backgrounds have been evaluated when interposed with glycerin (refractive index = 1.48) or air (refractive index = 1.00029).[51] Color comparisons could not be performed when the coupling medium was not the same as it significantly affected the color perception. In this study, an experimental cement without photoinitiators was used as a coupling medium to mimic a conventional cement's optical properties. It also allowed the multiple uses of the samples and substrates, consequently reducing the variation within the study and reducing the number of samples needed. Further research should be undertaken to evaluate the influence of different cements under the present study's conditions. Further data collection is required to support the applicability of the regression model for other dental ceramics (i.e., lithium disilicate and zirconium oxide).

The ability to use data to make better predictions lies at the core of the current AI revolution. A key aspect of many models—like supervised learning—is the focus on prediction. A key issue for designers of new prediction tools is how to evaluate whether the model is an improvement on the status quo—for instance, whether a shade selection software can outperform current human visual shade selection. From all 28 regression models tested, the decision tree regressor was the model that produced the lowest error and highest accuracy in predicting the restoration final color. A decision tree regression is a tree of questions that must be answered in a sequence to produce a predicted regression. A decision tree regression is a tree of questions that must be answered in a sequence to produce a predicted regression model. Figure 3 shows that the L_{sub} and the thickness are the most important features in determining the restoration color. This exemplifies the importance of the clinician understanding the limitation of using leucite-reinforced ceramic in discolored teeth/substrate as it might not mask dark substrates. Also, the results emphasize the importance of whitening/bleaching treatment to facilitate substrate masking when the desired final color is too discrepant from the initial substrate shade. Lastly, the model results highlight the importance of the preparation depth to accommodate a minimum ceramic thickness capable of masking the substrate and achieving the desired final color.

Although this research focused on the use of regression models, other studies[53,54] found that other AI methods, such as Principal Component Analysis and Artificial Neural Networks, are also suitable for the prediction of color restorations. However, more comprehensive AI modeling using deep learning is suggested since all AI models studied this far have a high risk of overfitting and might not be extrapolated to all clinical scenarios. Further research should be focused on expanding the machine learning model by adding more data and features (substrate shades, ceramics shades, ceramic translucencies, ceramic types, and cement shades); developing an intuitive interface to facilitate the use of the regression model by dentists and dental technicians and integrating it with the intra-oral scanner software to provide immediate feedback regarding the ideal preparation depth and ceramic material thickness.

5 | CONCLUSION

Within the limitations of this current study, it was concluded that:

- Different substrates, ceramic shades, and ceramic thicknesses influence the *L*, *a*, and *b* coordinates of the final restoration. The influence of the ceramic thickness on the final color depends on the difference between ΔE_{00} of the substrate and the ceramic.
- The decision tree regression model developed in the study was able to predict the *L*, *a*, and *b* of the ceramic restorations made with IPS Empress CAD HT and LT, based on the CIELab of the substrate and different ceramic thicknesses. Of all variables, the substrate *L* value influenced the final ceramic shade the most, followed by the ceramic thickness.

ACKNOWLEDGMENTS AND DISCLOSURE

This study was partially supported by the University of Florida Seed Grant (grant # 00129566) and to fulfill the requirement of the Master of Sciences in Dental Sciences with a Specialization in Operative and Esthetic Dentistry at the University of Florida. The authors do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

If the data are available from the corresponding author on request, please mention that "The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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How to cite this article: Kose C Jr., Oliveira D, Pereira PNR, Rocha MG. Using artificial intelligence to predict the final color of leucite-reinforced ceramic restorations. *J Esthet Restor Dent*. 2023;35(1):105-115. doi:10.1111/jerd.13007

Received: 23 April 2022 | Revised: 9 July 2022 | Accepted: 11 July 2022

DOI: 10.1111/jerd.12947

RESEARCH ARTICLE

WILEY

Pressable lithium disilicate ceramic versus CAD/CAM resin composite restorations in patients with moderate to severe tooth wear: Clinical observations up to 13 years

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Funding information
Ivoclar, Schaan, Liechtenstein

Abstract

Objective: To report the long-term clinical survival and failure rates of single-tooth restorations made of pressable lithium disilicate ceramics (LS_2) and CAD/CAM resin composite (RC) by two separate clinical observations.

Materials and methods: Twenty-one patients (12 female, nine male) were treated with 436 minimally invasive single-tooth restorations made of 274 pressed LS_2 ($n = 12$; posterior: monolithic IPS e.max Press; anterior: IPS e.max Ceram veneered, Ivoclar) or 162 milled from RC ($n = 9$; monolithic exp. CAD/CAM resin composite, Ivoclar). The mean age of patients was 44.1 ± 9.3 years and the mean observation time was 86.2 ± 13.5 months (7.7 ± 1.1 years), with 8.5 ± 2.7 years for LS2 and 6.7 ± 0.5 years for RC. All restorations were observed for technical/biological failures using the modified criteria of the United States Public Health Service (USPHS). Collected data were analyzed using Kaplan–Meier survival analysis and log-rank test ($\alpha < 0.025$).

Results: The 274 LS_2 restorations showed a survival of 100% and a total failure rate of 5.5%. The 162 RC restorations showed a survival of 100% and a total failure rate of 25.3%. RC restorations exhibited more material fractures ($p = 0.020$) and higher discoloration rates ($p < 0.001$).

Conclusions: Pressed LS_2 single-tooth restorations showed lower long-term failure rates than restorations made of RC.

Clinical significance: Despite the limitations of the clinical observations, single-tooth restorations of both materials can be recommended for permanent use in patients with severe tooth wear.

KEYWORDS
CAD/CAM resin composite, ceramics, failure rate, lithium disilicate, severe tooth wear, survival

1 | INTRODUCTION

Patients today retain their natural teeth into old age thanks improved medical and dental care with a growing awareness of the importance of oral hygiene.[1] However, there is a gradual physiological loss of dental hard tissue, particularly enamel, over the years, reportedly by about 15 μm in the premolar region and by 29–33 μm in the molar region.[2,3]

In addition, younger patients now often suffer from a pathological loss of dental hard tissue owing to dietary habits (acidic foods and drinks) or increased attrition, abrasion, or erosion, alone or in combination.[4–7] This accelerates the wear of the hard tissues, resulting in different manifestations of tooth wear that may, in severe cases, require a full-mouth rehabilitation.[4,5] Minimally invasive treatment approaches appear to be advantageous in this situation and is regarded as the first treatment modality by the expert field.[8–12] More emphasize should be expressed that minimally invasive treatment is regarded as the first treatment modality by the expert field.

Conventional crown preparations sacrifice approximately 45% more hard tissue than minimally invasive preparations for occlusal or full veneers.[8,9,13]

The variety of available tooth-colored materials has increased in recent years. These materials—especially silicate ceramics—can be produced either by layering, pressing, and milling (CAD/CAM technology), or a combination of these techniques. The technology selected appears to influence the material's mechanical properties.[14,15] Besides the material's influence, the fabrication process' influence, and the operator's influence the patient also has influence the long-term survival of restorative work.[16–18]

CAD/CAM can be used to fabricate not only silicate ceramics (such as lithium disilicate) but also zirconia, polymer-infiltrated ceramics, or various polymer-based materials.[19,20] They can be used for various indications, including with manual veneering for superior esthetical outcomes.[19,20]

Indirect CAD/CAM resin composite materials exhibit higher edge stability than ceramics, permitting restorations with very thin margins.[21–24] Standardized industrial fabrication of the CAD/CAM blanks under high pressure and temperature result in more homogenous and more abrasion-resistant restorations than chairside restorations using direct composite resins.[25] Ceramics are generally superior to CAD/CAM polymer-based materials in terms of flexural strength, abrasion resistance and discoloration rates, whereas CAD/CAM polymer-based materials are more antagonist-friendly.[26–31]

Lithium disilicate restorations were shown to result in a survival between 92% and 97.8% after 5 years and between 85.5% and 96.7% after 10 years.[32–34] Little data have been published on the clinical long-term performance of minimally invasive CAD/CAM resin composite single-tooth restorations, used for occlusal veneers and partial crowns over a three-year observation time,[35–42] and specifically as compared to lithium disilicate restorations for worn dentitions regardless of the fabrication method.[43,44]

The present clinical observation aimed to investigate the clinical outcomes and long-term survival and failure rates of single-tooth restorations made of pressed lithium disilicate ceramics (up to 13 years) and CAD/CAM resin composite (up to 7 years). Survival describes the retention of the restoration in situ at follow-up examination, even if a complication has occurred. The following hypotheses were analyzed:

1.Survival of evaluated restoration materials will be different for the respective follow-up period.

2.Failure rates (incidence of material fracture and discoloration) will be different for CAD/CAM resin composite and lithium disilicate ceramic restorations.

2 | MATERIALS AND METHODS

The Ethical Committee of the University Hospital in Munich had approved both prospective non-randomized clinical studies (projects 012-12 and 659-16) that were used for the present clinical observation. The requirements of the Declaration of Helsinki were observed, and written informed consent was obtained from all patients.

2.1 | Clinical population

A total of 21 patients (12 female, nine male) received restorations made of minimally invasive lithium disilicate ceramic ("lithium disilicate"; 12 patients) or experimental CAD/CAM resin composite ("CAD/CAM resin composite"; nine patients) restorations. The restorations were delivered between July 2007 and December 2014 within the framework of two different clinical studies. The recipients were regular patients of the Department of Prosthetic Dentistry at the University Hospital in Munich.

Inclusion and exclusion criteria were as follows:

a. Age between 18 and 70 years.
b. Adequate oral hygiene (BOP ≤2; PI ≤3).
c. Preparation guidelines for specific restoration materials can be followed.
d. Necessary increase in VDO due to attrition, abrasion and erosion of dental hard tissue alone or in combination (moderate to severe tooth wear) in the presence of excessive dentin exposure and patient demand for improved masticatory function and smile esthetics.
e. Absence of periodontal disease (GI ≤3; oral and vestibular PD ≤3.5 mm).
f. Absence of pregnancy and lactation.
g. Smoking status not relevant.

2.2 | Prosthetic treatment

Patients requested prosthetic treatment due to varying degrees of dental hard-tissue loss combined with losses in VDO, hypersensitivity or functional/esthetic impairments. The loss of dental hard tissue was caused predominantly due to erosion combined with functional wear (Figure 1).

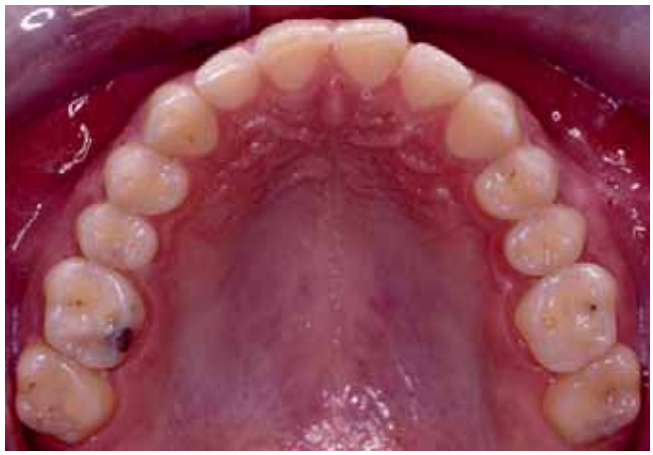

FIGURE 1 Pre-operative view of the maxilla of a 28-year-old patient with erosive and functional wear and numerous dentin exposures

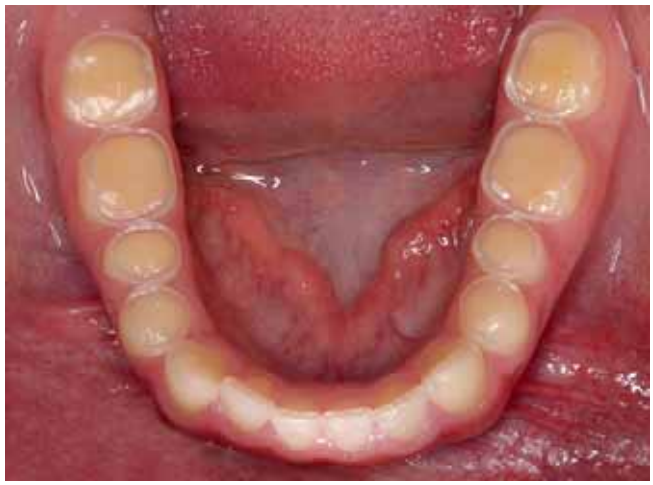

FIGURE 3 Pre-operative view of the mandible with erosive and functional wear and numerous dentin exposure

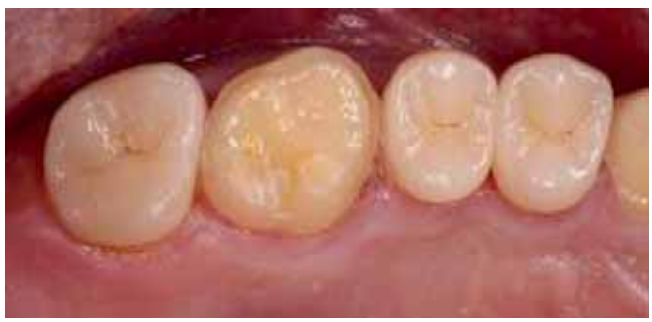

FIGURE 5 Try-in of pressed lithium disilicate monolithic occlusal onlays on teeth FDI 17, 15 and 14. Preparation design

All patients had received minimally invasive tooth-colored full-mouth rehabilitations made of either

a. lithium disilicate ceramic restorations, using monolithic lithium disilicate single-tooth restorations in the load-bearing posterior regions (IPS e.max Press, Ivoclar); and lithium disilicate frameworks with manual veneering in the esthetic anterior regions (IPS e.max Press with IPS e.max Ceram, Ivoclar; Figure 2); or
b. monolithic experimental CAD/CAM resin composite restorations (Ivoclar).

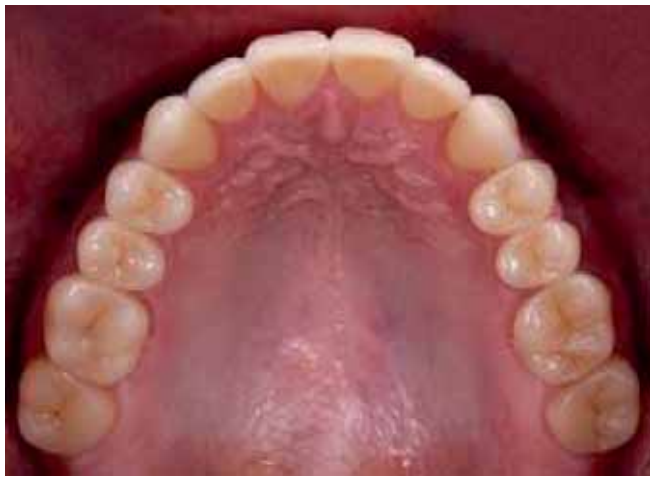

FIGURE 2 Post-operative view of patient's maxilla with monolithic (posterior) and partially veneered (anterior) lithium disilicate restorations

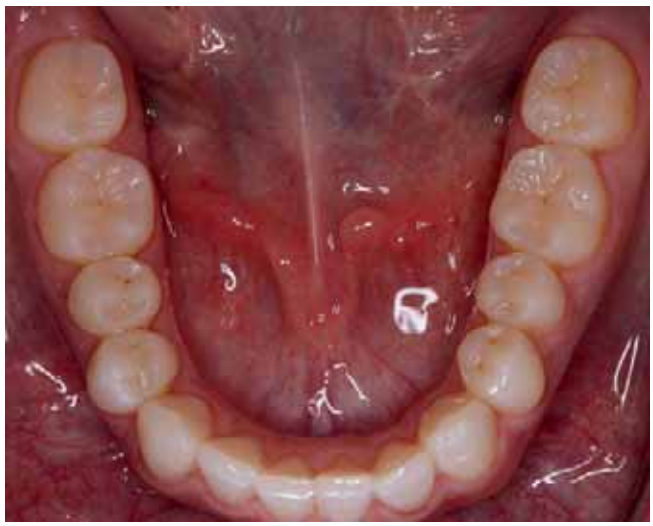

FIGURE 4 Post-operative view of patient's mandible with

Manufacturer reported about the composition of the experimental CAD/CAM composite material (Ivoclar), which consisted of 22% V_f matrix (dimethacrylate) and 78% V_f filler (barium glass fillers, 15%; ytterbium trifluoride, 9%; mixed oxides, 44%; silicon oxides, three; copolymers, 7%). The material showed mechanical properties as follows: flexural strength = 167 MPa, modulus of elasticity = 11.4 GPa, Vickers hardness = 915 MPa, and water absorption after 7 days = 28 μg/mm^3.

Most CAD/CAM resin composite restorations were additive restorations with no previous preparation. A single experienced dentist treated all the patients with lithium disilicate ceramic restorations,

whereas the patients with CAD/CAM resin composite restorations were treated by three different experienced dentists. All dentists had been calibrated in advance (Figures 3,4).

The data for the lithium disilicate restorations have been published previously,[43,44] but the present clinical observation featured extended observation rates (up to 13 years) and added a comparison to CAD/CAM resin composite restorations with observation rates of up to 7 years.

Each rehabilitative treatment—regardless of the material used—started with an esthetic and functional diagnostic wax-up in centric relation, which was evaluated with the patient using a direct mock-up (esthetic evaluation). The necessary increase in vertical dimension was determined according to (a) the incisal edge positions of the central incisors, (b) the width-to-length ratio of the incisors, (c) phonetics, (d) freeway space, and (e) the facial profile. A "test drive" (3 months or more) for functional/esthetic evaluation used either a repositioning-splint or adhesively bonded polymethyl methacrylate (PMMA) anterior and posterior veneers in case of planned lithium disilicate ceramic restorations, designed according to the increase in VDO implemented in the evaluated wax-up.[43,44]

The hard-tissue removal for the lithium disilicate ceramic restorations was guided by a template (prep guide)—either a thermoplastic template/foil (Duran transparent 0.5 mm; Scheu-Dental, Iserlohn, Germany) or Silicon index fabricated from the outer contour of the diagnostic wax-up and controlled with a special periodontal probe (CP-15UNC; Hu-Friedy, Tuttlingen, Germany). The preparation guidelines—especially for the lithium disilicate ceramic restorations have been described previously.[43–47] The preparation design was dependent on the degree of destruction, preexisting fillings, and the extension of the wax-up by the dental technician.

Polyether impressions were taken (Impregum penta; 3 M, Seefeld, Germany) and plaster casts were poured. The final restorations (IPS e.max Press monolithic or partial anterior veneering by IPS e.max Ceram or CAD/CAM resin composite veneers; all Ivoclar) were fabricated by the dental laboratory according to the manufacturer's instructions as published in previous articles.[43–45,48] The composition of the lithium disilicate crowns, onlays, and veneers was as follows: silicon dioxide, 57–80%; lithium dioxide, 11–19%; potassium oxide, 0%–13%; phosphorus pentoxide: 0%–11%, zirconia, 0%–8%; zinc oxide, 0%–8%; others, 0%–10%. The CAD/CAM resin composite restorations were composed of Bis-GMA, UDMA, Bis-EMA, and TEGDMA (total monomer 18.0 wt%) and inorganic fillers of barium glass, ytterbium trifluoride, silicon dioxide and mixed oxide (82 wt%, particle size, 40 nm–7 μm) with additional additives, initiators, stabilizers and pigments (0.2 wt%).

The prepared abutment teeth were—if necessary—covered with temporary restorations (C & B; Ivoclar), and bonded (Heliobond; Ivoclar) without etching. All restorations were tried in with glycerine gel (Figure 5). If minor (<1 mm in diameter) corrections were required for the lithium disilicate restorations, the surface was repolished at chairside prior to definite adhesive placement. Major corrections (>1 mm) were followed by a glaze firing at the dental laboratory. The CAD/CAM resin composite restorations were merely repolished after any corrections.

Prior to adhesive bonding, lithium disilicate ceramic restorations were cleaned/disinfected for 5 min in an ultrasonic bath filled with alcohol (Ethanol 90%); resin composite restorations were briefly swiveled in alcohol for disinfection and then cleaned in distilled water in an ultrasonic bath for 5 min. The internal surfaces of the lithium disilicate ceramic restorations were etched with hydrofluoric acid (IPS Ceramic Etching Gel <5%; Ivoclar) for 20 s, while the internal surfaces

TABLE 1 Modified United States Public Health Service (USPHS) Ryge criteria for clinical evaluation of ceramic and CAD/CAM resin composite restorations analyzed[44,45]

USPHS	Alpha (A)	Bravo (B)	Charlie (C)
Marginal discoloration	No visual evidence of marginal discoloration	Visual evidence of marginal discoloration at the junction of the tooth structure and the restoration, but the discoloration has not penetrated along the restoration in a pulpal direction	Visual evidence of marginal discoloration at the junction of the tooth structure and the restoration that has penetrated along the restoration in a pulpal direction, renewal necessary
Secondary caries	The restoration is a continuation of existing anatomic form adjacent to the restoration	Visual evidence of dark keep discoloration adjacent to the restoration	Renewal necessary
Marginal integrity	No probe catch	Slight catch on probing, no gap	Highly over or under-contoured, renewal necessary
Surface texture	Surface texture similar to polished enamel	Surface texture gritty or similar to a surface subjects to a white stone or similar to a composite containing supramicron-sized particles	Surface pitting is sufficiently coarse to inhibit the continuous movement of an explorer across the surface, renewal necessary
Restoration fracture	Restoration is intact and fully retained, no fracture	Restoration is partially retained, polishing or repair is possible	Restoration is completely missing or huge fracture, renewal necessary

TABLE 2 Survival and failure rates (FR) for lithium disilicate and CAD/CAM resin composite restorations analyzed according to USPHS criteria (A: Alpha; B: Bravo; C: Charlie); failures evaluated separately

Patient (number)	Age (years)	Gender (male/female)	Time in situ (months/years)	Number of restorations (no. anterior/no. posterior)	Survival rate (%)	FDI position	FR (USPHS criteria)	FR (months)	Type of intervention
Lithium disilicate restorations									
1	51	Male	149/13	28 (16 posterior, 12 anterior)	100	21	Minor chipping (B)	66	Intraoral repair
						22	Minor chipping (B)	66	Intraoral repair
						23	Minor chipping (B)	11	Intraoral repair
						32	Minor chipping (B)	120	Intraoral repair
						15	Marginal crack formation (B)	120	No intervention (Observation)
						27	Retention loss (B)	149	Cleaning and adhesive reattachment
						26	Marginal discoloration (B)	60	No intervention (Observation)
						33	Marginal discoloration (B)	120	No intervention (Observation)
						36	Marginal discoloration (B)	120	No intervention (Observation)
						43	Marginal discoloration (B)	108	No intervention (Observation)
						45	Marginal discoloration (B)	108	No intervention (Observation)
						46	Marginal discoloration (B)	108	No intervention (Observation)
2	41	Male	138/12	24 (16 posterior, eight anterior)	100				
3	40	Male	98/9	28 (16 posterior, 12 anterior)	100	21	Minor chipping (B)	20	Intraoral repair
4	43	Female	90/8	28 (16 posterior, 12 anterior)	100	11	Incisal crack (B)	38	No intervention (Observation)
5	40	Male	93/8	28 (16 posterior, 12 anterior)	100				
6	50	Female	78/7	20 (14 posterior, six anterior)	100				
7	28	Male	122/11	28 (16 posterior, 12 anterior)	100				
8	58	Female	89/8	10 (10 posterior)	100				
9	44	Female	129/11	26 (14 posterior, 12 anterior)	100	42	Marginal crack formation (B)	91	No intervention (Observation)
10	54	Male	57/5	22 (10 posterior, 12 anterior)	100				
11	35	Male	49/5	16 (16 posterior)	100				
12	46	Female	48/5	16 (16 posterior)	100				
CAD/CAM resin composite restorations									
1	43	Female	73/7	15 (15 posterior)	100	27	Endodontic treatment	7	Perforation of the restoration and Endodontic treatment covered with direct adhesive composite
2	44	Female	70/6	16 (16 posterior)	100	24 44	Retention loss Restoration fracture (B)	28 36	Cleaning and adhesive reattachment Intraoral repair

TABLE 2 (Continued)

Patient (number)	Age (years)	Gender (male/female)	Time in situ (months/years)	Number of restorations (no. anterior/no. posterior)	Survival rate (%)	FDI position	FR (USPHS criteria)	FR (months)	Type of intervention
3	51	Female	83/7	27 (15 posterior, 12 anterior)	100	17	Restoration fracture (B)	53	Intraoral repair
						46	Marginal discoloration (B)	65	No intervention (Observation)
						47	Marginal discoloration (B)	56	No intervention (Observation)
4	58	Male	77/7	28 (16 posterior, 12 anterior)	100	12	Restoration fracture (B)	33	Repolishing
						42	Restoration fracture (B)	35	Repolishing
						16	Marginal discoloration (B)	45	No intervention (Observation)
						15	Marginal discoloration (B)	45	No intervention (Observation)
						11	Marginal discoloration (B)	57	Repolishing
						21	Marginal discoloration (B)	57	Repolishing
						26	Marginal discoloration (B)	45	No intervention (Observation)
						27	Marginal discoloration (B)	45	No intervention (Observation)
						36	Marginal discoloration (B)	57	No intervention (Observation)
						33	Marginal discoloration (B)	57	No intervention (Observation)
						44	Marginal discoloration (B)	45	No intervention (Observation)
						46	Marginal discoloration (B)	57	No intervention (Observation)
						47	Marginal discoloration (B)	57	No intervention (Observation)
5	45	Female	83/7	Six (six posterior)	100	36	Marginal discoloration (B)	66	No intervention (Observation)
						37	Marginal discoloration (B)	66	No intervention (Observation)
						46	Marginal discoloration (B)	29	No intervention (Observation)
						47	Marginal discoloration (B)	30	No intervention (Observation)
						47	Restoration fracture (B)	30	Intraoral repair
6	44	Female	74/7	14	100	15	Marginal discoloration (B)	56	No intervention (Observation)
						16	Marginal discoloration (B)	56	No intervention (Observation)
						17	Marginal discoloration (B)	56	No intervention (Observation)
						26	Marginal discoloration (B)	69	No intervention (Observation)
						36	Marginal discoloration (B)	69	No intervention (Observation)
						46	Discoloration restoration (B)	56	No intervention (Observation)
						46	Restoration fracture (B)	56	Intraoral repair
						47	Restoration fracture (B)	56	Intraoral repair
7	26	Female	69/6	12	100	27	Restoration fracture (B)	13	Intraoral repair
						47	Restoration fracture (B)	13	Intraoral repair
8	57	Female	75/7	16	100	47	Restoration fracture (B)	74	Intraoral repair
9	28	Male	63/6	28 (16 posterior, 12 anterior)	100	27	Secondary caries (B)	52	Selective intraoral repair

of the CAD/CAM resin composite restorations were air-abraded using a modified procedure (Rocatec soft, 1 bar pressure, approximately 10 s exposure time, 90° angle). After cleaning in an ultrasonic bath (see above), a Primer (Monobond Plus, exposure time 60s; Ivoclar) was applied to the pre-treated internal surfaces of both restoration types, followed by a thin layer of bonding material (Heliobond; Ivoclar). A low-viscosity composite resin cement (Variolink II; either light-cured or dual-cured; Ivoclar) combined with a multiple step dentin adhesive system (Syntac; Ivoclar) was used for the final placement of the restorations.

The occlusal concept realized was anterior canine guidance with "freedom in centric". Annual recalls were performed using the modified United States Public Health Service (USPHS) criteria specified in Table 1 for both clinical analyses, as described previously,[49,50] with ratings Alpha (no problem observed), Bravo (minor complications observed), or Charlie (major complications observed, remake of the restoration necessary). The recall evaluations were performed by two examiners with 10 years of clinical expertise in all-ceramics and adhesive technique.

The analysis, in addition to the classical USPHS criteria chosen, further distinguished between technical and biological failures. Technical failures in the clinical observation also included additional measured criteria: restoration fracture (major chipping), minor chipping, marginal/incisal crack formation, retention loss, or marginal/restoration discoloration. Discolorations were checked visually and documented at follow-up. Biological failures include secondary caries, with necessary endodontic treatment as an additional criterion. Occlusal wear, marginal integrity, and surface quality were detected visually and haptically with a probe during the follow-up sessions.

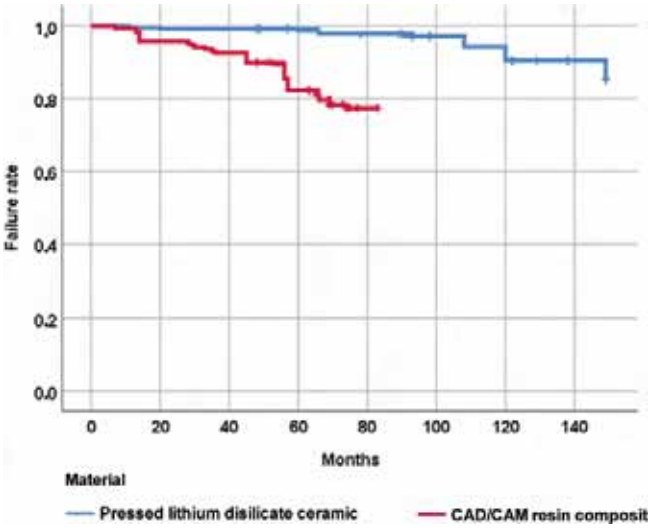

FIGURE 6 Kaplan–Meier rate of pressed lithium disilicate and CAD/CAM resin composite failures in total as comparison

FIGURE 8 Loss of retention of pressed lithium disilicate monolithic occlusal onlay after 149 months of clinical service. The composite built-up is still bonded to lithium disilicate ceramic representing an adhesive failure of the dentin adhesive on natural tooth structure

2.3 | Statistical analysis

Survival and failure rates for the lithium disilicate ceramic and CAD/CAM resin composite group were calculated using the Kaplan–Meier survival analysis and the log-rank test. Restorations were considered total failures if they had to be replaced (rated Charlie). Data

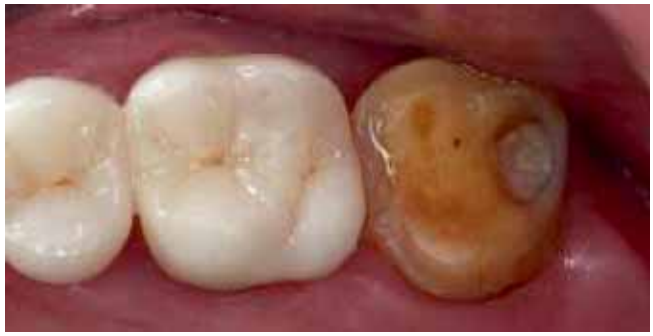

FIGURE 7 Loss of retention of posterior pressed lithium disilicate monolithic occlusal onlay (FDI 27) after 149 months of clinical service

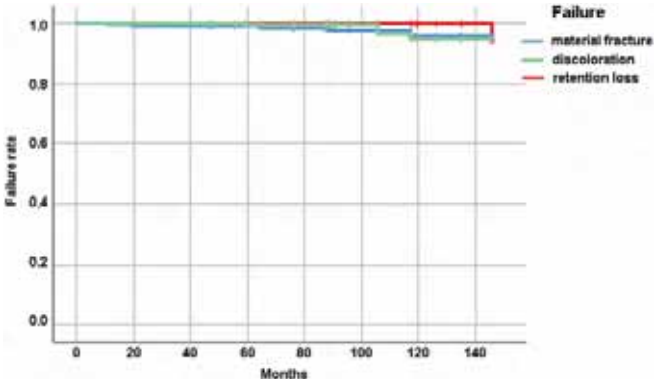

FIGURE 9 Kaplan–Meier rate for failure rates of pressed lithium disilicate restorations

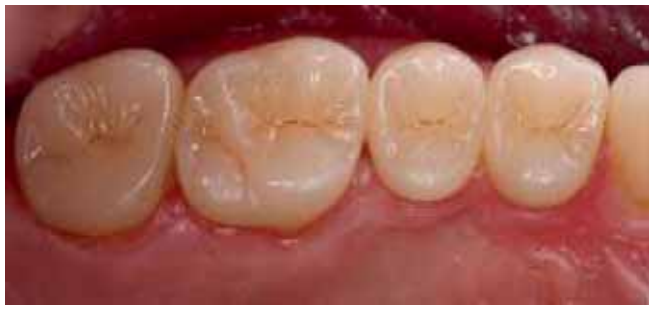

FIGURE 10 Pressed lithium disilicate monolithic occlusal onlays (Figure 5) after 49 months of clinical service with visible wear

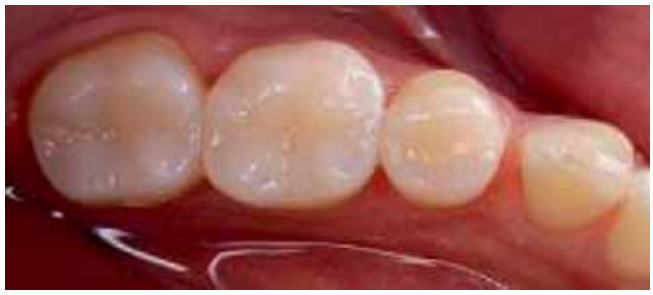

FIGURE 11 CAD/CAM resin composite restorations after adhesive bonding with high surface gloss at baseline recall

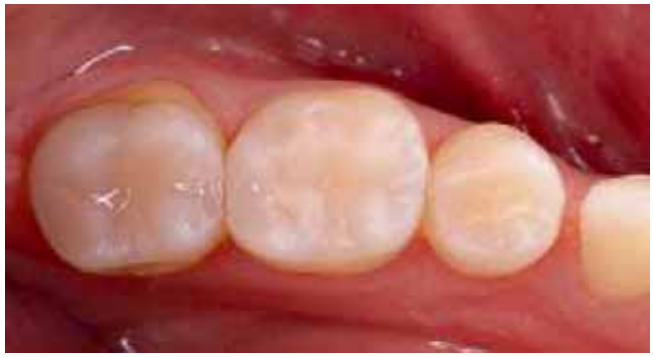

FIGURE 12 CAD/CAM resin composite restorations (Figures 11, 14) with marginal discoloration after 64 months of clinical use. The surface appeared dull with visible wear

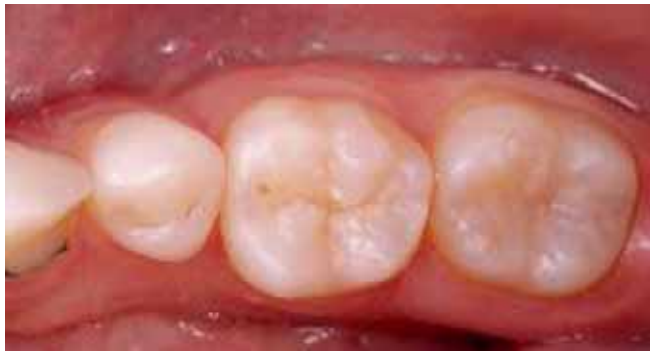

FIGURE 13 Repairable distobuccal fracture of CAD/CAM resin composite restoration (FDI 46) after 44 months of clinical service

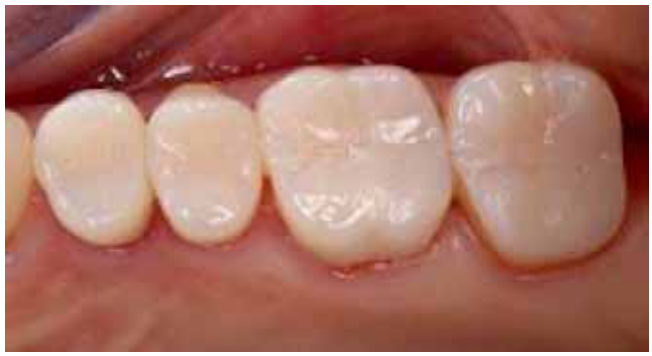

FIGURE 14 CAD/CAM resin composite restorations after adhesive bonding with high surface gloss at baseline recall

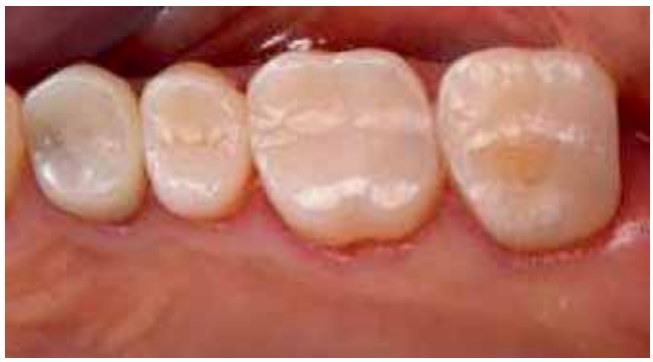

FIGURE 15 CAD/CAM resin composite restorations (Figure 14) with discoloration and crack of first premolar (FDI 24) and perforation on second molar (FDI 26) after 58 months of clinical service. Surface appeared dull with visible wear

were analyzed using SPSS 25 (SPSS) with a significance level of $p < 0.025$ to adjust for the variability in patient selection for the two different material groups.

3 | RESULTS

3.1 | General information

The mean age of the 21 patients was 44.1 ± 9.3 years and the mean observation period was 86.2 ± 13.5 months (7.7 ± 1.1 years). All patients were non-smokers and were seen at the clinic due to esthetic concerns, hypersensitivity, functional and masticatory problems, as well as in very rare cases pain.

All patients were treated with tooth-colored single-tooth restorations ($N = 436$), whereas 274 lithium disilicate ceramic restorations were made, of which 176 monolithic lithium disilicate restorations were placed in the load-bearing posterior regions (IPS e.max Press); 144 monolithic occlusal onlays, 32 crowns, and 98 lithium disilicate

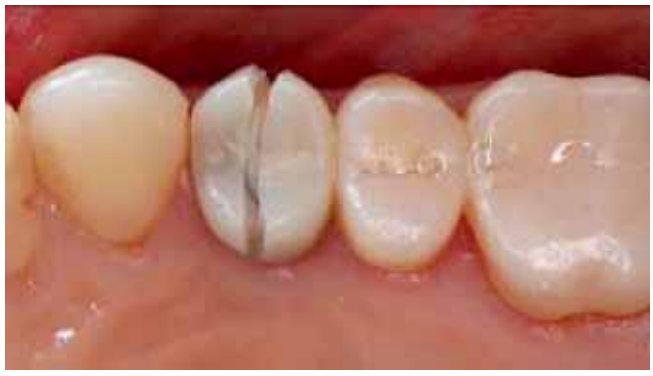

FIGURE 16 CAD/CAM resin composite restorations (Figure 14) with discoloration and crack of first premolar (FDI 24) prior to change of prosthetic rehabilitation from CAD/CAM resin composite to monolithic lithium disilicate restorations after separating of CAD/CAM resin composite crown after 72 months of clinical service. Discoloration resulted of an adhesive failure between CAD/CAM resin composite and luting composite

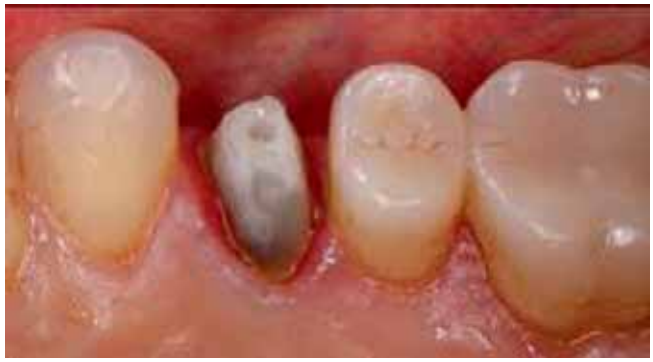

FIGURE 17 CAD/CAM resin composite restorations (Figure 14) with discoloration and crack of first premolar (FDI 24) prior to change of prosthetic rehabilitation from resin CAD/CAM composite to monolithic lithium disilicate restorations after removal of CAD/CAM resin composite crown after 72 months of clinical service. Luting composite remained on abutment tooth as a sign of adhesive failure on the inner surface of the restoration

frameworks with manual veneering in the esthetic anterior regions (IPS e.max Press with IPS e.max Ceram). In addition, 162 monolithic CAD/CAM resin composite restorations were fabricated, of which 140 were in the posterior region (77 occlusal onlays, 59 partial crowns, four full crowns), and 22 in the anterior region (20 veneers and two crowns).

3.2 | Lithium disilicate restorations

Within the group of lithium disilicate ceramic restorations, five female and seven male patients with a mean age of 41.2 ± 8.2 years (female, 48.2 ± 5.8; male, 41.3 ± 8.6) were treated with a mean observation time of 95.0 ± 33.3 months (8.5 ± 2.7 years).

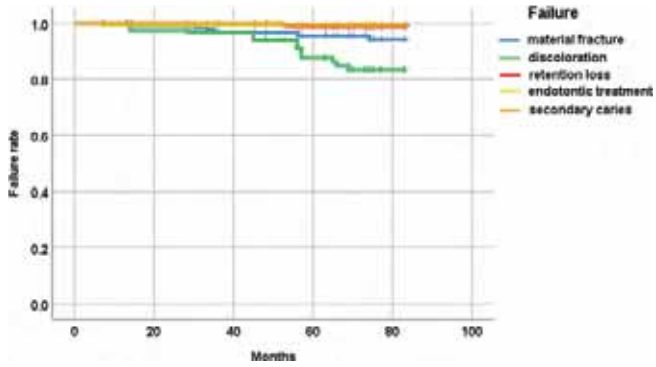

FIGURE 18 Kaplan–Meier rate for failure rates of CAD/CAM resin composite restorations

The total failure rate of lithium disilicate ceramic restorations was 5.5% with a total annual failure rate (AFR) of 0.5%. All technical failures were rated Bravo (Table 2 and Figure 6–9) with an AFR of 2.9% and discoloration with an AFR of 2.2%. For the lithium disilicate restorations, no biological complications were found. Visible occlusal wear (rated Bravo) occurred in 67.5% of the lithium disilicate restorations (Figure 10).

3.3 | CAD/CAM resin composite restorations

Within the group of CAD/CAM resin composite restorations, seven female and two male patients with a mean age of 44.0 ± 10.8 years (female, 44.3 ± 9.1; male, 43.0 ± 15.3) were treated with a mean observation time of 74.0 ± 6.3 months (6.7 ± 0.5 years). Details for the patients included are summarized in Table 2.

The total failure rate of CAD/CAM resin composite restorations was 25.3% (Figure 6) with a total AFR of 3.8%. CAD/CAM resin composite restorations exhibited more material fractures ($p = 0.020$, AFR: 6.2%) and higher discoloration rates ($p < 0.001$, AFR: 14.2%) analyzed with the log-rank test.

Thirty-nine technical failures and two biological failures occurred (one secondary caries after 52 months and one necessary endodontic treatment after 7 months), all rated Bravo (for details see Table 2). Occlusal wear (rated Bravo) was documented in 91.1% of the CAD/CAM resin composite restorations after 6 and 7 years in situ (Figures 11–18).

Neither restorative material presented any difference in survival, with no loss of restoration to follow-up.

Detailed survival and failure rates for both restoration types are listed in Table 3. Survival and failure rates as primary outcomes are listed in Table 4.

4 | DISCUSSION

Full-mouth rehabilitations of patients with moderate to severe loss of dental hard tissue with progressive VDO reduction usually represent a

TABLE 3 Descriptive results of total survival and failure rates of lithium disilicate and CAD/CAM resin composite restorations including most common failures separately

	Lithium disilicate		Composite resin	
	Total number	%	Total number	%
Total survival and failure rates				
Survival rate	274/274	100	162/162	100
Technical failure rate	15/274	5.48	34/162	24.1
Biological failure rate	0/274	0	2/162	1.20
Most common failures				
Chipping/fracture rate	8/274	2.92	10/162	6.17
Discoloration rate	6/274	2.19	23/162	14.2

TABLE 4 Results of modified USPHS criteria including number of restorations and percentages[49,50]

	Lithium disilicate			Composite resin		
	Alpha (A)	Bravo (B)	Charlie (C)	Alpha (A)	Bravo (B)	Charlie (C)
Marginal discoloration	268 (97.8%)	6 (2.19%)	0 (0%)	163 (99.4%)	22 (7.36%)	0 (0%)
Secondary caries	274 (100%)	0 (0%)	0 (0%)	189 (99.5%)	1 (0.53%)	0 (0%)
Restoration fracture	266 (97.1%)	8 (2.92%)	0 (0%)	180 (95.3%)	10 (4.74%)	0 (0%)

major challenge for the dental team. The most prevalent reasons why patients requested treatment were esthetic concerns (59%), followed by teeth sensitivities (40%), functional problems (17%), and pain (14%).[4,5,7] These reasons could be confirmed for the present study population.

Lithium disilicate ceramic is generally superior to CAD/CAM polymer-based materials in terms of flexural strength, abrasion resistance, and marginal/material discolorations.[19,20,24,25,26] These results were partially confirmed in the present clinical observation, as CAD/CAM resin composite restorations showed higher abrasion rates and significantly higher discoloration rates than lithium disilicate ceramic restorations. The annual failure rate was additionally higher for the CAD/CAM resin composite restorations.

It should be mentioned that this direct comparison between the two materials investigated is also a major limitation of the present observation, as not only the materials themselves differed but also the manufacturing methods (pressed vs. CAD/CAM). The latter can influence the mechanical and optical properties of the materials, as mentioned in the introduction for lithium disilicate ceramic.[19,21,22]

A further limitation is the inclusion gap of about 3 years of patients from the lithium disilicate ceramic population. The gap arose because the restorations were exclusively provided by a single practitioner, while the CAD/CAM resin composite observation was performed by three different practitioners within a short period. The lithium disilicate practitioner was also included in the CAD/CAM resin composite study, leading to the gap in between. It is still assumed that the clinical procedures of the lithium disilicate ceramic observation are stable, being performed only one practitioner using the same materials.

No long-term data for indirect CAD/CAM resin composite restorations in patients with worn dentitions are available.[35–39] Therefore, the present clinical observation used restorations made from a highly filled (82 wt%) CAD/CAM resin composite to evaluate long-term performance irrespective of the limitations mentioned.

Favorable long-term survival (85.5%–96.7% after 10 years and 100% for partial crowns after 7 years of clinical service) have been reported for single-tooth all-ceramic restorations[33,34,45]—and particularly for lithium disilicate ceramic restorations as investigated in the present clinical observation, with minimally invasive restoration geometries as described in the introduction.[32,34] These survivals are even surpassed by the 100% after up to 13 years of observation based on the present observational results. Fifteen minor technical failures occurred but did not require restorations to be replaced. Minor chippings (2.9%) were repaired with direct resin composite. The formation of marginal cracks is still under observation but has not changed clinically since the previous publication.[43,44] The repair rate was 1.8% for the lithium disilicate ceramic restorations examined. Even with minimally invasive geometries as used in the present clinical observation, with predominantly occlusal onlays and full veneers (lithium disilicate ceramic group), the literature shows that restorations can be stabilized by adhesive bonding, especially when applied with reduced thickness.[43,44]

The few discolorations (2.2%) of restoration margins were repolished with ceramic polishing sets. Some, however, could not be completely removed. Given their posterior location, patients did not consider this to imply an esthetic compromise and declined a remake of their restorations. Marginal discoloration occurred in one patient who was a non-smoker; the reason could not be finally determined. Most other instances of failures within the lithium disilicate group occurred in one patient with reduced compliance for the nighttime protective splint and an additional anterior trauma.

In the present clinical observation, CAD/CAM resin composite restorations exhibited the same survival as the lithium disilicate ceramic restorations, with no clinical loss of restorations—a favorable long-term outcome. Nevertheless, the failure rate for CAD/CAM resin composite restorations was significantly higher than for lithium disilicate ceramic restorations. This rate is mainly due to technical failures (24.1%) and two biological failures (1.2%). As for the technical failures, there were significantly more partial fractures (6.2%) and marginal/material discolorations (14.2%) (Figure 12). All failures with this material were amenable to repair. The favorable repair options for polymers have been described in the literature.[18]

Discoloration of the material occurred exclusively in posterior resin composite restorations, without no esthetic impairment and no replacement need. CAD/CAM resin composite restorations in this observation were significantly less resistant to abrasion than the lithium disilicate ceramic restorations and carried a higher risk for recurring VDO decrease, with occlusal wear rates of 91.1% and 67.5%, respectively. This material-specific behavior is confirmed by in-vitro as well as in-vivo data.[26,28,51] The 3-year wear data of 12 patients who were also restored using lithium disilicate ceramics and CAD/CAM resin composite as part of full-mouth rehabilitations confirm the results of the present study.[51]

An observation limitation is that the abrasion was not investigated quantitatively, but purely visually on a yes/no grid. The results obtained demonstrate the slight clinical advantages of lithium disilicate ceramic restorations over CAD/CAM resin composite ones. The clinical data cannot easily be compared with published in-vivo data, as limited data has examined CAD/CAM resin composite restorations vs. all-ceramic crowns beyond a 3-year study period.[32,33,43–45] In one study, the survival of the resin composite restorations at 3 years was already lower than in the present observation, for a survival of 87.9% with high abrasion.[35] This may be explainable by the different preparation designs in the two clinical setups. Minimally invasive restorations, such as those in the present observation, allow enamel to be preserved as an optimal substrate for adhesion rather than requiring the exposure of dentin associated with crown preparation. Both restorative materials were adhesively bonded with the same composite luting agent using a comparable method, so that differences in luting protocols should play a subordinate role. However, as in the clinical study by Vanoorbeek,[35] ceramic crowns are clearly superior to resin composite crowns and are therefore recommended for long-term use.

The hypotheses underlying the present observation, namely that there is no difference in clinical parameters or survival and failure rates between minimally invasive rehabilitation with lithium disilicate ceramic or CAD/CAM resin composite, could therefore be partially rejected, based on failure rates.

Another minor limitation of the present observation—apart from the selection of the patient cohort regarding gender and the small number of patients presenting divers lifestyle and eating habits (21)—was the influence of the treatment provider(s) (operator sensitivity) and the processing of the materials in the dental laboratory. This has been confirmed in the literature.[16,17] As the majority of prosthetic rehabilitations were performed from one operator, the influence seems to be smaller but still existent. In addition, the lack of sample size calculation is also a limitation, since the effort of total rehabilitations is very high and consequently a number was determined in advance.

The present patient cohort was highly balanced and enrolment bias should have played a rather subordinate role, with the two patients with the most failures being male. Increased chewing forces may have had an influence. In addition, there were no detailed technical investigations into possible bruxism. A further limitation was that the abrasion resistance of the two materials could only be observed between the material groups (ceramic–ceramic or composite–composite) and not with natural teeth as antagonists, as all patients had received full-mouth rehabilitations. Further clinical studies using prospective split-mouth method like restoring the upper and lower jaw or the left and right posterior region with diverse materials, or a higher number of patients should be performed.

5 | CONCLUSIONS

Within the limitations of the present clinical observations, the following conclusions may be drawn:

1. Both restoration materials presented identical survival (100%) for the respective follow-up period.
2. Failure rates were higher for CAD/CAM resin composite restorations (24.1%), including mainly technical failures, than for lithium disilicate ceramic restorations, with 5.48% technical failures. CAD/CAM resin composite restorations had a higher incidence of material fracture and higher discoloration rates.

AUHTOR CONTRIBUTIONS

Anja Liebermann, Daniel Edelhoff: Conceived and designed the observation. Anja Liebermann, Daniel Edelhoff, Kurt Erdelt, and Bogna Stawarczyk: Contributed to analysis and interpretation of data. Anja Liebermann and Daniel Edelhoff: Wrote manuscript. All authors: Read, revised, and accepted the manuscript prior to submission.

ACKNOWLEDGMENT AND DISCLOSURE

Open Access funding enabled and organized by Projekt DEAL. The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

FUNDING INFORMATION

The clinical observation was supported in part by Ivoclar, Schaan, Liechtenstein. The funders had no role in conduct, analysis, interpretation or reporting of the observation.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Edelhoff D, Erdelt K-J, Stawarczyk B, Liebermann A. Pressable lithium disilicate ceramic versus CAD/CAM resin composite restorations in patients with moderate to severe tooth wear: Clinical observations up to 13 years. *J Esthet Restor Dent*. 2023;35(1):116-128. doi:10.1111/jerd.12947

Received: 30 September 2022 | Revised: 8 November 2022 | Accepted: 11 November 2022

DOI: 10.1111/jerd.12984

RESEARCH ARTICLE

WILEY

Bond strength to different CAD/CAM lithium disilicate reinforced ceramics

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Abstract

Objective: To evaluate the microstructure and the influence of applying universal adhesive only versus universal adhesive with additional silane application on shear bond strength (SBS) to four different lithium disilicate ceramic (LDC) materials.

Material and Methods: Specimens ($n = 240$, 1.5 mm thick) cut from four different CAD/CAM materials were polished and etched with 4.5% hydrofluoric (HF) acid according to manufacturers' instructions (20 s: IPS e.max CAD, n!ce; 30 s: Amber Mill, CEREC Tessera). For cementation, either universal adhesive only or silane + universal adhesive were applied before prefabricated composite cylinders were cemented using a dual-cure resin cement. SBS testing was performed either after 24 h or after 20,000 cycles thermocycling +2 months water storage. Surfaces were analyzed with stereomicroscope for failure mode and with scanning-electron microscopy for microstructure of the LDC. Statistical analysis of the data was performed with non-parametric tests at $\alpha = 0.001$.

Result: SBS values for non-aged specimens ranged from 29.08 to 17.87 MPa and for aged specimens from 22.24 to 3.01 MPa. SBS was significantly reduced when silane was omitted after aging, ($p < 0.001$). Failure mode was mostly mixed with some cohesive failures in the LDC.

Conclusion: Bond strengths are highly affected by the CAD/CAM LDC and their microstructures. The application of silane after hydrofluoric etching is still essential to obtain long-term bonding, irrespective of the presence of silane in the universal adhesive. Water degradation can significantly affect long-term bonding to novel LDC.

Clinical Significance: When using a universal adhesive for bonding to LDC restorations, the best long-term bond is achieved if an additional application of silane precedes the universal adhesive.

KEYWORDS
CAD CAM, lithium disilicate glass ceramic, resin cement, SBS, silane, universal adhesive

1 | INTRODUCTION

Lithium disilicate reinforced glass ceramic (LDC) was first introduced by Stookey at Corning Glass Works in the 1950s.[1] This ceramic is derived from the SiO_2–Li_2O system and contains up to 70% of fine rod-like $Li_2Si_2O_5$ crystals, combined with a small amount of lithium orthophosphate (Li_3PO_4) crystals. Together, these crystals disperse in a random but uniform distribution to make up the unique glassy matrix.[2] For a long time, this type of ceramic had been available from a single manufacturer in form of a pressable (IPS e.max Press, Ivoclar Vivadent) and a millable CAD/CAM block (IPS e.max CAD).

With the expiration of one of the LDC patents,[3] various other companies introduced their own derivates of the LDC. Current products are available either as "labside" or "chairside" materials. The "labside" materials (IPS e.max Press/CAD or Amber Mill, HassBio, Kangreung, Korea)[4] require crystallization after milling by the end-user. The "chairside" materials (n!ce, Straumann, Basel Switzerland[5]; CEREC Tessera, Dentsply Sirona, Charlotte, NC, USA)[6] already come fully crystallized from the manufacturer and are said to achieve esthetic and mechanical properties, comparable to traditional lithium disilicate.[6]

One of the main advantages of LDC is the possibility of being etched and bonded to dental structures.[7,8] For bonding to happen, the intaglio surface of the LDC should be modified to achieve optimal adhesion to resin-based cements. This can be achieved by two mechanisms: micromechanical interlocking after surface modification by mechanical or chemical means[9] and/or chemical bonding through the application of coupling agents.[10,11]

To obtain chemical adhesion to LDC, silanes and hybrid organic–inorganic compounds should be used and may act as mediators that increase adhesion between different inorganic and organic materials via dual reactivity. These are termed coupling agents, based on their function and substrates. The most frequently used silane-coupling agent is the mono-functional γ-methacryl-oxypropyltrimethoxysilane (or 3-trimethoxysilylpropyl methacrylate). Silanes are effective in increasing bonding by forming siloxane bonds at the interface between the ceramic and the resin.[12,13]

Although all previously mentioned factors are essential for the long-term and predictable clinical outcomes of ceramic restorations, there has been a pressing need for materials that work on both, tooth structure and restoration, which can decrease operation time, diminish errors during the bonding process, but still accomplish adequate bonding.[14] Conventional bonding processes usually comprise numerous steps, such as etching, primer, and adhesive application on the tooth and restoration side.[15] Universal adhesive attempts to address both interfaces at the same time by adding silanes and functional monomers to the adhesive to provide a chemical bond to various substrates (tooth structure, glass ceramics, and oxide ceramics) without the need to any additional coupling agents, as claimed by the manufacturer.[16]

Currently, in dentistry bonding plays a major role to resolve many restorative issues. However, there are many bonding agents presently available to choose from when deciding on a technique and material on various procedures. Although bonding permits the ability for a more cautious restorative method, achieving a strong bond remains to be a challenge in the oral environment. The current study aims to assess the bonding durability to various types of lithium disilicate ceramic as well as to explore the influence of a chemical coupling agent when bonding with a universal adhesive.

The main hypotheses of the study were three-fold: (a) there is no difference in shear bond strength to the four different lithium disilicate reinforced glass–ceramic materials, based on their micro-structure; (b) additional silane application compared to the omission of silane before application of a silane-containing universal adhesive does not influence the bond strength to different lithium disilicate reinforced glass ceramic materials; and (c) artificial aging does not affect the bond strength to different lithium disilicate reinforced glass ceramic materials.

2 | MATERIALS AND METHODS

2.1 | Sample preparation

Four different lithium disilicate reinforced glass ceramic materials (LDC) [IPS e.max CAD (EX), Amber Mill (AM), n!ce (NC), and CEREC Tessera (TS)] were cut into 240 rectangular specimens ($N = 60$ per material), with a thickness of 1.5 mm. The sample size was calculated using G-power (version 3.1.9.6, Heinrich Heine University, Düsseldorf, Germany) with effect size 1.8, power 95% and alpha error 5%, resulting in a sample size of 13 specimens per group. On the non-bonding side of the specimens, all irregularities were removed, and a notch was carved to distinguish it from the bonding side. On the bonding side a 600 grit of silicone paper was used for 30 s to remove any irregularities on the surface and to standardize the surface for all specimens. The list of all materials and their composition used in the current investigation can be found on Table 1.

EX and AM specimens were crystallized using a sintering furnace (Programat CS3 Furnace, Ivoclar Vivadent Schaan, Liechtenstein). Firing parameters followed the respective manufacturer recommendations and differed slightly for both materials. Crystallization of EX occurred at higher temperature (840°C)[17] than that of AM (815°C)[4].

The specimens of each material were then divided into two subgroups ($N = 30$) according to the bonding protocol (silane application vs. no silane, universal adhesive only) and were further subdivided ($N = 15$) according to their artificial aging protocol (non-aged vs. aged).

2.2 | CAD/CAM LDC surface treatment

Prior to bonding procedures, all specimens were thoroughly cleaned by immersion in distilled water in ultrasonic bath for 10 min. The etching time varied among the CAD/CAM LDC and followed the

TABLE 1 Materials used and composition

Material	Composition	Lot no.	Manufacturer
IPS e.max CAD (EX)	SiO_2: 57.0%–80.0%	W37102	Ivoclar Vivadent, Schaan, Liechtenstein
	Li_2O: 11.0%–19.0%	Z018HT	
	K_2O: 0.0%–13.0%		
	P_2O_5: 0.0%–11.0%		
	ZrO_2: 0.0%–8.0%		
	ZnO: 0.0%–8.0%		
	Other and coloring oxides: 0.0%–12.0%		
Amber Mill (AM)	SiO_2: <78%	EBE05MK1101	HassBio, Kangreung, Korea
	Li_2O: <12%		
	Other oxides and coloring: <12%		
n!ce (NC)	SiO_2: 64%–70%	YZ781	Straumann
	Li_2O: 10.5%–12.5%	CRR61	Freiburg, Germany
	Al_2O_3: 10.5%–11.5%		
	Na_2O: 1%–3%		
	K_2O: 0%–3%		
	P_2O_5: 3%–8%		
	ZrO_2: 0%–0.5%		
	CaO: 1%–2%		
	Coloring oxides: 0%–9%		
CEREC Tessera (TS)	$Li_2O_5Si_2$: 90%	16007942	Dentsply Sirona, York, PA, USA
	Li_3PO_4: 5%		
	$LiAlSi_2O_6$ (Virgilite): 5%		
IPS ceramic etching gel	Hydrofluoric acid 4.5%	Z015FK	Ivoclar Vivadent, Schaan, Liechtenstein
Ultra-Etch	35% Phosphoric acid, water, cobalt aluminate blue spinel, glycol, siloxane	BKJKW	Ultradent Products, South Jordan, UT, USA
Silane coupling agent	Methacryloxy propyl trimethoxy silane; isopropyl alcohol	BKLH2	Ultradent Products, South Jordan, UT, USA
Scotchbond universal plus	BPA derivate free dimethacrylate monomers, MDP phosphate monomer, HEMA, Vitrebond copolymer, silica fillers, ethanol, water, mixture of silanes, photoinitiator system, dual-cure accelerator	7061823, 6840217	3M, St. Paul, MN, USA
RelyX universal cement	BPA derivate free dimethacrylate monomers, phosphorylated dimethacrylate adhesion monomers, photoinitiator, amphiphilic redox initiator system, rheological additives, filler, pigments	7602171, 6982138	3M, St. Paul, MN, USA

respective manufacturer's recommendation. EX and NC were etched for 20 s with 4.5% hydrofluoric acid (IPS ceramic etching gel, Ivoclar Vivadent, Schaan, Liechtenstein), whereas AM and TS were etched for 30 s.[18,19] Immediately after HF etching, the etched surface of the CAD/CAM LDC were thoroughly rinsed with distilled water for 60 s and air-dried with oil-free air for 5 s at a distance of 30 mm. After HF etching, the specimens were cleaned with 35% phosphoric acid for 60 s to remove any precipitated silica-fluoride salts,[20] followed by rinsing with distilled water for 60 s. All specimens were then air-dried using an oil-free air and the bonding protocol described was followed the experimental groups.

2.3 | Silane application

For each material, one subgroup ($N = 30$) was treated with silane, while for the other subgroup ($N = 30$) silane application was omitted. For the groups EX, NC, and TS, silane application was performed by spreading one drop of silane (Silane, Ultradent Products, South Jordan, UT, USA) over the bonding surface with scrubbing motion with a microbrush for 10 s.[5,6] For AM, the silane was applied onto the bonding surface with scrubbing motion for 20 s according to the manufacturers' instruction.[4] The silane was then left for 1 min to evaporate. After that, non-evaporated silane was removed with oil-free air.

2.4 | Bonding protocol

Two-hundred and forty composite resin cylinders were fabricated from a nano-hybrid composite (IPS Empress Direct A1E, Ivoclar Vivadent, Schaan, Liechtstein) using a preformed polytetrafluoroethylene mold with an internal diameter of 2.4 mm and a height of 3.0 mm (bonding mold insert, Ultradent, South Jordan, UT, USA). The mold was pressed against a glass slide and then the composite was placed into the mold in two increments using composite instruments; after each increment, the composite was light cured at a distance of 1 mm for 20 s, using a LED curing light (Valo, Ultradent, South Jordan, UT, USA). The surface of the composite cylinder that faced the curing light was marked with a permanent marker.

A universal dental adhesive (Scotchbond Universal Plus, 3M, St. Paul, MN, USA) was applied to the bonding surface of all LDC specimens using disposable microbrushes in a rubbing motion for 20 s, followed by air-thinning for 20 s for evaporation of solvent. The adhesive was left uncured and immediately after that a dual-cure universal resin cement[21] (Rely X universal cement, 3M ESPE, St. Paul, MN, USA) was applied to the unmarked end of the composite cylinder before it was seated on to the middle of the bonding surface of each rectangular LDC specimen. Using a seating device, a standardized weight of 1 kg was applied to the composite cylinder while excess of resin cement was cleaned off with a microbrush, followed by light-curing for 20 s with two polywave LED curing lights (Valo, Ultradent, South Jordan, UT) positioned opposing each other at a distance of 3 mm. Then an air-blocking gel (Sterile Lubricating jelly, Medline, Northfield, IL, USA) was applied around the bonding interface, and the specimens were again light-cured for 20 s from all sides totaling 40 s of photopolymerization. The irradiance of the curing light units was regularly tested using a radiometer (Bluephase Meter II, Ivoclar Vivadent, Schaan, Liechtenstein). The samples were removed from the seating device and rinsed with distilled water to remove the air-blocking gel. Specimens were then stored in separate containers for each group, filled with distilled water, and stored at 37°C in an incubator (5510, National Appliance, Portland, OR, USA).

After bonding, each group was further divided into two sub-sets ($n = 15$) to be tested either after 24 h or after artificial aging. The first sub-set was stored in distilled water for 24 h (non-aged groups: NA). The remaining specimens were subjected to thermal fatigue (aged groups: A).[22–26] Artificial aging was performed by storing the specimens in distilled water at 37°C for 2 months in an incubator and by thermal fatigue using thermo-mechanic cycling (20,000 cycles) in distilled water at temperatures of 5 and 55°C (Thermocycler THE-1100, SD Mechatronik, Westerham, Germany) with 15 s dwell time and 10 s transfer time.[25,27–30]

All specimens were assessed for shear bond strength using a universal testing machine (Model 6596; Instron, Norwood, MA, USA) with a notched-edge blade (Crosshead assembly, Ultradent, South Jordan, UT, USA) at a crosshead speed of 1 mm/min.[31]

After testing SBS, the failure mode was analyzed and categorized as: adhesive at the composite cylinder, adhesive at CAD/CAM material, cohesive in the resin cement, cohesive in CAD/CAM, cohesive in the composite cylinder. For this purpose, a stereomicroscope (Extaro 300, Carl Zeiss Meditec, Jena, Germany) at 20× magnification was used under white light and under fluorescent light. The fluorescent light allowed to distinguish between remnants of the resin cement and composite cylinder due to their difference in fluorescence. The area of failure was recorded, and the obtained image was imported into an image analysis software (Fiji ImageJ, V1.0). The surface area of the different fracture types was measured in pixels and recorded in an Excel spreadsheet. Data was transformed from pixels to percentage by dividing the measured area by the area of bonding surface and then multiplied by 100.

Statistical analysis was performed with statistical software (SPSS 19; SPSS Inc., Chicago, IL, USA). A non-parametric test (Kruskal–Wallis) was used to detect overall differences for: material (EX, AM, NC, and TS), time (24 h vs. 2 months), and silane application (silane adhesive vs. adhesive only). Group-wise comparisons were conducted separately for each material with Mann–Whitney test using Bonferroni correction due to multiple comparisons ($\alpha = 0.001$).

Representative specimens from each type of CAD/CAM lithium disilicate glass–ceramic (EX, AM, NC, and TS) were selected for scanning electron microscopy (SEM) evaluation.[32]

3 | RESULTS

For statistical analysis, an ANOVA model was not supported because of lack of homogeneity (Levene's test $p < 0.05$) and normality (Kolmogorov–Smirnov test $p < 0.05$). Therefore, non-parametric tests were used. Kruskal–Wallis tests were performed for the following variables: material, silane application, and time. Post-hoc comparison using Multiple Mann–Whitney were used to compare data between the different groups. The significance level had to be adjusted due to multiple comparisons to $\alpha = 0.001$.

The mean notched SBS values are displayed in (Table 2). All tested LDC yielded comparable SBS before aging and with additional application of a silane coupling agent. The highest mean SBS was observed for TS (29.08 ± 4.68 MPa) and EX (27.38 ± 7.17 MPa) when additional silane coupling agent had been applied. The lowest mean SBS was recorded for AM (3.01 ± 6.03 MPa), followed by EX (8.75 ± 4.27 MPa) when bonded using universal adhesive alone and after artificial aging. Pre-test failures were observed only for AM without additional silane application, where the specimens debonded during thermocycling aging.

Group-wise comparisons showed that only groups AM and NC were significantly different from each other ($p = 0.0001$). The SBS for all other LDC materials were not significantly different from each other ($p > 0.001$).

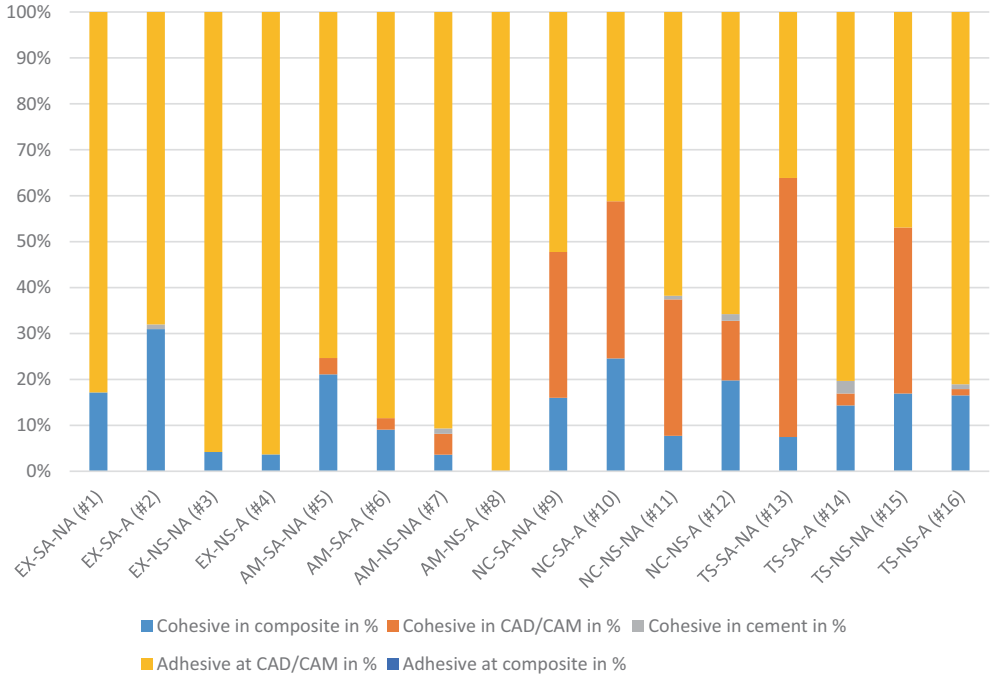
The use of universal adhesive alone, without the application of additional silane coupling agent, revealed a significant decrease in SBS values for all experimental groups ($p < 0.001$).

TABLE 2 Shear bond strength values ± standard deviation in MPa

	Silane		No Silane	
Material	Non-aged	Aged	Non-aged	Aged
IPS e.max CAD	27.38 ± 7.17^{aA}	16.63 ± 5.67^{bA}	20.62 ± 9.74^{abdA}	8.75 ± 4.27^{cA}
Amber Mill	25.94 ± 3.53^{aA}	17.54 ± 8.41^{aA}	17.87 ± 6.99^{aA}	3.01 ± 3.84^{bA}
n!ce	26.40 ± 3.87^{aA}	22.24 ± 7.55^{abA}	24.74 ± 7.48^{acA}	19.77 ± 5.36^{bcB}
CEREC Tessera	29.08 ± 4.68^{aA}	18.91 ± 5.18^{abA}	25.88 ± 6.17^{aA}	16.84 ± 4.20^{bB}

Note: Within same row: Same lower-case letters are not significantly differently from each other. Within same column: Same upper-case letters are not significantly differently from each other.

FIGURE 1 Failure mode analysis



Artificial aging decreased the mean SBS for all experimental groups ($p < 0.001$). For EX and TS, the highest bond strength was achieved for the non-aged specimens when silane was applied as an additional step along with the universal adhesive.

Failure analysis (Figure 1) revealed that EX and AM showed more adhesive failures at the CAD/CAM material than that of TS and NC. A higher frequency of mixed failures was observed to the CAD/CAM LDC additional sintering step is not required by the manufacturer (TS and NC).

The following failure modes were observed: adhesive failure at CAD/CAM material, cohesive in composite, cohesive in ceramic, and cohesive in cement.

Adhesive failure at the bonded interface was the dominant mode of failure in comparison to other types of failures. Cohesive failure in cement was recorded as the least frequent type of failures. Cohesive failures in CAD/CAM LD ceramics were influenced by silane application and the type of ceramic. TS and NC revealed the highest amount of cohesive failures in the ceramic of all tested CAD/CAM lithium disilicate glass–ceramic blocks, with an average percentage of 46.28% and 30.72% respectively. EX showed no cohesive failures (0%), and a low number of cohesive failures were recorded in AM (4.05%).

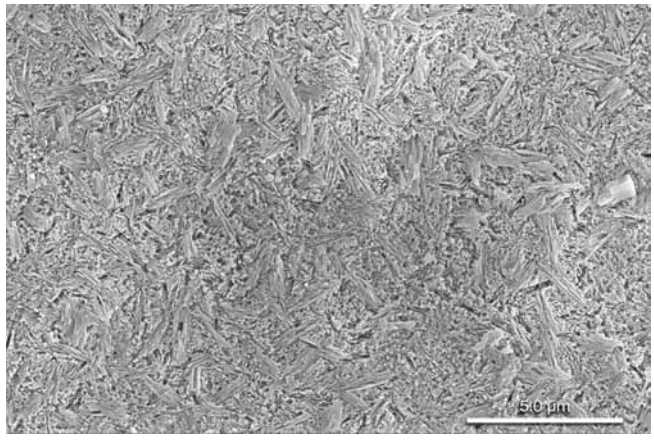


FIGURE 2 Scanning electron micrograph of IPS e.max CAD (magnification 10,000×)

The number of cohesive failures in CAD/CAM LDC significantly reduced after artificial aging, particularly for TS. However, NC sustained a high percent of cohesive failures in CAD/CAM after aging, especially when the silane was applied.

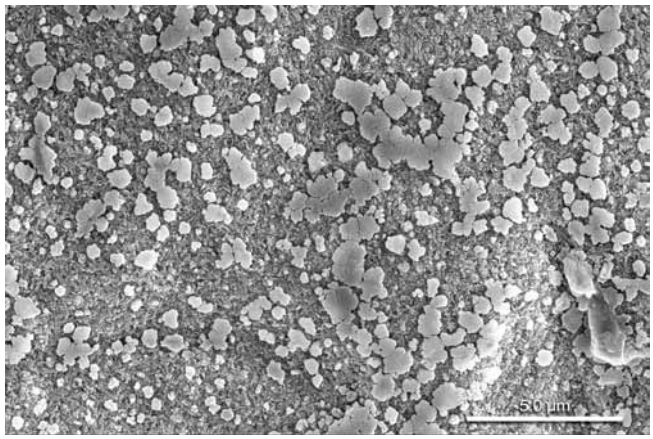


FIGURE 3 Scanning electron micrograph of Amber Mill (magnification 10,000×)

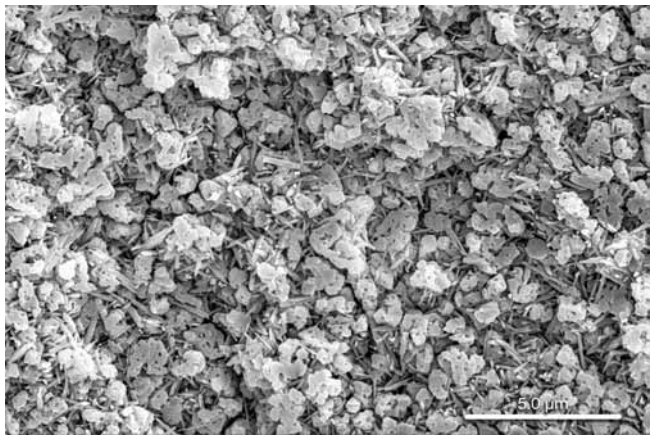


FIGURE 4 Scanning electron micrograph of n!ce (magnification 10,000×)

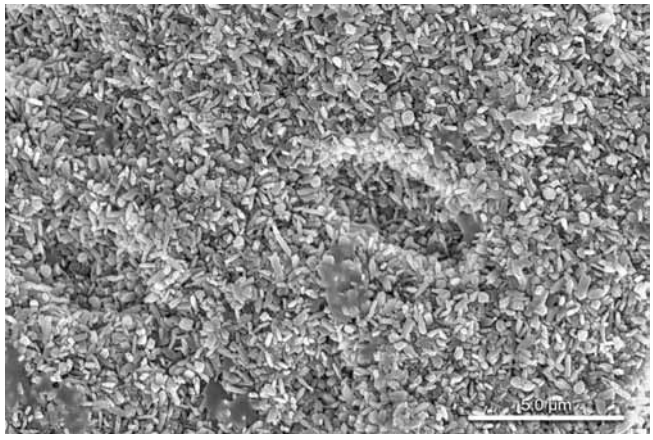


FIGURE 5 Scanning electron micrograph of CEREC Tessera (magnification 10,000×)

3.1 | SEM ultra-structural analysis

After surface treatment conditioning, several ceramics showed numerous microstructures, and surface topographies, which ultimately affect the strength of bond between ceramic and resin-cement.[10]

3.1.1 | IPS e.max CAD

Hydrofluoric etching revealed a dense and homogeneous microstructure of fine-grain needle like lithium disilicate crystals with length of approximately 1.5 μm embedded into a glassy matrix (Figure 2).

3.1.2 | Amber Mill

Hydrofluoric etching exposed a loose microstructure of numerous fine and delicate lithium disilicate crystals with length of approximately 0.2 μm in diameter and areas of apparently unetched glassy matrix (Figure 3).

3.1.3 | n!ce

Hydrofluoric etching revealed loose microstructure of fine-grain needlelike lithium disilicate crystals with length of approximately 0.75 μm into areas of apparently unattached etched glassy matrix (Figure 4).

3.1.4 | Tessera

Hydrofluoric etching revealed loose microstructure of numerous lithium disilicate crystals with length of approximately 0.5 μm as well as lithium aluminum silicate crystals (virgilite) over an etched glassy matrix (Figure 5).

4 | DISCUSSION

The results of this study revealed that bond strength to CAD/CAM lithium disilicate glass ceramic materials is significantly affected by their microstructure, surface treatment, and aging. Hence, the first null hypothesis was rejected. Additional application of silane coupling agent before application of the universal adhesive yielded significantly higher bond strengths than the use of universal adhesive alone, thus the second null hypothesis was also rejected. Aging, by long-term water storage and thermal fatigue reduced the bond strengths to all experimental groups. Thus, the third null hypothesis was also rejected.

All CAD/CAM LDCs revealed significant differences in composition and microstructure as seen in the SEM micrographs. The findings of this are in agreement with a previous report.[32] Consequently, the etching pattern created by the application of hydrofluoric acid is different for all tested ceramics, resulting in differing bond strength values. Etching efficiency of hydrofluoric acid depends on several

factors such as: concentration, etching time, temperature, and dilution of the acid solution.[18,22] All experimental groups revealed differences in the size of the lithium disilicate crystals. In EX, lithium disilicate crystals were densely embedded into the glass ceramic matrix after HF etching,[32] supporting the finding that no cohesive failure was observed for this material. AM exhibited higher numbers of adhesive failures than other materials. In addition, pre-testing failures were observed for half of all aged specimens for AM. Areas of apparent unetched glass matrix may contribute to the high number of adhesive failures. Conversely, NC and TS exhibited the highest number of cohesive failures in the ceramic. This fact could be related to the presence of loose distribution of the lithium disilicate crystals (NC) and loose distribution of the lithium disilicate crystals and virgilite (TS) which were not fully embedded into the glassy matrix. Additionally, areas of etched glass matrix appeared to be unattached from the main glass matrix. Both occurrences may explain the cohesive failure within the ceramic for both materials. The size of the lithium disilicate crystals in all LDCs does not appear to interfere with the resin permeation into the etched microstructure of the ceramics. Overall, the tested LDCs yielded adequate adhesive properties after HF etching; however, bonding was significantly affected by silane application.

Long-term success of CAD/CAM glass–ceramic restorations is highly determined by the adhesive procedures used. As such, the application of a silane coupling agent plays an essential role to bond to glass-based ceramic. Silane acts as mediators that increase adhesion between dissimilar inorganic and organic materials via dual reactivity. Silane forms siloxane bonds at the interface between the ceramic and resin cement. A silane solution of organo-functional trialkoxysilane esters can copolymerize with the remaining C═C bonds of the resin cement. Notably, the silane's hydrolyzed alkoxy groups can react with hydroxyl groups of the lithium disilicate and glass matrix to form covalent siloxane bonds. After the application of the silane three different structures are observed at the interphase[12,23]: The outermost layers comprise of small oligomers which are physically absorbed to the glass so that they can be easily washed away by either organic solvents or water at room temperature. The second region is nearer to the glass surface. It consists of oligomers similar to the outer layers, apart from a few siloxane bonds connecting the oligomers and is hydrolyzable by hot water. In the region close to the glass, uniformity and extent of cross linking of the layers increases and a regular 3D network is formed, which is quite hydrolytically stable. Only this last layer of coupling agent on the surface is critical for stability and bond strength to ceramic.[13] All experimental groups yielded adequate bond strengths when silane was applied. The wettability of the silane appeared to be appropriate for most of the tested LDC. AM displayed some resistance for silane wettability, most likely caused by low critical surface tension of glass phase,[33] which could also explain the lower SBS and the high amount of pretesting failures obtained for this experimental group. Thus, bonding to lithium disilicate glass ceramic still requires etching with hydrofluoric acid followed by the application of a silane coupling agent to ensure a chemical interaction between the resin cement and the ceramics by forming strong siloxane linkages.[11]

One of the latest trends in adhesive dentistry has been to simplify bonding procedures and reduce the application steps by incorporating silane into universal dental adhesives.[8] The silane-containing universal adhesive (Scotchbond Universal Plus, 3M) tested in this study is characterized by the presence of aminosilane and by being Bis-GMA monomer free, which may interfere with the condensation between silane's silanol groups and the hydroxyl groups of ceramics. The presence of a pre-hydrolyzed silane (aminosilane) helps to stabilize the silane by intramolecular hydrogen bonding.[23] Yet, the amount of silane in its composition has not been reported by the manufacturer and clearly was insufficient to provide long-term bond strength to most of the LDC tested. Hydrophilic monomers and solvents found in the universal adhesive are more susceptible to water sorption and hydrolytic degradation.[24] Another study reported that when silane is incorporated in a universal adhesive, it does not seem to provide the same adhesive strength as when a silane agent is used separately. This is perhaps because the acidic MDP included in universal adhesives neutralizes the silane, rendering it unstable over time.[25] Therefore, silane may be practically ineffective when contained in universal adhesives. This can explain the reduced bond strength values observed with the experimental groups where universal adhesive was used alone. Interestingly, less accentuated decrease of bonding was observed for TS and NC after aging could be due to hydrophilic-hydrophobic capacity of both resinous materials and adhesive systems, due to the variation in composition allows greater or lesser water absorption. Therefore, the application of a silane coupling agent is essential for long-term bonding to novel LDC and, at the moment, cannot be substituted by a universal adhesive alone.[19,25]

Long-term water storage is the most commonly applied artificial aging technique. It allegedly simulates the wet conditions that a bonded interface is exposed to, in the oral cavity. To determine the bonding performance and stimulate the physiological aging, water storage for 2 months in combination with thermocycling which involves a repeated alternation of temperatures,[29] was performed to mimic the intra-oral environment.[27,30] It has been shown that lithium disilicate specimens bonded using a universal adhesive showed a reduction in shear bond strength after being subjected to 500 thermocycles,[21] which is the minimum recommended by ISO.[7] Other studies considered the ISO thermal fatigue standards not enough to represent a clinical reality.[26] The regimen for thermocycling in this study was 20,000 cycles which equal 2 years of clinical function.[27,30] In the present study, the bond strength was significantly influenced by water storage and thermal fatigue. The findings showed that hydrolysis of the bonded interface occurred leading to deterioration of the resin interface most likely because of plasticizing effect of water infiltration into the resin polymer.[23] This can ultimately lead to breaking of the resin polymer covalent bonds, leading to loss of the resin mass, monomer leaching, and bond degradation. Therefore, the bonding interface of LDC can be significantly affect by water degradation for both silane and silane-containing universal adhesive experimental groups. Nevertheless, clinically, other factors, for example, stresses due to masticatory forces, thermal changes, and chemical degradation through enzymes, bacteria, toxins, might play an additional role in the degradation of LDC adhesive interface.

Further studies are necessary to evaluate differences in etching time and effect of different resin cements on bonding to the different LDC materials.

5 | CONCLUSION

Based on this investigation, the following conclusions can be drawn:

1. Bond strength is highly affected by the CAD/CAM lithium disilicate ceramic materials used and their microstructures.
2. The additional application of silane after hydrofluoric acid etching is still essential for all LDC CAD/CAM materials to obtain long-term bonding, irrespective of the presence of silane in the universal adhesive.
3. Water degradation can significantly affect long-term bonding to such LDCs.

DISCLOSURE

The authors do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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How to cite this article: Alhomuod M, Phark J-H, Duarte S Jr.. Bond strength to different CAD/CAM lithium disilicate reinforced ceramics. *J Esthet Restor Dent*. 2023;35(1):129-137. doi:10.1111/jerd.12984

Received: 3 August 2022 | Revised: 24 November 2022 | Accepted: 26 November 2022

DOI: 10.1111/jerd.12996

CLINICAL ARTICLE

WILEY

Facial implant gingival level and thickness changes following maxillary anterior immediate tooth replacement with scarf-connective tissue graft: A 4–13-year retrospective study

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Abstract

Objective: A scarf-shaped connective tissue graft can be placed at the facial and proximal aspect of the peri-implant soft tissue zone during immediate implant placement and provisionalization (IIPP) procedures in the esthetic zone to optimize implant esthetics without the need of flap reflection. This retrospective study evaluated soft tissue stability after scarf-connective tissue graft (S-CTG) in conjunction with IIPP procedures in the esthetic zone.

Materials and Methods: Patients who received IIPP with S-CTG with a minimum 1-year follow-up were evaluated. Mid-facial gingival level (MFGL) change and mid-facial gingival thickness (MFGT) change were measured and compared at the pre-op (T0), IIPP + S-CTG surgery (T1), follow up appointment with MFGT measurement (T2), and latest follow-up appointment (T3). Implant success rate and graft necrosis were also recorded.

Results: A total of 22 IIPP and S-CTG procedures in 20 patients were evaluated in the study. After a mean follow-up of 8.2 years (3.9–13.4) (T3), all implants remained osseointegrated (22/22 [100%]), with statistically insignificant mean midfacial gingival level change of −0.19 mm (−1.5 to 0.8). Statistically significant difference in mid-facial gingival thickness (MFGT) was noted (2.5 mm [1.8–3.5 mm]) after a mean follow-up time (T2) of 2.3 years (1–8.6) when compared with MFGT at baseline (1.1 mm [0.6–1.3 mm]) (T1). Necrosis of S-CTG during initial healing phase was noted in 9% (2/22) of the sites.

Conclusions: Within the confines of this study, scarf-connective tissue graft at time of immediate implant placement and provisionalization can thicken the gingiva and maintain the gingival level at the critical soft tissue zone.

Clinical Significance: Managing the soft tissue zone is as important as that of the hard tissue zone for peri-implant esthetics. Connective tissue graft is one of the

methods that can enhance the final esthetic outcomes. This retrospective study has demonstrated that Scarf-CTG technique is an effective treatment modality to maintain soft tissue stability.

KEYWORDS

contoured connective tissue graft, esthetics, hard tissue zone, immediate implant placement, immediate provisionalization, immediate tooth replacement, scarf-connective tissue graft, soft tissue zone

1 | INTRODUCTION

Maxillary anterior single immediate implant placement and provisionalization (IIPP) has been advocated since 1998,[1] and the success and viability of this treatment have been validated over the years.[2–4] The goal for IIPP is not only to shorten treatment time and eliminate the need of a removable provisional prosthesis, but also, to maintain the facial vertical and horizontal gingival profile. The facial gingival profile of an intact anterior extraction socket comprises of two distinct zones: one with underlying bone support (hard tissue zone) and one without (soft tissue zone).[5] The soft tissue zone spans from the facial free gingival margin to the underlying bony crest, and the area beyond that point apically is considered the hard tissue zone. While they co-dependently exist, the soft and hard tissue zones respond differently to surgical insults and, therefore, demand different management for their preservation and/or reconstruction. Methods such as grafting into the implant-to-socket wall gap,[6] hard and soft tissue contour grafting facial to the bony plate,[7] and socket shield technique[8] have been advocated to maintain the hard tissue zone. For the soft tissue zone, contoured connective tissue graft (C-CTG) as well as the dual zone grafting procedures have been suggested.[5,9–11]

Numerous studies have shown the benefits of C-CTG spanning from soft to hard tissue zone apicocoronally to maintain the esthetic facial contour at time of IIPP.[12–14] Unfortunately, flap refection or tunneling procedure is required for the placement of C-CTG. This results in the separation of the periosteum from the facial bony plate, compromising the blood supply and increasing risk of facial bony plate resorption.[15] The question is whether a less invasive procedure involving a scarf shaped connective tissue graft at the soft tissue zone only, without flap reflection, would be as effective as C-CTG, with flap reflection, in maintaining the soft tissue contour.

This retrospective study was to evaluate the implant success rate as well as the vertical and horizontal tissue changes at the soft tissue zone after placing scarf-connective tissue graft (S-CTG) at the facial and proximal aspect of the peri-implant soft tissue zone simultaneously with IIPP.

2 | MATERIALS AND METHODS

This study was approved by the Institutional Review Board of Loma Linda University and was conducted in the Center for Implant Dentistry, Loma Linda, California. Treatment records were evaluated for patients who received flapless maxillary anterior (#6–11) single or multiple adjacent IIPP with gap grafting with xenograft (Bio-Oss, Geistlich Pharma North America, Princeton, NJ) or combination of xenograft (Bio-Oss) and allograft (Puros, Zimmer Biomet, Palm Beach Gardens, FL) in conjunction with simultaneous S-CTG with minimally 1-year follow-up between January 2007 to December 2021. The cases included must have had intact facial bone following tooth extraction and applicable data at pre-op (T0), at tooth extraction, IIPP and S-CTG (T1), at last follow-up with midfacial gingival thickness measurement (T2), and /or at the latest follow-up (T3) (Figure 1).

2.1 | Data collection

2.1.1 | Implant success rate

The implant was considered a failure if there was significant radiographic marginal bone loss (>2 mm), peri-implant radiolucency, mobility, pain and/or discomfort between T1 and T3.

2.1.2 | Mid-facial gingival thickness

The mid-facial gingival thickness (MFGT) and its changes at and between T1 and T2 was evaluated by direct measurement using tension free caliper[16] to the nearest 0.1 mm at approximately 2 mm apical to the free gingival margin on the midfacial aspect of the extraction socket. The gingival phenotype was considered thin if the measurement was less than or equal to 1.1 mm, and thick if measurement was greater than 1.1 mm.

2.1.3 | Mid-facial gingival level change

The midfacial gingival level (MFGL) was recorded with photos taken at 1:1 magnification at right angle to the failing tooth (T0), and the latest follow-up with the definitive implant crown (T3). The measurement was made at $\times$10 magnification to the nearest 1 mm. The line connecting the MFGL of the two adjacent teeth was used as reference line.[2] The changes in the MFGL of the implant crown were evaluated by measuring the distance from the reference line at the respective time interval.

FIGURE 1 Appointment timeline

2.1.4 | Presence or absence of cross sling suture

The presences or absence of cross sling suture placed to secure the S-CTG between the free gingival margin of the extraction socket and the provisional at time of IIPP and S-CTG was recorded (T1).

2.1.5 | Presence or absence of S-CTG necrosis

Necrosis of the S-CTG during the healing phase (between T1 and T3) was noted, and the necrosis was categorized as either partial or complete.

2.2 | Statistical analysis

Means and standard deviation were calculated for each clinical parameter at each time interval where applicable. A rank-based repeated measures ANOVA was conducted to compare midfacial gingival thickness at T1 and T2. A Wilcoxon W procedure was conducted to evaluate the midfacial gingival level change between T0 and T3. Statistical significance was denoted when $p < 0.05$.

2.3 | Case 1: IIPP and S-CTG clinical procedures

2.3.1 | Immediate implant placement

A 38-year-old female patient presented with a fractured right central incisor (#8). Clinical evaluation showed good oral hygiene with slight facial gingival recession of the failing tooth (Figure 2). Radiographic evaluation showed peri-apical radiolucency (Figure 3A) and a Class I sagittal root position with sufficient bone for immediate implant placement procedure (Figure 3B).[17] Bone sounding of the tooth revealed intact facial bone and normal gingiva-to-osseous relationships (Figure 4).[18] After treatment options were presented, the patient elected to replace the failing #8 with IIPP and simultaneous S-CTG.

A composite resin provisional shell (Gradia, GC America, Alsip, IL) was fabricated prior to the surgery. After anesthesia, the failing tooth was extracted without flap reflection. After the integrity of the facial bone plate was verified with a periodontal probe, an implant was immediately placed (Figure 5) according to the following guidelines[19]:

Apico-coronal implant position: Implant platform was positioned 3–4 mm apically from the pre-determined facial gingival margin of the definitive crown.

Bucco-lingual implant position: Implant was placed palatally, leaving at least 1.5 mm of gap distance between implant and the facial bony plate of the extraction socket, and about 1 mm gap between implant and the palatal bone (Figure 6).

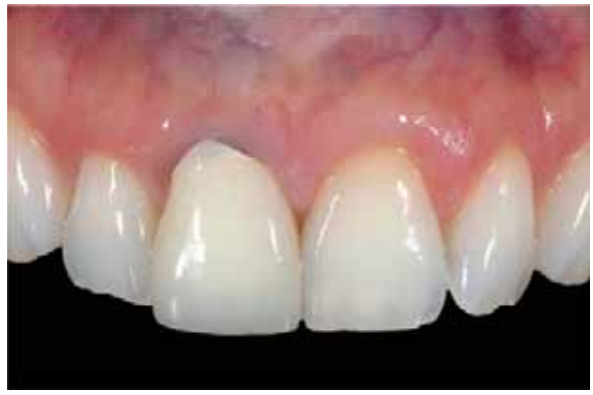

FIGURE 2 Preoperative facial view of the failing right central incisor (#8)

Sagittal implant position: Implant was placed aiming at the incisal edge of the definitive crown.

Small size particle xenograft (Bio-Oss) was condensed into the implant-socket gap with sufficient force to ensure no void was present within the gap (Figure 7). The prefabricated provisional shell was relined (Revolution composite resin, Kerr, Pomona, CA) onto the prepared prefabricated zirconia abutment (Nobel Procera abutment, Nobel Biocare, Yorba Lina, CA). The facial sub-critical emergence profile[20] of the provisional restoration was under-contoured (concave) and polished to create space and for the S-CTG (Figure 8A).

2.3.2 | Scarf-connective tissue graft harvesting and placement

A rectangular shaped subepithelial connective tissue graft was harvested from the lateral palate.[21] The S-CTG was then trimmed into a curved band that followed the height and length of the facial soft tissue zone from the mesial interproximal to distal interproximal aspect of the socket, and with a minimal thickness of 1.5 mm (Figure 8B).[22] It is not necessary to extend the S-CTG circumferentially around the socket, since the palatal masticatory tissue tends to be thick and has little impact on esthetics. After the prepared prefabricated zirconia abutment was hand tightened onto the implant, the S-CTG was placed against the buccal marginal soft tissue wall (within the soft tissue zone) of the immediate implant extraction socket with gap grafting before the provisional restoration was cemented (Temp-bond clear, Kerr, Pomona, CA) onto the abutment

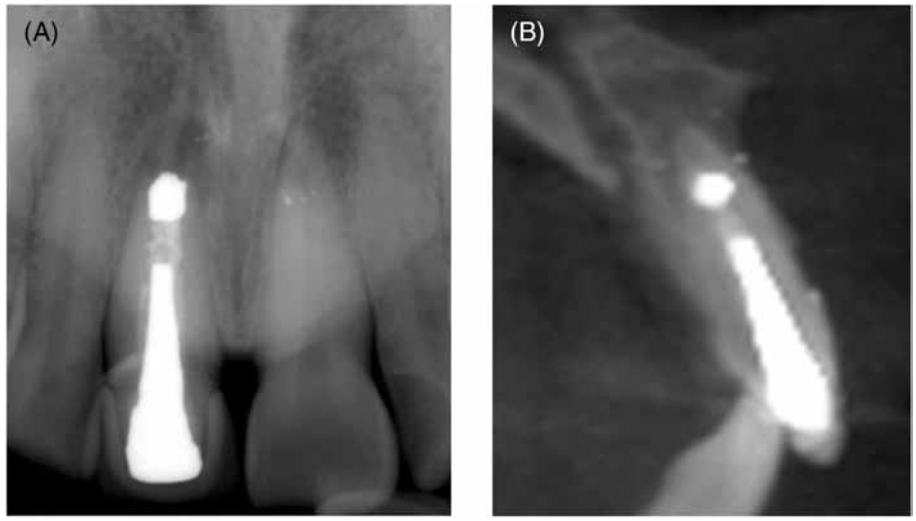

FIGURE 3 (A) Preoperative periapical radiograph of failing right central incisor (#8). (B) Sagittal CBCT view of failing right central incisor with class 1 sagittal root position

FIGURE 4 Bone sounding measurement of 3 mm at mid-facial aspect of right central incisor showing intact facial bone

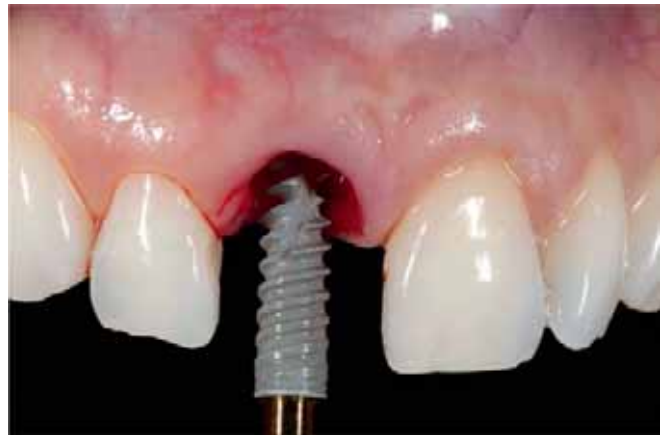

FIGURE 5 A 3.5 × 13 mm implant was placed immediately into the socket

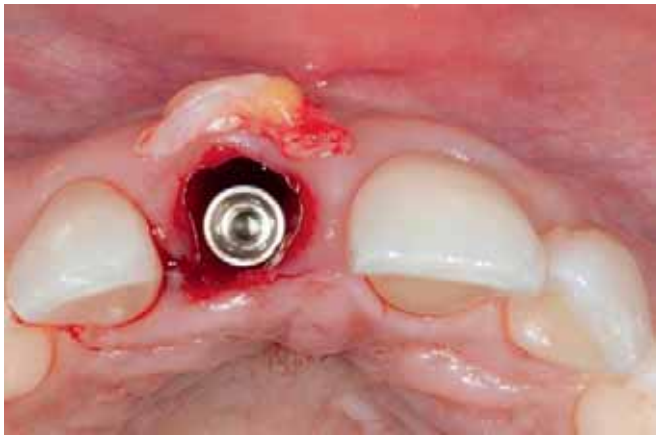

FIGURE 6 The implant was placed palatal to the socket leaving a minimal facial gap of 1.5 and 1.0 mm gap palatally. A Scarf-CTG (S-CTG) was harvested from the lateral palate to be placed at the soft tissue zone

FIGURE 7 A 50/50 mixture ratio of small particle xenograft and allograft was placed within the gap between implant and the extraction socket

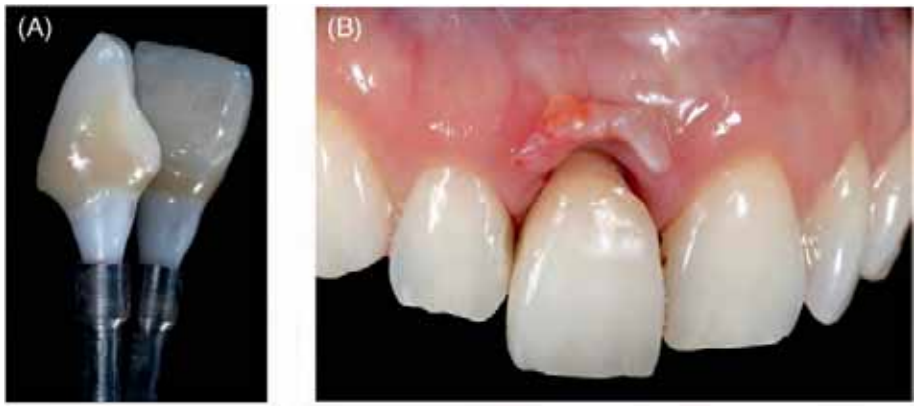

FIGURE 8 (A) The facial and interproximal emergence profile of the subcritical area of the provisional-abutment complex was contoured in a concave manner to allow space for the S-CTG. (B) The harvested CTG was trimmed and shaped into scarfed shape with a minimal thickness of 1.5 mm following the height and length of the facial soft tissue zone from mesial interproximal to distal interproximal aspect of the socket.

FIGURE 9 (A) Incisal view showed Zr abutment with polyvinyl siloxane blocking screw access channel to prevent cement from getting into the abutment screw head during implant provisional cementation. The S-CTG was then placed at soft tissue zone spanning from mesial interproximal to distal interproximal aspect of the socket. (B) The relined provisional was cemented onto the pre-fabricated Zr abutment. (C) Periapical radiograph immediately following IIPP and S-CTG

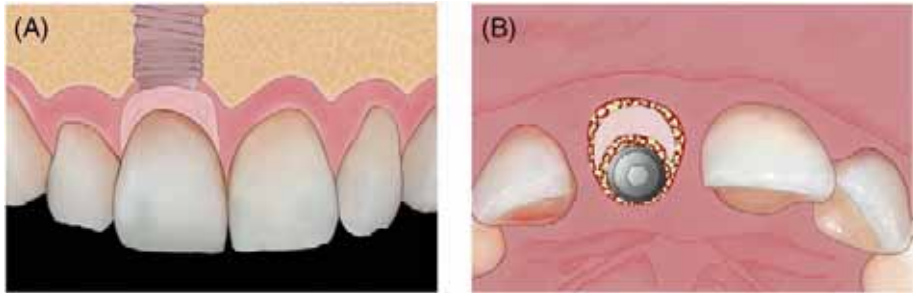

FIGURE 10 (A) Illustration showing facially the location the S-CTG was placed. (B) Illustration showing incisally the location the S-CTG was placed

(Figure 9A–C). The CTG intimately and precisely covered the facial sub-critical emergence profile of the provisional restoration along the soft tissue zone like a scarf wrapping around a neck, thus the term "Scarf-CTG" (Figure 10A,B).

2.3.3 | Postoperative instructions

Appropriate antibiotics and analgesics were prescribed for post-operative use. The patient was instructed not to brush the surgical site for 2 weeks, but rinse gently with 0.12% chlorhexidine gluconate (Pride, Procter & Gamble, Cincinnati, OH) and was placed on a liquid diet for 2–3 days. Soft diet was recommended for the duration of the healing phase (3 months) and the patient was advised against functioning on the surgical site.

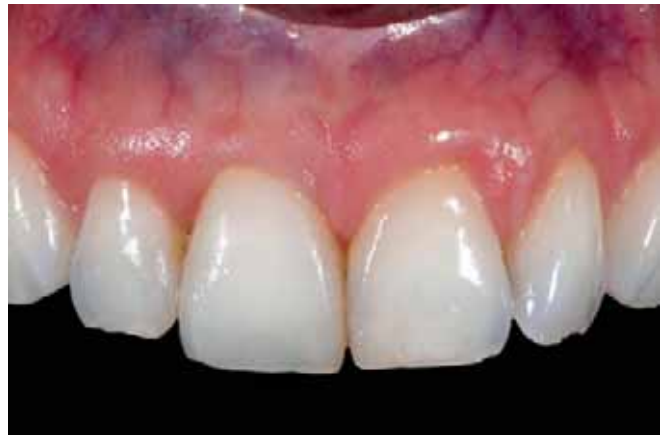

FIGURE 11 Facial view of the implant provisional 10 months following IIPP and S-CTG

FIGURE 12 (A) Facial view 1 month after cementation of the definitive implant crown. (B) Incisal view 1 month after cementation of the definitive implant crown

FIGURE 13 (A) Facial view at 12 years following IIPP and S-CTG showed well maintained peri-implant gingival architecture. (B) Incisal view 12 years following IIPP and S-CTG showed well maintained facial gingival profile. (C) Periapical radiograph showing stable proximal bony architecture 12 years after IIPP and S-CTG)

2.3.4 | Definitive restoration

The definitive implant impression was made 10 months following IIPP and S-CTG (Figure 11). At 2 years, the definitive zirconia abutment was placed and torqued to 35 N cm (manufacturer's recommendation), and the final implant crown was cemented (Rely-X Unicem) (Figure 12A,B). Clinical and radiographic follow-up at 12 years (Figure 13A–C) showed that the facial gingival contour had been stable and well-maintained vertically and horizontally with IIPP and S-CTG.

2.4 | Case 2: IIPP and S-CTG necrosis

A 28-year-old female was present with oblique fracture of right lateral incisor (#7) (Figure 14). Scarf-CTG and IIPP was performed (Figure 15A,B) without cross sling suture. Partial necrosis of S-CTG was noted at 2 weeks following the surgery (Figure 16). The definitive implant crown was placed with minimal midfacial recession at follow-up (Figure 17A,B).

FIGURE 14 Preoperative facial view of the failing right lateral incisor (#7)

3 | RESULTS

Twenty patients (14 female, 6 male) with a mean age of 41.1 years old (25–64) underwent IIPP and S-CTG. A total of 22 implants (21 Nobel Active, 1 Nobel Perfect, [Nobel Biocare, Yorba Linda, CA]) were evaluated (1 implant in 18 patients, 4 implants in 2 patients placed adjacent to each other), which included 18 central incisors and 4 lateral incisors. Tooth failures were attributed to facture ($n = 7$), endodontic failures ($n = 7$), periodontal disease ($n = 5$), and root resorption ($n = 3$). All 22 implants had the implant socket gap grafted with either xenograft (Bio-Oss) [5/22] alone, or a combination of xenograft (Bio-Oss) and allograft (Puros, Zimmer Biomet, Palm Beach Gardens, FL) [17/22]. At T1, direct measurement showed thin gingival phenotype in 13 implant sites, whereas thick gingival phenotype was found in nine implant sites. Cross sling sutures were placed in six sites (27.2% [6/22]) at T1.

At T3, after a mean follow-up of 8.2 years (3.9–13.4), all implants remained osseointegrated with an overall implant success rate of 100% (22/22). There was statistically insignificant mean midfacial gingival level change at T3 (−0.19 mm [−1.5–0.8]) comparing with baseline (T0). The mean MFGL change at T3 is similar among the 13 thin phenotype sites (−0.18 mm [−1.5–0.8]), and the 9 thick phenotype sites (−0.19 mm [−0.7–0.2]) (Table 1).

FIGURE 15 (A) Right lateral incisor was extracted, and immediate implant was placed. (B) Pre-fabricated abutment placed and Scarf-CTG was harvested

FIGURE 16 Partial necrosis of S-CTG was noted at 2 weeks following the surgery

The mean MFGT was 1.1 mm (0.6–1.3 mm) at T1 and 2.5 mm (1.8–3.5) at T2 after a mean follow-up time of 2.3 years (1–8.6) (Table 1). This represented a mean MFGT gain of 1.4 mm with S-CTG grafting. After adjustment for follow up time, the MFGT at T2 (mean = 2.46), 95% CI (2.28, 2.65) was statistically significantly greater ($p < 0.001$) than it was at T1 (mean = 1.06), 95% CI (0.962, 1.17). The MFGT at T2 ranges (1.8–3.5 mm) showing all 22 implant sites have been converted to thick gingival phenotype after Scarf-CTG.

Two of 22 (9%) sites had necrosis of the Scarf-CTG (1 partial, 1 complete necrosis) within 2 weeks post-surgery. It is interesting to note, neither of the Scarf-CTG necrosis sites had cross sling suture placed at free gingival margin of the extraction socket at surgery. In additional, neither of the sites had significant MFGL change at T3 (partial necrosis [−0.2 mm], complete necrosis [0 mm]).

4 | DISCUSSION

Facial gingival recession (−0.3 to −1.1 mm) has been reported following IIPP procedures.[23,24] Thin gingival phenotype has been associated with even greater facial implant tissue recession over time (−1.5 mm).[17] Because of that, C-CTG at both hard and soft tissue zone have been advocated for IIPP procedures and had shown to minimize facial gingival recession (−0.05 to 0.25 mm).[12,25,26] In this study, despite isolating the Scarf-CTG within the soft tissue zone and not extending it apically into the hard tissue zone, there was only minimal overall mean MFGL change at T3 (−0.19 mm [−1.5–0.8]) suggesting that minimally invasive Scarf-CTG can be equally effective in maintaining vertical tissue height long term (8.2 years [3.9–13.4]).

While maintaining soft tissue topography is important, increasing thickness of the peri-implant soft tissue zone is also crucial as the naturally existing gingival thickness, more often than not, is insufficient to mask most underlying restorative/implant materials.[16,27,28] The facial gingival thickness of maxillary anterior teeth has been reported to range between 0.7 and 1.5 mm.[16] Interestingly, one study noted >2.0 mm of tissue thickness is needed to mask underlying zirconia restorative material.[28] Although it has been reported an increase in peri-implant free gingival tissue thickness after IIPP without connective tissue graft by undercontouring the facial emergence profile of the prosthesis,[16] this increase is still considered to be inadequate to mask the underlying restorative materials.[28] On the other hand, when C-CTG was performed in conjunction with IIPP, the resulting gingival thickness has been shown to be adequate in concealing various implant restorative materials.[27] Numerous studies have since been conducted and reached the same conclusion regarding effectiveness of C-CTG at time of IIPP.[12,25,26,29–31] In this study, the mean MFGT at T2 (2.5 mm [1.8–3.5]) after a mean follow-up time of 2.3 years, demonstrating the effectiveness of Scarf-CTG in thickening the facial gingiva. Furthermore, the comparable mean MFGL change for both thin (−0.18 mm [−1.5–0.8]) and thick (−0.19 mm [−0.7–0.2]) phenotype group reported in this study, suggested the important consideration of Scarf-CTG in thin gingival phenotype in IIPP procedures.

The survival of the connective tissue grafts depends on graft vascularization and stabilization.[32] The size of the connective tissue grafts dictates the size on vascular bed needed. While studies have shown the benefit of C-CTG spanning from soft to hard tissue zone to maintain esthetic contour at the time of IIPP,[12–14] flap refection or tunneling procedure is required for the placement of oversized C-CTG to provide adequate vascularization. This results in the separation of the periosteum and the facial bony plate, compromising the blood supply and subsequently increasing the risk of facial bony plate resorption. This shows a cause-effect loop relationship of flap refection to accommodate for the oversized C-CTG, and placement of an oversized C-CTG to compensate for facial bone resorption due to flap reflection. Oversized C-CTG can also increases the morbidity of the donor site.

The Scarf-CTG, which follows the height and length of the facial soft tissue zone with thickness of approximately 1.5 mm, is relatively small. During IIPP, the S-CTG receives adequate vascularization from the plasma elements originating from the organized blood clot

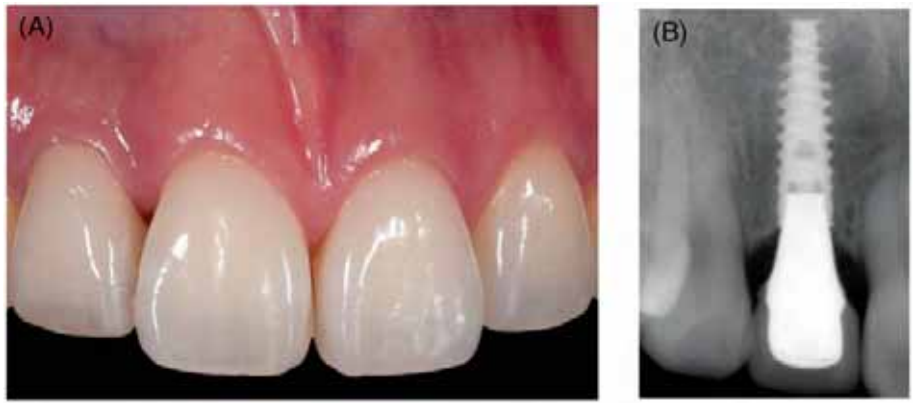

FIGURE 17 (A) Facial view at 4 years following IIPP and S-CTG showed minimal recession. (B) Periapical radiograph showing stable proximal bony architecture 4 years after IIPP and S-CTG)

TABLE 1 Midfacial gingival level and thickness related to study time

	Follow-up appointment					
	T1 (time of surgery)		T2 (tissue thickness measurement Follow-up)		T3 (latest follow-up)	
	Mean	Range	Mean	Range	Mean	Range
Time duration (years)			2.3	1–8.6	8.2	4–13.4
MFGT (mm)	1.1	0.6–1.3	2.5	1.8–3.5		
ΔMFGL (mm)					−0.19	−1.5 – 0.8

Abbreviations: MFGT, mid-facial gingival thickness; MFGL, mid-facial gingival level.

formation from the extraction socket underneath[33–35] and the socket marginal soft tissue wall. It has been suggested that removal of peripheral epithelium circumferentially within the socket marginal wall may further enhance blood supply to the graft,[36] ensuring its survival. Stabilization of S-CTG is achieved by its intimate contact between facial socket marginal wall and the provisional restoration without the need of suturing. The facial and interproximal aspects of the subcritical area of the provisional crown must be under-contoured to create a concave surface that fits intimately to the S-CTG to seal the entrance of the extraction socket preventing exposure of the S-CTG, but with minimal pressure. Excessive/undue pressure can lead to graft exposure and/or S-CTG necrosis. The benefit of S-CTG during IIPP is that this technique is not only minimally invasive, but also the amount of recession noted is inconsequential in the event of necrosis, since it is isolated within the soft tissue zone without flap reflection. In this study, despite 9% (2/22) of the S-CTG necrosed during healing, neither of the 2 S-CTG necrosis resulted in significant facial gingival recession (partial necrosis recession [−0.2 mm], complete necrosis recession [0 mm]). This is similar to the C-CTG necrosis rate reported in other studies with IIPP (20%),[26,37] immediate implant placement (10%),[38] and on root coverage (30%)[39] procedures. It is interesting to note that despite S-CTG necrosis reported in this study, minimal mean midfacial gingival level changes were noted (−0.1 mm). This minimal impact on MFGL change has also been reported[37–39] after C-CTG necrosis except with one study,[26] in which a greater mean recession 1.25 mm was shown. Scarf-connective tissue graft necrosis may be caused by graft exposure and/or presence of unremoved adipose tissue on the graft. In this study, cross sling suture was utilized at socket entrance in 27.2% (6/22) of the cases when graft exposure may be a concern. It is interesting of note that neither of the two necrosis in this study had cross sling suture placed. Therefore, it may be beneficial to place cross sling sutures when under contouring the facial and proximal subcritical contour of the provisional alone is not sufficient to contain the S-CTG. Besides, adipose tissue remained in the S-CTG can act as a barrier both to diffusion and vascularization,[33] increasing risk of graft necrosis.

5 | CONCLUSIONS

Within the confines of this study, scarf-connective tissue graft at time of immediate implant placement and provisionalization is a noninvasive technique and can thicken facial gingiva and maintain the gingival level at the critical soft tissue zone, providing that the implant is placed at the correct position and bone graft materials are placed into the implant socket gap.

ACKNOWLEDGMENTS AND DISCLOSURE

The authors have no financial interests in any of the products mentioned in the manuscript and would like to thank Dr. Udochukwu Oyoyo for statistical analysis and Katsuhiro Hatate for fabrication of the definitive restorations.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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How to cite this article: Kan JYK, Yin S, Rungcharassaeng K, Zucchelli G, Urban I, Lozada J. Facial implant gingival level and thickness changes following maxillary anterior immediate tooth replacement with scarf-connective tissue graft: A 4–13-year retrospective study. *J Esthet Restor Dent*. 2023;35(1): 138-147. doi:10.1111/jerd.12996

Received: 19 December 2022 | Accepted: 20 December 2022
DOI: 10.1111/jerd.13006

CLINICAL ARTICLE

WILEY

Transmucosal abutments in the esthetic zone: Surgical and prosthetic considerations

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Abstract

Objective: This article describes an updated step-by-step protocol for transmucosal abutment selection and treatment sequencing after immediate implant placement in the esthetic zone.

Clinical Considerations: Current surgical and prosthetic concepts strive to preserve hard and soft-tissues to provide optimal esthetics at the implant-abutment interface. Consequently, restoring implants in the esthetic zone with transmucosal abutments presents a great challenge and must take into consideration implant depth, angulation, and bucco-lingual position as well as transmucosal height and space for an optimized emergence profile of the restoration and the dimensions of the anterior tooth to be restored. The proper selection of the type, shape, and dimensions of implant components and connections, determined by the product portfolio offered by the implant manufacturer, play a critical role in the ability to adequately address these challenges. This article provides an update on surgical and prosthetic workflows for single implant restorations in the esthetic zone.

Conclusions: Following esthetic, mechanical, and biologic principles, the long-term success of implant-supported restorations in the esthetic zone is directly correlated to proper execution and sequencing of surgical and prosthetic treatment steps, especially after immediate implant placement. These steps must be critically assessed based on the current scientific evidence to achieve the desired clinical outcomes on a predictable and consistent basis.

Clinical Significance: Selection of surgical and prosthetic treatment protocols to achieve ideal esthetic outcomes and emergence profiles in implant dentistry is often a great challenge, not only determined by technical and clinical skills of the provider but also by the type and dimensions of implant components and connections offered by the manufacturer. Following certain decision-making principles and workflows are key for clinical success with implant-supported restorations after immediate implant placement the esthetic zone.

KEYWORDS
emergence profile, implant abutment, soft tissue, transmucosal, zirconia

Management of the peri-implant restorative interface is the key to anterior implant esthetics.[1] All surgical and prosthetic concepts strive to preserve the hard and soft-tissues to provide optimal esthetics at this interface. Consequently, the restoration of implants in the esthetic zone presents a great challenge. To achieve long-term stable outcomes, implant depth, angulation, and bucco-lingual position as well as transmucosal height and space for an optimized emergence profile of the restoration and the dimensions of the anterior tooth to be restored must be taken into consideration. The proper selection of the type, shape, and dimensions of implant components and connections play a critical role in the ability to adequately address these challenges. Therefore, clinical success is not just determined by clinical and technical skills of the provider but also by the availability and degree of customization of these components, determined by the product portfolio offered by the implant manufacturer.

This article discusses updated clinical and technical steps for successful treatment with single implant-supported restorations in the esthetic zone. Guidance for treatment planning, selection, and execution of these steps to maximize clinical outcomes in a challenging esthetic situation is presented in a step-by-step manner. While component selection is demonstrated with an implant system and components offered by one manufacturer, the general concepts and strategies are not limited to one manufacturer and may also be applied to other systems.

1 | BONE REMODELING

All two-piece implants have a microgap between the implant and the supra structure, either an abutment or screw-retained restoration. The internal compartment of the implant is contaminated with microbes and histological evidence reveals an inflammatory cell infiltrate located 1–1.5 mm adjacent to the microgap.[2] Bone remodeling (1.5–2 mm) during the first year after loading and an annual bone resorption of less than 0.2 mm was generally accepted as success for two-piece implants.[3] This is a multifactorial reaction due to interproximal bone loss, including surgical trauma, microgap, biologic width, location of implant-abutment microgap or type and connection design characteristics.[4,5]

2 | IMPLANT-ABUTMENT MICROGAP

Position of the implant-abutment microgap at the level or below the bone crest results in a more intense bone remodeling, due to the displacement of the bone as a consequence of bacterial colonization.[6] To overcome this phenomenon, the concept of platform switching has been introduced[7]: abutments of smaller diameter are connected to the implant to create a horizontal offset to relocate microgap away from the bone.[8] All conical connections provide a horizontal off-set besides a degree of conicity (morse cone) with minimal tolerances to decrease the space and, consequently, amount of bacterial colonization. The length of the connection also plays a significant role in the sealing ability of the implant-abutment interface. A lower degree of conicity paired with a longer connection creates a press fit connection. By reducing the friction angle, the insertion torque of the prosthetic components can be lowered.

FIGURE 1 Zirconia crown, universal base, transmucosal abutment, and implant (Nobel Biocare N1 system, Nobel Biocare).

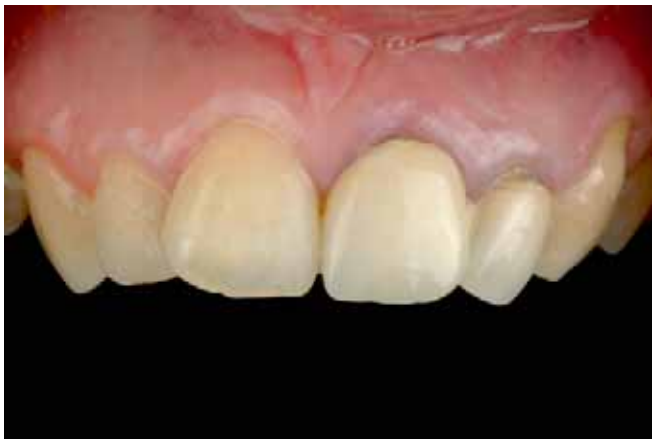

FIGURE 2 Preoperative intraoral view of a failing left maxillary lateral incisor and insufficient crown on the left maxillary central incisor.

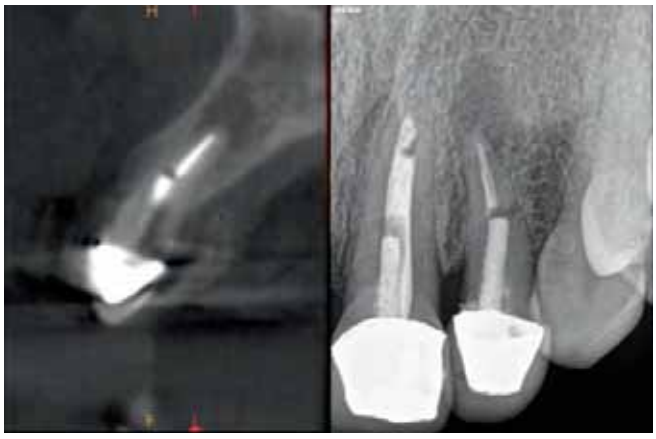

FIGURE 3 Preoperative radiographic views reveal root fracture and periapical granuloma on the left maxillary lateral incisor. The adjacent central incisor shows an insufficient crown and endodontic post.

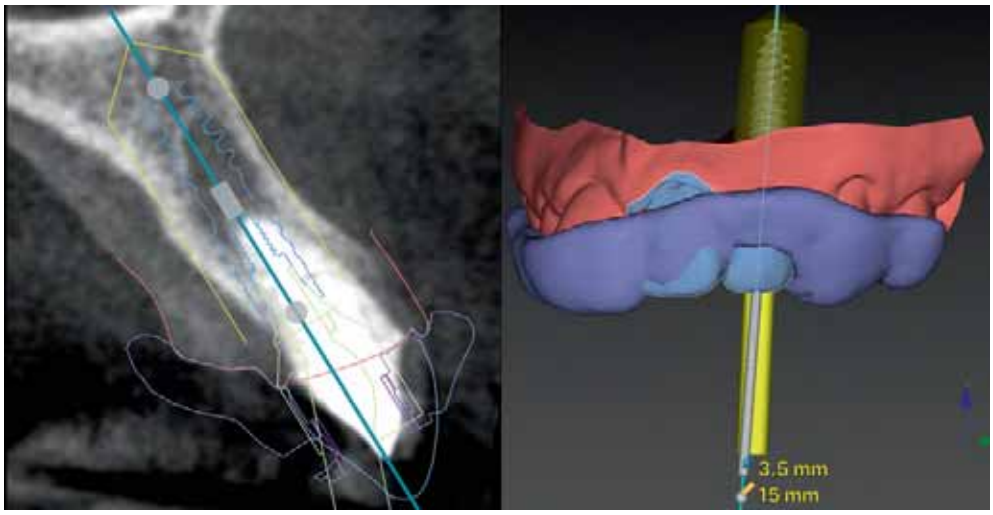

FIGURE 4 Digital implant planning and design of the surgical implant guide.

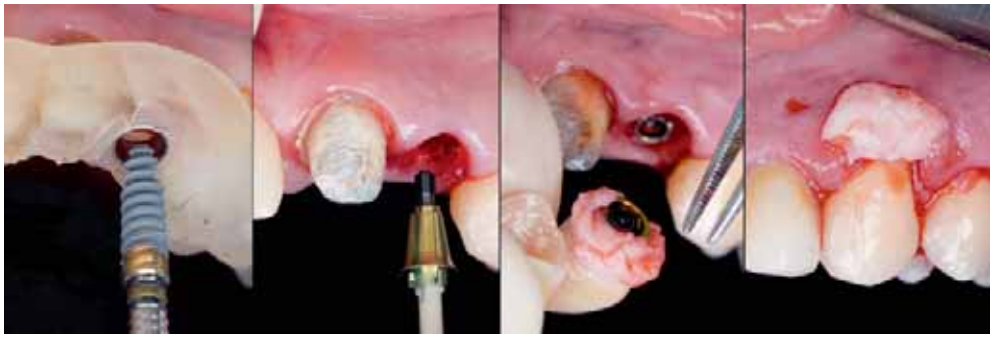

FIGURE 5 Surgical sequence of implant placement, circular connective tissue graft (CTG), abutment and provisional placement. Another CTG was placed to treat soft-tissue recession on the adjacent canine.

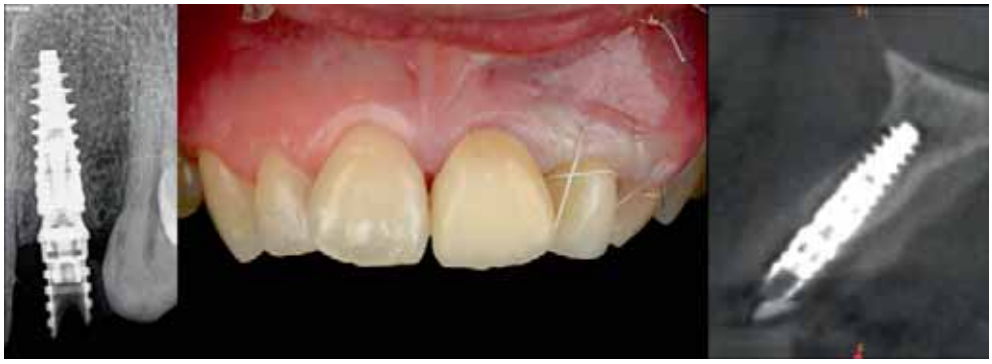

FIGURE 6 Postsurgical radiographic and clinical views.

3 | TRANSMUCOSAL ABUTMENT

A factor that has been largely neglected in scientific research is the influence of the shape of the emergence profile of the transmucosal abutment on clinical outcomes. Early studies already indicated that converging abutments have less soft tissue recession in immediate implant placement than convex abutments.[9] More recent research showed that flat and wide abutments induce a downshift of the biological width and crestal bone resorption than slim abutments in an animal experiment.[10,11] Therefore, current abutment designs intend to emerge slim or concave from the implant shoulder to avoid any pressure on the crestal bone and the supra-crestal connective tissue. Less peri-implant marginal bone loss was observed when a higher transmucosal abutment was used to allow the establishment of the biologic width and avoid disruption at the implant-bone level.[12] Similarly, some studies have demonstrated that abutment height may influence interproximal marginal bone levels.[13–16] They concluded that greater abutment height is related to lower marginal bone loss and greater stability of interproximal bone levels.

It can be hypothesized that the reason for this is the establishment of the biologic width at the abutment instead of the implant level, protecting the peri-implant bone. This would allow for soft tissue healing at abutment level while protecting the osseointegration of the implant.[17,18]

The material and surface microstructure of the abutment also play a significant role in the degree of soft tissue attachment. While milled

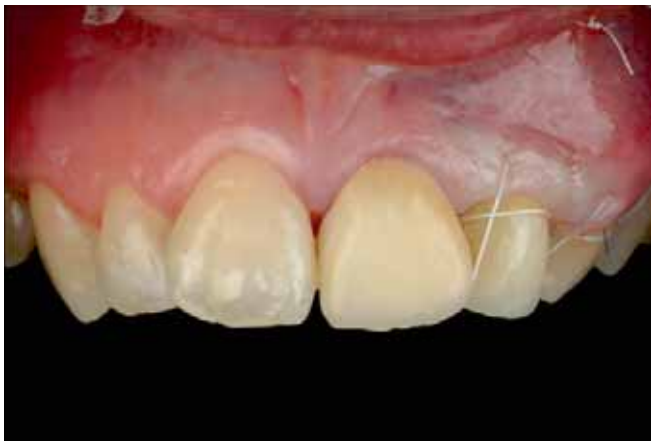

FIGURE 7 Clinical situation immediately after surgery.

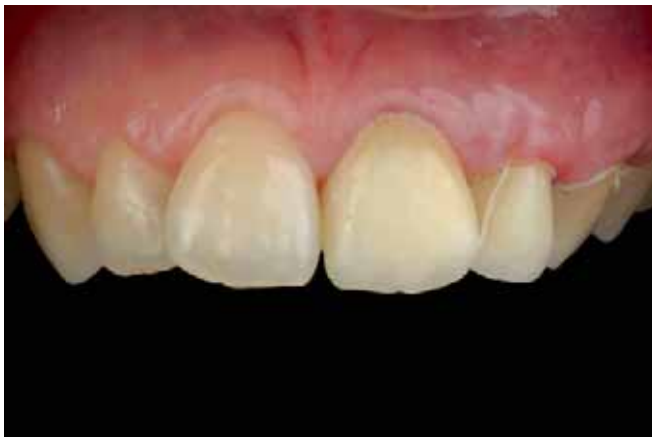

FIGURE 8 Clinical situation 2 weeks after surgery.

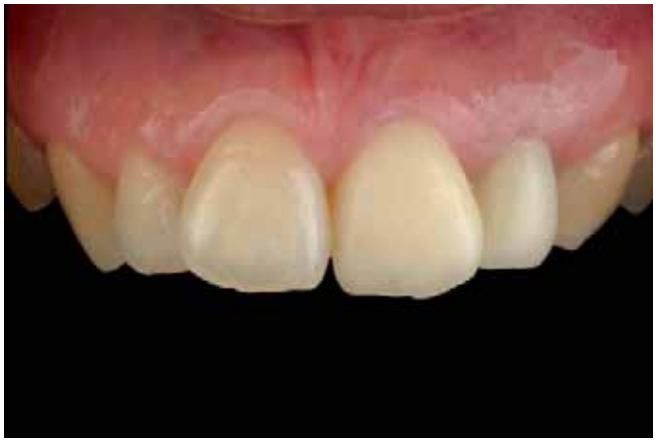

FIGURE 9 Clinical situation 3 months after surgery.

FIGURE 10 Soft-tissue condition 3 months after implant placement, illustrating the integration of the circular CTG for adequate tissue volume.

FIGURE 11 Full contour wax up establishing proportions for ideal emergence profile.

FIGURE 12 Creating ideal emergence profile on master cast.

titanium has preferred properties, an anodized and nanostructured surface of the abutment and collar of the implant provides even better soft tissue outcomes and a lower bleeding index at abutment removal at 2-year follow-up.[19]

The scientific evidence is fairly clear on the negative effects of frequent abutment connection and reconnection on the peri-implant soft and hard-tissues levels, with several studies and systematic

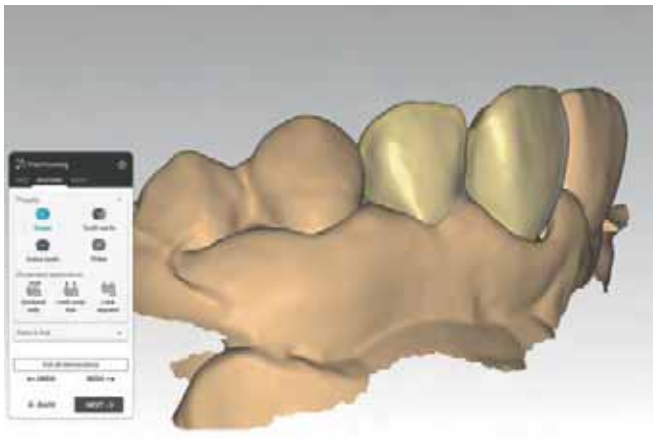

FIGURE 13 Digital design for zirconia crowns with cut back for porcelain veneer microlayer.

FIGURE 14 Porcelain layering of zirconia crown copings.

FIGURE 15 For bisque bake try in, the crown was attached to the titanium base with cyanoacrylate for fixation during try in and easy removal afterwards.

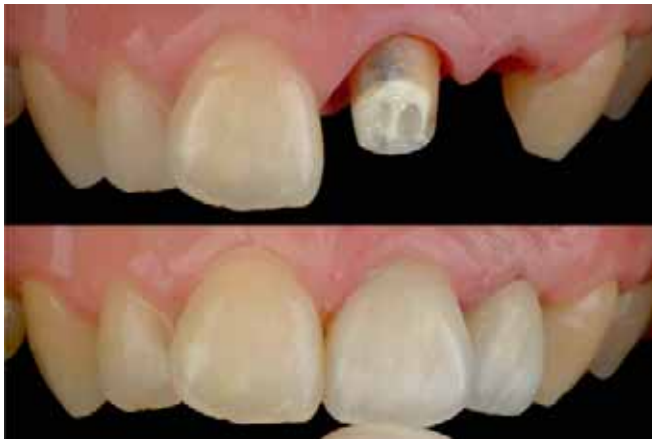

FIGURE 16 Intraoral bisque bake try in. Control of value is a challenge without opaque resin cement.

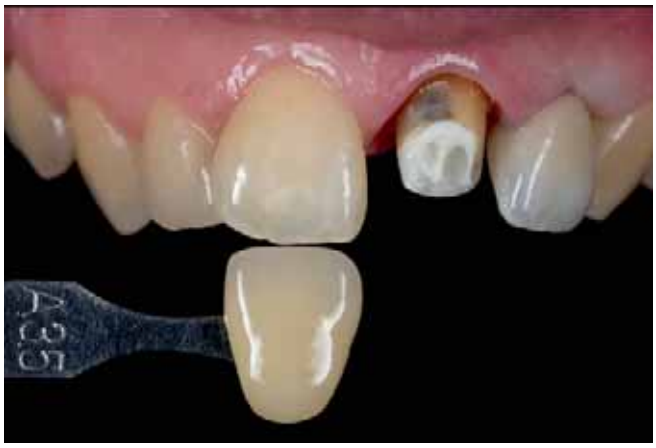

FIGURE 17 Shade communication with the dental laboratory with photos.

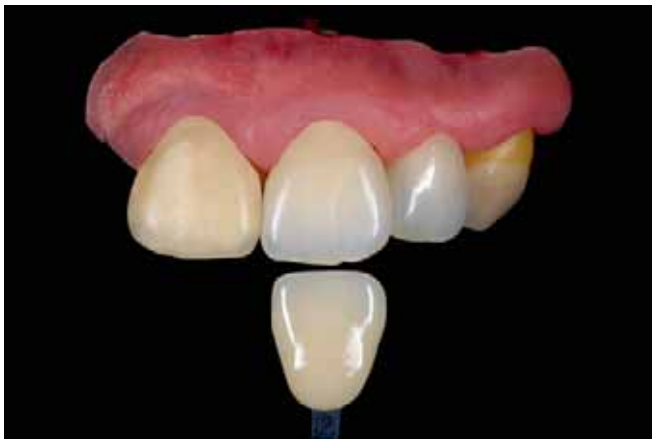

FIGURE 18 A customized master cast was fabricated, simulating the shade of adjacent teeth and underlying structures to optimize shade match and adapt chroma and value of the restorations.

literature reviews indicating significantly greater bone loss around implants with frequent abutment dis and reconnections.[20–24]

In terms of macro design, there two distinct zones at the implant-abutment-crown complex, the critical contour and the subcritical contour.[25] Gomez-Meda et al.[26] proposed a concept for the design of abutments in the esthetic zone and refer to it as "the esthetic biological contour concept". The abutment should be narrow at the implant-restorative interface and flaring to the desired scallop. Since the prosthetic design greatly impacts the peri-implant soft tissue architecture, precise communication with the laboratory technician is of fundamental importance to control the final outcome.

FIGURE 19 Definitive restorations on the master cast. The crown on the natural tooth was fabricated with a palatal retentive hole to facilitate a wire splint of the natural teeth and prevent their shifting due to continuous maxillary growth.

4 | CASE REPORT

A 48-year-old male patient presented with a failing left maxillary lateral incisor. The step-by-step clinical and laboratory protocols and implant component selection for the replacement of the lateral incisor are demonstrated (Figure 1). Preoperative clinical and radiographic views are shown in Figures 2 and 3. Periapical radiograph and CBCT evaluation revealed a granuloma and root fracture of the lateral incisor as well as a deficient crown and insufficient endodontic post on the adjacent central incisor. The treatment plan included immediate implant placement to replace the left maxillary lateral incisor and reconstruction of the central incisor after replacing the existing post with a fiber post, two all-ceramic zirconia-based crowns, and coverage of the soft-tissue recession on the left maxillary canine.

For this specific case, a novel implant system (N1, Nobel Biocare, Zurich, Switzerland), which was optimized for immediate implant placement, was selected. The system was developed based on new concepts and tools for the osteotomy to preserve bone viability.[27,28] It features a trioval conical connection with an 8° and 2.5 mm high contact surface, creating a very strong connection and tight seal with a reduced insertion torque of 20 Ncm,[29] allowing for slim prosthetic components. This connection reduces stress on the bone and has platform shift integrated by design. The slim and long concave transmucosal abutments provide an ideal emergence profile and support for the surrounding soft tissues, enhanced by the anodized and nanostructured surface on the abutment and implant collar (Xeal, Nobel Biocare).[19]

First, a provisional restoration was fabricated with ideal soft tissue support to transfer the shape, dimensions, and outline of the natural tooth to the immediate implant provisional restoration. An impression was made with a polyvinyl siloxane impression material and the master cast fabricated with an epoxy resin material to allowed complete seating of the 3D printed surgical guide onto the cast

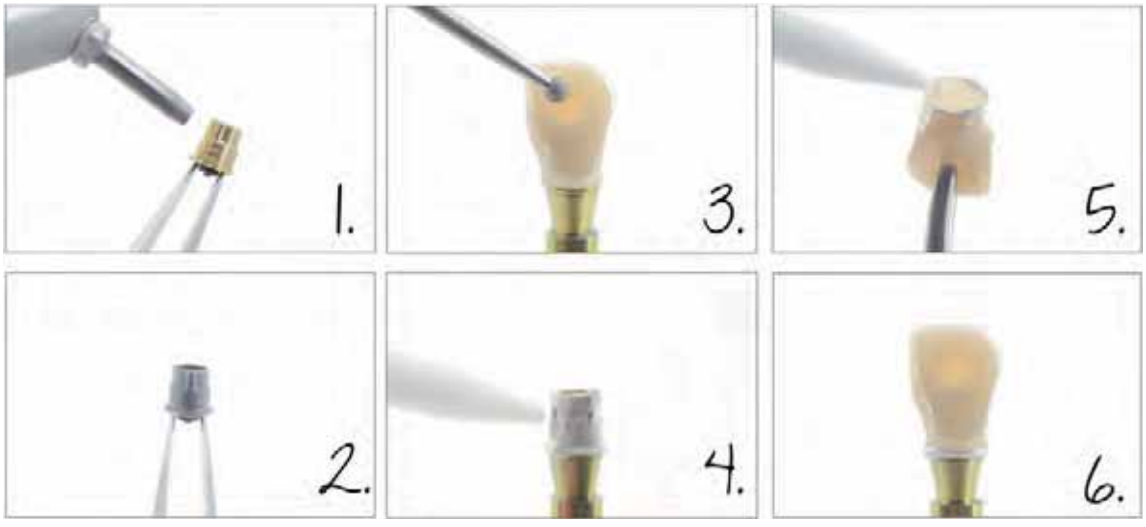

FIGURE 20 Bonding of the zirconia crown on the titanium base with opaque composite resin cement following "APC" technique": Air-particle abrasion with alumina, primer application, and composite resin cement on both materials.

FIGURE 21 Definitive zirconia restoration cemented on titanium base with a 2.5 mm transmucosal abutment on N1 implant (Nobel Biocare).

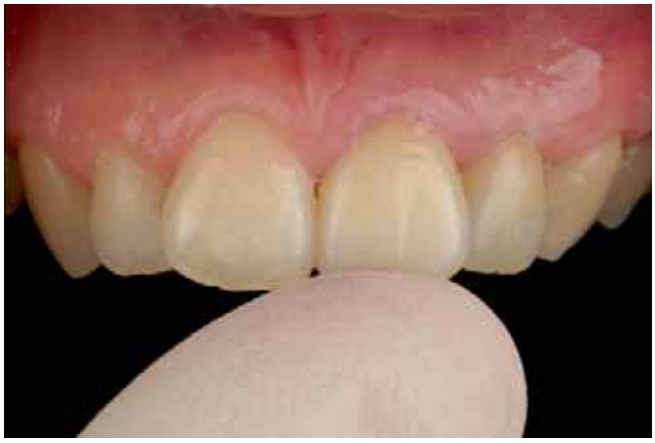

FIGURE 23 Final try in to verify chroma and value of the restorations before cementation.

without damaging it. A full-contour wax up of the tooth to be extracted was made and both the master cast and the wax up were scanned. The digital scans of the reduced master cast, the preparation finish line, and the wax up were digitally "fused" together with the CBCT (Smart Fusion, Nobel Biocare), serving as a stable reference for optimal implant planning in the design software (DTX Studio, Nobel Biocare; Figure 4).

The preparation finish line is critical for determining the depth of the implant, and its angulation should be oriented along the long axis of the tooth. The precise length of the transmucosal abutment was determined with the software. An additional 1.5–2 mm was allocated to the emergence profile of the screw-retained definitive restoration. The transmucosal base includes a small screw (Omnigrip, Nobel Biocare), which facilitates an angulated screw channel for compensation of the implant angulation of up to 25°.

The surgical guide was designed and 3D printed. After atraumatic tooth extraction, the implant (N1 4 × 13 mm, Nobel Biocare) was inserted fully guided and a 2.5 mm transmucosal abutment was placed. In this restorative approach, the provisional restoration on the tooth becomes key to control the tissue interface below the peri-implant soft-tissue margin. The same provisional restoration is

FIGURE 22 Definitive crown on the natural central incisor with a palatal retentive hole for splining wire.

connected to the provisional abutment above the transmucosal one, leaving a concave or straight shape to provide space for a circular connective tissue graft (CTG) and 360° support of the soft tissues. The provisional crown had the same shape and diameter as the root of the failing tooth, providing a seal for the underlying tissues vertical support for the peripheral soft tissues. It supports the formation and stability of a blood clot and the circular CTG. In addition to the implant graft, the surgical tunnel technique was extended to the adjacent canine and a buccal CTG was sutured in place. The surgical steps are depicted in Figure 5. The postoperative clinical situation and healing were documented on the day of surgery (Figures 6 and 7), 2 weeks (Figure 8) and 3 months (Figures 9 and 10) after surgery.

A full-contour wax up was fabricated (Figure 11) and an ideal emergence profile designed on the master cast (Figure 12). The wax up was scanned, and zirconia crowns were designed digitally with a cut back for a porcelain veneer microlayer (Figure 13). The zirconia crowns copings were veneered with a thin labial layer of veneering porcelain for improved esthetics (Figure 14). Both restorations were internally lined with several layers of white opaque procelain to block out the dark color of the central incisor and the implant abutment. To facilitate bisque bake try in, the implant crown was glued to the titanium base with cyanoacrylate (Figure 15) to facilitate and simplify adjustment of contact points, occlusion, and color. Afterward, it can be easily removed without damage. Color control is rather challenging as the dark appearance of the abutment and the transparent glue distort the value of the implant restoration (Figure 16). Clinical photographs were made to transfer the correct value and chroma to the final restorations (Figure 17). A customized master cast was fabricated, simulating the shade of adjacent teeth and underlying structures to optimize shade match and adapt chroma and value of the restorations in the laboratory (Figure 18). The definitive restorations on the master cast are depicted in Figure 19. The crown on the natural tooth was fabricated with a palatal retentive hole to facilitate a wire splint of the natural teeth and prevent their shifting due to continuous maxillary growth.

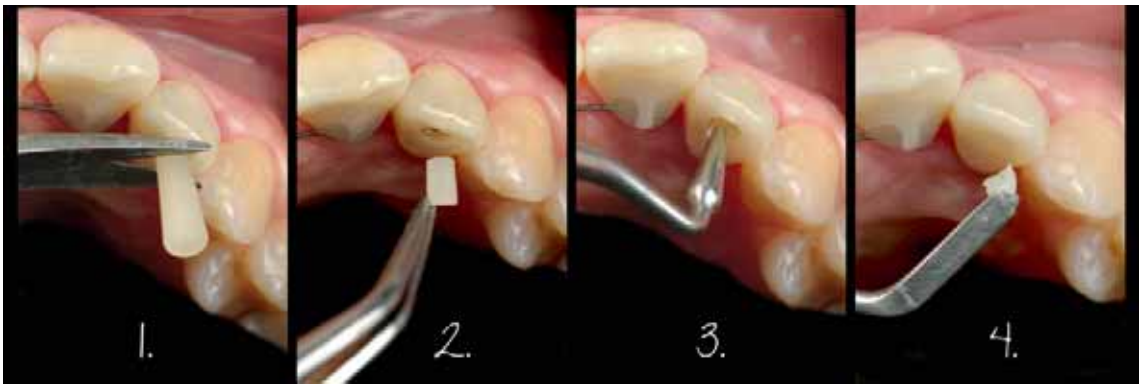

FIGURE 24 After splinting of the anterior teeth from the right maxillary canine to the crown on the left central incisor, the implant restoration was inserted. The screw access hole was filled with a silver plug and sealed with composite resin.

FIGURE 25 Occlusal view of the soft-tissue condition 6 months after restoration delivery.

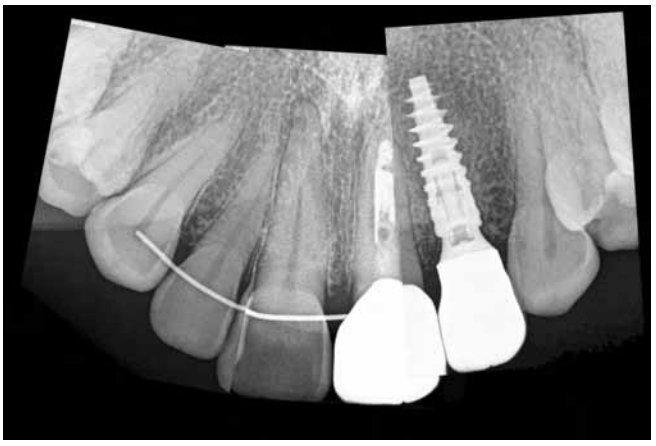

FIGURE 26 Postoperative radiographic view.

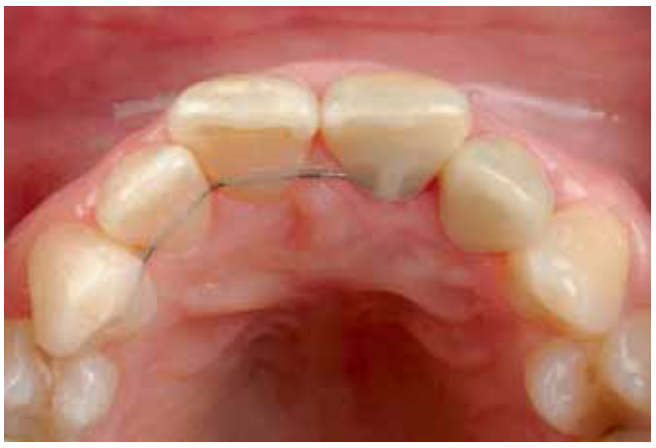

FIGURE 27 Postoperative intraoral occlusal view.

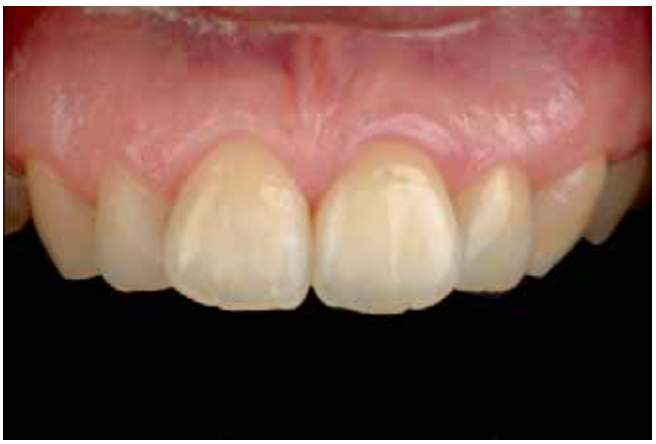

FIGURE 28 Postoperative intraoral anterior view: implant-supported crown on the left maxillary lateral and crown on central incisor.

The zirconia implant crown was bonded to the base with composite resin cement (Multilink hybrid abutment cement, Ivoclar Vivadent, Schaan, Liechtenstein) following the "APC" technique": Air-particle abrasion with alumina, primer application, and composite resin cement on both materials (Figures 20 and 21).[30] The central incisor crown was inserted with a try-in cement to evaluate its value and blending of both restorations (Figures 22 and 23). Then, it was adhesively

bonded to the abutment with composite resin following common zirconia-bonding protocols.[30]

The implant the screw was torqued down to 20 Ncm after 10 min of glutaraldehyde disinfection. Then, a silver plug was adapted to the screw channel to avoid bacteria contamination and sealed with composite resin (Figure 24).

The natural teeth were splinted with a wire from the right maxillary canine to the left central incisor crown through the hole on the palatal aspect to avoid any future tooth movements due to continuous maxillary growth, which could impact the long-term esthetic outcome.

Soft-tissue condition and emergence profile 6 months after restoration insertion are shown in Figure 25. The peri-apical radiograph (Figure 26) reveals ideal bone response to the base-implant interface. Figures 27 and 28 demonstrate the clinical outcomes, soft tissue situation, and blending of the restorations with the adjacent teeth.

5 | DISCUSSION

The protocol for immediate implant placement using a transmucosal abutment and restoration in the esthetic zone described in this article serves as a clinical guide for the practitioner. Immediate implant placement and loading have demonstrated excellent long-term success rates and esthetic outcomes.[31] It was shown that, in general, oral well-being was significantly better after implant therapy, but that patient satisfaction was particularly greater when implants were loaded immediately.[32,33]

In the presented case, a novel and in some respects highly innovative implant system with a unique connection and abutment design was used to replace a lateral incisor. In this case, due to a Class 2 malocclusion, anterior tooth splinting was suggested to maintain the desired esthetic result in the long term as the patient refused any orthodontics that could compensate the effects of continuous maxillary growth. These effects include movements and further eruption of teeth next to the implant, causing asymmetries that are often difficult to correct, and, in some severe cases even require implant removal.

However, there are two important factors to consider before implementing new concepts into daily practice. First, the suggested protocols are techniques sensitive and there is evidence that implant success is directly correlated to the surgeon's technique, skill, and judgment.[34] It is, therefore, recommended to become well familiarized with any newly adapted techniques and implant systems. They should be practiced on a model before using them in a patient for the first time.

Second, a single technique should not be applied without being integrated in a complete, comprehensive concept and strict workflow. There are numerous alternative techniques to the ones described and illustrated in this article. However, the proposed concept incorporates a sequence of consecutive techniques, which build on one another. While adaptations to each individual patient situation are always necessary, major aberrations or changes in sequence may compromise the desired outcomes.

The suggested techniques and materials were discussed based on the existing scientific evidence. While the protocols were demonstrated with a specific implant system from one manufacturer, the fundamental clinical and laboratory treatment principles also apply to other systems. As technologies are constantly evolving and further clinical research becomes available, the proposed concepts are expected to be revised and updated in the future to best serve the needs and expectations of our patients.

6 | CONCLUSIONS

Following esthetic, mechanical, and biologic principles, the long-term success of implant-supported restorations in the esthetic zone is directly correlated to proper execution and sequencing of surgical and prosthetic treatment steps, especially after immediate implant placement. These steps must be critically assessed based on the current scientific evidence to achieve the desired clinical outcomes on a predictable and consistent basis.

DATA AVAILABILITY STATEMENT

Research data not shared.

DISCLOSURE

Drs. Gamborena and Blatz have received honoraria as scientific consultants and speakers for Nobel Biocare in the past.

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How to cite this article: Gamborena I, Sasaki Y, Blatz MB. Transmucosal abutments in the esthetic zone: Surgical and prosthetic considerations. *J Esthet Restor Dent*. 2023;35(1): 148-157. doi:10.1111/jerd.13006

Received: 1 September 2022 | Revised: 20 October 2022 | Accepted: 21 October 2022

DOI: 10.1111/jerd.12980

REVIEW ARTICLE

WILEY

Periodontal phenotype modification of complexes periodontal-orthodontic case scenarios: A clinical review on the applications of allogenous dermal matrix as an alternative to subepithelial connective tissue graft

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Abstract

Objectives: The aim of this review is to address the potential applications of allogenous dermal matrix (ADM), as an alternative to subepithelial connective tissue graft (SCTG), in promoting periodontal phenotype modification (PPM) of challenging periodontal-orthodontic clinical scenarios.

Overview: The rationale behind the need of changing thin to thick gingival tissues is associated to the superior and more stable treatment outcomes promoted by PPM therapy. PPM, via soft tissue grafting, leads to clinical and histological changes of the pre-established original genetic conditions of the gingiva. Although SCTG-based procedures are recognized as the "gold standard" for the treatment of sites requiring root coverage and gingival augmentation, ADM has been recognized as the most suitable alternative to SCTG, particularly in clinical scenarios where the use of autogenous grafts is not possible. Thus, ADM is considered an optimal option for the treatment of patients with a history (or in need) of orthodontic tooth movement, due its two-fold potential indication: (1) the promotion of periodontal soft tissue phenotype modification; and (2) its use, as a barrier membrane, in hard tissues augmentation procedures.

Conclusions: ADM is a viable option for soft tissue augmentation, as well as for treatment approaches involving buccal bone gain.

Clinical Significance: Periodontal phenotype modification therapy, when applied in challenging periodontal-orthodontic clinical scenarios, promotes root coverage and prevents the onset and development clinical attachment loss.

KEYWORDS

clinical decision-making, gingival recession, phenotype, plastic surgery, tissue grafts

1 | INTRODUCTION

The development of gingival recession defects (GRD) is one of the potential adverse events (i.e., "unexpected and undesirable detrimental effects and events occurring following the delivery of a procedure or therapy"),[1] caused by inappropriate orthodontic therapy.[2–6] The onset and progression of GRD in orthodontic patients is associated to an intrinsic relationship between the gingiva, attachment apparatus (i.e., alveolar bone and periodontal ligament), root anatomy and mechanical stresses promoted by the direction, intensity and strength of orthodontic forces acting on the teeth during the alignment of the dentition.[4,5] An excessive orthodontic tooth movement in a buccal

direction can origin a disruption of the alveolar process by the tooth root, marginal buccal bone and connective tissue loss, and the consequent development of GRD[4,5] Besides, patients who developed single GRD during orthodontic treatment are at an increased risk of developing multiple GRD after treatment.[6]

Of the different soft and hard tissues forming the periodontium, the gingiva plays a key role in onset and progression of GRD.[2,3,7–9] The dimension of the so called "keratinized tissue (KT) band" (i.e., the portion of the soft tissue formed by the free and attached gingiva) is regarded as one of the main pillars for the maintenance of periodontal health[10] and gingival margin stability.[11] Outcomes from individuals with good oral hygiene, followed up for at least a 2-year period, showed that sites lacking a minimum 2 mm of KT width are more prone to clinical attachment loss (CAL)[11]: there was a high risk of recession depth (RD) increase and CAL among pre-existing GRD (i.e., 78.1% of the GRD experienced RD increase), as well as there was an increase in the number of new GRD over time (i.e., a 79.3% increase in the total number of GRD).[11] Moreover, other systematic reviews commissioned by the American Academy of Periodontology (AAP) clearly indicate that teeth presenting thin and narrow gingiva are at an increased risk of developing GRD compared to teeth surrounded by thick and wide gingiva.[12,13]

Different soft tissue grafts and substitutes have been used to increase the width and thickness of the KT band in root coverage and non-root coverage sites,[2,3,7–9,14,15] based on a concept known as "periodontal phenotype modification" (PPM).[7,16] Originally described as "biotype modification",[7] this term is grounded on a two-fold property required by any soft tissue grafting material: the capability of stimulating both clinical and histological changes to the pre-established, original genetic conditions of the recipient site. Clinically, PPM increases the width and thickness of the gingiva/KT, as well as alters the texture and color (mainly when free gingival grafts are used) of the treated site compared to untreated adjacent areas.[7,12,16–18] Histologically, PPM is able to increase the thickness of the epithelial layer and the amount and density of collagen bundles of the recipient site.[19] Independently of the primary outcome measures anticipated by the proposed therapy (e.g., complete root coverage, aesthetic condition change), the short-term results of PPM (i.e., 6–12 months follow-up) should lead to the achievement of a minimum 1 mm thickness and width of attached gingiva, a condition that will favor the stability of the gingival margin over time.[7]

Of the available autogenous grafts and soft tissue substitutes used to achieve concomitant root coverage and PPM, the subepithelial connective tissue graft (SCTG) and the allogeneic dermal matrix (ADM) are considered the primary and secondary treatment options, respectively.[7–9,14,15] Although the use of SCTG-based procedures is recognized as the "gold standard" therapy in root coverage, the amount of grafting material required to treat the defects may be a limiting factor for patients displaying multiple sites of GRD (i.e., those patients requiring greats demands of donor tissue).[7–9,14,15] Taking into consideration these issues, the aim of this review is to address the potential applications of ADM, as an alternative to SCTG, in the decision-making process involving periodontal phenotype modification (PPM) approaches, in challenging periodontal-orthodontic clinical scenarios.

2 | OVERVIEW

2.1 | The rationale behind promoting PPM in orthodontic patients

The rationale behind promoting PPM in orthodontic patients is associated to three central-cores: (1) the anatomic characteristics of the site and the etiology of the mucogingival "defect/condition"; (2) the short-term results achieved with root coverage and gingival augmentation procedures; and (3) and the long-term stability (≥5 years) of the gingival margin of sites submitted to PPM. These features are depicted as follows.

2.1.1 | The anatomic characteristics of the site and the etiology of the mucogingival "defect/condition"

It is well documented that the anatomic characteristics of the site and the etiology of the mucogingival "defect/condition" should be taken into consideration during the decision-making process.[2,3,20,21] It is important to note that the histologic extension of attachment loss associated to GRD is superior than the clinical measurements retrieved during periodontal examination.[22] It has been reported that gingival recessions displaying a 1 mm RD show, on average, an additional 2.8 mm of "non-exposed" bone dehiscence over the root surface (that is, there is a "hidden" bone defect covered by gingival tissue).[22] Thenceforth, there is an increase of 0.98 mm in alveolar bone dehiscence for every 1 mm of increase in RD.[22]

With respect to orthodontic case scenarios in need of periodontal plastic surgery, most of the anatomical and structural changes in the attached gingiva and alveolar mucosa that may occur during active orthodontic treatment are also associated to the tooth's position and angulation in the alveolar ridge.[4–6] Together with the characteristics of the soft tissues, the alveolar buccal bone wall is a key factor in the development of GRD, even in the absence of a biofilm-induced gingival inflammation scenario. Anatomically, the buccal bone wall is thinner than the lingual wall,[23] as well as it may contain bone dehiscence (i.e., "areas in which the root is denuded of bone and portions of the root surface are covered only by soft tissue, and the area extends to through the marginal alveolar bone")[21] and fenestrations (i.e., "window-like apertures or openings in the alveolar bone over the root without comprising the marginal crestal bone").[21,24–27] Indeed, bone dehiscence and fenestrations can be found in approximately 60% of the individuals and affecting 10% of the overall number of teeth.[24] However, in the anterior mandibular region, the presence of malocclusions may lead to a noteworthy increase in the frequency of fenestrations and dehiscence to approximately 35% and 50%, respectively.[26,27] Consequently, these anatomical features in combination to a buccal tooth movement (and its resulting effect of bone resorption

caused by osteoclastogenesis triggered by the application of pressure forces on the bone walls) may induce the onset and progression of GRD,[5,28] as well as lead to clinical scenarios where PPM therapy (via soft tissue augmentation) shall be required to "intercept" the problem. Therefore, the assessment of the dentoalveolar bone changes influenced by an orthodontic tooth movement deserves special attention, as well. In that sense, the 2017 AAP Best Evidence Consensus on the use of cone-bean computed tomography (CBCT) for multidisciplinary periodontal approaches[29] highlighted that: (1) the use of this technology allows "for a precise assessment/diagnostic acumen of alveolar bone dimensions (i.e., buccal bone plate thickness and height and detection of bone dehiscence), improving decision-making and helping to prevent the development of iatrogenic sequelae;"[29] and (2) "the use of this diagnostic tool may be considered for patients with a thin periodontal phenotype before treatment (especially the anterior mandible and maxillary premolar regions), as they are at an increased risk of developing additional periodontal tissue loss".[29]

2.1.2 | The short-term results achieved with root coverage and gingival augmentation procedures

With respect the available soft tissue grafting materials, autogenous grafts (i.e., free gingival grafts [FGG] and SCTG) are considered the best treatment options, in terms of promoting soft tissue phenotype modification. Although the use of FGG promotes superior KT width and thickness gains compared to SCTG, its anticipated root coverage outcomes (i.e., number of sites exhibiting complete root coverage [CRC], mean root coverage [MRC] and esthetics) are substantially inferior to those achieved by SCTG.[2,7–9] Current knowledge shows that the use of SCTG + coronally advanced flap (CAF) stands as the "gold-standard" procedure for the treatment of single and multiple GRD, with and without interproximal tissue loss, requiring soft tissue phenotype modification (i.e., sites <1 mm of attached gingiva and <1 mm gingival thickness).[2,7–9,14,15] Moreover, compared with four treatment alternatives (i.e., ADM + CAF, FGG, platelet-rich fibrin [PRF] + CAF and XCM + CAF), the SCTG + CAF usually promotes superior CRC, MRC and KT width gains (except for the FGG which is superior to SCTG in terms of KT improvements) at short-term follow-up (i.e., 6–12 months).[7–9,14]

It should be noted that the selection of a soft tissue grafting procedure is not only influenced by the outcomes of treatment approach per se, but also by local conditions and the patient's preferences.[2,3,7–9,14,15,21] For instance, the use of soft tissue substitutes may be better indicated in four specific conditions: (1) in the treatment of multiple GRD with great demands of grafting / donor tissue and reduced availability of donor areas (this includes the need of harvesting the same donor site more than once); (2) in reducing the early palatal morbidity associated to palatal soft tissue harvesting procedures, especially in extensive donor areas; (3) treatment of patients who do not want to be submitted to a secondary surgical procedure at the hard palate / tuberosity; and (4) medical contraindications for SCTG harvesting.[2,3,7–9,14,15,21] Also, it can be suggested that the use of ADM can reduce the complexity of the surgical procedure (because of the absence of a second surgical site) and chair-time.[30,31] Taking into consideration the above-mentioned aspects for the treatment of patients in need of root coverage and soft tissue phenotype modification (i.e., KT thickness and width gains), treatment options based on ADM + CAF (primarily), followed by XCM + CAF (secondarily) and PRF + CAF (tertiarily) have been ranked as the most suitable alternatives to the use SCTG + CAF.[8,9,14]

2.1.3 | The long-term stability of the gingival margin of sites submitted to PPM

Like untreated sites, the stability of the gingival margin at long-term (i.e., ≥ 5 years after treatment) seems to be directly associated to a minimum 2 mm amount of attached gingiva achieved by soft tissue augmentation therapy. It has been demonstrated that FGG-based procedures, when performed in patients with high standards of oral hygiene and a thin soft tissue phenotype (i.e., keratinized tissue width ≤1 mm), could not only preclude the development of GRD, but promote a coronal displacement of the gingival margin as well (i.e., 83.5% of treated sites displayed 1–4 mm of creeping attachment after a 25-year follow-up period).[17] Moreover, sites treated with FGG showed less formation and progression of non-carious cervical lesions (i.e., sites lacking a minimum 2 mm band of attached gingiva or presenting a thin gingival phenotype were associated to a 3.5 times increased chance of developing these lesions, compared to teeth exhibiting at least 2 mm of attached gingiva or a thick gingival phenotype).[16]

Regarding the use of a SCTG associated to a coronally advanced flap (CAF), it was effective in promoting root coverage of GRD (with and without interproximal tissue loss) at short-term, as well as these sites displayed a clinically evident stability of the gingival margin after 20 years of treatment (that is, approximately 2/3 of the sites showed no apical migration of the gingival margin). It has been demonstrated that teeth without a minimum width of 2 mm of attached gingiva and presenting NCCL were more likely to develop gingival recession recurrence.[32]

In addition, another 20 years follow-up root coverage study on the effectiveness of CAF demonstrated that the use of a of flap procedure alone (without the adjunct use of a soft tissue graft) was not able to promote a clinical or statistical increase of KT band, nor to prevent the relapse of GRD at long-term, when a minimum 2 mm attached gingiva width was not present.[33]

2.2 | Use of ADM for periodontal soft and hard tissues phenotype modification

Ideally, the prevention of GRD development should be critically assessed prior initiating an orthodontic therapy, but most of the time, clinicians may foresee the need of grafting procedures only after the development of a mucogingival deformity. Therefore, in the presence

FIGURE 1 Baseline—prior orthodontic treatment (A), 12 months after the beginning of orthodontic treatment (B), Allogenous dermal matrix trimmed to fit the recipient site (C), tunnel flap coronally advanced and fixed by composites (D), gingival recontouring performed 18 months after soft tissue grafting (E,F), 1 month after removal of orthodontic appliances (G), soft tissue profile during ceramic veneers preparation (H), and 5 years follow-up after delivery of ceramic veneers (I–K). Figures 1A through 1K reproduced from TISSUES: CRITICAL ISSUES IN PERIODONTAL AND IMPLANT-RELATED PLASTIC AND RECONSTRUCTIVE SURGERY, by Leandro Chambrone & Gustavo Avila-Ortiz, with permission from Quintessence Publishing Co Inc, Chicago.[3]

of thin alveolar bone and gingiva, PPM therapy should be provided to prevent or treat deleterious sequelae resulting of orthodontic therapy,[29] As previously mentioned in this review, ADM may be considered a viable clinical option for clinical scenarios involving multiple GRD (i.e., those involving high demands of grafting material) and the need of PPM. Ideally, the use of ADM is mostly not suggested in areas lacking completely the KT band (i.e., its efficacy seems associated to sites presenting ≥1 mm of KT).[14] Clinically, the use of ADM can unquestionably change thin to thick soft tissue phenotypes of multiple GRD, promote a favorable environment for CRC achievement and lead to satisfactory aesthetic results, independently of the type of flap (i.e., with or without vertical releasing incisions) used to cover the graft.[30,31] Histologically, ADM promotes wound healing outcomes like those achieved by other root coverage procedures (flap-based procedures and SCTG + CAF)[7,34]: (a) the formation of a long junctional epithelium[7,34]; and (b) a connective tissue attachment (with fibers

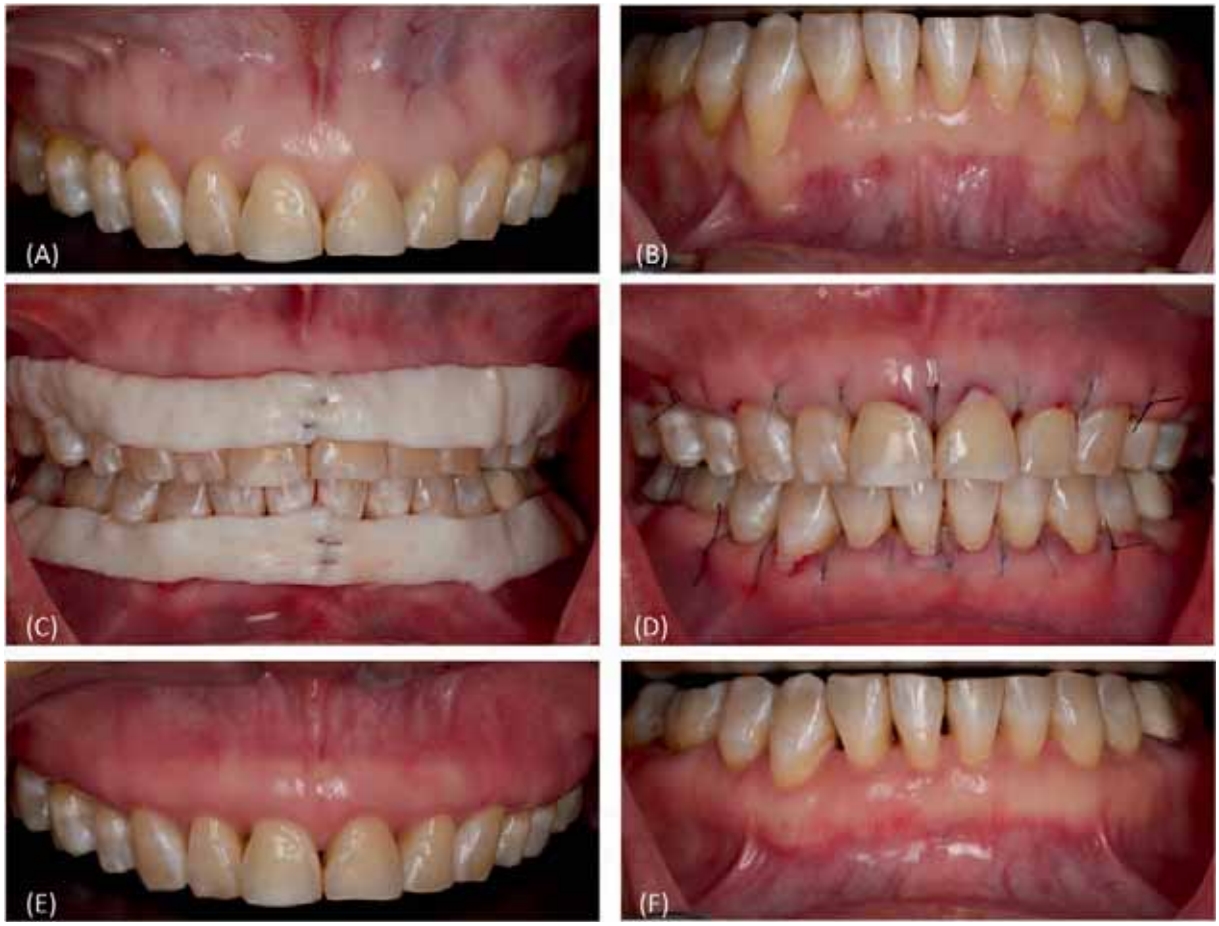

FIGURE 2 Baseline (A,B), allogenous dermal matrix used to treat maxillary and mandibular teeth (C), tunnel flap coronally advanced and sutured (D), 12 months follow-up (E,F)

running parallel to the root surface).[7,34] Evidence also indicates that ADM should be used as part of a bilaminar approach and should remain fully covered by the flap (e.g., CAF, tunnel flap, envelope flap, etc.),[3,7–9,14] mostly because it is a non-vital soft tissue substitute, where its healing will be dependent on vascularization and cells coming from recipient site bed and overlaying flap.[31] On the one hand, the full coverage of ADM may avoid the occurrence of potential adverse events during the early wound healing stages (e.g., extensive shrinkage[35] and acute infection due to microorganisms colonization) (Appendix S1). On the other hand, evidence suggests that ADM might be used partially exposed with the aim of increasing the KT band or as a barrier membrane[36] (i.e., recent evidence showed the beneficial effects of PPM, via ADM + bone grafting, in patients undergoing orthodontic tooth movement[37–41]). Therefore, ADM may be used in combination with "periodontally accelerated osteogenic orthodontics"[38] or "surgically facilitated orthodontic therapy"[39] (i.e., the use of corticotomy surgical procedures associated to bone augmentation to facilitate orthodontic therapy) to improve the periodontal phenotype (soft and hard tissues) of patients with an unfavorable periodontal anatomy and in need of orthodontic treatment.[37–41]

Consequently, the potential applications of PPM (particularly the use of ADM-based treatment approaches), should focus on the presence of GRD, the clinical assessment of the KT band characteristics and, when deemed necessary, the use CBCT imaging. Based on these factors, PPM therapy can be applied in two "big scenarios":

1 Soft tissue phenotype modification:
   - Prior orthodontic treatment (Appendix S1)
   - During orthodontic treatment (Figure 1 and Appendix S2)
   - After orthodontic treatment (Figure 2)
   - Prior orthodontic re-retreatment (Appendices S3 and S4)

2 Soft and hard tissues phenotype modification:
   - Prior orthodontic treatment (Appendix S5)
   - During orthodontic treatment (Appendix S6)
   - After orthodontic treatment (Figures 3 and 4)
   - Prior orthodontic re-treatment (Appendix S7)

2.2.1 | Case #1: Soft tissue phenotype modification

A 40-year-old smoking woman with a history of periodontitis was referred for periodontal treatment. Following initial examination, the patient underwent oral hygiene instruction, full-mouth supra- and

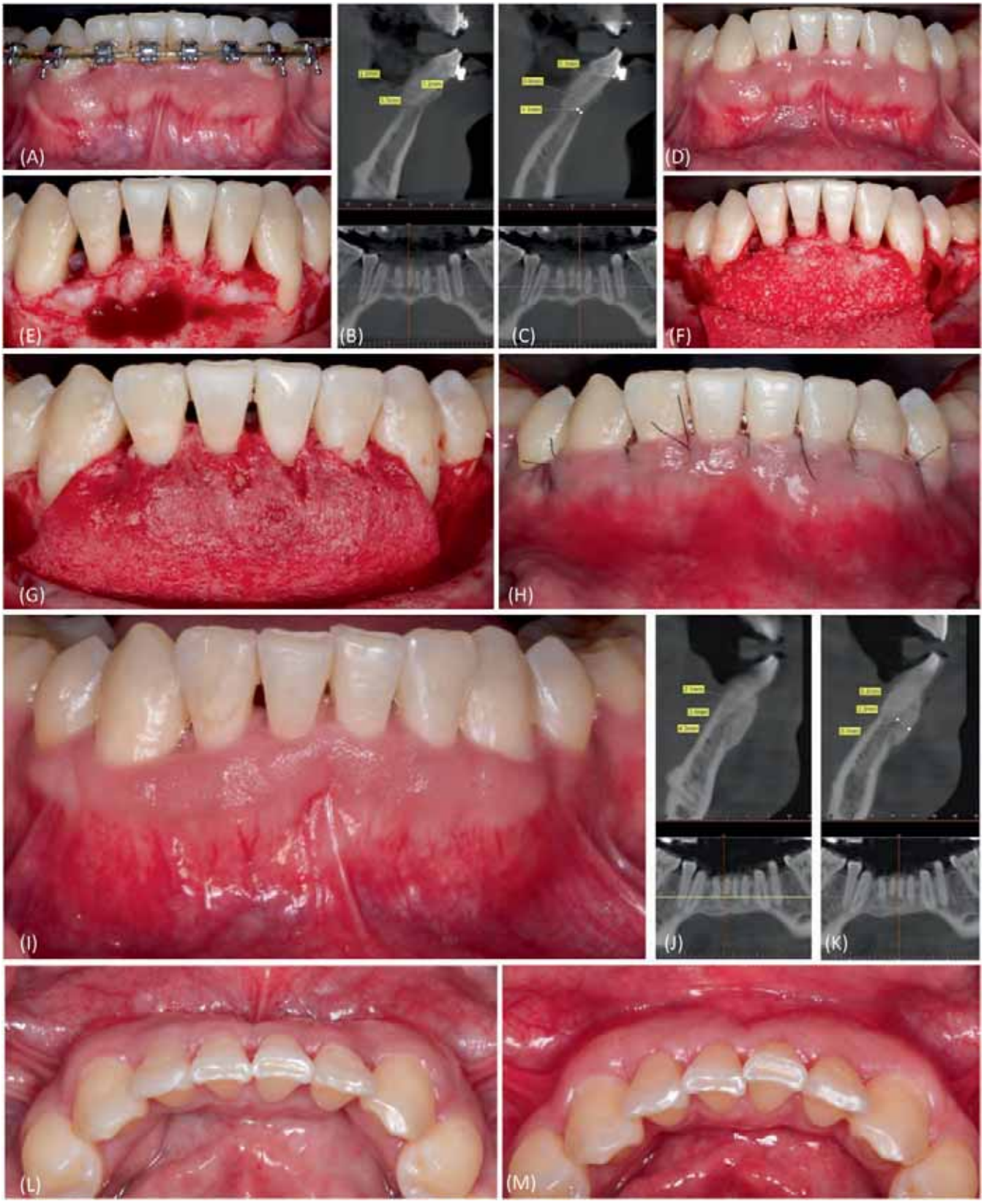

FIGURE 3 Baseline—clinical and CBCT outcomes prior orthodontic appliance removal (A–C), baseline—at the day of surgery (D), flap elevation (E), grafting procedures (allogeneic bone graft + ADM (F,G), flap suture (H), 12 months follow-up—clinical and CBCT outcomes (I–K), baseline versus 12 months follow-up—occlusal view (L,M)

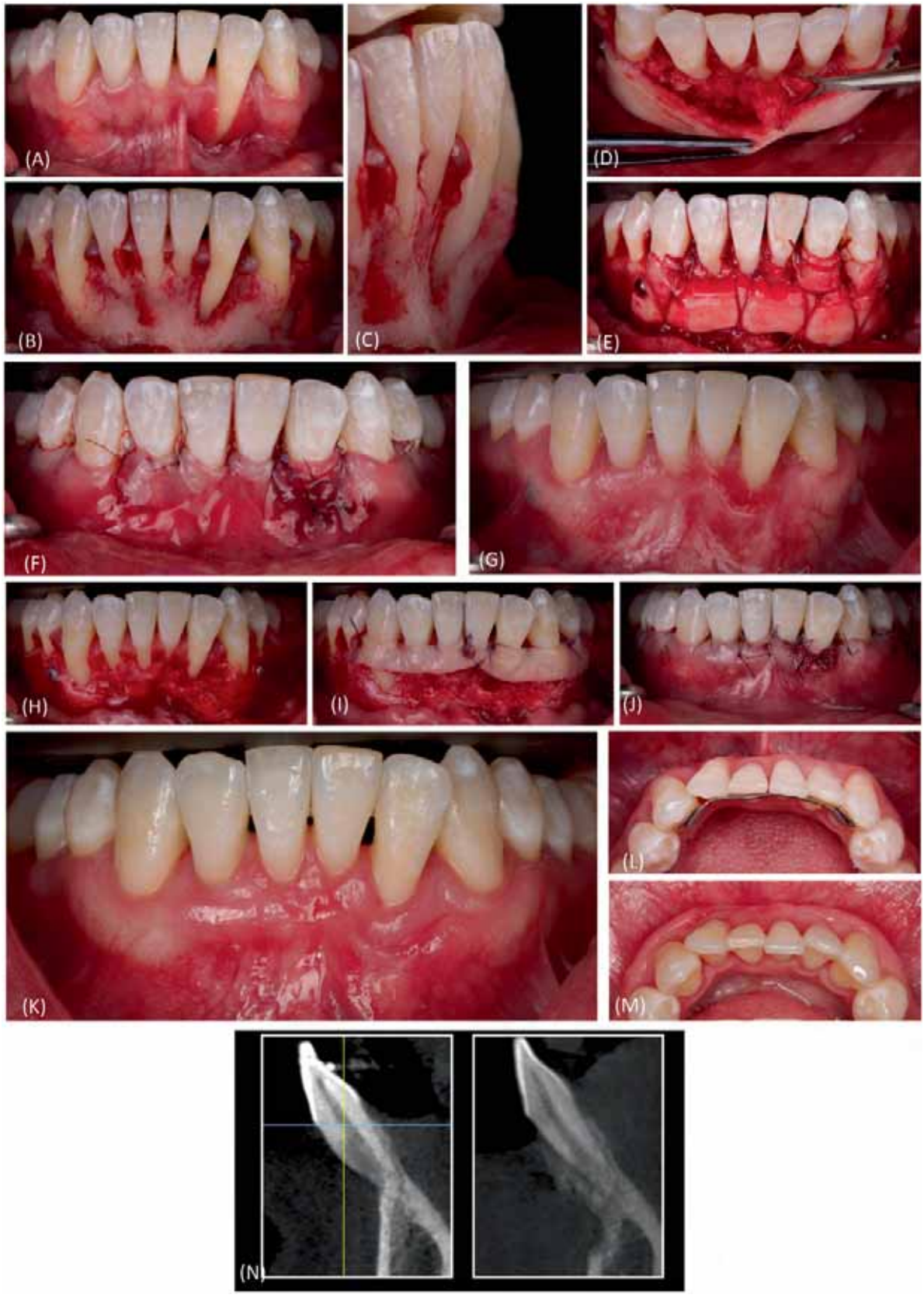

FIGURE 4 Baseline (A), full-thickness flap elevation and exposure of deep bone dehiscence at anterior mandibular teeth (B,C), grafting procedures (autogenous bone + ADM + SCTG (D,E), flap coronally advanced and sutured (F), 5 months follow-up (G), SCTG + CAF (H–J),4 months after the 2nd surgical procedure (K), baseline versus 12 months follow-up of the first surgery—occlusal view (L,M), baseline versus 12 months follow-up of the first surgery—cone-bean computed tomography imaging (N)

subgingival scaling and root planning, and localized open flap debridement at teeth #7. After phases I and II of periodontal treatment, the remission of the inflammatory process led to post-treatment recession of the gingival margin (Figure 1A). At this stage, the potential treatment options available to improve the interproximal embrasures esthetics (i.e., reduce the black triangles) and the gingival contours of upper anterior teeth were discussed with the patient. Because of the presence of multiple GRD (RT2[42] /GRD-II,[20] mainly at teeth #7, #8, and #9), the amount of soft tissue required to promote PPM and the need of establishing a proper aligning and leveling of the six maxillary anterior teeth, a multi-disciplinary treatment plan involving orthodontic tooth movement, PPM and the installation of ceramic veneers (teeth #7, #8, #9, and #10) was designed, based on the following steps: (a) initial 12-month period of orthodontic treatment (Figure 1B); (b) use of an ADM to improve the soft tissue phenotype of upper anterior segment (Figure 1C) in combination with a coronally advanced tunnel flap (sutured by 6–0 nylon sutures fixed with composites, Figure 1D); (c) additional 18-month period of orthodontic treatment - at the end of tooth movement a gingival recontouring was performed to improve the gingival zeniths (Figure 1E–G); and (d) restorative phase (Figure 2H). After a five-year follow-up period, it can be noted that the recession depth reduction and soft tissue phenotype modification established after treatment could be maintained long-term, as well as the position of the gingival margins remained stable over time.

2.2.2 | Case #2: Soft tissue phenotype modification

A 32-year-old woman with a history of orthodontic treatment during adolescence was referred for treatment with chief complaints of multiple sites of gingival recession (Figure 2A,B). Following initial examination, the patient underwent oral hygiene instruction and full-mouth supragingival scaling. Based on the amount of soft tissue required to treat the multiple GRD (RT1 an RT2[42] /GRD-I and GR-II[20]), the surgical procedure involved the following: (a) the combination of a tunnel flap + ADMG used to improve the soft tissue phenotype and reduce recession depth of maxillary and mandibular teeth (Figures 2C); and (b) coronal advancement and suture of the tunnel flap (by 6–0 polypropylene sling sutures) (Figure 2D). One year after treatment, recession depth reduction and soft tissue phenotype modification was achieved in all treated sites (note that the amount of recession coverage varied according the type of defect and level of interproximal tissue loss) (Figure 2E,F).

2.2.3 | Case #3: Soft and hard tissue phenotype modification

A 35-year-old man with a history of periodontitis was referred for soft tissue grafting at the mandibular, anterior teeth. Clinical and CBCT outcomes revealed the extension of periodontal tissue loss (Figure 3A–C). The patient presented with thin buccal bone walls and gingival tissues. After removal of the orthodontic appliance, oral hygiene instruction and full-mouth supragingival scaling was performed. At this stage, the potential advantages and risks associated with PPM therapy were discussed with the patient. Based on his periodontal characteristics (Figure 3D), the following treatment approach was established: (a) full-thickness flap elevation (Figure 3E); (b) hard and soft tissue grafting, based on the combination of an allogeneic bone graft + ADM (used also as a barrier membrane and fixed by surgical pins) to improve the periodontal phenotype (Figure 3F,G); and (c) flap suture by sling sutures (6–0 nylon) to its original position (Figure 3H). Clinically significant gains in gingival and bone thickness, promoted by PPM, were observed after 12 months. (Figure 3I–M).

2.2.4 | Case #4: Soft and hard tissue phenotype modification

A 37-year-old man with a history of previous orthodontic therapy was referred for root coverage at tooth #23 (Figure 4). Clinical (Figure 4A) and CBCT outcomes revealed the extension of buccal bone wall loss, as well as the presence of thin soft tissue phenotype. Initially, oral hygiene instruction and full-mouth supragingival scaling was performed. Like case #3, the following surgical sequence was originally established to achieve PPM: (a) full-thickness flap elevation (Figure 4B,C); (b) bone and soft tissue grafting, based on the use of autogenous bone shavings obtained with a bone collector + ADM (a 20 × 40 mm thick graft used as a barrier membrane and fixed by surgical pins) + SCTG (harvested from the tuberosity and sutured at the level of the CEJ of teeth #22 and #23) to improve the periodontal phenotype (Figure 4D,E); and (c) coronal advancement and suture of the flap (by 6–0 nylon sling sutures) (Figure 4F). Five months after surgery (Figure 4G), it was opted to perform a second root coverage procedure, based on the use of a SCTG + CAF, to further reduce recession depth at teeth #22 and #23 (Figure 4H–J). Clinical outcomes observed 4 months (Figure 4K) after the beginning of therapy show an evident reduction of recession depth at mandibular anterior teeth. In addition, the positive gingival and bone gains achieved by PPM could be demonstrated by both clinical and CBCT imaging outcomes obtained 12 months after initial therapy (Figure 4L,M).

3 | CONCLUSIONS

The advantages of achieving periodontal soft tissue phenotype modification are clearly demonstrated in the literature, both in terms of preventing the onset / development of gingival recessions and improving the short- and long-term predictability of root coverage procedures. Regarding the treatment of patients that will undergo orthodontic therapy, soft tissue phenotype modification appears as a clinically driven approach indicated in reducing the risk of clinical attachment loss caused by potentially deleterious tooth movements, outside the buccal alveolar bone envelope. For patients that already underwent orthodontic treatment, soft tissue phenotype modification reestablishes partially

or completely the lost gingival tissues, improves the clinical attachment level and offers a physical-mechanical barrier against occlusal forces and other local / environmental factors. The use of ADM is a viable and potentially interesting clinical approach, not only for soft tissue augmentation of challenging periodontal-orthodontic clinical scenarios, but also for cases where buccal bone gain is the focus of treatment. The advantages of an unlimited source of grafting material, as well as the potential clinical use of this soft tissue substitute as a "barrier membrane" (when combined with a bone graft material) highlights the directions of future research and possible applications of treatment in case scenarios requiring periodontal phenotype modification.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Chambrone L, Garcia-Valenzuela FS. Periodontal phenotype modification of complexes periodontal-orthodontic case scenarios: A clinical review on the applications of allogenous dermal matrix as an alternative to subepithelial connective tissue graft. *J Esthet Restor Dent*. 2023;35(1):158-167. doi:10.1111/jerd.12980

Received: 31 May 2022 | Revised: 31 August 2022 | Accepted: 12 September 2022

DOI: 10.1111/jerd.12967

REVIEW ARTICLE

WILEY

Single-rooted extraction socket classification: A systematic review and proposal of a new classification system based on morphologic and patient-related factors

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Abstract

Taxonomy and classification of a disease contributes to facilitating the diagnosis and treatment planning process and simplifies communication between clinicians. The aim of this study was to provide a critical appraisal based on a systematic review of the single-rooted extraction socket (ES) classifications and subsequently, introduce a new classification system combining the cornerstones of the previously proposed systems and based on the latest consensus in implant dentistry. Following the systematic search process in PubMed, EMBASE, and SCOPUS databases 13 ES classifications were detected. The most repeated hard and soft tissue factors in the previous classifications were buccal bone dehiscence, interproximal bone, gingival recession, and soft tissue phenotype. However, there was minimal attention to patient-related factors such as systemic conditions and smoking. Therefore, a new classification system based on the combination of patient-related factors, clinical and radiographical parameters was proposed. This divides an ES into three types. Class I and II sockets are candidates for receiving immediate implant placement and conversely, a class III socket includes a compromised condition that requires multiple-stage reconstruction mostly suitable for standard delayed implant placement with alveolar ridge preservation. Within the limitations of this study, the new classification system not only provides comprehensive inclusion of various crucial parameters in implant placement (such as prediction of future implant position and osteotomy difficulty, etc.) but also, in contrast to the previously introduced systems, is able to classify the ES prior to extraction and also, takes into the account the patient-related factors as the class modifiers following the extraction.

KEYWORDS
classification, dental socket, extraction socket, immediate implants

1 | INTRODUCTION

Tooth extraction is indicated when a tooth has a hopeless prognosis.[1–3] Following the extraction, alveolar ridge resorption is often unavoidable, which may lead to compromised implant placement.[4] Depending on the hard and soft tissue conditions of the extraction socket (ES), various treatment approaches such as alveolar ridge preservation (ARP) or immediate implant placement (IIP) have been attempted.[5] The buccal plate thickness, buccal bone morphology, overlying soft tissue, and the pathologic condition of the socket are among the most important factors affecting the treatment decision-making and prognosis.[6,7]

Classification of a disease is crucial as it helps clinicians to identify the pathophysiology, symptomatology, diagnosis, and treatment approach. Likewise, it could be beneficial for the patients if an ES decision tree can be developed based upon the above available information. Generally, classification serves as a valuable tool for better communication between clinicians and patients and among researchers.[8] Ideally, a classification system should be user-friendly, precise and comprehensive without any overlaps between the disease entities, and based on the latest knowledge of pathophysiology and biology.[9]

Several single-rooted ES classification systems are available today, most of these classifications aim to predict the IIP according to the remaining buccal bone and/or overlying soft tissue components. However, the presence of many ES classification systems may create unnecessary confusion among involved parties. Moreover, there is lack of consensus with regards to which ES classification should be used. Each of the proposed systems possesses strengths as well as limitations. For instance, one may include a thorough evaluation of the hard tissue without considering the soft tissue elements whereas another one may only focus on soft tissue.[10] Therefore, the aim of this article was to provide a critical appraisal of current existing ES classifications within the framework of a systematic review and propose a new single-rooted ES classification that takes into consideration all important factors based on the latest evidence and consensus in implant dentistry.

2 | MATERIALS AND METHODS

2.1 | Protocol and registration

The analysis and interpretation methodology of this study were defined within the framework of a protocol and registered prior to initiation in PROSPERO portal (CRD42022345141). Moreover, the protocol and the search strategy were created based on the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) statement (Appendix S1).

2.2 | Problem, intervention, comparison, and outcome (PICO) statement

Problem (P): Lack of consensus regarding the single-rooted ES classification.

Intervention (I): Evaluation of available ES classification systems.

Comparison (C): Comparison of the included variables and factors into each ES classification.

Outcome (O): Proposal of a new single-rooted ES classification system to ease the decision-making process.

2.3 | Focused question

Based on the stated PICO design, the focused question for this study was proposed as follows:

What are the currently available ES classification systems for single-rooted sockets, the factors concerning ES that are considered and the suggested treatment approaches?

2.4 | Systematic search strategy

A systematic search approach was performed by two authors (Hamoun Sabri, Shayan Barootchi) in the electronic databases of: PubMed (MEDLINE), Embase, and Scopus, aiming to identify all proposed ES classification systems until January 1, 2022. The main keywords were: "extraction socket" OR "tooth socket" AND "Classification." The complete performed searching process and keywords are available as the Appendix 2.

The inclusion criteria were reserved to the following articles:

1. Presenting a new single-rooted ES classification system compared to the previously introduced ones.

On the contrary, the exclusion criteria were as follows:

1. Articles in which the authors implemented one of the previously published systems.
2. Studies with focus on a different topic besides ES classification.
3. Molar (multi-rooted) ES classifications.
4. Theses, abstracts, letters to the editors and editorials.

Moreover, no limitations were applied in terms of the language and date of the publication.

The search results were imported into EndNote (version X9) and deduplicated based on title, and additionally, the automatically identified duplicates were double-checked manually. Two reviewers (Hamoun Sabri, Shayan Barootchi) screened the results independently against the eligibility criteria using Review manager (REVMAN) software (version 5.3.5). The full-text reading of the selected articles was performed searching for the other classification systems (if had not been included) and those detected from the screening of the reference list of the included articles were also added. In case of any discrepancies between the two reviewers, this resolved by referring to the senior reviewer (Hom-Lay Wang). The inter-reviewer reliability in the screening and inclusion process were assessed with Cohen's k test. The included articles were thoroughly reviewed and analyzed.

2.5 | Types of included studies

This systematic review contained prospective, retrospective, cohort, case–control, review studies without any language and date limitation.

2.6 | Data extraction

Based on the aim of the study, the following data were extracted independently from the included ES classifications: Study design, date of publication, proposed ES types and description in each classification, parameters based on which the ES classification was performed and suggested treatment approach and considerations for each type of socket.

2.7 | Quality assessment of the included studies

The full texts of the included ES classifications were determined with regards to their methodological quality and validity. This was performed based on the COnsensus-based Standards for the selection of health Measurements (COSMIN) checklist.[11,12] Fundamentally, this checklist was applied to thoroughly investigate the methodological quality of each classification.[13,14] This checklist evaluates three measurement property of reliability, validity, and responsiveness. Based on these three components, 10 Boxes have been defined on the COSMIN platform (patient reported outcomes, internal consistency, reliability, measurement error, content validity, structural validity, hypothesis testing, cross-cultural validity, criterion validity, and responsiveness) 8 of which were eligible for this study (patient reported outcomes and cross-cultural validity were excluded). Two reviewers performed the quality assessment (Hamoun Sabri, Shayan Barootchi) and in case of disagreement the third investigator (Hom-Lay Wang) confirmed the decision.

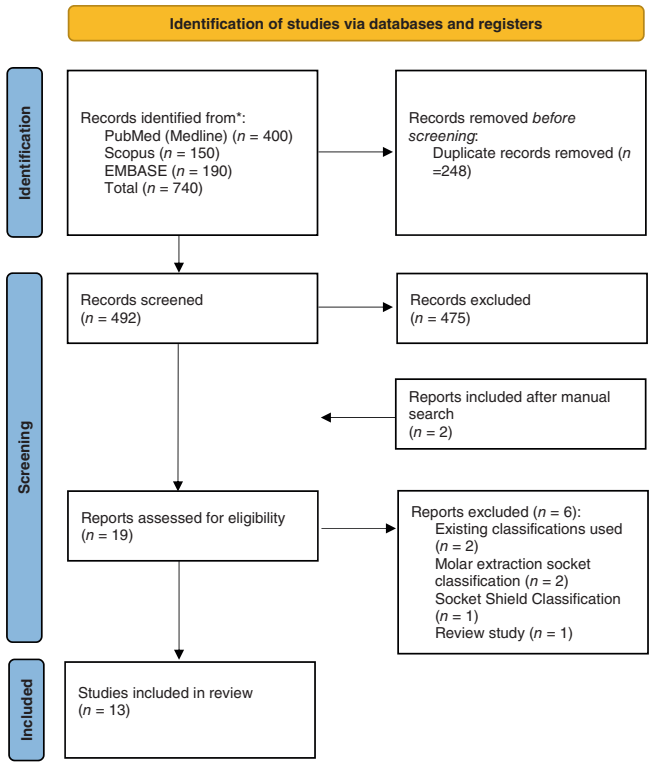

FIGURE 1 The PRISMA chart of the identification, screening, and selection process of the present systematic review. ES, extraction socket; PRISMA, Preferred Reporting Items for Systematic Review and Meta-analysis

3 | RESULTS

3.1 | Search results and study selection

The literature search process, based on the PRISMA guidelines is shown in Figure 1. This consisted of two stages. Firstly, following the primary search, 740 articles were identified. Following removal of duplicates, 492 records remained for screening by titles and abstracts. After thorough evaluation of the titles and abstracts 17 articles were selected. As the second stage, after the manual screening of the reference list of the articles, two additional ES classifications were also detected and included to the study. Following the full-text assessment of these studies and based on predetermined inclusion criteria, 13 articles were included in the qualitative analysis. The reasons for exclusion of the six records are provided in Table 1. The inter-reviewer reliability in the screening and inclusion process, as assessed with Cohen's k, corresponded to 0.91 and 0.88 for assessment of titles and abstracts and full-text evaluation respectively.

TABLE 1 Excluded studies and the reasons for exclusion

Authors	Type of study	Reason for exclusion
Kumar and Kher[51]	Case report and review	Socket shield classification
Juodzbalys et al.[39]	Systematic review	Review of socket augmentation and ARP
Al-Shabeeb et al.[52]	Pilot animal study	An existing ES classification was implied
Juodzbalys and Wang[53]	Pilot clinical study	An existing ES classification was implied
Smith and Tarnow[54]	Technical note	Molar extraction socket classification
Bleyan and Gaspar[55]	Retrospective	Molar extraction socket classification

Abbreviations: ARP, alveolar ridge preservation; ES, extraction socket.

3.2 | Findings from the COSMIN quality assessment of the classifications

Using the COSMIN checklist, the quality of the ES classification systems included in this study was evaluated (Table 2). Out of 13 classifications, none of them met the criteria for adequate internal consistency and responsiveness. 10 of the included classifications lacked "adequate" or "very good" properties in any of the 8 evaluated entity.[10,15–23] Overall, the classification system by Juodzbalys et al.,[6] had "adequate" reliability and testing "measurement error". Moreover, although the classifications by Chang and Cheng[4] and Kim et al.,[24] yielded "adequate" hypothesis testing and structural validity respectively, all the other tested parameters were either "inadequate" or "doubtful." Overall, the results of this quality assessment revealed a strong deficiency in terms of the validity and reliability of the existing classification systems.

TABLE 2 COSMIN[a] checklist for the quality assessment of the existing extraction socket classification systems

		Reliability			Validity				
Classification system	Components	Internal consistency	Reliability	Measurement error	Content validity	Structural validity	Hypotheses testing	Criterion validity	Responsiveness Responsiveness
Salama and Salama, 1993[15]	Apical residual bone Defect walls Dehiscence	Inadequate	Inadequate	N/A	N/A	Inadequate	Doubtful	N/A	Inadequate
Tinti and Parma-Benfenatti, 2003[19]	Bone housing around the placed implant	Inadequate	Inadequate	Inadequate	N/A	Inadequate	Inadequate	N/A	Inadequate
Caplanis et al., 2005[23]	Tissue phenotype Number of affected walls Ht loss Past medical and dental history Systemic risk factors	Inadequate	Inadequate	Inadequate	Inadequate	Doubtful	Inadequate	Inadequate	Inadequate
Elian et al., 2007[16]	Buccal HT Buccal ST	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
Juodzbalys et al., 2008[6]	Alveolar process height Apical residual bone Labial plate thickness and position Pathology St phenotype	Doubtful	Adequate	Adequate	Doubtful	Doubtful	Doubtful	Doubtful	Inadequate
Al-Hezaimi et al., 2011[10]	Blood supply Adjacent teeth	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
Iyer et al., 2014[20]	Buccal plate thickness Number of affected walls	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
Chu et al., 2015[22]	Residual buccal bone (intact ST in all types)	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
El Chaar et al., 2016[17]	Residual buccal bone Interproximal bone Apical residual bone ST phenotype	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
Al-Yafi et al., 2019[21]	Dehiscence and fenestration Buccal plate thickness Interproximal bone ST phenotype Recession Esthetic concern	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
Chang and Cheng, 2021[4]	HT destruction ST destruction Infection Systemic disease	Inadequate	Inadequate	Doubtful	Doubtful	Inadequate	Adequate	Inadequate	Inadequate

(Continues)

TABLE 2 (Continued)

Classification system	Components	Reliability			Validity				Responsiveness
		Internal consistency	Reliability	Measurement error	Content validity	Structural validity	Hypotheses testing	Criterion validity	Responsiveness
Kim et al., 2021[24]	Buccal bone loss Palatal bone loss Remaining HT walls ST Destruction Etiology of extraction	Inadequate	Inadequate	Inadequate	Doubtful	Adequate	Inadequate	Doubtful	Doubtful
Cardaropoli et al., 2021[18]	ST level Buccal Plate resorption Local bone anatomy	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate

Abbreviations: HT, hard tissue; N/A, not available; ST, soft tissue.
[a]Patient reported outcome results and cross-cultural validity were not applicable to this study.

3.3 | Description of the included studies

A summary of all ES classifications including the factors considered, treatment protocols for each subtype is provided in Table 3.

3.4 | Brief history of ES classifications

The very first attempt to introduce a classification system for single-rooted ESs was proposed by Salama and Salama[15] in 1993. This was within the framework of the regenerative potential based on the guidelines of infrabony periodontal defects, local topography and specifically, the remaining buccal plate. Later on, in 2003, another classification was introduced by Tinti and Parma-Benfenatti.[19] This was based on the remaining bony housing around the future implants and its regenerative potential. Caplanis et al.;[23] however, were the first group to add the soft tissue parameters to the classification system in addition to the hard tissue components.

Later on, Elian et al.,[16] introduced a simplified classification as well as a non-invasive approach for the management of ESs where the soft tissue is present, but the buccal plate is compromised. A sub-classification for this system was introduced in 2015 by Chu et al.,[22] in which they aimed to provide a more detailed description for the type 2 defects. Similar to Elian's classification, Juodzbalys et al.,[6] aimed to classify the ESs based on the quantitative and qualitative evaluations of both soft and hard tissue adjacent to the socket.[6] The only animal study that was included to this review was conducted by Al-Hezaimi et al., in 2011.[10] They concluded that a compromised interdental blood supply, and consequently, the interdental remaining bone contributes to the bone resorption in ES and proposed their classification based on the presence of adjacent teeth and the situation of interdental bone. Another ES classification was introduced by El Chaar et al.,[17] group, mainly based on the bone topography of the socket.

More recently proposed classifications consist of Iyer et al.,[20] in 2019, which was solely based on the hard tissue components, and Chang and Cheng,[4] Kim et al.,[24] and Cardaropoli et al.,[18] classifications all published in 2021. The Chang and Cheng's[4] system is a modification for Elian's classification, which is based on the amount of tissue destruction in all four walls of ESs. The classification by Kim et al.,[24] refers to the pathologically affected, single-rooted ESs. Fundamentally, this was done based on the hard and soft tissue condition of ESs following tooth loss due to periodontal and/or endodontic infection. Similarly, identical variables were also taken into consideration by Cardaropoli's classification.[18]

3.5 | Included factors in existing classification systems

After a thorough evaluation of the detected ES classification systems, the proposed parameters that are taken into account to classify sockets for all the classifications were evaluated. Generally, the

TABLE 3 The characteristics of the included single-rooted extraction socket classification systems

Classification	Study design	Soft tissue parameters	Hard tissue parameters	Patient related factors	Subtypes	Treatment approach	Considerations
Salama and Salama, 1993[15]	Case series	None	Residual bone around apex Defect walls Dehiscence	None	T1	IIP/Adjunctive treatments if compromised or severe case	–
					T2	DIP + ARP or forced eruption	–
					T3	DIP + regeneration with DFDB allografts + tetracycline covered by a membrane	–
Tinti and Parma-Benfenatti, 2003[19]	Case series	None	Bone housing around the placed implant	None	C1	N/A	–
					C2	N/A	–
Caplanis et al., 2005[23]	Review	Tissue phenotype Soft tissue predictability	Number of affected walls HT Loss	Past medical and dental history Detection of systemic risk factors	EDS-1	IIP	–
					EDS-2	ARP + IIP or ARP + DIP	–
					EDS-3	ARP + DIP	–
					EDS-4	ARP + Site development + DIP (three stage)	–
Elian et al., 2007[16]	Case series	Remaining buccal ST	Remaining Buccal HT	None	TI	IIP/DIP	The easiest and most predictable
					TII	Staged approach with HT and with or without ST augmentation	Risk of misdiagnosing as type I/difficult to diagnose
					TIII	Staged approach with HT with or without ST augmentation	Require experience, dexterity, and time
Juodzbalys et al., 2008[6]	Case series	Tissue phenotype ST quality (color, consistency, contour)	Alveolar process height Residual bone around apex Labial plate thickness and position Pathology	None	TI	IIP	Optimal esthetic outcomes expected
					TII	IIP or DIP with ST or HT augmentation	–
					TIII	DIP after ST or HT augmentation or orthodontic forced eruption	–
Al-Hezaimi et al., 2011[10]	Animal study	Blood supply to the area	Presence of adjacent teeth	None	CI	N/A	–
					CII	N/A	–
					CIII	N/A	–
Iyer et al., 2014[20]	Review and case series	None	Buccal plate thickness Number of affected walls	None	CI	IIP without ARP/ARP + DIP	–
					CII	IIP + graft/DIP + graft or ARP	
					CIII	Particulate graft + IIP if primary stability achievable	
					CIV	Socket walls regeneration + DIP	
					CV	Augmentation with autogenic or allogenic grafts + DIP	
					CVI	Major interventions (e.g., distraction osteogenesis and etc.) + DIP	
Chu et al., 2015[22]	Case series	Intact Labial ST in all types	Residual buccal bone	None	T2A	IIP + GBR (caution on T2C sockets)	–
					T2B		–
					T2C		–

(Continues)

TABLE 3 (Continued)

Classification	Study design	Soft tissue parameters	Hard tissue parameters	Patient related factors	Subtypes	Treatment approach	Considerations
El Chaar et al., 2016[17]	Case series	ST phenotype	Apical topography Buccal plate loss% Interproximal bone	None	GI	IIP with without provisionalization and bone graft	–
					GII	Thin phenotype: DIP + ARP Thick phenotype: IIP without temporization	–
					GIII	ARP or forced eruption	In case of compromised apical topography→ DIP + GBR
Al-Yafi et al., 2019[21]	Review	Tissue phenotype Recession	Dehiscence and fenestration Buccal plate thickness Interproximal bone height	Esthetic concern	CIA	IIP/2 Stage	3 Stage approach: ARP + Site development + implant placement
					CIB	IIP/2 Stage	
					CIIA	IIP with grafting/2 Stage	
					CIIB	2 Stage/3 Stage	
					CIIIA	IIP with grafting/2 Stage	
					CIIIB	2 Stage/3 Stage	
					CIVA	IIP with grafting/2 stage	
					CIVB	3 Stage	
Chang and Cheng, 2021[4]	Retrospective	ST destruction	HT destruction	Systemic disease Infection	CI	Varies based on the patient related factors: Natural healing to ridge augmentation	IIP can be performed if primary stability is achievable
					CII		
					CIII		
					CIV		
Kim et al., 2021[24]	Cohort	Buccal ST level	Number of remaining walls Buccal and palatal bone loss	Etiology of the tooth loss	TI	IIP	If no infection or thin buccal plate is present
					TII	IIP + GBR or DIP	Risk of compromised esthetics in IIP DIP preferred in extensive destruction
					TIII	ARP + CTG or FGG	–
					TIV	Ridge augmentation	Augmentation beyond the present envelope of bone
					TV	Extensive ridge augmentation (complementary bone augmentation after healing)	–
Cardaropoli et al., 2021[18]	Case series	ST level	Buccal Plate resorption Local bone anatomy	None	CI	IIP/ARP + DIP	–
					CII	Ridge augmentation + DIP/ DIP + simultaneous bone augmentation	
					CIII	Ridge augmentation W/WO ST augmentation + DIP/DIP with simultaneous bone augmentation	
					CIV	Ridge augmentation W/WO ST augmentation + DIP/Delayed bone augmentation + DIP/	

Abbreviations: ARP, alveolar ridge preservation; C, class; CTG, connective tissue graft; DFDB, demineralized freeze-derived bone; DIP, delayed implant placement; EDS, extraction defect sounding; ES, extraction socket; FGG, free gingival graft; G, grade; GBR, guided bone regeneration; HT, hard tissue; IIP, immediate implant placement, ST, soft tissue; T, type.

parameters which have been used to evaluate the socket prior to the classification can be divided into three groups: hard tissue parameters, soft tissue parameters and patient related factors. Figure 2 shows the pie chart of the included factors to all the selected ES classifications.

3.5.1 | Hard tissue parameters

Remaining buccal bone dimensions

The buccal bone dimensions, including thickness, buccal bone loss such as dehiscence, are taken into account in almost all ES classifications. Only two studies introduced the hard tissue dehiscence as a main factor to consider.[15,21] However, this consisted of solely qualitative evaluation (presence or absence).

The extent of buccal bone loss was considered as a parameter to classify the socket in nine studies.[4,6,16–18,21–24] According to the reviewed studies, the amount of acceptable buccal bone loss allowing for IIP is up to 2 mm or 20%–25% of resorption.[6,17,18,23] Moreover, one study also added the amount of bone loss on the palatal aspect in addition to buccal.[24] The thickness of the buccal plate is also included in four systems.[6,20,21,23] All classification systems considered at least 2 mm of buccal bone thickness as an acceptable parameter for IIP.

Defect walls

This parameter has taken into account in four systems.[15,23,20,24] Overall, it can be stated that based on the included classifications, the regenerative potential as well as the vascularity of the socket decreases in 3- or less-wall defects compared to a 4-wall intact bony structure and the prognosis of an IIP in 4-wall defects, provided that the other parameters are also in optimum levels, can be considered as "good."[17,20,21]

Apical topography

Three of the selected ES classification systems considered the apical topography as a main factor to classify defects.[6,15,19] Moreover, the rationale to bear in mind is the amount of remaining bone in the apical region to be engaged with the implant. For instance, the minimum amount of remaining bone is around 3 to 4 mm, to be in contact with the implant.[6,17]

Future peri-implant hard tissue

The foreseeable amount of bone housing around the future implants were considered by Tinti and Parma-Benfenati[19] for the single-rooted socket classification. This refers to the importance of an intact envelope of bone for clot stability.

Finally, El Chaar et al.,[17] and Al-Yafi et al.,[21] added the interproximal bone parameter to the previous criteria, as the level of

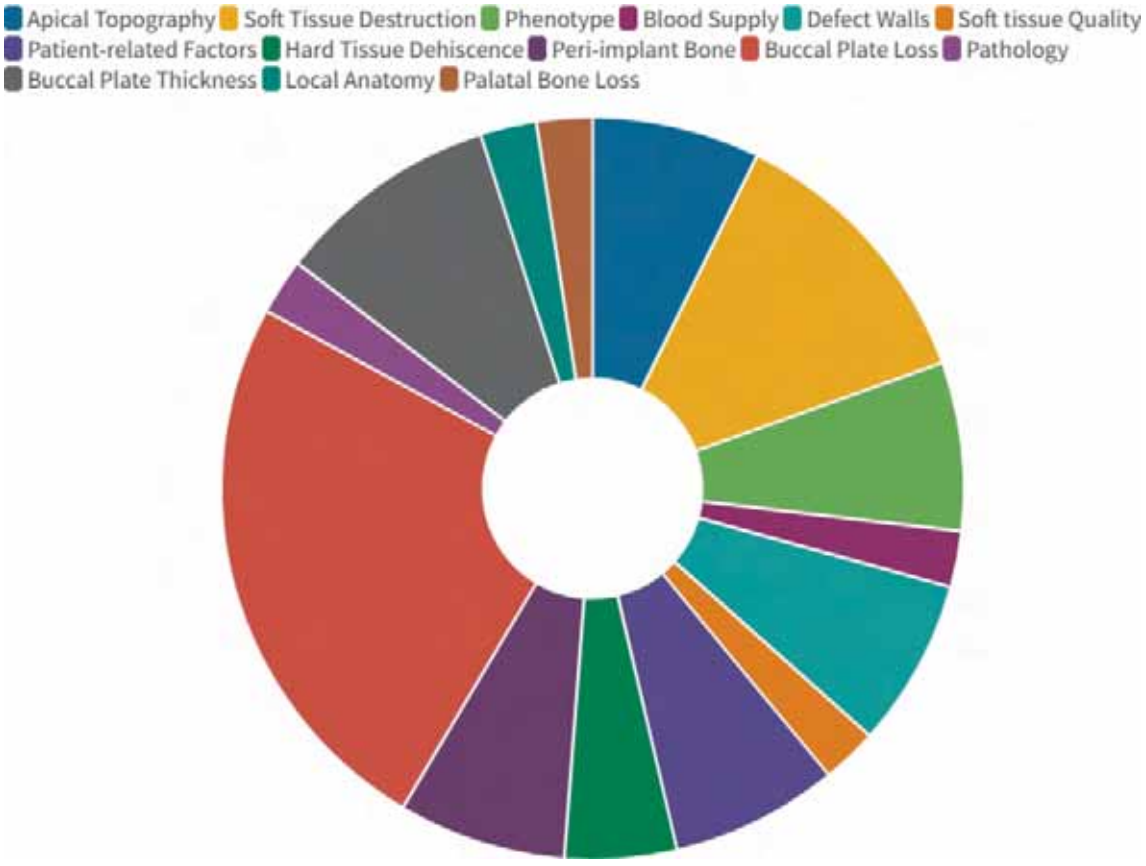

FIGURE 2 The pie chart of all parameters that are taken into account by the previous classification systems included to this study

TABLE 4 The new extraction socket classification. Class I: refers to a socket with ideal condition and able to receive IIP. The etiology for extraction is not periodontitis-related and mostly includes endodontic-related origins and excessive caries or fracture. The amount of gingival recession does not exceed 3 mm. the soft tissue phenotype is thick. In the radiographic images, at least 2 mm of buccal bone thickness without dehiscence, interproximal bone loss and apical pathology can be seen. The root position is ideal for IIP planning. Class II: Whenever the ES includes at least one of the proposed criteria in this class, it will be considered as a Class II socket. This consists of a mildly affected socket. A thin phenotype can be detected. Radiographic parameters include less than 2 mm of buccal bone thickness and less than 50% dehiscence with or without interproximal bone loss and/or apical lesion. The root position is adjacent to the palatal plate. Mild periodontal or endo-perio origin can be a feature of class II sockets. Class III: The etiology of a class III socket can be severe perio or endo-perio lesions. The gingiva has more than 3 mm of recession also severe loss of buccal plate in terms of dehiscence puts a socket into class III. The root position in unfavorable with only 2/3 of the root engaging the buccal and palatal plates. In order to facilitate classification process, even one criteria that meets the features of each class will put the ES into the respective socket type. For instance, a socket with ideal clinical and radiographic parameters but gingival recession of more than 4 mm would be considered as a class III

	Single-rooted extraction socket classification		
	Class I	**Class II**	**Class III**
Etiology	Non periodontal	Mild periodontal or endo-perio lesion	Severe periodontal or endo-perio lesion
Gingival recession (mm)	≤3	–	>3
Soft tissue phenotype	Thick	Thin	–
Buccal bone width (mm)	≥2	<2	–
Buccal bone loss	Intact	<50%	>50%
Interproximal bone loss	No	Yes	–
Apical pathology	No	Yes	–
Root position	Adjacent to vestibular plate/at the center	Adjacent to palatal plate	At least 2/3 of the root engaging both buccal and palatal plates

interproximal bone dictates the presence or absence of the soft tissue and interproximal papillae.

3.5.2 | Soft tissue

Soft tissue phenotype (previously named biotype)

Four ES classifications pointed out to the important role of the tissue phenotype.[6,17,21,23] This is because tissue phenotype plays an important role in the implant esthetics. In general, thick tissue phenotype often achieve better esthetic outcomes as well as to be more inclined to IIP.[6] However, for a thin tissue phenotype, more conservative approaches are often suggested to minimize the potential esthetic challenges.

Buccal soft tissue level/loss

The destruction and amount of the remaining soft tissue was included in six classifications.[4,6,16,18,21,24] This variable was assessed qualitatively in all studies except, in the classification by Juodzbalys et al.,[6] it was stated that a soft tissue loss of more than 2 mm contributes to a poor prognosis for ESs.

Soft tissue quality

This consisted of soft tissue predictability which was proposed by Caplanis et al.,[23] and the soft tissue quality by Juoudzbalys et al.[6] The former comprises evaluation of various factors affecting the outcomes of future soft tissue and the latter refers to qualitative features of the soft tissue such as consistency, color, and contour.

Blood supply

One of the included systems took the blood supply to the ES into account in the classification.[10] This concept was investigated by Al-Hezaimi et al.,[10] and they suggested that the blood supply to the ES is derived from interdental bone (the internal walls of the socket) and this is an important factor in terms of the soft tissue contours and prevention of bone resorption. Thus, the presence of adjacent (proximal) teeth serves an important consideration in maintaining the blood supply to the area.

3.5.3 | Patient- and tooth-related factors

Etiology, pathology, and systemic factors

The presence of socket pathology prior to extraction and the etiologic factors were only considered in three classifications.[4,23,24] This mainly consisted of pre-extraction evaluation of the systemic health and risk factors and the cause of extraction (e.g., infection, fracture, etc.) which can affect the prognosis of the treatment. Generally, none of the classification systems clearly mentioned the exact factors to consider. Finally, in one classification system the authors considered the esthetic concern of the patient as one of the main factors.[21]

3.6 | Evaluation tools

All classification systems performed the socket evaluation using clinical and radiographical findings. Moreover, some classification systems specifically mentioned the CBCT images should be taken and evaluated[18] whereas in others the necessity of CBCT image acquisition was not

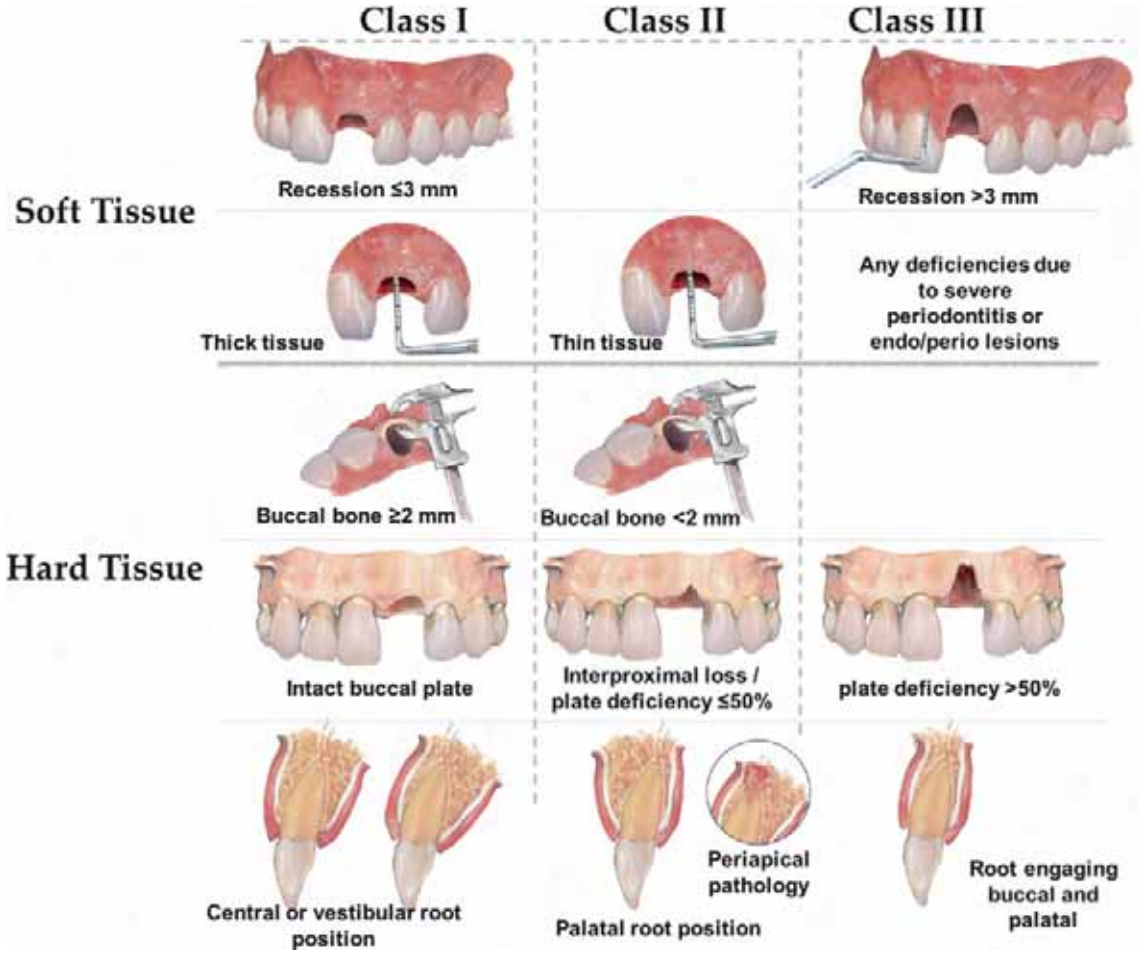

FIGURE 3 the new single-rooted extraction socket classification system. (note that the presence of even one criterion from each class will put a socket into that group. For instance, more than 50% of buccal bone deficiency, even without presence of gingival recession of >3 mm would still be considered as a class III socket)

FIGURE 4 Clinical evaluation of the ES prior to the extraction. (A) a chronic fistula and presence of interproximal attachment loss. Based on clinical findings this would be put into class II. (B) More than 3 mm of gingival recession and interproximal attachment loss in a class III socket tooth. ES, extraction socket

stated. In one classification, the authors utilized a prefabricated prosthetic guide to evaluate the hard and soft tissue around the socket.[23]

4 | PROPOSAL OF A NEW CLASSIFICATION SYSTEM

Based on the proposed quality assessment and critical appraisal, and also, taking the latest consensus reports[7,25–28] into consideration, a new single-rooted ES classification was proposed. The new classification system is presented in Table 4 and Figure 3. This consists of three main steps to apply as follows:

The first two steps determine the sockets' class based on the morphologic and anatomical features. The first step is determining clinical factors with regards to ES (Figure 4):

1. Determining the etiology of extraction: extractions with the etiology of excessive caries, endodontic failure, root fractures yield superior prognosis compared to tooth loss due to severe periodontitis or severe endo-perio lesions (Figure 4A).[25]

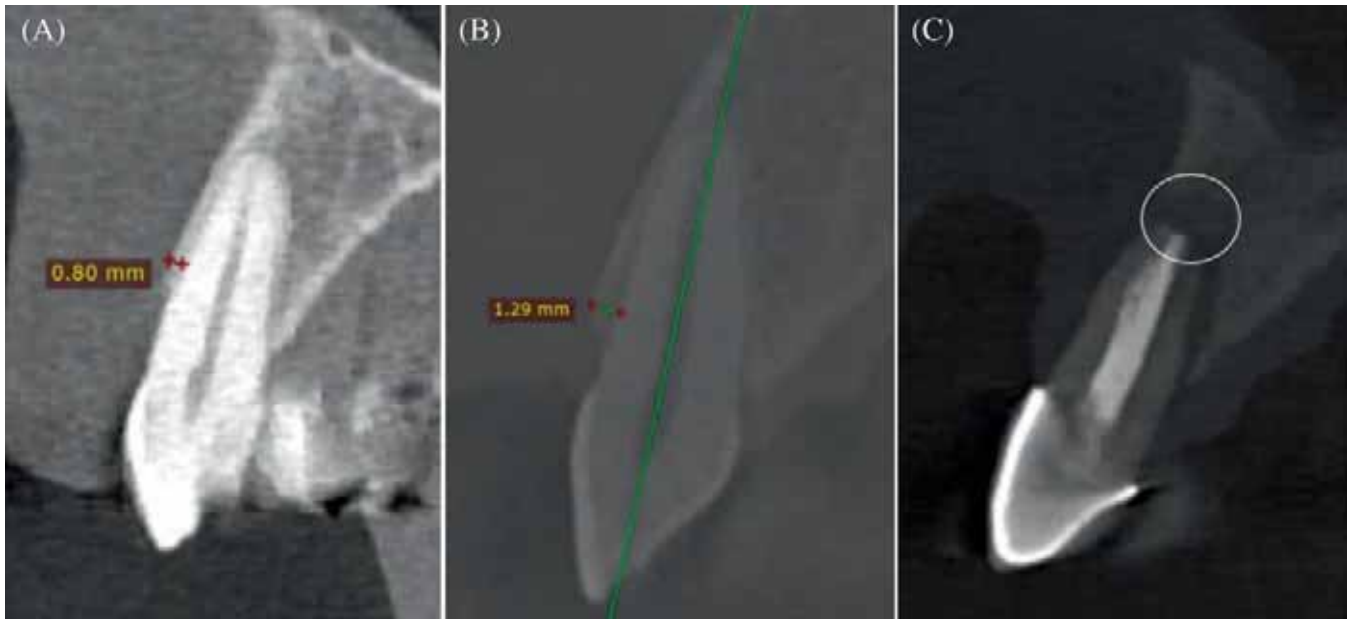

FIGURE 5 Examples of radiographic evaluation of the future ES prior to extraction. (A) A future class II extraction socket with thin (<1 mm) buccal bone thickness and moderate buccal plate dehiscence (<50%). (B) A class II socket with buccal bone thickness between 1 and 2 mm and sagittal root position adjacent to the vestibular plate. (C) A class III socket with more than 50% of buccal bone dehiscence and an apical lesion. ES, extraction socket

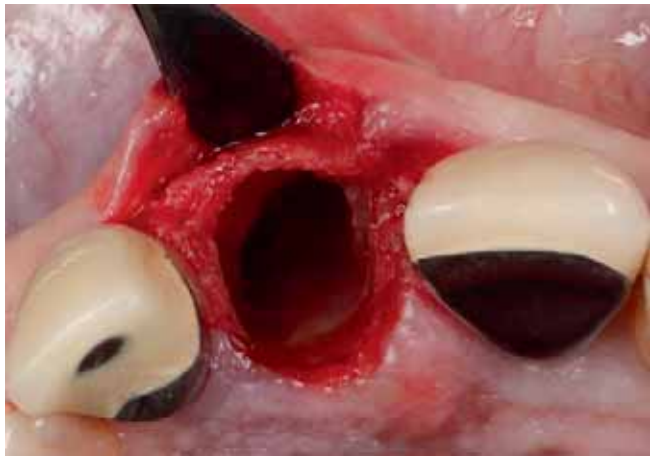

FIGURE 6 The third step of the extraction socket classification: evaluation of the post-extraction socket to confirm the classification. This consists of confirming the amount of remaining buccal bone as well as interproximal plates and the apical topography

2. The amount of gingival recession at the extraction site. A gingival recession of more than 3 mm is considered to be associated with risk of soft tissue deficiency following IIP[6,29] (Figure 4B).
3. Determination of soft tissue phenotype: this parameter can be either thin or thick and plays a key role in determination of future peri-implant soft tissue.[25,27]

Following the clinical examination, the radiographic examination can be performed based on available radiographs and CBCT as the second step (Figure 5).

1. Buccal Bone: the thickness and amount of dehiscence should be considered. Up to 50% of buccal plate loss could be manageable if IIP is considered (Figure 5A,B).[25]
2. Interproximal bone loss: is especially important in the esthetic zone as it contributes to future papilla fill and prevents future interproximal soft tissue defects.[30]
3. Apical Lesions: current evidence indicates favorable success rates for IIP in sockets with periodontal lesion and/or periapical pathology.[31,32] However, before placing the implant careful and thorough decontamination and removal of the infected tissue is required[25,27] (Figure 5c).
4. Root position: this parameter predicts the future three-dimensional position of the implant. In IIP more palatal/lingual positioning of the implant is desired to avoid excessive contact with the residual buccal plate[25,27] to fulfill "prosthetically driven" concept[33,34] (Figures 3 and 5).

Following the second step the initial classification of the socket can be achieved. This allows the dentist to preliminarily diagnose and perform treatment planning. Nevertheless, if the tooth is extracted, the third step (Figure 6) can be initiated, which considers possible class modifiers that are only examinable following removal of the tooth and by inspection of the residual socket, based on possible events during extraction surgery and future implant osteotomy factors, patient-related factors, and also any adverse events during the extraction following criteria:

1. Presence of poorly controlled systemic disease: factors such as diabetes mellitus, smoking and advanced autoimmune conditions may affect the socket healing process as well as pregnancy or adolescence. Therefore, in such scenarios caution would be required.[25]

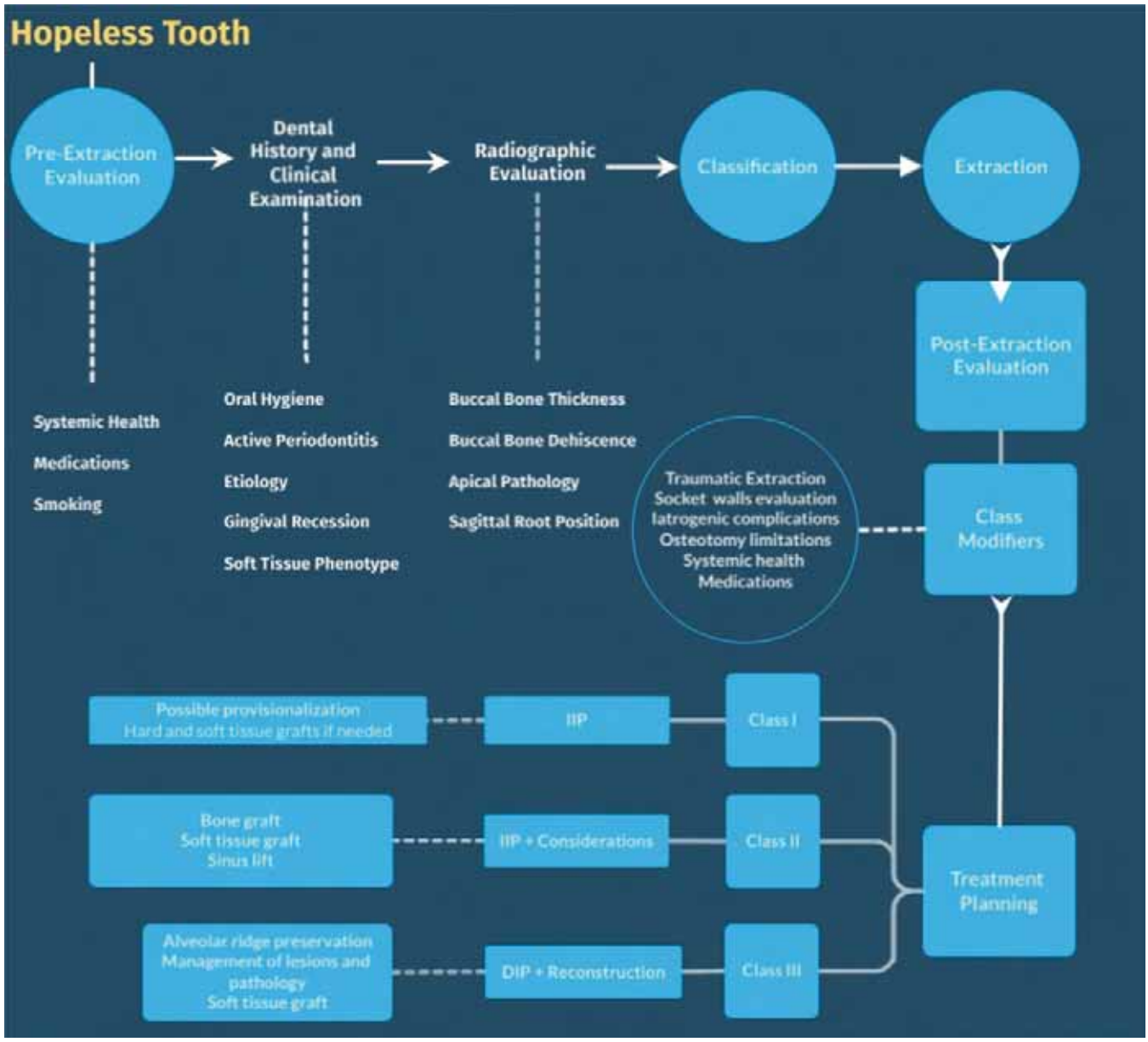

FIGURE 7 The suggested flow-chart to follow for the management of extraction sockets. DIP, delayed implant placement; IIP, immediate implant placement.

2. Smoking: smoking more than 10 cigarettes per day would be considered as a risk indicator in the IIP.[32]
3. Medication history: if the patient takes any medications which can affect favorable healing of the socket, despite scarcity of the literature supporting this point of view, in certain cases (such as bisphosphonate, chemotherapy agent, etc.), caution is necessary.[25,35]
4. Presence of active periodontitis in the same sextant. Although data regarding detrimental impact of previous periodontitis on IIP is controversial[27,36,37] presence of active periodontitis within the same sextant could serve an additional risk for IIP.[38,39]
5. Evaluation of oral hygiene: poor oral hygiene may increase the failure and complications in IIP.[5]
6. Any major trauma during the procedure; which causes failure in preservation of hard and soft tissue quality.[40]
7. Occurrence of iatrogenic complications: such as sinus membrane perforation, buccal plate fracture, and so forth.
8. Re-evaluation of buccal bone thickness and bone quality. This step is advised to be followed in order to re-evaluate and confirm the pre-extraction diagnosis and apply any changes if needed.
9. Osteotomy related factors: including the presence of possible limitations in osteotomy sequence of implant (e.g., risk of damage to the adjacent root or nerves,[41] location of nasopalatine canal, etc.).[28,42]

Lastly, based on the proposed classification system, a decision-making flowchart is presented in Figure 7 demonstrating the suggested approach in the management of ESs. (Table 5)

TABLE 5 Extraction socket class modifiers. The modification proceeds the classification step. This aims to include factors that are not properly examinable prior to the extraction and designed to adjust the initial classification if required. These can be divided into patient-, extraction- and osteotomy-related factors. If the extraction process occurs invasively and cause any damage to the adjacent structure this will transform class I and II to class III. Similar scenario is applicable for iatrogenic complications such as nerve damage or sinus floor perforation. Finally, post extraction evaluation of the socket is required to determine whether it is possible to place implant in the correct position in correspondence to adjacent structure (nerve proximity, etc.) and if not possible, classes I and II will be considered as class III

	Post-extraction class modifiers		
Patient-related factors	Active periodontitis in the same sextant		Class I and II to III
	Poor oral hygiene		Class I and II to III
	Medications affecting healing		Class II to III
	Poorly controlled systemic disease		Class II to III
	Smoking	More than 10/day	Class I and II to III
Extraction-related factors	Invasively traumatic extraction (extensive bone removal)		Class I and II to III
	Iatrogenic complications (sinus floor damage, nerve damage, Buccal plate fracture)		Class I and II to III
	Post-extraction evaluation of buccal bone thickness and bone quality		If compromised, Class I and II to III
Osteotomy-related factors	Possible limitations in implant osteotomy (nerve proximity, adjacent roots, etc.)		If IIP not possible, Class I and II to III

5 | DISCUSSION

This article systematically reviewed all single-rooted ES classifications and proposed a new classification based on a critical appraisal and quality assessment of the previously available systems and with the aim of providing a system with combination of all crucial parameters to consider while performing dental extractions in the esthetic zone.

It is important to be able to discuss the treatment planning prior to the extraction of the tooth. This emphasizes the need for a classification system allowing to classify before the extraction. However, most of the existing ES classification systems lack this feature. Thereby, the introduced new classification system in this paper, allows clinicians to perform the initial classification prior to extraction (as demonstrated in Figures 4 and 5) and next, if proceeded to extraction, one can modify the class by the mentioned class modifiers accordingly (Figure 6). Needless to mention that a critical step (step 3) consists of clinically confirming the pre-extraction determined class by inspection.

Unfortunately, the importance of possible multiple ESs is underappreciated.[43] Although Al-Hezaimi et al.,[10] intended to consider this, the nature of the animal study leaves room for the further research. As a possible approach, condition of the interproximal walls between the adjacent ES was entered into the new ES classification.

All the previous systems, to some extent, covered the anatomical factors affecting the treatment approach. However, it should be noted that there was little attention to the patient related factors such as systemic diseases or smoking or even diabetes, which can easily transform a favorable ES to a questionable despite its undamaged structure. Therefore, one of the main goals of the newly proposed system was to include systemic conditions, as possible class modifiers, following the examination of the anatomical and topographic factors. In a study by Urban et al.,[44] it is indicated that smoking can be a risk factor for molar area IIP. Similarly, it is reported in the literature that despite its acceptable success rate, infectious ES needs adjunctive therapy and additional considerations if IIP is planned.[39,45] Also, it is elaborated throughout the studies that health-related systemic conditions such as diabetes and hypertension could possibly affect the ES healing process and therefore, alter the expected outcomes.[46,47] Therefore, all the aforementioned parameters included as the class modifiers the novel ES classification system.

An important aim of using classifications is to facilitate the communication among all involved parties. This needs the implementation of well-described and precise variables comprising the classification system.[8,48] However, it can be noted that most of the proposed ES classifications assess the defects qualitatively or at best a combination of qualitative and quantitative. This causes discrepancies in terms of diagnosis as it leads to intra- and inter-observer bias as well as several gray zones defining a defect and considering it adequate or compromised.[49] Further investigation on the repeatability of the classifications is suggested. In our classification system, we attempted to provide quantitative and/or dichotomous values for the parameters which increases the reproducibility and quality of assessment.

All included studies implemented radiographic images, either periapical, panoramic and CBCT or combination of these, for the examination of the hard tissue situation and periapical diagnosis. Nevertheless, in terms of the soft tissue evaluation there is a lack of standardized techniques to diagnose. Overall, CBCT images seem to be one of the cornerstones of the ES classification, thus, it is strongly suggested to perform classification by the means of this image modality. And for soft tissue parameters, currently the conventional clinical measurements are suggested.[50]

Lastly, it is suggested that a thorough soft and hard tissue evaluation in combination with patient related factors should be followed. Subsequently, the decision for either IIP or DIP with the suitable modification can be made and applied. Figure 7 illustrates the factors and the flowchart that is suggested to be take into account when performing tooth extractions using the new classification system. That being mentioned, within the limitation of systematic reviews, in this paper

we aimed to merely provide an overview concerning the available classifications and possible gaps within them and describe the characteristics of each one as well as the parameters that are included into each system. Moreover, the readers should bear in mind that the newly introduced classification system is solely based on the most recent consensus reports in implant dentistry[25,28] and despite its benefits in terms of updating the previous systems, it requires further studies to evaluate its validity, responsiveness, and reliability.[11,13,14]

6 | CONCLUSIONS

The present study provided a systematic review and a critical appraisal on the previous single-rooted extraction socket classifications and proposed a new classification system. This classification revises and updates the definitions and criteria from the former systems. An important feature is including the factors affecting future implant treatment, especially in the esthetic zone. Likewise, the most recent consensus-based criteria for immediate implantation such as soft tissue esthetic considerations as well as the sagittal root position was taken into consideration. Lastly, this classification considered the patient-related and extraction-related factors for the first time, as the class modifiers in case they have an impact on the prognosis and treatment planning following the extraction.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Sabri H, Barootchi S, Heck T, Wang H-L. Single-rooted extraction socket classification: A systematic review and proposal of a new classification system based on morphologic and patient-related factors. *J Esthet Restor Dent*. 2023;35(1):168-182. doi:10.1111/jerd.12967

Received: 21 October 2022 | Revised: 13 December 2022 | Accepted: 13 December 2022

DOI: 10.1111/jerd.13003

REVIEW ARTICLE

WILEY

Impact of peri-implant soft tissue characteristics on health and esthetics

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Abstract

Objective: To review the impact of key peri-implant soft tissue characteristics on health and esthetics.

Main Considerations: The keratinized mucosa width (KMW), the mucosal thickness (MT), and the supracrestal tissue height (STH) are essential components of the peri-implant soft tissue phenotype. An inadequate KMW (<2 mm) has been associated with local discomfort upon oral hygiene performance and increased risk for the onset of peri-implant diseases. A minimum buccal MT (≥2 mm) is generally required to prevent esthetic issues related to the effect of transmucosal prosthetic elements on the color of the mucosa and can also contribute to long-term mucosal stability. STH is directly related to marginal bone remodeling patterns during the early healing process that follows the connection of transmucosal prosthetic components. Short STH, generally defined as <3 mm, has been consistently associated with marginal bone loss resulting from the physiologic establishment of the mucosal seal. Insufficient STH may also derive into the fabrication of unfavorable transmucosal prosthetic contours, which frequently results in unpleasing esthetic outcomes and predisposes to submarginal biofilm accumulation. Peri-implant soft tissue dehiscences (PISTDs) are a type of peri-implant deformity that are associated with esthetic issues and often occur in sites presenting KMW, MT, and/or STH deficiencies. PISTDs should be correctly diagnosed and treated accordingly, usually by means of multidisciplinary therapy.

Conclusion: Understanding the impact of different dimensional and morphologic features of the peri-implant mucosa on health and esthetic outcomes is fundamental to make appropriate clinical decisions in the context of tooth replacement therapy with implant-supported prostheses.

KEYWORDS
implants

1 | INTRODUCTION

In contemporary implant dentistry, survival is no longer the ultimate endpoint. Other treatment outcomes related to peri-implant health and esthetics have been set to define therapeutic success.

Two tissue compartments support and surround implant fixtures and implant-supported prostheses: the peri-implant mucosa and the peri-implant bone. Since the inception of implant dentistry, for decades, clinical practice and research pivoted around the relevance of the peri-implant bone, specifically on how to predictably achieve osseointegration in the shortest possible time and on the optimization

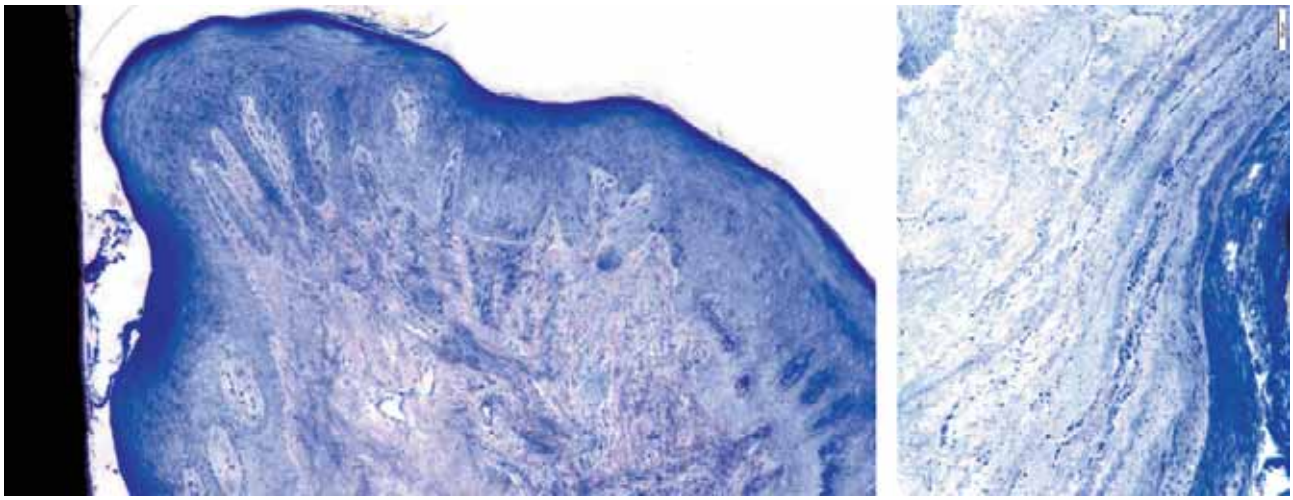

FIGURE 1 Photomicrograph of a sample of human keratinized peri-implant marginal mucosa (left). Note arrangement of the fibers contained within the connective tissue compartment (right). Histology processed by Peter Schüpbach. (Reprinted with permission from Monje & Avila-Ortiz)[84]

of bone-related implant site development interventions. However, in recent times the focus has shifted towards the peri-implant soft tissue and the clinical relevance of its phenotypical features.

Three distinct components of the peri-implant soft tissue phenotype (i.e., the morphologic and dimensional features of the peri-implant mucosa) deserve special attention: the keratinized mucosa width (KMW), the mucosal thickness (MT), and the supracrestal tissue height (STH).[1] Mounting scientific evidence has demonstrated the crucial role that each one of these elements plays on the outcomes of implant therapy. Therefore, careful analysis of each individual constituent of the peri-implant soft tissue phenotype and the identification of related deformities is required for proper diagnosis and treatment planning.

The objective of this narrative review is to provide an up-to-date evidence-based perspective on the effect that phenotypical (morphological and dimensional) peri-implant soft tissue characteristics have on health and esthetic outcomes, as well as a brief overview the therapeutic management of peri-implant soft tissue deformities that may compromise the success of implant therapy.

2 | THE PERI-IMPLANT MUCOSA

The peri-implant mucosa is oral mucosa adapted to the presence of an osseointegrated implant and its transmucosal prosthetic components.[2]

On its oral surface, the peri-implant mucosa is covered by a stratified squamous epithelium that may be keratinized or not (Figure 1). Keratinized mucosa (KM) is masticatory in nature and its external surface is covered by a keratinized stratified squamous epithelium identical to the oral epithelium that lines the gingiva (Figure 2). If present, this keratinized epithelium extends apically from the mucosal margin to the mucosal junction, where it meets the lining alveolar mucosa, which is non-keratinized. In the absence of keratinized mucosa, only alveolar lining alveolar mucosa can be observed around implant fixtures and transmucosal components.

On its internal surface, three different peri-implant soft tissue compartments may be observed from the mucosal margin to the peri-implant bone crest: 1. The sulcular epithelium, which may be partly keratinized on its coronal aspect; 2. The junctional epithelium, which is non-keratinized; and 3. the supracrestal connective tissue.

Although often indistinguishable from the gingiva and alveolar lining mucosa that is typically observed around teeth after a simple visual assessment, the peri-implant mucosa presents some important biological and structural differences. Notably, the connective tissue of the peri-implant mucosa normally contains a higher proportion of collagen fibers and exhibits lower cellularity and vascularity. In addition, there is no connective tissue attachment to the transmucosal implant surfaces, but rather epithelial adhesion through hemidesmosomes and a direct contact of the underlying connective tissue.[3,4] Also, the supracrestal soft tissue is generally taller around implants.[5,6] These features result in a reduced protective response, and a higher susceptibility to the onset and progression of microbial-based inflammatory diseases compared to the periodontal tissues.[7]

3 | SIGNIFICANCE OF KMW ON PERI-IMPLANT HEALTH AND ESTHETICS

KMW is the vertical dimension of keratinized soft tissue that runs in an apico-coronal direction from the mucosal margin to the mucosal junction. As previously mentioned, this phenotypic component may be present or not, as there are peri-implant sites that do not exhibit any keratinized mucosa.

3.1 | KMW and peri-implant health

According to existing evidence in the field of periodontology, the presence of attached gingiva, which is keratinized by definition, is beneficial

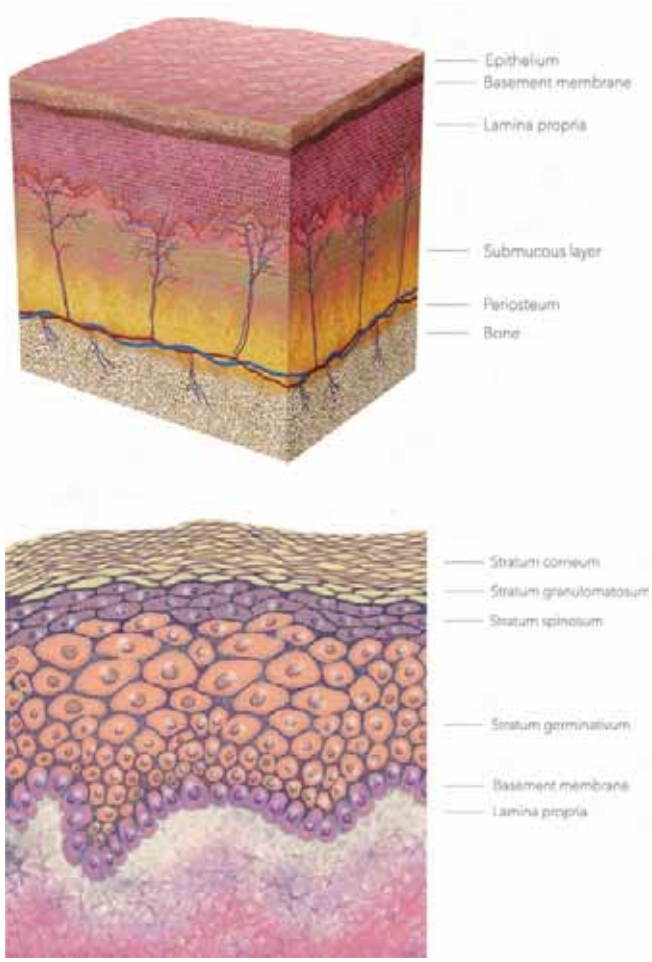

FIGURE 2 Illustrations showing (A) the arrangement of the main components of the oral mucosa and (B) the layers of the keratinized stratified squamous epithelium of the oral mucosa (Reprinted with permission from Monje & Avila-Ortiz)[84]

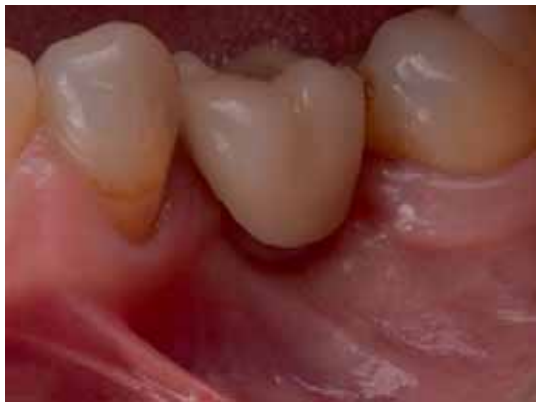

FIGURE 3 Alveolar mucosa is often associated with a shallow vestibulum. This often interferes with self-performed plaque-control measures and typically leads to mucosal inflammation.

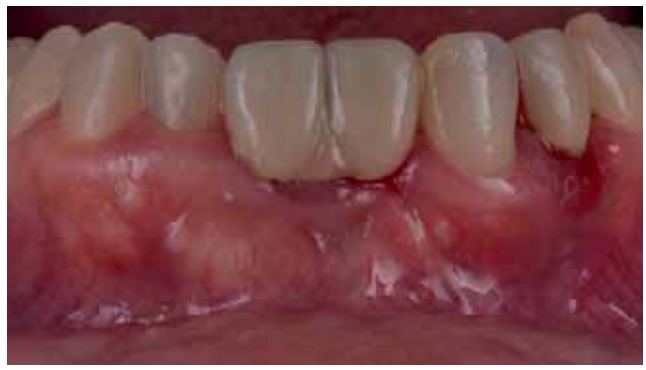

FIGURE 4 The presence of keratinized mucosa does not ensure an effective soft tissue sealing in sites where microbial biofilm control is suboptimal and in absence of partial attachment of that keratinized tissue to the underlying bone.

in patients with suboptimal oral hygiene; whereas patients with adequate plaque control may not benefit from the presence of a minimum width attached gingiva.[8] However, it must be noted that absence of or a reduced width of gingival tissue (<2 mm, of which 1 mm should be attached) has been linked to an increased risk for the appearance of gingival recession defects and non-carious cervical lesions.[9,10]

Although it is well established that there is no connective tissue attachment around implants, when there is sufficient KMW and part of it is attached to the alveolar bone, the peri-implant soft tissue collar is more firmly adapted to the transmucosal prosthetic components and the mucosal seal is, therefore, more efficient in preventing bacterial apical migration.[11,12] On the contrary, friable and movable non-

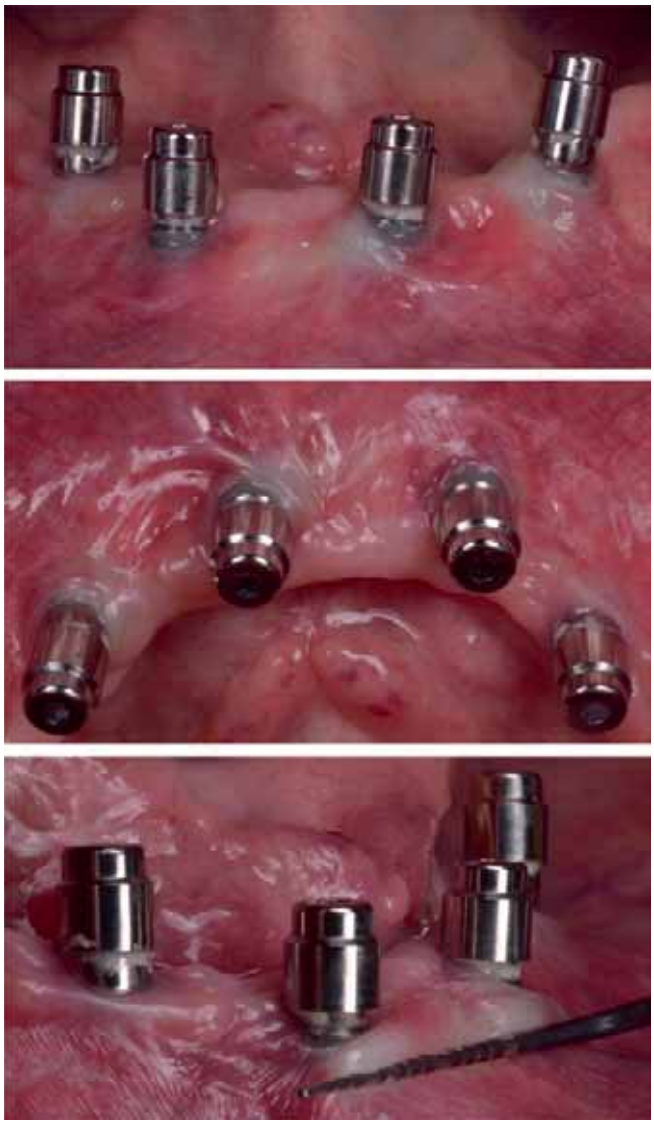

FIGURE 5 Edentulous and atrophic alveolar ridges often display a lack of keratinized mucosa. In these scenarios, adequate biofilm control is often challenging due to discomfort during brushing and the inefficient mucosal sealing. In sites presenting thin mucosa, this combination of factors frequently leads to apical displacement of the mucosal margin.

keratinized mucosa, predisposes for biofilm accumulation, leading to a steady status of inflammation and sparse soft tissue healing.[8,11]

Interestingly, it has been shown that pro-inflammatory mediators, such as prostaglandin E2, interleukin-1beta, and tumor necrosis factor-alpha, are upregulated in sites lacking KM.[1314] This may explain why the severity of mucositis is increased in peri-implant locations that do not exhibit KM[15] and why presence of KMW is correlated to resolution of peri-implant mucositis in humans.[12] In addition, it must be noted that the lack of KM has been associated with shallow vestibular depth.[16] This may hamper the patient's ability to achieve an adequate plaque control and may further contribute to the onset and progression of peri-implant diseases (Figures 3 and 4).

Early studies on this topic suggested that a lack of KM is not necessarily correlated with a higher prevalence of peri-implant disease.[17] Recent data has demonstrated, however, that the presence of ≥2 mm of KM is associated with reduced plaque and bleeding scores, and a lower risk for apical displacement of the mucosal margin, patient discomfort upon oral hygiene performance, and bone loss (Figure 5).[11,18–20] Furthermore, it has been shown that in erratic maintenance compliers (<2 visits/year) the incidence of peri-implant inflammation and marginal bone loss were substantially higher in sites presenting <2 mm of KMW.[21] In alignment with these findings, Kungsadalpipob et al. observed in a cross-sectional study that peri-implant sites presenting no KM were associated with a higher prevalence of plaque accumulation, apical migration of the mucosal margin, marginal bone loss and peri-implantitis.[22] Conversely, Roos-Jansåker et al. found only a slightly higher rate of peri-implantitis in sites that lacked KM.[23] However, it was also observed that those sites lacking KM were associated with a higher prevalence of peri-implant mucositis, which always precedes peri-implantitis in susceptible individuals. Similarly, Lim et al. in a retrospective 5-year analysis of clinical data from a population of compliant patients showed that the band of KM had a negligible role on peri-implant tissue conditions (Table 1).[24]

Hence, in light of existing evidence it seems that the lack of or <2 mm of KMW should be considered as a local predisposing factor for the occurrence of peri-implant disease and apical migration of the mucosal margin in patients not enrolled in an adequate supportive maintenance program and in sites where self-performed oral hygiene measures are inefficient (Figure 6).

3.2 | KMW and peri-implant esthetics

Compared to KM, non-keratinized lining mucosa is less stable and more friable, which increases the risk for progressive apical migration of the mucosal margin, particularly in sites also presenting thin MT, which will be addressed in the next section of this article. Lining mucosa also exhibits a darker red color, in contrast with the coral pink tone of healthy KM. For those reasons, sites lacking KM on the buccal aspect are more prone to present esthetic problems.[25]

3.3 | Clinical management of KMW deficiency

The use of an autogenous free epithelized mucosal graft is generally acknowledged as the gold standard therapy to treat sites presenting a complete absence of or a reduced KMW with the purpose of preventing disease onset and progressive deterioration of the mucosal architecture.[26] Furthermore, in peri-implantitis sites presenting KM deficiency, predictable and favorable KM gain and disease resolution have been reported after a dual therapeutic approach combining a partial thickness flap and implantoplasty for surface decontamination with the subsequent application of an autogenous free mucosal graft (Figure 7).[27] Interestingly, the use of collagen matrices for KMW

TABLE 1 Summary of relevant clinical evidence on the effect of KMW on peri-implant health, in chronological order

Authors (year)	Study type	Length of observational period	Number of patients/implants	Supportive maintenance	Buccal KMW threshold (mm)	Number of implants	Clinical parameters				Comments
							Mean SBI	Mean PPD (mm)	Mean PI	Mean apical migration of mucosal margin (mm)	
Wennstrom et al. (1994)[17]	Prospective	5–10 years	39/171	RC	<2	63	NR	NR	NR	NR	• Data on GI, PPD and PI was reported as % values, hence mean values could not be enclosed in this table. • Authors reported that absence of keratinized mucosa did not influence peri-implant conditions.
					≥2	108	NR	NR	NR	NR	
Kim et al. (2009)[85]	Retrospective	13 months (mean)	100/276	NR	<2	90	0.44	2.62	0.74	0.72	• No significant differences in terms of GI, PI and PD were observed regardless of KMW. However, apical migration of the musical margin and MBL significantly increased in the KM deficient group
					≥2	186	0.38	2.84	0.74	0.32	
Boynuegri et al. (2013)[14]	Prospective	12 months	15/36 (implants retaining overdentures were included in the analyses)	NR	<2	17	0.5	NR	0.2	NR	• GI and PI values were significantly higher for implant sites presenting inadequate KMW • Expression of TNF-α increased significantly after 12 months in sites showing inadequate KMW
					≥2	19	0	NR	0	NR	
Romanos et al. (2015)[86]	Retrospective	6.4 years	118/320 (platform switched dental implants)	42 RC / 76 EC	<2	199	NR	NR	0.7	0.2	• A band of ≥2 mm of KM was associated with significantly lower mBI, PI and less apical migration of the mucosal margin
					≥2	121	NR	NR	0.4	0.06	
Roccuzzo et al. (2016)[87]	Prospective	10 years	98	82% exhibiting KM and 68% with no KM were RC	0	42	NR	2.7	NR	2.08	• The absence of KM was associated with higher plaque accumulation, increased incidence of
					≥1	86	NR	3.1	NR	0.16	

(Continues)

TABLE 1 (Continued)

Authors (year)	Study type	Length of observational period	Number of patients/implants	Supportive maintenance	Buccal KMW threshold (mm)	Number of implants	Clinical parameters				Comments
							Mean SBI	Mean PPD (mm)	Mean PI	Mean apical migration of mucosal margin (mm)	
											soft tissue dehiscences, and a higher number of sites that required additional surgical and/or antibiotic treatment.
Bonino et al. (2018)[88]	Prospective	6 months	238/216 implants with mucositis/46 implants diagnosed with peri-implantitis)	RC	0 ≥1	15 13	NR NR	NR NR	NR NR	NR NR	• Patients without peri-implant KM were less satisfied with the esthetic outcome • Lack of KM was not associated with brushing discomfort • There was greater apical migration of the mucosal margin around implants without KM after 3 months, but not after 6 months
Perussolo et al. (2018)[89]	Prospective	4 years	54/202	RC	≥2 <2	112 90	NR NR	2.7 2.7	0.54 0.91	NR NR	• Marginal bone loss was higher in sites exhibiting an inadequate KMW • In the group presenting <2 mm of KMW, 51.4% patients reported brushing discomfort
Monje et al. (2019)[21]	Cross-sectional	NA	37/66 implants: 26 implants <2 mm/40 implants ≥2 mm	EC	≥2 <2	40 26	NR NR	3.6 4.8	0.2 1	NR NR	• Except for suppuration, all clinical and radiographic parameters were significantly less favorable in sites with KMW <2 mm • Patients reported no brushing discomfort if KMW was at least 2.5 mm

TABLE 1 (Continued)

Authors (year)	Study type	Length of observational period	Number of patients/implants	Supportive maintenance	Buccal KMW threshold (mm)	Number of implants	Clinical parameters				Comments
							Mean SBI	Mean PPD (mm)	Mean PI	Mean apical migration of mucosal margin (mm)	
Lim et al. (2019)[24]	Prospective	5 years	87/87	RC	NR	NR	NR	NR	NR	NR	• Correlation between buccal KMW and PD, BOP, PI and MBL was weak at baseline and after three years of follow-up
Ravidà et al. (2020)[90]	Retrospective	52.4 months (mean)	40/68	RC	≥2	42	NR	5.67	NR	NR	• Sites exhibiting KMW <2 mm exhibited increased SUP and MBL • The presence or absence of KM does not influence the outcomes following surgical treatment of peri-implantitis
					<2	26	NR	5.75	NR	NR	
Kungsadalpipob et al. (2020)[22]	Cross-sectional	52 months (mean)	200/412	RC	≥1	380	0.31	2.83	0.15	0	• Lack of peri-implant KMW was associated with increased plaque accumulation, soft tissue dehiscences ≥1 mm, MBL ≥3 mm, and peri-implantitis.
					0	32	0.25	2.74	0.18	1.17	

Abbreviations: BOP: bleeding on probing; EC: erratic compliers; KMW: keratinized mucosa with; KT: keratinized tissue; MBL: marginal bone loss; NA: not applies; NR: not reported; PI: plaque index; PPD: probing pocket depth; RC: regular compliers; SBI: sulcular bleeding index; SUP: suppuration; TNF-α: tumor necrosis factor alpha.

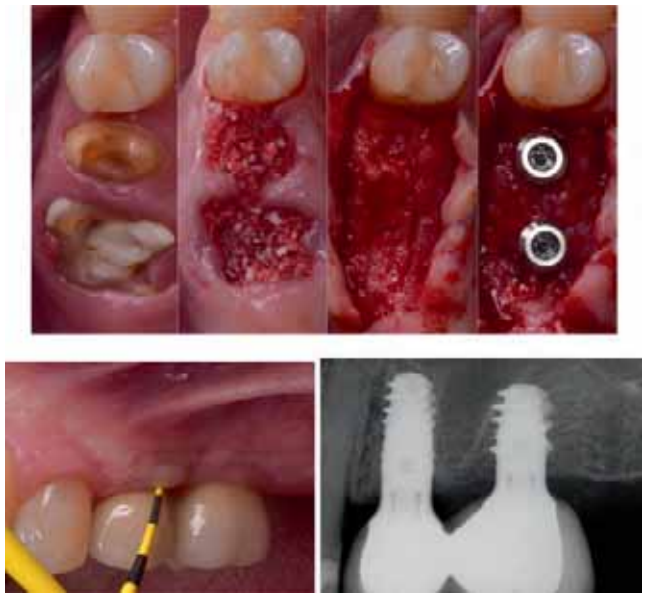

FIGURE 6 Significance of keratinized mucosa on peri-implant health. (A) Hopeless teeth were extracted and (B) ridge preservation was performed to attenuate dimensional changes. (C) After 4 months of healing the site was surgically re-entered and (D) implants were placed with adequate primary stability. (E) Clinical and (F) radiographic assessment after 12 months of functional loading revealed mucosal and bone stability, in consistency with peri-implant health.

augmentation has been shown to render acceptable clinical outcomes compared to the free autogenous graft in areas free of disease and in sites presenting peri-implantitis.[28,29]

While an autogenous free mucosal graft approach is the most predictable therapeutic option to gain keratinized tissue and recreate peri-implant health in a site presenting deficient KMW,[26] this approach usually results in poor tissue color integration, which can be problematic in esthetic areas due to low patient satisfaction.[30] In situations where esthetics are priority other alternatives may be considered. For example, in sites presenting adequate vestibular depth (≥4 mm),[16] a bilaminar technique consisting of the combination of an autogenous connective tissue graft together with a coronally advanced flap,[31] either with a trapezoidal or tunnel design, can be a viable option. In the presence of shallow vestibular depth, the use of collagen matrices alone or in conjunction with an autogenous mucosal strip graft can result in favorable outcomes.[32,33]

4 | SIGNIFICANCE OF MT ON PERI-IMPLANT HEALTH AND ESTHETICS

MT is the horizontal dimension of the peri-implant soft tissue, which may or may not be keratinized. It is important to recognize that MT may vary at different vertical locations, from the mucosal margin to the vestibular fornix, within the same peri-implant area. The relevance of MT is particularly critical in the cervical, most coronal region of the peri-implant mucosa. Although the minimum MT required to maintain long-term peri-implant health and to achieve predictable esthetic results may vary from site to site as a function of local anatomical features and the characteristics of the implant-supported prosthesis, current evidence suggests that a minimum of 2 mm is often associated with favorable outcomes.[34]

4.1 | MT and peri-implant health

According to the findings of a systematic review that analyzed the effect of soft tissue augmentation on peri-implant health, thicker MT is associated with peri-implant marginal bone stability.[35] Although thicker peri-implant soft tissue seems to be generally beneficial for peri-implant health (Figures 8 and 9), the effect of MT on other clinical parameters, such as implant survival, prevention of biofilm accumulation, and the subsequent onset of peri-implant disease, has not been elucidated yet (Figure 9).

4.2 | MT and peri-implant esthetics

In general, the esthetic appearance of the peri-implant mucosa is inferior to the gingiva around teeth,[36] which is often correlated with a MT deficit. In fact, the importance of MT on the esthetic outcomes of implant therapy has been well documented. Empirical and clinical evidence indicates that a minimum MT, particularly in the most coronal area, is required to prevent tissue discoloration due to partial transparency of the transmucosal abutment. This is particularly critical around implants that are placed in the esthetic zone in patients with a high smile line and when abutments with a gray shade (e.g., conventional titanium abutments) are employed. An in vitro study by Ioannidis et al. revealed that while all reconstructive materials resulted in variable degree of mucosal discoloration this decreased with increasing MT. They also observed that the use of fluorescent zirconia or gold alloy led to less mucosal discoloration.[37] Other investigations on this topic have consistently shown that the mucosal discoloration effect can be predictably avoided if MT is at least 2 mm.[36,38–41]

There is also evidence indicating that thick mucosa is associated with a lower risk of developing apical migration of the mucosal margin in patients that have been carrying implant-supported restorations for an extended period of time (mean follow-up = 7.65 years).[42] In a recent study, Fürhauser et al. observed that the more palatal the implant is positioned and, therefore, the thicker the facial peri-implant bone, the less apical migration of the mucosal margin.[43] According to these findings, it could be extrapolated that implant position largely influences buccal MT and the stability to the mucosal margin. Additionally, a systematic review on the topic of peri-implant soft tissue phenotypic features and esthetics concluded that the pink esthetic score[44] is usually higher in sites presenting at least 2 mm of MT. Additionally, apical migration of the marginal mucosa is more prone to occur in the presence of thin phenotype, which usually leads to unpleasant esthetic outcomes and low patient satisfaction.[45]

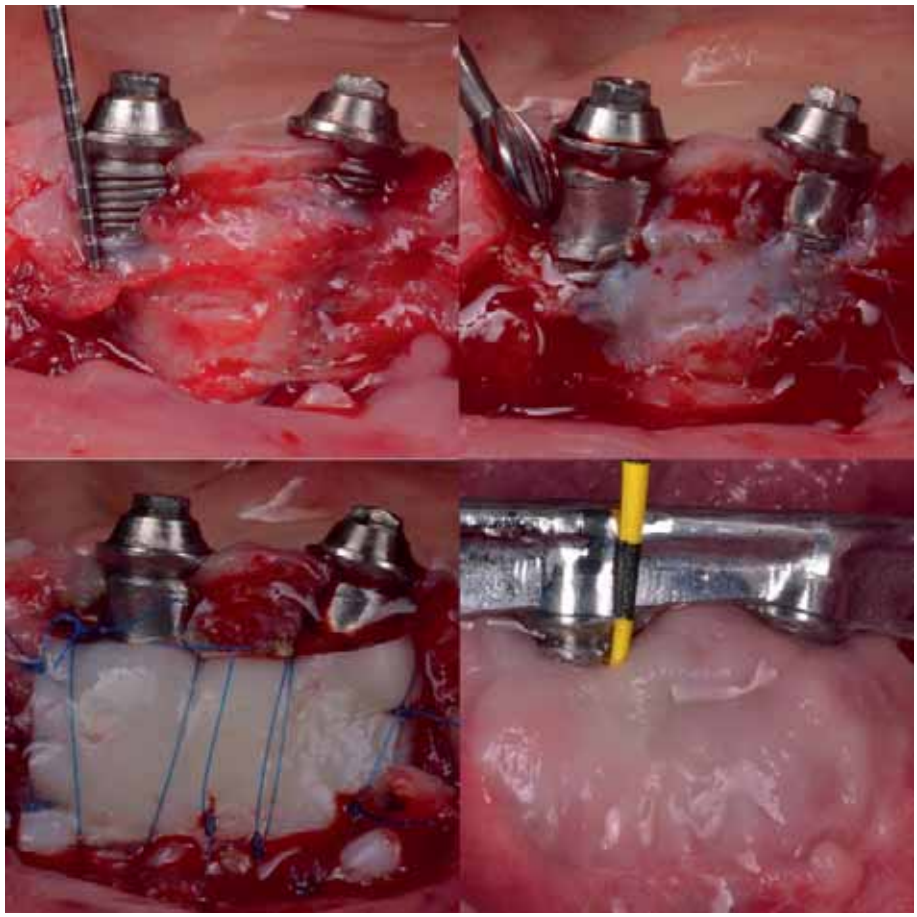

FIGURE 7 Peri-implant bone dehiscence defects resulting from peri-implantitis are often associated with lack of keratinized mucosa (A). In this case, implantoplasty was performed (B) prior to soft tissue augmentation using an autogenous free mucosal graft (C). Note the presence of an increase in keratinized mucosa width and the absence of clinical signs of peri-implant soft tissue inflammation (D).

4.3 | Clinical management of MT deficiency

Surgical interventions aimed at thickening the mucosa at implant sites are frequently indicated to prevent esthetic problems prior to or after the delivery of the final implant-supported prosthesis with the purpose of enhancing the appearance of sites that already exhibit discolorations due to the presence of thin mucosa. A bilaminar approach consisting of the combination of a repositioned or a coronally advanced flap (depending on the anatomical configuration of the site and the treatment goals a tunnel approach may be preferred to preserve the integrity of the interproximal papillae) in combination with an autogenous connective tissue graft or a soft tissue graft substitute is generally recommended to correct MT deficiencies.[26]

5 | SIGNIFICANCE OF STH ON PERI-IMPLANT HEALTH AND ESTHETICS

The peri-implant supracrestal tissue height (STH) is the vertical dimension of peri-implant soft tissue that surrounds a dental implant from the mucosal margin to the crestal bone.

In the periodontal literature, the classic term "biologic width", which has been recently replaced with "supracrestal tissue attachment" (STA),[46] refers to the vertical compartment extending from the most coronal point of the junctional epithelium to the base of the connective tissue.

Although similar, the concept of STH around implants is not analogous to the STA around teeth. The peri-implant STH encompasses the entire vertical dimension of the peri-implant mucosa from the mucosal margin to the peri-implant bone crest, including the sulcular epithelium, the long junctional epithelium, and the supracrestal connective tissue, which is directly in contact with, but not attached to transmucosal prosthetic components.

As previously discussed in this article, compared to the lamina propria of the gingiva, the peri-implant connective tissue typically has lower cellularity, less density of blood vessels, and a higher proportion of collagen fibers that mainly run in parallel to the implant surface.[5] Additionally, the vertical dimension of the peri-implant supracrestal tissue is taller than its counterpart around teeth by an average of 1.0 to 1.5 mm.[6,47,48]

5.1 | STH and peri-implant health

Establishment of the STH is a physiologic event that results from the adaptation of the oral mucosa around an implant-supported transmucosal component. In sites presenting limited baseline STH, this process usually occurs at the expense of physiologic bone remodeling, the magnitude of this effects is typically larger around bone level

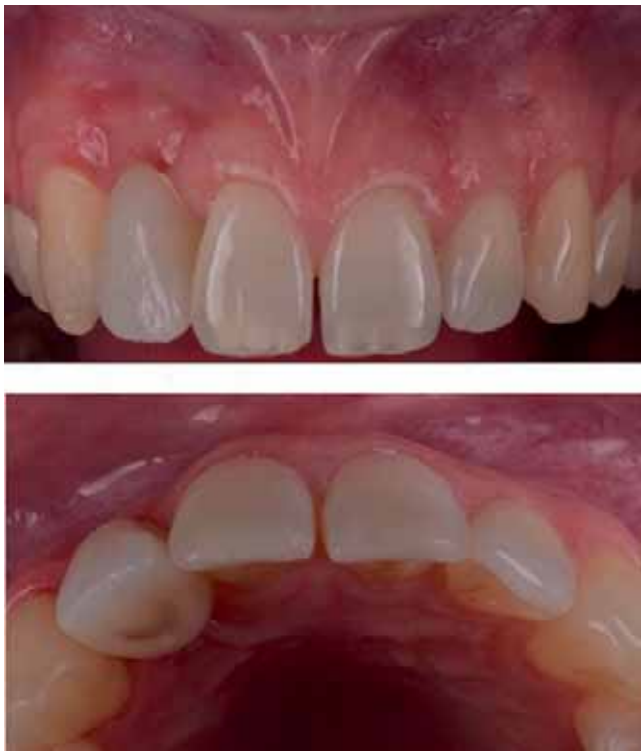

FIGURE 8 Thin mucosal phenotype is frequently associated with esthetic issues and lower patient satisfaction. Note the horizontal collapse (a and b).

FIGURE 9 This clinical example illustrates an implant-supported fixed prosthesis where peri-implantitis has occurred around the implant that exhibits thinner mucosa (A). Note suppuration and bleeding on probing (B) that correlates with radiographic (C) and clinical bone loss (D)

implants with the restorative platform placed juxtacrestally.[34] While some investigators have defined short STH as <2 mm,[49,50] in other studies on this topic this dimension has been set at 3 mm.[51–54] This range may be justified depending on macroscopic implant feature and the anatomical location, as STH tends to be taller in anterior sites. At any rate, the most widely accepted threshold to define short STH is <3 mm.[1]

Although there is no conclusive clinical evidence indicating that there is a direct link between a certain threshold of STH and an increased risk for the development of peri-implant diseases, early marginal bone loss, although often self-limiting, may jeopardize long-term health. In fact, it has been shown that if initial marginal bone loss exceeds ~0.5 mm over the first 6 months, it is very likely that the loss will extend to 2 mm after 2 years, increasing the risk for the occurrence and progression of peri-implantitis.[55] A 10-year prospective study validated that implants that exceed 0.5 mm during the first year of function are 5.43 times more prone for future peri-implantitis development.[56] In relation to these observations, it has been speculated that the partial exposure of implant surface to the peri-implant sulcus can facilitate bacterial colonization, which may increase the risk for inflammatory disease.[57] This can also be related to the fact that insufficient STH due to shallow implant position is also often associated with the fabrication of esthetically unpleasant and non-cleansable transmucosal prosthetic contours, which may lead to patient dissatisfaction and onset or progression of disease (Figure 10).

It must also be acknowledged that STH directly correlates with abutment height, which may explain why it has been consistently reported by different investigators that the taller the abutment, the lower the extent of early marginal bone loss around bone level implants.[58–60] It is relevant to note, though, that abutment height may be pivotal on early bone loss even around subcrestal implants surrounded by thin mucosa,[61] irrespective of STH.[62]

It is, however, important to recognize that an excessively tall STH, far from being exponentially beneficial, may be associated with some disadvantages in patients with suboptimal microbial biofilm control. According to the findings of a study aimed at assessing the effect of STH on the development and resolution of experimental peri-implant mucositis, mucosal tunnel ≥3 mm was associated with a less favorable pattern of disease resolution compared to sites presenting a mucosal tunnel of ≤1 mm.[63] Therefore, it is important to carefully plan and appropriately execute the surgical intervention to place the implant fixture at the ideal depth, balancing anatomical, implant and prosthetic factors.[64]

5.2 | STH and peri-implant esthetics

While the esthetic implications of STH are not as relevant as those related to KMW and MT deficiencies, a short STH usually forces the fabrication of unfavorable emergence profiles that could have detrimental esthetic consequences. Additionally, incomplete interproximal papillary fill, although not necessarily, can be associated with short STH. Insufficient papillary height can predispose for debris impaction

FIGURE 10 Short STH as consequence of shallow implant placement derived into the fabrication of an implant-supported prosthesis with unfavorable contours. This made plaque control very challenging and eventually lead to peri-implantitis, which was likely preceded by early physiologic marginal bone remodeling, also because of shallow implant placement (Images courtesy of Dr. Theodoros Katsaros, private practice in Toronto, Canada)

and lead to poor esthetic outcomes, particularly in the esthetic zone. Interestingly, sites exhibiting stable marginal mucosa levels are associated with papillary height stability.[65]

5.3 | Clinical management of STH deficiency

To prevent the occurrence of marginal bone loss as a consequence of initial physiologic remodeling, it is important to select an implant with adequate dimensions, accommodate the implant position according to baseline STH, to employ prosthetic components with contours that can help drive the establishment of the STH, and to perform soft tissue augmentation, if necessary. Soft tissue augmentation procedures may involve the use of autogenous connective tissue grafts or substitute materials.[66–69] In sites presenting unpleasant papillary height, the use of "platform" autogenous soft tissue grafts has been associated with successful clinical outcomes.[70–72]

6 | PERI-IMPLANT SOFT TISSUE DEHISCENCES

Peri-implant soft tissues dehiscences (PISTDs), also known as peri-implant marginal mucosa defects, are a type of clinical entity that deserves special attention given its correlation with the peri-implant soft tissue phenotype. These deformities have been defined as alterations of the peri-implant soft tissue morphology characterized by an apical discrepancy of the mucosal margin respective to its ideal position with or without exposure of transmucosal prosthetic components or the implant fixture surface.[73]

On the other hand, gingival recession defects (GRDs) are defined periodontal deformities characterized by an apical migration of the gingival margin respective to the cementoenamel junction (CEJ) resulting in partial exposure of the root surface to the oral cavity, which may have important esthetic, functional, and periodontal health implications.[74]

In the natural dentition, GRDs are assessed by determining the relative position of the gingival margin respective to the cementoenamel junction (CEJ). However, due to the wide variety of implant fixtures and prosthetic interfaces that can be encountered, a standard reference comparable to the CEJ that could be utilized consistently and universally does not exist. It should also be noted that, depending on the prosthetic design, apical migration of the mucosal margin does not always lead to the exposure of unesthetic transmucosal components.

Furthermore, PISTDs may be caused by true apical migration of the mucosal margin (i.e., recession) because of, for example, local inflammation, sustained trauma, or the effect of iatrogenic dentistry (i.e., too facial implant position),[25,75] by progressive marginal mucosa discrepancies respective to adjacent teeth due to lifelong craniofacial growth (passive pattern), or a combination of both patterns. Therefore, the use of the term "recession" at implant sites is generally not recommended.[76] At any rate, the presence of PISTDs should be determined after the establishment of the peri-implant soft tissue height once a transmucosal component is present.

Interestingly, the presence of an adjacent implant, a longer time of the implant in function, limited MT, a reduced band of KM, and increased buccal bone crest distance have been associated with the presence of PISTDs. In turn, KMW ≥2 mm, presence of adjacent natural teeth, cemented restorations, and two-piece implants have been identified as protective factors.[25]

Treatment of PISTDs primarily aims at recreating an adequate peri-implant mucosa architecture considering all the phenotypical components previously addressed in this review (i.e., KMW, MT, and STH). Proper management of these defects can be very challenging and may require a purely surgical[77,78] or, in most situations, a combined multidisciplinary approach, including surgical, prosthetic, and even orthodontic therapy.[73,79]

7 | FINAL REMARKS

The dimensional and morphological characteristics of the peri-implant mucosa, particularly in the cervical region, have a major importance in implant therapy as they can greatly influence short- and long-term health and esthetic outcomes. Careful assessment and consideration of each individual component (i.e., KMW, MT and STH) and their dimensional correlation,[80] as it is not uncommon to identify concomitant deficiencies (e.g., absence/minimal KMW, thin peri-implant mucosa, and PISTD), is fundamental to outline treatment needs and make appropriate clinical decisions.

It is also critical to note that the clinical appearance and structural configuration of the peri-implant mucosa can be influenced by the position of the implant fixture[81] and the contours of the transmucosal prosthetic components.[82,83] Hence, prior to indicating surgical

interventions to modify the peri-implant soft tissue phenotype it is important to assess whether the implant fixture is in a restorable position and, if so, determine the need for replacement or modification of the existing implant-supported prosthesis.

Finally, as previously mentioned elsewhere, it should be acknowledged that the threshold values proposed in this article, although derived from a meticulous analysis of relevant available evidence, "may vary depending on location (anterior versus posterior) and may not be applicable in specific situations in which the characteristics of the implant-supporting apparatus deviate from normal, including sites undergoing local inflammatory processes that may directly influence the dimensions, morphology and/or integrity of the peri-implant tissues."[1]

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Research data not shared.

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How to cite this article: Monje A, González-Martín O, Ávila-Ortiz G. Impact of peri-implant soft tissue characteristics on health and esthetics. *J Esthet Restor Dent*. 2023;35(1):183-196. doi:10.1111/jerd.13003

Received: 24 June 2022 | Revised: 7 September 2022 | Accepted: 8 September 2022

DOI: 10.1111/jerd.12965

RESEARCH ARTICLE

WILEY

The L-shape technique in guided bone regeneration with simultaneous implant placement in the esthetic zone: A step-by-step protocol and a 2–14 year retrospective study

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Funding information
Geistlich; Geistlich Pharma AG; University of Zurich

Abstract

Objectives: To describe the methodology of the "L-shape" technique in guided bone regeneration (GBR) with simultaneous implant placement and report on the clinical, esthetic, and patient satisfaction outcomes up to 14 years of follow-up.

Material and methods: Fourteen patients treated with the "L-shape" technique were included in this retrospective study. The L-shape technique was performed by trimming and placing a soft-type bone block made of deproteinized bovine bone mineral with 10% collagen at the buccal-occlusal aspect of the dental implant. The remaining gaps were filled with deproteinized bovine bone mineral granules and the augmented area was covered with a collagen membrane. The following parameters were recorded: probing depth (PD), bleeding on probing (BOP), plaque index (PI), keratinized tissue width (KT) and marginal bone level (MBL). Esthetic outcomes were assessed according to the pink esthetic score (PES) and the white esthetic score (WES). Patient satisfaction was evaluated by means of a numerical rating scale (0–10). The stability of each augmented site was assessed by measuring the volumetric changes between baseline (crown delivery) and the respective follow-up.

Results: A total of 13 maxillary incisors and one maxillary canine in 14 patients were included. The mean follow-up period was 7.7 ± 3.8 years. PES values amounted to 10.7 ± 3.3 and WES to 8.8 ± 1.4. Patient satisfaction reached 9.4 ± 0.8. Mean PD at implant sites were 2.7 ± 0.7 mm while BOP amounted to 15.0 ± 0.2% and PI to 5.0 ± 0.0%. Volumetric analyses revealed minimal changes at the augmented sites irrespective of the region of interest. Radiographic MBL remained relatively stable.

Conclusions: Within the limitation of the present study the L-shape augmentation procedure seems to be a reliable technique when performing GBR with simultaneous implant placement in the esthetic zone. Outcomes encompassed stable clinical and esthetic results accompanied by high levels of patient satisfaction. Future randomized controlled trials are warranted to confirm possible benefits of the L-shape technique over traditional approaches.

Anina Zuercher and Leonardo Mancini contributed equally to the manuscript and should be considered as joint first authors.

Clinical significance: The L-shape appears to be a simple yet promising technique in GBR with simultaneous implant placement that can easily be translated into clinical practice.

KEYWORDS
dental implants, esthetics, GBR, guided bone regeneration, L-shape, L-shape technique, PROMs

1 | INTRODUCTION

Guided bone regeneration (GBR) is a common and well-documented procedure carried out either prior to or simultaneously with implant placement.[1,2] The aim of GBR is to regenerate missing hard tissue based on the principle that a barrier membrane limits the ingrowth of soft tissues allowing the re-population of the missing bone area by osteoprogenitor cells. GBR allows implant placement in a prosthetically driven position and in esthetically demanding areas, it can be used to augment the buccal contour of the alveolar ridge to achieve esthetically pleasing outcomes.[3]

Currently, the most common GBR technique involves the use of a resorbable membrane.[4] These membranes, however, lack space-making capacity per se and therefore are combined with a particulated bone substitute material underneath. Even though this combination is well documented, a recent systematic review has revealed that the mean defect resolution after implant placement with simultaneous GBR amounts to 81.3% with a range of 56.4%–97.1%.[5] This large variability indicates that still further improvements can be made to increase the predictability of GBR procedures.

One alternative for improvement is a better stabilization of the bone substitute itself. This can be obtained by adding 10% of collagen to the bone substitute obtaining a so-called soft-type bone block. Theoretically, this soft-type bone block could prevent the displacement of bone particles that frequently occurs after flap closure when traditional bone substitutes are used.[6] An in vitro study revealed that a stabilization of the graft material can significantly reduce bone graft displacement after flap closure.[7] This is clinically relevant, as displacement of the underlying bone substitutes can result in a significant loss of buccal contour, eventually leading to unpleasant esthetic results. In this context, it is reasonable to hypothesize that the improved properties of the soft-type bone block in combination with the rigid network provided by the 10% of collagen --might hinder the substitute displacement, resulting in an enhanced preservation of the augmented area[8] and more favorable esthetic outcomes.

Based on these presumable advantages, a new technique called "L-shape technique" has recently been introduced. This technique involves the use of a soft-type bone block trimmed into an "L" shape. This geometry enables to increase the volume at the buccal and occlusal l aspect, which are the most critical areas from an esthetic point of view. It is thought that this technique may have the ability to maintain the augmented area to a great extent. However, the clinical evidence to support this claim is scarce. This lack of evidence is not unexpected as the technique itself has never been described in detail, thereby hampering its wide application by the dental community.

Therefore, the aim of the present study was to describe the L-shape technique step by step and to retrospectively assess clinical, esthetic, volumetric and patient satisfaction outcomes following L-shape technique up to 14 years post-loading.

2 | MATERIALS AND METHODS

2.1 | Surgical technique step-by-step

2.1.1 | Flap design and implant placement

A sulcular incision at both adjacent teeth of the implant site is made. This is followed by a palatally oriented crestal incision connecting the two adjacent teeth (Figure 1A,B). One vertical releasing incision is cautiously performed at the distal aspect of the lateral incisor starting in a 90° angle mimicking a 'hockey stick' (Figure 1C). Subsequently, a full-thickness flap is raised starting from the vertical incision (Figure 1D). The flap should be sufficiently elevated to allow assessment of the dimension of the alveolar ridge. This facilitates implant placement in a prosthetically oriented position and the assessment of the need for GBR. In the presence of granulation tissue remnants, these are removed with a curette or an excavator before preparing the implant bed (Figure 2A). The implant is then placed in an ideal prosthetic position by means of a surgical stent under a conventional or a digital workflow (Supporting Information). After implant placement, two perforations are prepared at the apical portion of the dental implant using a pilot drill or a fine round bur for anchoring. This will allow the collagen membrane to be fixated by the use of two pins (Figure 2B,C). A collagen membrane (Geistlich Bio-Gide, Geistlich Pharma AG, Wolhusen, Switzerland) is trimmed according to the defect dimensions and placed in the desired position (Figure 2D). The membrane is fixed with the corresponding resorbable pins (LeadFix, Biovision, Ilmenau, Germany) and tacked to the bone (Figure 2E). Once the membrane is fixed, the L-shape block is prepared.

2.1.2 | L-shape preparation

The soft-type bone block (Geistlich Bio-Oss Collagen, Geistlich Pharma AG, Wolhusen, Switzerland) is moisturized with sodium

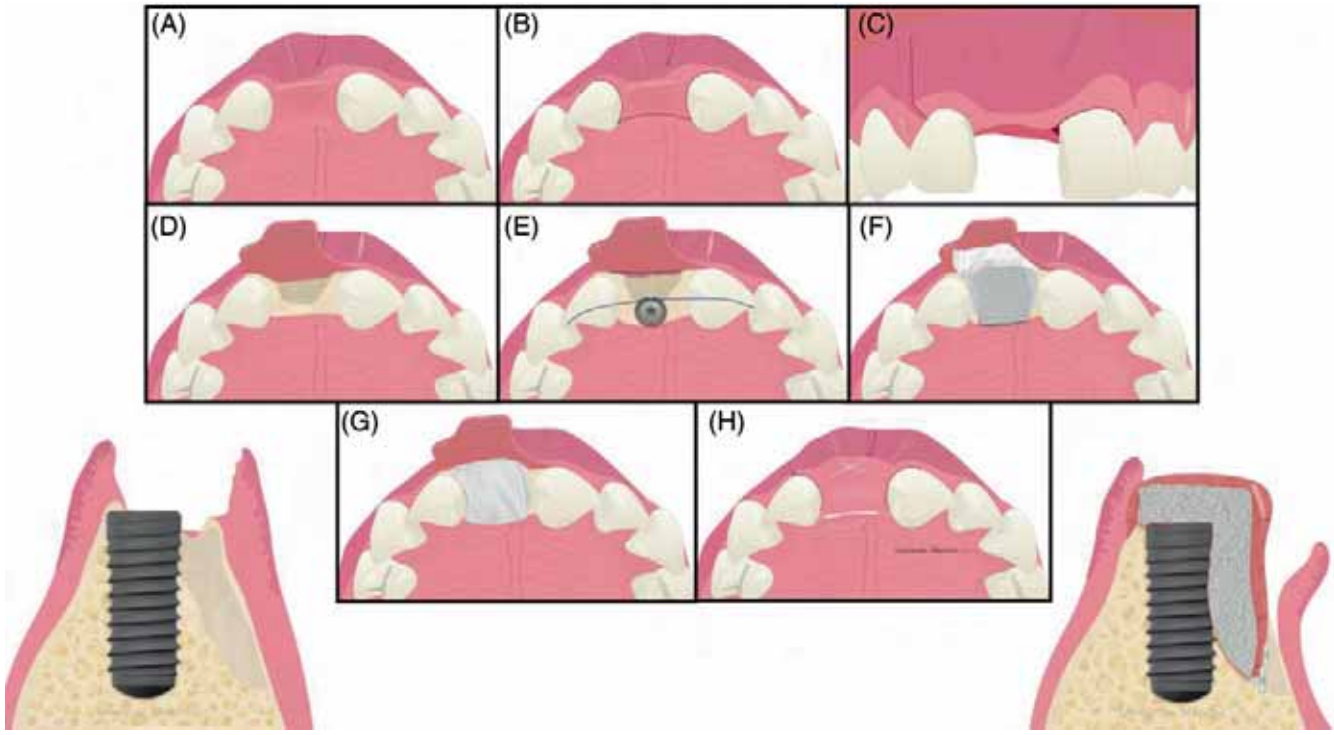

FIGURE 1 Graphical illustration of the L-shape technique (occlusal and lateral view). (A) occlusal view of a single-tooth gap; (B) crestal incision; (C) vertical releasing incision; (D) exposure of the bony defect; (E) implant placement in an ideal prosthetically driven position; (F) membrane fixation and positioning of the L-shaped block; (G) membrane adaptation over L-shaped block; (H) wound closure with horizontal mattress suture. A lateral view of the technique before and after placing the L-shaped block is shown in the lower corners

chloride and trimmed into an "L-shape"using a scalpel. Any remaining material can be used later for augmenting the area next to the "L-shape". The L-shaped soft-type bone block is placed buccally and crestally at the implant, thereby covering the bony defect (Figure 1E,F, Figure 2F). Remaining voids and concave areas are filled with the excess of the material or with a traditional granular bone substitute (Geistlich Bio-Oss Granules, Geistlich Pharma AG, Wolhusen, Switzerland). The collagen membrane (Geistlich Bio-Gide, Geistlich Pharma AG, Wolhusen, Switzerland) is then folded over the augmented area and carefully adapted under the palatal flap using an elevator (Figures 1G, 2G). Periosteal releasing incisions are made allowing for a tension-free wound closure (e.g., it should be possible to advance the flap 2–3 mm over the palatal incision) (Figure 2H). Wound closure starts in the papilla region of the vertical incision with interrupted sutures (Dafilon 6.0, Braun Medical AG, Sempach-Station, Switzerland) (Figure 2I). A vertical mattress suture fixates the papilla in its correct position. One horizontal mattress suture (GORE-Tex Suture 5.0, W. L. Gore & Associates, Flagstaff, Arizona, USA) is performed to counteract the post-operative swelling, with needle entry at the level of the mucogingival junction (Figure 1H). Single interrupted sutures are applied at the crestal incision (Figure 2I). Finally, the vertical incision is sutured with single interrupted sutures (Figure 2I). Second-stage surgery is usually performed 3–4 months after implant placement. De-epithelization of the crestal soft tissue area is performed, followed by a U-shaped incision allowing the mini-flap to be folded towards the buccal side to the buccal contour. The cover screw is removed and replaced by a healing abutment holding the mini-flap buccally in the desired position. In the rare case of encountering bone on top of the implant, this can be safely and easily removed by using curettes, ultrasonic scalers or specially designed trephine burs manufactured by the respective implant manufacturer.

2.2 | Study design

The present study was designed as a retrospective study and conducted according to the Helsinki declaration of human studies and received approval from the ethics committee of the canton of Zurich, Switzerland (KEK-ZHNr. 2021-01459). The manuscript is reported according to the STROBE statement.[9]

2.3 | Study population

Patients who underwent single implant placement and simultaneous GBR applying the "L-shape" technique in the anterior maxilla. The following inclusion criteria were applied:

- ≥20 years of age
- Follow-up of ≥2 years
- At least one adjacent tooth

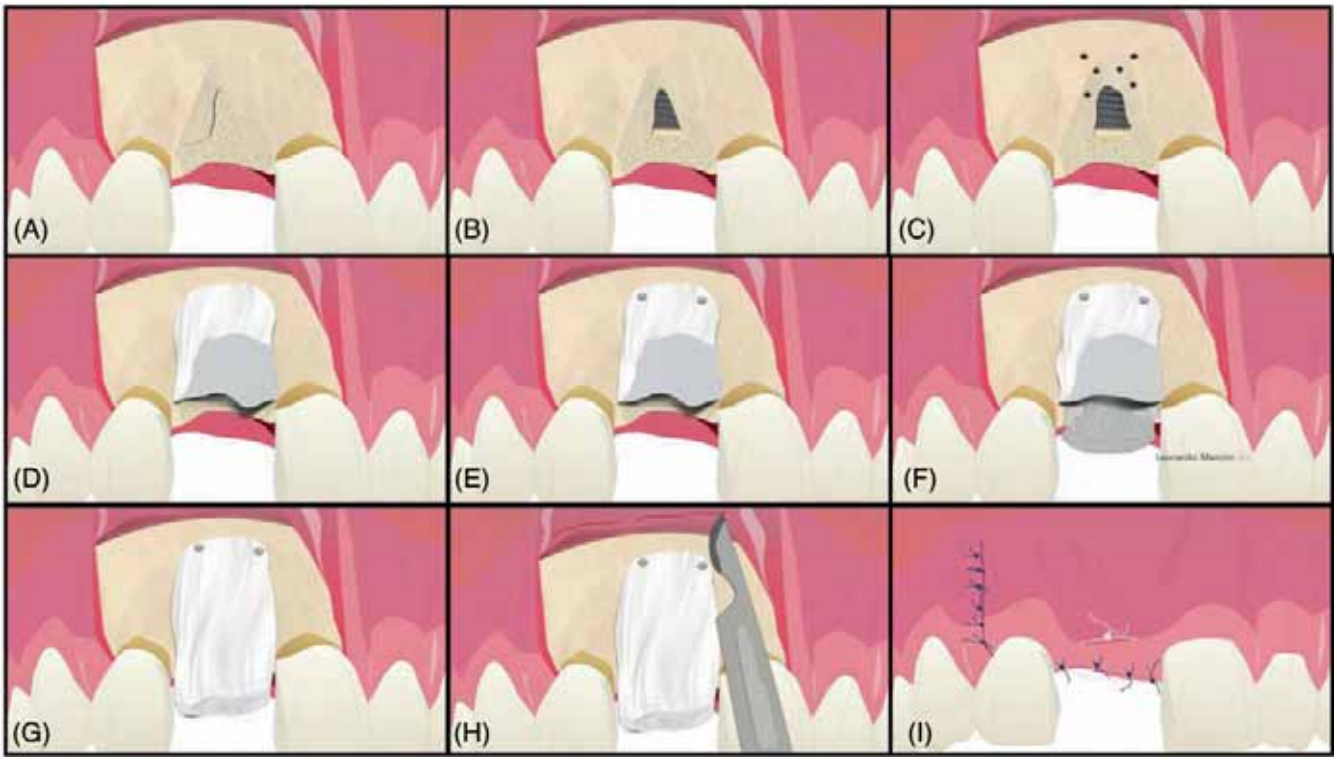

FIGURE 2 Graphical illustration of the L-shape technique (frontal view). (A) Flap elevation; (B) implant placement; (C) bone perforations; (D) membrane adaptation; (E) membrane fixation with resorbable pins; (F) positioning of L-shaped soft-type bone block; (G) adaptation of the membrane over the soft-type bone block (H) releasing periosteal incision; (I) wound closure with horizontal mattress sutures and single interrupted sutures

- Signed informed consent form

2.4 | Clinical assessment

The following clinical parameters were assessed at six sites at the recall appointment using a North Carolina Probe (UNC 15, Hu-Friedy, Chicago, USA):

- Probing depth (PD) (mm)
- Bleeding on probing (BOP) (%)[10]
- Plaque control record (PI) (%)[11]
- Keratinized mucosa (KT) (mm) by measuring the distance from the free mucosa margin to mucogingival junction at mid-buccal position

Technical and biological complications were also recorded. All the measurements were performed by a calibrated examiner who was not involved in the surgical or prosthetic treatment.

2.5 | Radiographic assessment

Standardized intraoral radiographs were obtained at the follow up visit using a paralleling technique with Rinn-holders. X-rays were then imported into an open-source software (ImageJ 1.43; National Institute of Health, Bethesda, USA). The marginal bone level (MBL) change was determined both at the time of delivery of the final restoration and again at the follow-up visit by measuring the distance between the flat top of the implant shoulder and the bone crest. The known pitch distance between two implant threads was used for calibration. Differences were then calculated for each assessed implant. All marginal bone level assessments were performed by one examiner on two separate occasions at least 1 month apart. Subsequently, intra-examiner reliability was calculated using the intraclass correlation coefficient (ICC).

2.6 | Esthetic evaluations

Esthetic parameters were assessed on standardized buccal photographs (Nikon z6, twin flash R1C1, Nikon Imaging Japan Inc., Tokyo, Japan) applying both the pink esthetic score (PES)[12] and the white esthetic score (WES).[13] All photographs were taken according to the guidelines of the Clinic of Reconstructive Dentistry at the University of Zurich. A 90-degree angle was obtained to ensure optimal assessment of the soft tissues adjacent to the implant site. One investigator performed all PES and WES scores at two different occasions one month apart. Subsequently, the intraclass correlation coefficients (ICC) for PES and WES were calculated.

2.7 | Buccal contour changes

An intra-oral scan (Trios 3, 3Shape, Copenhagen, Denmark) of the maxilla was obtained at the follow-up visit to generate a digital model. Whenever available, stone models from the time of delivery of the final restoration were digitized. This allowed for analyzing the long-term contour changes between crown delivery and the follow-up visit. The obtained Standard Tessellation Language (STL) files were imported into an engineering software (GOM Inspect, GOM, Braunschweig, Germany) allowing for superimposition and calculation of linear and volumetric changes of the soft tissue. A semi-automated alignment, based on the selection of reproducible points on the digital models and on a best-fit algorithm, was used to superimpose the STL files. The region of interest (ROI) was defined as previously described at the buccal aspect of the implant site.[14,15] The volumetric outcomes of interest were: (a) volume change in mm^3 (Vol), (b) the mean distance between the surface/mean thickness of the reconstructed volume in mm (ΔD), and (c) linear dimensional (LD) changes from 1 to 5 mm from the soft tissue margin.

2.8 | Patient satisfaction

Patients' esthetic perception and satisfaction was assessed using a numerical rating scale (NRS)[16] ranging from -10 at the follow-up visit. Patients were instructed to indicate their level of satisfaction in terms of overall esthetic satisfaction (including tooth shape, color match and soft tissue appearance) by marking a box on the NRS scale.

2.9 | Statistical analysis

A software program (Excel, Microsoft Corporation, Redmond, Washington, USA) was used to process the data. For the metric variables, mean, standard deviations, median and quartiles were calculated. Due to the exploratory nature of this study, descriptive statistics were performed using Prism v9 (Graphpad Software Inc., La Jolla, California, USA).

3 | RESULTS

Fourteen patients (seven women and seven men) with a mean age of 38.3 ± 11.0 years participated in the present study. Demographics, clinical, esthetic and patient-reported outcomes are presented in Table 1. All implants were located in the upper dental arch and in the esthetic zone. Based on the defect classification by Benic & Hammerle,[1] defect morphology at implant placement was classified as Class I in one patient, Class II in eight patients and Class III in five patients. The intra-examiner reliability of PES/WES, MBL and buccal contour changes (BCC) was calculated using the intra-class correlation coefficients (ICC).

3.1 | Esthetic assessments PES/WES

The mean PES values amounted to 10.7 ± 3.3 according to the Fürhauser criteria[12] (Figure 3). According to Belser criteria[13]

TABLE 1 Demographics, clinical, esthetic and patient satisfaction outcomes

Patient	Age (years)	Implant site	PI (%)	BOP (%)	PD (mm)	KT (mm)	MBL (mm)	Patient satisfaction (NRS)	PES (Fürhauser) total score	WES (Belser) total score	Follow-up (years)
1	51.8	21	0.0%	0.0%	2.3	5.0	0.0	10	14	10	2.6
2	35.2	11	0.0%	0.0%	3.0	5.0	0.6	9	10	8	8.8
3	37.7	12	0.0%	0.0%	1.8	4.0	2.1	10	13	10	14.3
4	30.4	11	0.0%	0.0%	2.5	3.0	0.2	9	9	8	8.36
5	33.2	21	0.0%	16.0%	2.6	3.0	0.0	10	11	6	5.4
6	31.1	11	0.0%	0.0%	3.2	4.0	2.9	10	14	10	8
7	28.6	11	0.0%	16.0%	3.5	1.0	0.0	10	9	7	5
8	48.8	11	0.0%	0.0%	1.6	0.0	0.0	8	4	10	3.6
9	29.6	12	0.0%	0.0%	3.2	3.0	0.3	8	14	10	8.8
10	26.1	23	16.0%	0.0%	1.8	3.0	1.7	10	13	10	3.4
11	56.1	21	33.0%	83.0%	3.2	3.0	0.1	8	10	9	14.1
12	48.8	11	16.0%	16.0%	2.6	2.0	0.7	10	5	7	5.8
13	53.1	21	0.0%	66.0%	4.5	2.0	2.1	10	14	10	9.6
14	25.1	11	0.0%	16.0%	2.3	3.0	0.0	10	14	10	3.1
MEAN	38.2		5%	15%	2.7	2.9	0.7	9.4	10.7	8.8	7.2
SD	11.0		0.09	0.2	0.7	1.3	1.0	0.8	3.3	1.46	3.7
MEDIAN	35.2		0%	0%	2.6	3	0.2	10	12	10	6.9

Note: NRS satisfaction is an 11-point ordinal scale from 0 (completely dissatisfied) to 10 (completely satisfied).
Abbreviations: BOP, bleeding on probing; KT, keratinized tissue; MBL, marginal bone level; PD, probing depth; PI, plaque control record.

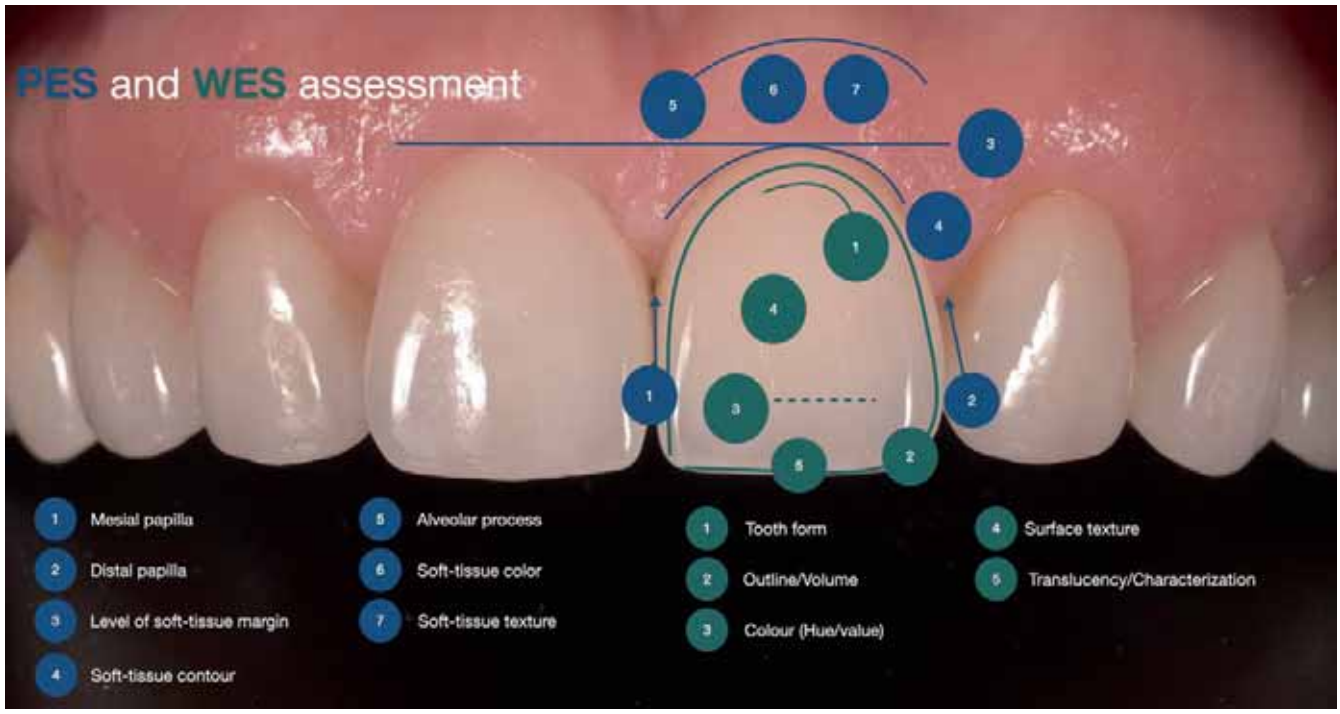

FIGURE 3 Esthetic assessment based on pink esthetic/white esthetic scores[12,13]

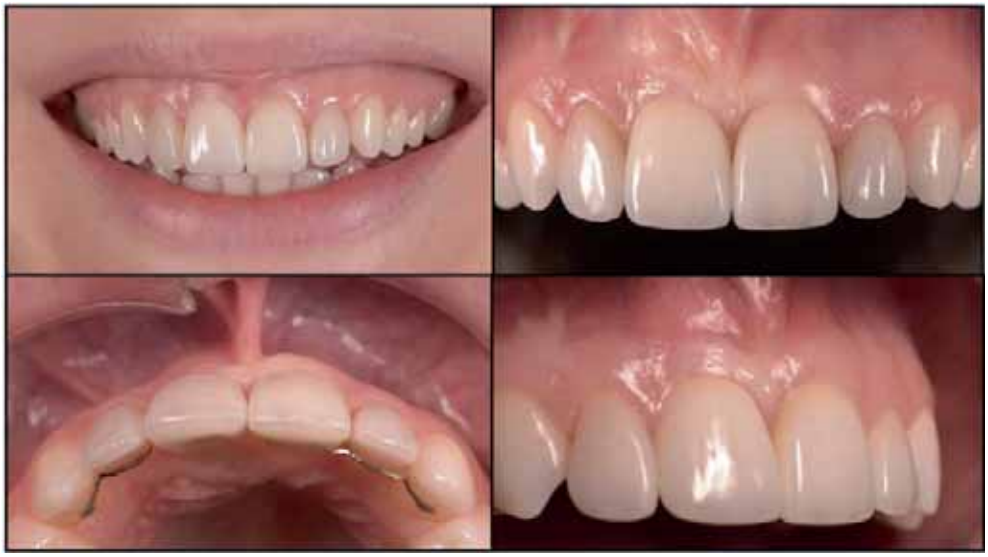

FIGURE 4 Representative clinical case of a female patient treated with the L-shape technique in region 11 at the follow-up examination. Frontal and occlusal views showing the esthetic results of the implant-supported restoration with adequate and sufficient tissue volume around the implant

the WES values amounted to 8.8 ± 1.4. The mean ICC amounted to 0.98 (95% IC 0.96–0.99) for PES and 0.87 (95% IC 0.60–0.96) for WES revealing an excellent intra-examiner reliability (Figure 3). A representative clinical case at the follow-up examination treated with the L-shape technique in region 11 is presented in Figure 4.

3.2 | Clinical assessment

Peri-implant soft tissues showed a BOP of 15% ± 0.26%. PI resulted in a mean value of 5.0% ± 0.09% and mean PD amounted to 2.72 ± 0.76 mm. The mid-facial keratinized mucosa had a mean extension of 2.93 ± 1.38 mm, indicating a sufficient band of keratinized mucosa on the buccal aspect of the implant-supported restoration.

3.3 | Marginal bone level measurements

Mean MBL was 1.74 ± 1.82 mm at baseline and decreased to 0.76 ± 1.00 mm after a mean period of 7.73 ± 3.83 years. The ICC on the marginal bone loss was 0.99 (95% IC 0.97–0.99) suggesting an excellent intra-examiner reliability.

TABLE 2 Volumetric analysis of five representative clinical cases

Patient	Volume discrepancy (mm^3)	Region of interest	Mean distance (ΔD) (mm)	Linear changes at 1 mm (mm)	Linear changes at 3 mm (mm)	Linear changes at 5 mm (mm)	Follow-up (years)
1	80.2	143.7	−0.6	0.8	−0.7	−1.0	2.6
4	16.1	60.1	0.0	0.1	−0.1	−0.4	8.3
8	161.1	90.32	1.4	1.0	1.98	2.6	3.6
10	90.7	190.7	−0.4	0.2	−0.7	−1.0	3.4
14	58.3	74.6	−0.4	−0.1	−0.4	1.0	3.1
MEAN	81.28	111.9	0.0	0.40	0.0	0.2	4.2
SD	53.00	54.23	0.8	0.47	1.1	1.5	2.3

3.4 | Buccal contour changes (profilometric measurements)

Five out of 14 baseline models were available for the analyses of the volumetric changes between crown delivery and the follow-up visit (Figure S1). The mean Vol gain was 81.2 ± 53.0 mm^3 (Table 2). The mean distance (ΔD) between the surfaces of the reconstructed volume was 0.0 ± 0.8 mm (Table 2). Horizontally, the linear measurements showed a gain of 0.4 ± 0.4 mm at 1 mm, 0.0 ± 1.1 mm at 3 mm and 0.2 ± 1.5 mm at 5 mm from the mucosal margin (Table 2). A representative volumetric analysis with the corresponding region of interest is shown in Figure S1. The ICC on buccal contour changes was 0.99 (95% IC 0.98–1.00), indicating an excellent intra-examiner reliability of the measurements.

3.5 | Patient satisfaction

The mean level of satisfaction rated by numerical rating scale amounted to 9.4 ± 0.8, indicating that all patients were entirely satisfied with their treatment and result.

4 | DISCUSSION

The present retrospective study, assessing the L-shape technique up to 14 years of follow-up predominantly revealed: (i) favorable esthetic and clinical outcomes, (ii) volume and contour stability of the augmented sites and (iii) high levels of patient satisfaction.

The replacement of an anterior tooth with a dental implant remains one of the most challenging procedures in implant dentistry, partly due to the increasing awareness and emphasis on esthetic outcomes. The present study revealed favorable esthetic outcomes. This is indicated by the high PES values found, which amounted to 10.7. These high values are largely consistent with recent studies performing implant placement with simultaneous GBR in the anterior region, also resulting in PES values of ≈10.[3,17] Similarly, pleasing outcomes were reflected by the high WES values (mean score: 8.8), likely attributed to the many years of experience of the dental technician who fabricated the restorations. Interestingly, from the patient's point of view, the esthetic perception was even higher and amounted to 9.4 on the numerical rating scale, which indicates a higher acceptance by patients than by practitioners. This discrepancy in the esthetic evaluation between patients and practitioners is a well-known phenomenon that has been demonstrated in several publications, with the latter being more critical.[18–20]

No biological complications were observed during the observation period. Mean PD amounted to 2.7 ± 0.7 mm and mean BOP was below 20% in all patients. These healthy parameters were consistent with low plaque levels. These observations are consistent with other studies applying GBR.[21] Furthermore, the MBL changes over time were clinically negligible (0.8 mm) which again is in agreement with previous studies investigating GBR.[22,23]

The greatest advantage of the L-shaped technique supposedly is the retention of the augmented volume in one of the most esthetically critical areas, namely the buccal and occlusal aspect of the dental implant. The sites augmented applying the L-shape technique showed good long-term stability as indicated by the negligible changes in volume and contour over time. In fact, the mean linear changes at the corresponding ROI (1, 2, and 3 mm below the mucosal margin) revealed changes below 1 mm. These values are relatively superior compared to those reported in a previous retrospective study showing changes between 2.5 and 4.5 mm applying a similar technique.[24] This discrepancy can most likely be explained by methodological differences. In addition to the different region of interest applied, the previously mentioned study[24] compared volume changes between implant placement and abutment connection. The present study investigated contour changes between crown delivery and follow-up visit. Furthermore, no pins were used in the previous study. The absence of pins may have led to the displacement of the bone graft, thus explaining the higher volume changes observed in that study.[25,26] It is worth noting that volumetric analysis based on STL files has become a standardized method for evaluating hard and soft tissue changes over time.[14]

A possible explanation for the negligible volume changes observed in the present study could be the robust stability of the graft provided by the use of a soft-type bone block and the fixation of the membrane with pins. Recent in vitro studies showed that membrane fixation with pins[25] and the use of soft-type blocks[7] can significantly reduce bone graft displacement after flap closure. Moreover, in a more recent pre-clinical study, it was shown that membrane fixation can enhance bone formation by increasing the expression of osteogenic factors.[27] In addition, the pre-clinical study revealed that membrane

fixation was able to mitigate the expression osteoclast markers that mediate bone resorption.[27] In other words, the fixation of the membrane was capable of attenuating bone resorption, which may partly explain the favorable volume and contour stability observed in the present study. Clinically, a robust stabilization can positively influence blood clot formation and subsequently osteogenesis.[28] It must be noted, however, that the additional clinical benefits of membrane fixation and the use soft-type blocks still remain to be elucidated,[29] ideally with adequately powered clinical trials. Nonetheless, the present findings seem to support the notion that the combination of membrane fixation and soft-type blocks can favor GBR-related outcomes.

Regarding the morphology of the peri-implant defects treated, the majority were classified as Class II, followed by class III. According to Benic and Hämmerle[1] Class II defects have a reduced buccal bone, while class III have no buccal bone and lack sufficient adjacent bony walls (mesial/distal) to provide volume stability to the augmented area. This is clinically relevant as these anatomical aspects at the augmented sites may have facilitated the regenerative potential and contributed to the positive outcomes found. In fact, a recent randomized controlled trial analyzed biopsies from damaged sockets 4 months after bone grafting revealing a positive correlation between the residual height and the amount of newly formed bone.[30] The same authors concluded that the residual ridge morphology appears to play critical role in the regenerative potential at augmented sites.[30] Collectively, this suggests that the L-shape may be suitable and indicated for class II and class III peri-implant defects.

In recent years, there has been a paradigm shift in implant dentistry moving away from standard clinical parameters towards patient-reported outcome measures (PROMs). These PROMS aim to capture the patient's perspective on benefits and harms before or after a specific procedure. The present study showed a high level of satisfaction after treatment, as indicated by a mean score of 9.4 on an ordinal scale ranging from 0 (completely dissatisfied) to 10 (completely satisfied). These results are consistent with the existing literature on implant-supported restorations.[31–34] Together, these results indicate that L-shape can lead to high patient satisfaction in both, the short and long term.

Limitations of the present study mainly include the small sample size and the retrospective study design with the corresponding selection bias. Furthermore, due to the long follow-up of some of the patients, not all baseline dental casts were available for the volumetric analyses. Consequently, the volumetric findings should be interpreted with care. Finally, in more severe cases, such as class IV or V where the implant cannot be stabilized, the L-shape might not be indicated. Certainly, the current study could not represent all possible clinical scenarios and therefore, the current findings should be interpreted cautiously.

5 | CONCLUSIONS

Within the limitations of the present study, the L-shaped technique appears to be reliable in conjunction with simultaneous implant placement in the esthetic zone leading to predictable and stable clinical and esthetic results accompanied by high patient satisfaction. Future randomized controlled trials are warranted to confirm the advantages of the L-shape over traditional approaches.

ACKNOWLEDGMENTS AND DISCLOSURE

The study was mainly funded by the Clinic of Reconstructive Dentistry, University of Zurich, Zurich, Switzerland. In addition, the study was partially financially supported by Geistlich Pharma AG. The authors would like to thank Gisela Müller and Christa Fritschi for their assistance in conducting the study. Drs. Naenni, Thoma and Jung have provided lectures sponsored by Geistlich Pharma AG. Drs. Strauss, Zuercher and Mancini report no conflicts of interest related to this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Zuercher A-N, Mancini L, Naenni N, Thoma D-S, Strauss F-J, Jung R-E. The L-shape technique in guided bone regeneration with simultaneous implant placement in the esthetic zone: A step-by-step protocol and a 2–14 year retrospective study. *J Esthet Restor Dent*. 2023; 35(1):197-205. doi:10.1111/jerd.12965

Received: 18 October 2022 | Revised: 15 December 2022 | Accepted: 20 December 2022

DOI: 10.1111/jerd.13011

RESEARCH ARTICLE

WILEY

A comparative analysis of dual-axis implants placed into maxillary anterior extraction sockets versus virtual planning with uniaxial implants: A simulated cone beam computed tomography study of implant length and diameter

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Abstract

Objective: The biaxial nature of the anterior maxilla poses a surgical and restorative challenge in implant dentistry. The present study sought to investigate the apical socket perforation rate (ASPR) from a simulated uniaxial implant placement and to determine the effect of implant length and diameter on ASPR when a uniaxial implant was placed compared with the orientation of the pre-existing dual-axis implant.

Material and Method: Cone beam computed tomography (CBCT) scans from the database of three private practices were searched for patients who received dual-axis implants within the esthetic zone in immediate tooth replacement therapy. A uniaxial implant was virtually placed using the pre-existing screw access channel of the dual-axis implant as a reference. The closest length and diameter were selected for the simulated implant. ASPR by the uniaxial implant was recorded. In addition, the affordable maximum length of a corresponding uniaxial implant that would avoid apical socket perforation was measured.

Result: Eighty-one patients with a total of 101 dual-axis dental implants were selected for analysis. A simulated virtual surgical planning with uniaxial implants revealed high ASPR (48.51%). When the length of the uniaxial implant was reduced to 11 and 9 mm, ASPR was decreased to 41.58% and 20.79%, respectively.

Conclusion: Dual-axis implant design effectively evades anatomical challenges in the anterior maxilla (esthetic zone). Considering the current evidence, efforts should be made to carefully consider the angular disparity between the extraction socket-alveolus complex and the future restorative emergence so that a harmonious biologic-esthetic result may be more predictably and consistently obtained.

KEYWORDS
digital dentistry, implants, periodontics/prosthodontics, radiology

1 | INTRODUCTION

The anatomy of the maxilla presents unique challenges to immediate implant placement into anterior extraction sockets. One such challenge is the proclination of the alveolar ridge that is frequently not perpendicular to the occlusal plane, complicating prosthetically driven implant placement.[1] In addition, the sagittal orientation of the tooth root axis is frequently positioned directly against the facial cortex of the alveolus.[2] Often, this bone is composed of exclusively bundle bone with a limited dimension,[3,4] therefore immediate implants are usually placed by engaging apical and palatal bone.

The three-dimensional implant position plays a significant role in the way prostheses are connected. It has been reported that there is a high incidence of perforation that would occur with a cingulum emergence of most uniaxial anterior implants.[5–7] Although there is inconclusive evidence pertaining to fenestration/dehiscence defects and long-term survival of implants,[8] one would wish to avoid possible fenestration as it has been recommended that implants be encased in 1.5 to 2 mm of bony housing.[9,10] In attempts to avoid this potentially detrimental outcome, most immediate implants are placed in a slightly facial-inclined manner, necessitating that most maxillary anterior implants be restored with cement-retained restorations.[6,7] However, this spatial position of the implant placement can lead to soft tissue recession and compromised esthetics over time as there tends to be less soft and hard tissue thickness around the implant and abutment complex.[11] Even with angulated screw-channel abutments, the restorative angle correction emerges coronal to the level of the crestal facial bone within the confines of the peri-implant soft tissues. This can be associated with unwanted pressure on the supracrestal mucosa, leading to apical migration of the free gingival margin and esthetic complications.[12]

Recently, a novel implant with an inverted body-shift design and dual-axis restorative interface was introduced to address the shortcomings of conventional uniaxial tapered implants. This implant features an apical portion consisting of a tapered design with aggressive threads to enhance primary stability and a narrower, cylindrical coronal portion with shallower threads that provides more space for grafting with biomaterials for augmentation while maintaining greater distance between adjacent natural teeth and implants. Importantly, this implant features a 12° sub-crestal prosthetic angle correction (SAC) within the implant body to allow for ideal positioning with a mitigated risk of apical socket perforation and facilitation of screw-retention of the prosthesis.[13]

Traditionally, clinicians tend to treatment plan with wider and longer implants as each increase of 1 mm in implant diameter may increase the functional surface area by 30%, depending on the implant macrogeometry.[14] Additionally, to ensure sufficient initial stability, the presence of apical bone consisting of 20%–35% of the proposed implant length has been recommended.[5–7] This increase in surface area and length may lead to enhanced stability imperative for immediate implant placement and loading protocols. Recent studies have shown that the ability to deliver a direct or straight channel screw-retained restoration without apical socket perforation occurs at a rate of only 10%–24% with uniaxial implants.[7] Furthermore this rate is dependent upon implant length and diameter; that is, the greater the implant length and diameter, the lower the incidence of screw-retention of the restoration.[7] However, no study exists on comparing dual-axis implants that have been placed into maxillary extraction sockets with virtual planning of uniaxial implants within the same cases.

Therefore, the purpose of this virtual study was twofold: (1) to determine the apical socket perforation rate (ASPR) when a uniaxial implant was simulated in position to deliver a screw-retained restoration in the anterior maxilla (maxillary second premolar to second premolar) and, (2) to determine the affordable maximum length of a corresponding uniaxial implant that would avoid apical socket perforation.

2 | MATERIALS AND METHODS

This observational cross-sectional study was compliant with strengthening the reporting of observational studies in epidemiology (STROBE). The data used for this study was extracted from the Inverta Data Registry, secure repository for the implant with an inverted body-shift design and dual-axis restorative interface (INVERTA Implants, Southern Implants). The registry was approved by the Western Institutional Review Board (study number 1252367), and registered patients provided consent in accordance with the Declaration of Helsinki of 1975, as revised in 2013. Dual-axis implants with a 12° SAC were placed in accordance with the manufacturer's recommendation. The surgical protocol required incisal edge orientation during osteotomy preparation and implant placement (Figure 1A). Since the SAC is incorporated into the body of the implant, the ability to deliver a direct screw-retained restoration increases significantly and is much more consistent (Figure 1B).

2.1 | Patient selection

Cone beam computed tomography (CBCT) scans (Veraviewepocs 3D R100, Morita, Irvine, CA; GALILEOS Comfort^{PLUS}, Dentsply Sirona; Planmeca ProMax 3D, Planmeca) from the database of three private practices were searched for patients who received dual-axis implants (Co-Axis Implants; INVERTA Implants) within the anterior maxilla (maxillary second premolar to second premolar) in immediate tooth replacement therapy (e.g., with adequate initial torque value enabling immediate placement of provisional restoration) between November 2019 and August 2022. Exposure parameters were 90 kV, 8 mAs, 9.3 s, voxel size 125 μm; 85 kV, 28 mAs, 14 s, voxel size 125 μm; 96 kV, 29 mAs, 4.8 s, voxel size 150 μm, respectively. All included scans were of patients with direct or straight channel screw-retained restorations taken immediately after implant placement and subsequent provisionalization void of apical socket perforation. Scans were excluded if one of the following exclusion criteria applied: presence of artifacts[15] (scattering and blooming) affecting the visualization of the facial bone plate; distorted images such as double margins; a field of view that did not capture the entirety of the dental implant (Figure 2).

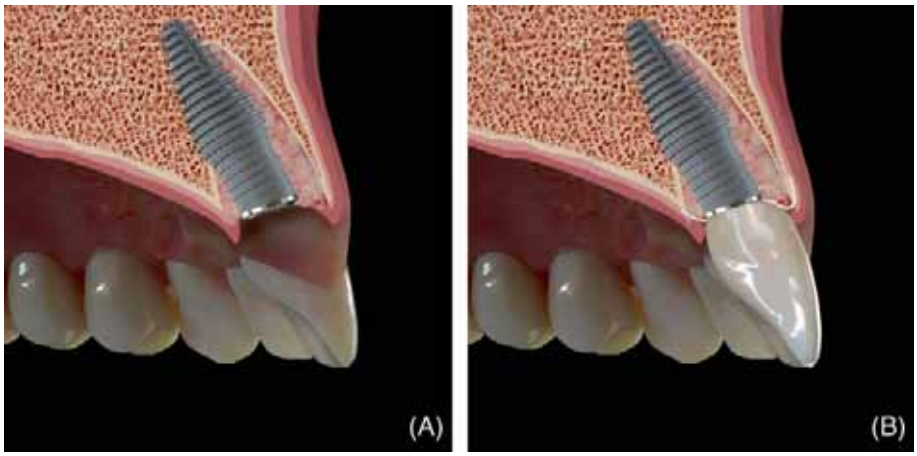

FIGURE 1 (A) The osteotomy is prepared, and implant is placed following incisal edge orientation; (B) a screw-retained restoration is readily attainable due to the SAC design feature incorporated into the body of the implant. *Source*: Reprinted from Chu et al., 2021 with permission

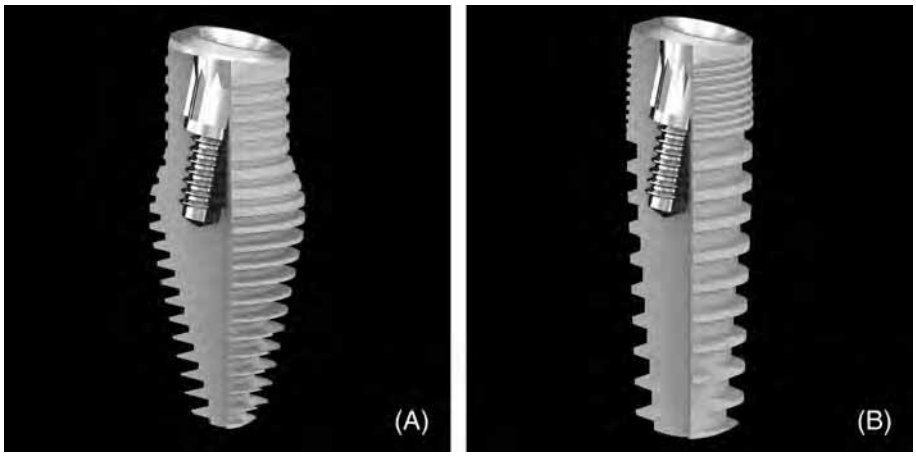

FIGURE 2 Dual-axis implants with 12° SAC. (A) INVERTA implant; (B) PROVATA implant

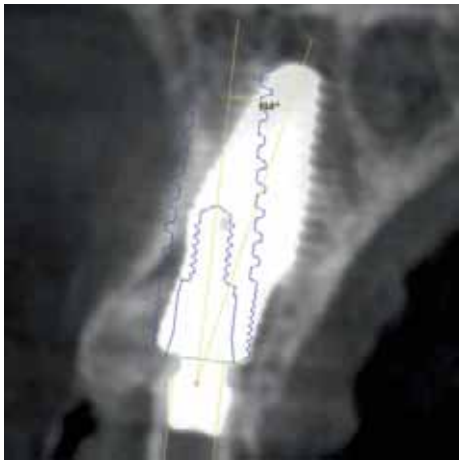

FIGURE 3 Screw access channel was utilized as a reference to align uniaxial implant to dual-axis implant

2.2 | Demographic variables

The recorded demographic variables included age, gender and tooth/implant site.

2.3 | Image analysis

CBCT data sets were saved in Digital Imaging and Communications in Medicine (DICOM) files. DICOM files were exported in multi-file, uncompressed format and were processed using a virtual surgical planning software (coDiagnostiX, Dental Wings Inc.). Data was reconstructed by using cross-sectional slices in the radial plane, perpendicular to the alveolar ridge at 1.0 mm intervals.

Virtual surgical planning was subsequently performed by one prosthodontist (SS). Patient coordination was adjusted to better align the point-of-view to the long axis of the existing dual-axis implant. A simulated uniaxial implant (Deep Conical Tapered Implants) was aligned to the existing dual-axis implant (Co-Axis Implants, Southern Implants; INVERTA Implants, Southern Implants) utilizing the screw access channel as a reference line (Figure 3). The crest module of the simulated implant was aligned with the existing dual-axis implant. For the initial simulation, simulated implants were of a similar length and diameter in accordance with the dual-axis implant placed as the implant was chosen by clinicians to obtain primary stability from the bone apical to and palatal aspect of the pre-extraction tooth (Figure 4). For example, if the dual-axis implant was at its narrowest diameter

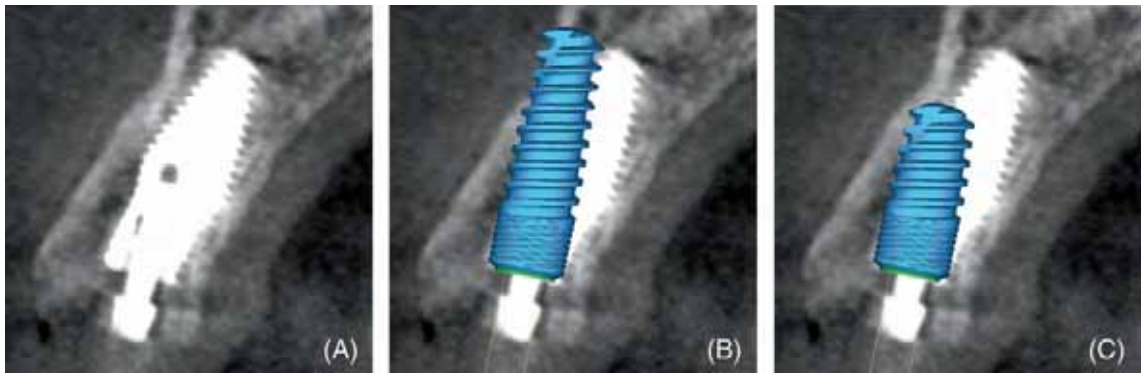

FIGURE 4 (A) Cross sectional view of post-operative CBCT of dual-axis implant (3.5/4.5 × 13 mm) placement; (B) simulated placement of 4.0 × 13 mm which exhibits apical socket perforation; (C) simulated placement of 4.0 × 9 mm which is within the confines of alveolus

FIGURE 5 (A) Uniaxial implant aligned to dual-axis implant; (B) apical socket perforation annotated in red with a graphics editor program. *Source*: Adobe Photoshop 2022, Adobe Inc., San Jose, CA

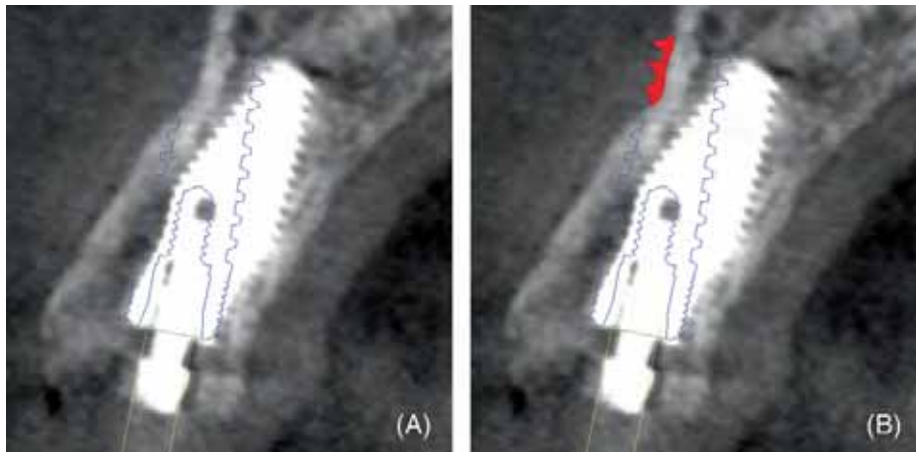

TABLE 1 Specification of simulated implants

	Initial simulation	Shortened length simulation
3.5/4.5 × 11.5	4.0 × 11.0	4.0 × 9.0
3.5/4.5 × 13	4.0 × 13.0	4.0 × 11.0, 4.0 × 9.0
3.5/4.5 × 15	4.0 × 15.0	4.0 × 13.0, 4.0 × 11.0, 4.0 × 9.0
4.0/5.0 × 10	5.0 × 11.0	5.0 × 9.0
4.0/5.0 × 11.5	5.0 × 11.0	5.0 × 9.0
4.0/5.0 × 13	5.0 × 13.0	5.0 × 11.0, 5.0 × 9.0
4.0/5.0 × 15	5.0 × 15.0	5.0 × 13.0, 5.0 × 11.0, 5.0 × 9.0

Note: Initial simulation was done with similar dimension implants. In the case of apical socket perforation, shortened length implants were simulated to identify the longest affordable implant length which can avoid perforation.

measuring 3.5 mm and at its widest diameter measuring 4.5 and 13 mm in length, the simulation was performed using a uniaxial implant with the diameter of 4 mm and length of 13 mm. ASPR by the uniaxial implant was recorded (Figure 5). In the cases with apical socket perforation, reduced implant lengths were simulated to identify the longest length of the uniaxial implant attainable while avoiding perforation. Implant length and diameter for initial and shortened length simulation are presented in Table 1.

2.4 | Data analysis

A Cohen intra-examiner agreement rate was calculated to test the accuracy of the examiner during radiographic assessment. The measurement started when the examiner reached > 90% agreement in a representative sample of 30 patients. Descriptive statistics were used to delineate the recorded data. Frequencies and percentages were used to summarize the incidence rate of observed ASPR.

3 | RESULTS

A total of 108 patients and 132 implants were screened. After the inclusion and exclusion criteria were applied, 81 patients (71.35% were female, age ranging from 22 to 91 year old with an average of 55.45 year old) with a total of 101 dual-axis dental implants (INVERTA, Southern Implants; PROVATA Implants, Southern Implants) placed within the esthetic zone (maxillary second premolar to second premolar) were selected for analysis. The reasons for the

TABLE 2 Overall distribution of length and diameter of dual-axis implants

	Central incisor	Lateral incisor	Canine teeth	Premolars	Total
3.5/4.5 × 11.5	3	2	0	2	7 (6.93%)
3.5/4.5 × 13	28	18	6	4	56 (55.45%)
3.5/4.5 × 15	7	0	5	0	12 (11.88%)
4.0/5.0 × 10	1	0	0	0	1 (0.99%)
4.0/5.0 × 11.5	3	0	0	4	7 (6.93%)
4.0/5.0 × 13	9	0	2	1	12 (11.88%)
4.0/5.0 × 15	4	0	0	2	6 (5.94%)
Total	55 (54.45%)	20 (19.8%)	13 (12.87%)	13 (12.87%)	101 (100%)

TABLE 3 Overall simulated incidence of apical socket perforation by implant length and diameter

	Central incisor	Lateral incisor	Canine teeth	Premolars	Total
3.5/4.5 × 11.5	3 (2)	2 (0)	0	2 (2)	7 (4)
3.5/4.5 × 13	28 (14)	18 (11)	6 (3)	4 (0)	56 (28)
3.5/4.5 × 15	7 (4)	0	5 (2)	0	12 (6)
4.0/5.0 × 10	1 (0)	0	0	0	1 (0)
4.0/5.0 × 11.5	3 (1)	0	0	4 (0)	7 (1)
4.0/5.0 × 13	9 (7)	0	2 (2)	1 (0)	12 (9)
4.0/5.0 × 15	4 (1)	0	0	2 (0)	6 (1)
Total	55 (29)	20 (11)	13 (7)	13 (2)	101 (49)

Note: Similar dimension (length and diameter) implant was used. The number of perforations is denoted in parentheses.

TABLE 4 Overall simulated incidence of apical socket perforation by implant length and diameter when shortened length (11 mm) uniaxial implant was used

	Central incisor	Lateral incisor	Canine teeth	Premolars	Total
3.5/4.5 × 11.5	3 (2)	2 (0)	0	2 (2)	7 (4)
3.5/4.5 × 13	28 (11)	18 (10)	6 (1)	4 (0)	56 (22)
3.5/4.5 × 15	7 (4)	0	5 (2)	0	12 (6)
4.0/5.0 × 10	1 (0)	0	0	0	1 (0)
4.0/5.0 × 11.5	3 (1)	0	0	4 (0)	7 (1)
4.0/5.0 × 13	9 (6)	0	2 (2)	1 (0)	12 (8)
4.0/5.0 × 15	4 (1)	0	0	2 (0)	6 (1)
Total	55 (25)	20 (10)	13 (5)	13 (2)	101 (42)

Note: The number of perforations is denoted in parentheses.

exclusion were difficulty in delineating facial bone plate and cone cut noted in the CBCT scans. A Cohen intra-examiner agreement rate of 95% was reached for the examiner before the initiation of the study. Among the 101 implants, 54.45% were placed in central incisor, 19.8% in lateral incisor, 12.87% in canine teeth, and 12.87% in premolar (first and second) position (Table 2).

Overall, the most used length of the implants was 13 mm (67.33%) and the average insertion torque value (ITV) was 54.05 N/cm (range 30–90 N/cm). Incidence of apical socket perforation noted in the initial simulation is presented in Table 3.

Initial simulation with similar dimension implants revealed overall ASPR of 48.51%. Central incisor, lateral incisor and canine teeth exhibited similar ASPR of 52.72%, 55% and 53.84%, respectively. Premolars showed a reduced ASPR of 15.38%. 33.33% of 10 and 11.5 mm, 54.41% of 13 mm, and 38.89% of 15 mm implants were shown to perforate with a simulated uniaxial implant. When a shortened length implant was used for simulation, no difference was noted with 13 mm implants. Similarly, only a marginal difference was observed with 11 mm implants. However, the overall ASPR was reduced to 20.79% with 9 mm implants. Results from a shortened length simulation with 11 and 9 mm implants are presented in Tables 4 and 5.

4 | DISCUSSION

The three-dimensional positioning of immediate implants in fresh extraction sockets is of particular concern as patients' esthetic demands grow. The average width of the facial bone plate in the anterior maxilla has been shown to be <1 mm thick, with an average of

TABLE 5 Overall simulated incidence of apical socket perforation by implant diameter and length when shortened length (9 mm) uniaxial implant was used

	Central incisor	Lateral incisor	Canine teeth	Premolars	Total
3.5/4.5 × 11.5	3 (2)	2 (0)	0	2 (2)	7 (4)
3.5/4.5 × 13	28 (5)	18 (5)	6 (1)	4 (0)	56 (11)
3.5/4.5 × 15	7 (0)	0	5 (1)	0	12 (1)
4.0/5.0 × 10	1 (0)	0	0	0	1 (0)
4.0/5.0 × 11.5	3 (0)	0	0	4 (0)	7 (0)
4.0/5.0 × 13	9 (4)	0	2 (1)	1 (0)	12 (5)
4.0/5.0 × 15	4 (0)	0	0	2 (0)	6 (0)
Total	55 (11)	20 (5)	13 (3)	13 (2)	101 (21)

Note: The number of perforations is denoted in parentheses.

0.5 mm at the most crestal aspect.[16] Any insult to this already thin and highly avascular bony wall can result in loss of primary stability, unpredictable resorption patterns, and potential esthetic sequelae.

Furthermore, thin hard tissue phenotypes have also been correlated with correspondingly thin soft tissue phenotypes[17] posing further risk for esthetic complications. Frequently, such esthetic complications around implants result from surgical and prosthetic errors in three-dimensional positioning within the confines of a limited alveolar housing and potentially over-contoured restorations necessitated by facially angulated placement that is required by the available volume of bone to engage with a uniaxial implant. Pre-surgical three-dimensional treatment planning is of utmost importance as the relationship of the anterior maxillary teeth within the alveolar housing poses unique anatomical challenges to the surgeon attempting prosthetically driven immediate implant placement.

4.1 | Interpretation of data and comparison with similar investigations

The present study reports an overall ASPR of 48.51% when utilizing a similar dimension uniaxial implant for virtual surgical planning. One study reported overall ASPR of 81.7% in a similar virtual investigation.[5] Comparable results have been reported by another study in which only 14% of 1600 simulated cases were eligible for immediate implant placement with direct or straight screw-channel screw-retained prostheses. The considerable discrepancy between the present study result may be due to the virtual implant selection, as those authors chose an implant 4- to 5-mm longer than the root length of the natural tooth whereas we have selected similar and shorter length implants in reference to the existing dual-axis implant for comparison. Another attributing factor may be the inclusion of premolar teeth, which revealed a lower ASPR (15.38%). One other virtual investigation reported 35 out of 144 cases (24%) were ideal for an immediate tooth replacement therapy with a screw-channel ideal for a screw-retained prosthesis.[6] Additionally, in 103 of the remaining 109 cases an abutment with corrected angle (within 25° and mean value of 12.7°) enabled a screw-retained prosthesis.[6] In the present study 49 out of 101 cases (48.51%) could be corrected by a dual-axis implant with 12° SAC.

4.2 | Anatomy of the maxillary anterior teeth

Variations in tooth morphology dictate the three-dimensional position of the tooth.[18] The maxillary anterior teeth particular have a disparity between the crown and root angulations, with the two having a biaxial relationship ranging up to 25° (Figure 6A).[18,19] Immediate implant therapy for a tooth with an increased crown-root angle can thus pose a potential restorative conundrum. It would naturally follow that a replacement implant should mimic the biaxial relationship of the crown and root, offered by a dual-axis implant with SAC.

4.3 | Anatomy of the maxillary anterior alveolus in relation to the tooth positioning

The maxillary anterior alveolus is a nonuniform structure that frequently undulates in a corono-apical direction. The exact curvature of the facial alveolar housing apical to the root apex of the maxillary anterior teeth has been measured via CBCT studies.[20] Specifically this curvature constricts toward the caudal direction, resulting in a facial undercut of about 1 mm for maxillary anterior teeth, often complicating the negotiation of immediate implant placement as the implant may encroach on a very thin avascular shell of bone.[21]

Other radiographic studies analyzing the root position in relation to the available bone for osteotomy preparation in immediate implant therapy have shown that most maxillary anterior teeth (about 80%) are retroclined and positioned directly up against the facial bone plate, with a triangle of palatal bone available for implant placement.[2,22] Yet due to the more common location of maximum bone palatal to the root, uniaxial implant positioning in a fresh extraction socket frequently occurs along a more acute angle in relation to the future restoration's cingulum emergence. In addition, an interesting report[23] has shown that in the maxillary anterior region, the average angle of divergence between the long axis of the tooth and the long axis of its associated alveolar bone ranges between 10 to 20°,[23,24] with a subset of canine teeth and lateral incisors displaying up to 30° of divergence,[23] confirming the findings of previous studies (Figure 6B).[2,22]

That is to say, more often than not, during immediate tooth replacement therapy in the maxillary anterior zone, angulations of 10 to 30° may result between a uniaxial implant's emergence and the

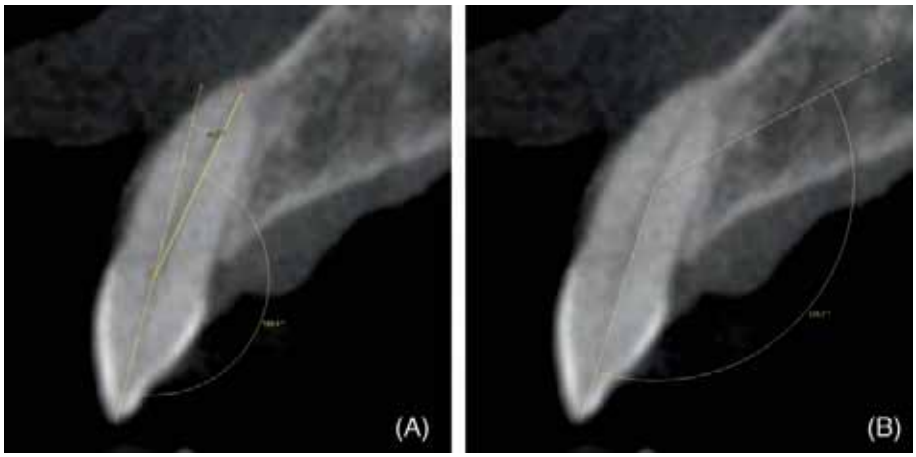

FIGURE 6 (A) Crown to root angle disparity measured to be 11.6° in a maxillary lateral incisor; (B) tooth to alveolus angle disparity to be ~45°

ideal cingulum access emergence, which is in line with the high frequency of ASPR noted in this three-dimensional simulation study.

In a simulation to provide an alternatively shorter implant that would potentially avoid the incidence of apical socket perforation, 9 mm was found to be the maximum implant length allowable (Table 5). Theoretically, this is sensible as there would be a shorter implant length that could possibly not interfere with the facial bone plate. However, in practice such an option is not feasible due to the anatomy of the roots and dimensions of the resultant extraction socket.

The average length of succedaneous maxillary central and lateral incisor roots, when measured from the CEJ to the root apex, is about 13 mm and that of maxillary canines is about 17 mm.[25] The most coronal portion of the root in reality lies 3- to 4-mm supracrestal due to supracrestal attachment dimension.[26] Immediate implants are usually placed at the level of the mid-facial osseous crest, 3- to 4-mm subgingival, accounting for this very same supracrestal attachment.[27] In immediate tooth replacement therapy, the placement of a fixture relies upon enough native bone beyond the socket apex available for mechanical engagement, usually advocated as 3- to 4-mm.[6,7]

Taking these aforementioned elements into consideration, the necessary length of an appropriate implant with enough primary stability would be at least the length of the root, which is in line with the fact that the majority (67%) of dual-axis implants placed in this study were 13 mm in length, corresponding exactly with the average length of the maxillary incisors. It would thus follow that a 9 mm length implant, despite having a less frequent ASPR, does not suffice in order to engage enough native bone apical to the socket periphery and at an appropriate level relative to the mid-facial osseous crest for biologic-esthetic harmony. Thus, the clinician is left with employing a longer implant, which may be associated with aforementioned sequelae.

Summating all these incongruities in the dimension, positioning, and angulation of the tooth-alveolus complex, one can see that there is very limited amount of viable alveolar bone available for implant engagement with resultant sufficient primary stability required for immediate placement of provisional restoration while respecting the biologic confines of the extraction socket-alveolus complex and most importantly, in a prosthetically appropriate position. Notably, none of the included implants in this simulation study perforated as detected via CBCT scan and the mean ITV for all implants was 54 N/cm, well above standards accepted for immediate loading protocols.[28]

This highlights the utility of a dual-axis design as the clinician can then more directly follow the path of available bone.[29] This offers many advantages: mitigating the risk of apical socket perforation and need for additional grafting; engaging more bone for increased primary stability; higher frequency of the ability to deliver screw-retained retorations[30–32] and avoidance of potential biologic complications from cement[33] or over-contoured restorations that may place unwanted pressure on gingival tissues[34]; increased buccal gap distance resulting in optimization of thick buccal plate for functional and esthetic longer-term stability.[10] It has been shown in a recent prospective study that the average Pink Esthetic Score (PES)[35] of these dual-axis body-shift implants with SAC, when placed immediately into flapless extraction sockets in combination with dual-zone socket management and immediate provisionalization, is 12.79.[32] Notably, a retrospective study compared the PES of conventional tapered uniaxial implants versus body-shift dual-axis implants, with both groups of implants immediately placed via a flapless extraction protocol and dual-zone socket management with immediate provisionalization. The average PES recorded for the tapered group was 10.33, versus 13.29 for the body-shift dual-axis group.[31]

4.4 | Limitations of present study

Although virtual evaluation based on radiographic datasets could be considered a limitation, a previous publication reported that there is minimum underestimation or overestimation when virtual measurements were compared with direct measurements.[36] However, the findings of the present study should be interpreted with caution as clinical application will not be as exacting as virtual simulation. Another limitation of the study is the heterogeneity (multiple clinicians, multiple CBCT devices) of the datasets evaluated.

5 | CONCLUSION

A simulated virtual surgical planning with uniaxial implants in sites which previously had dual-axis implants placed with screw-retained prostheses revealed a high ASPR (48.51%). When the length of the uniaxial implant was reduced to 11 and 9 mm, the ASPR was decreased to 41.58% and 20.79%, respectively. A dual-axis implant design effectively evades anatomical challenges in the anterior maxilla (esthetic zone). Considering the current evidence, efforts should be made to carefully consider the angular disparity between the extraction socket-alveolus complex and the future restorative emergence so that a harmonious biologic-esthetic result may be more predictably and consistently obtained.

ACKNOWLEDGMENTS AND DISCLOSURE

Stephanie M. Chu, Stephen J. Chu, Hanae Saito, Barry P. Levin, Nicholas L. Egbert, Guido O. Sarnachiaro, Dennis P. Tarnow are consultants for Southern Implants. The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Song SJ, Chu SM, Chu SJ, et al. A comparative analysis of dual-axis implants placed into maxillary anterior extraction sockets versus virtual planning with uniaxial implants: A simulated cone beam computed tomography study of implant length and diameter. *J Esthet Restor Dent*. 2023;35(1):206-214. doi:10.1111/jerd.13011

Received: 21 April 2022 | Accepted: 21 April 2022
DOI: 10.1111/jerd.12920

CLINICAL ARTICLE

WILEY

The crown lengthening double guide and the digital Perio analysis

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Abstract

Objective: This article describes a surgical crown lengthening double guide, which was digitally obtained to improve diagnosis, treatment outcome, and follow-up.

Clinical considerations: The rehabilitation of anterior dental esthetics should involve interdisciplinary and facially driven planning for achieving pleasant long-term outcomes. Surgical crown lengthening is one of the most common periodontal surgery, which can be assisted by digital tools to improve surgical planning and follow-up.

Conclusion: The double guide for surgical crown lengthening allows the proper management of hard and soft tissues for achieving a predefined goal based on biological requirements and facially driven planning. In addition, the digital quality control allows the follow-up compared with the pre-operative condition and planned treatment plan.

Clinical significance: The use of digital tools allow the clinician to develop a facially driven planning with proper communication with the team and patient, leading to a shorter, more predictable, and less invasive surgical technique, reducing postoperative inflammation and increasing patient comfort.

KEYWORDS
CAD-CAM, facially driven planning, periodontics, surgical crown lengthening, surgical guide

1 | INTRODUCTION

The excessive gingival display is a multifactorial condition, often referred as "gummy smile," that requires accurate diagnosis and treatment planning for achieving long-term esthetic outcomes.[1] To improve tooth exposure and reestablish the biological width, a surgical crown lengthening is required, which comprises gingivoplasty and osteotomy.[2]

Due to the increasing digitalization of dentistry in recent years, countless novel concepts have emerged, leading to new ways of diagnosing, planning, communicating, and performing dental treatments. The introduction of digital tools and the creation of a digital workflow facilitates the guidance of dental procedures. In this sense, outcomes can be compared with the initial planning, according to the concepts of Guided Dentistry and Digital Quality Control.[3–5]

Guided dentistry refers to the three-dimensional (3D) virtual simulation of treatment before it is performed, making it possible to visualize the final result even before it is done. In addition, appliances can be developed to help the clinician to achieve surgically the expected result. Digital planning begins with bidimensional (2D)[6,7] virtual simulations (digital smile design). These simulations in turn will guide the 3D virtual designs that are produced in specific

computer-aided design (CAD) software. With the virtual design finalized and approved by both the dentist and the patient, it is possible to produce guides for the execution of the procedures, increasing the predictability and effectiveness of the results through computer-aided manufacturing (CAM).[8]

FIGURE 1 2D facially driven smile frame showing the need for surgical crown lengthening

Digital quality control consists of comparing the final result of the treatment with the initial simulation, allowing the professional to verify the effectiveness of the procedure, or if necessary to make adjustments to achieve the proposed objective. This control is done by scanning the final result and superimposing the 3D file of the virtual simulation of the treatment.[9] For instance, among the main advantages and reasons for the high success of nowadays aligners, is the possibility to examine the outcome before the start of the treatment and the possibility to compare the outcome with the initial proposition presented to the patient.[10]

These are two important concepts of modern digital dentistry because besides improving diagnosis, planning, and execution, they also generate a positive psychological impact on the patient by improving patient education, confidence, and motivation since they demonstrate a commitment by the team to deliver results respecting the preapproved simulations. In addition, they generate

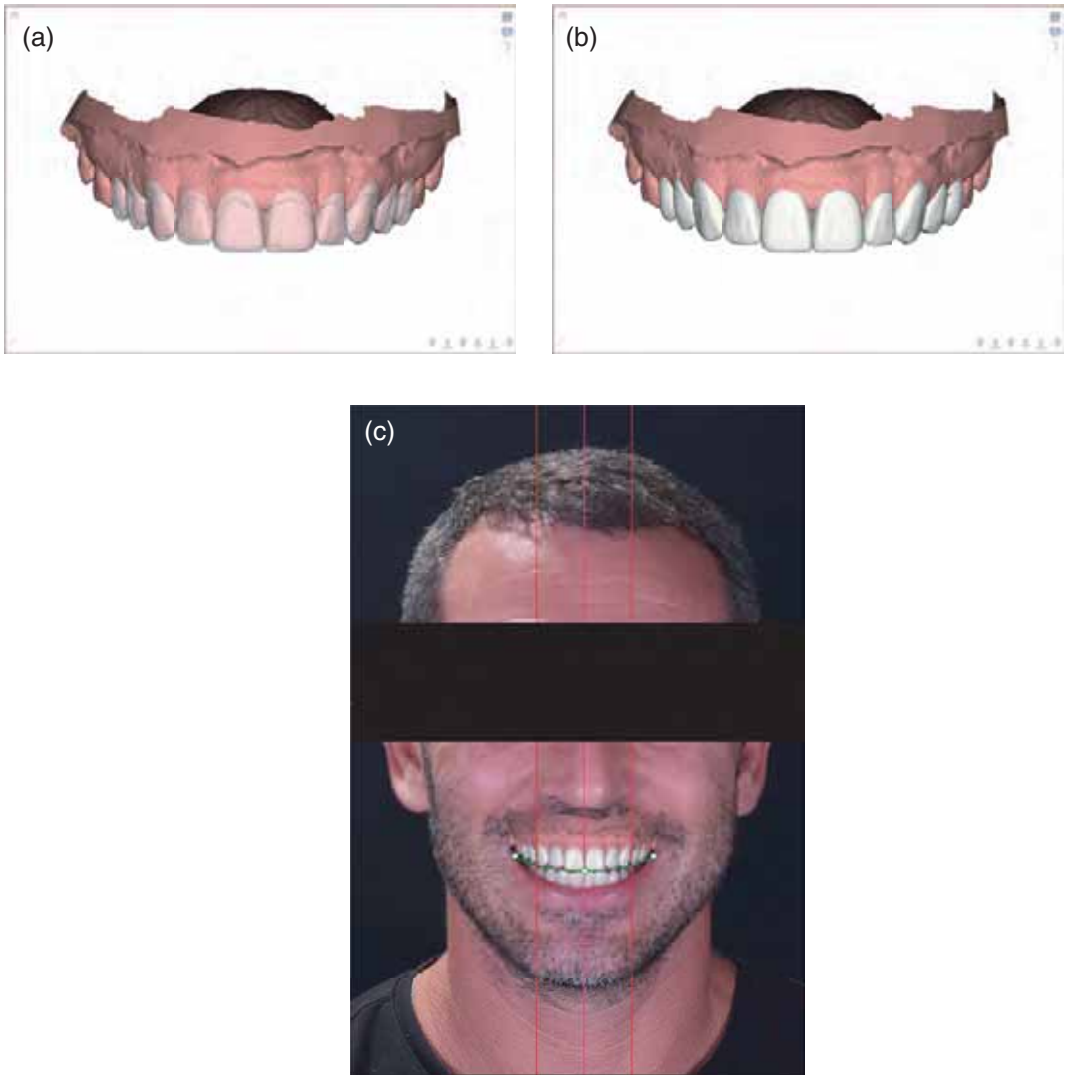

FIGURE 2 3D diagnostic wax-up performed and presented for the patient. (A) transparent diagnostic wax-up showing the amount of gingivoplasty required. (B) opaque diagnostic wax-up showing the planned teeth surface. (C) facially driven planning.

more efficiency and confidence for the professional, since the use of guides speeds up the process and makes the procedure less dependent on the operator's manual and artistic skills.

Nearly all specialties of modern dentistry can take advantage of this benefit, with these two concepts, as a rule, to achieve effective and predictable results.[11,12] This article aims to describe how these

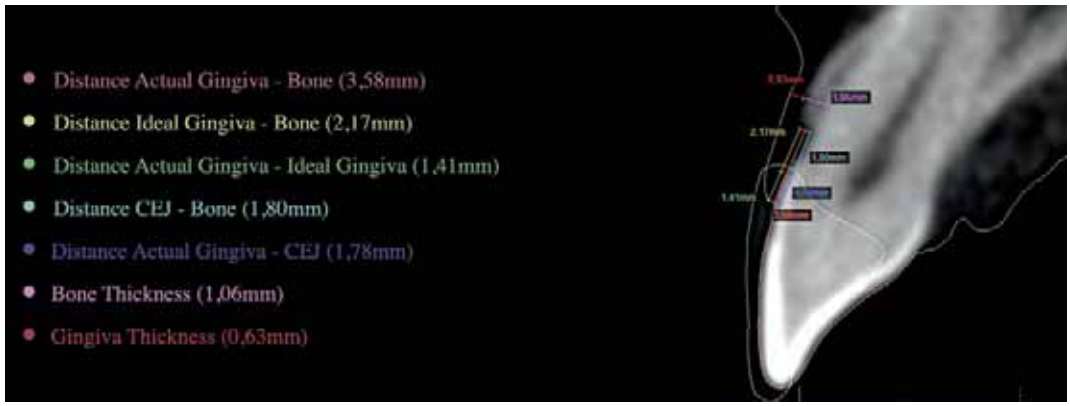

FIGURE 3 Perio Analysis showing the measurements performed for surgical procedure

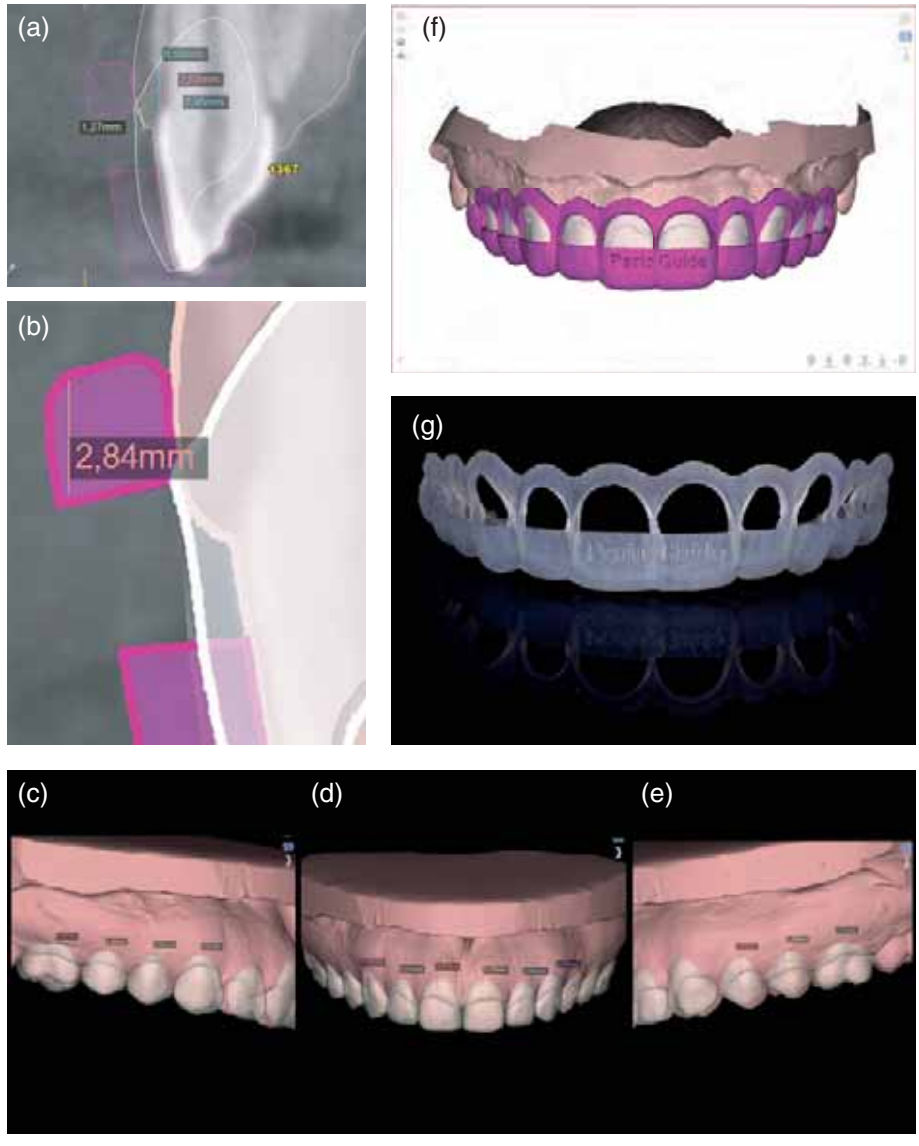

FIGURE 4 Double guide design and manufacturing. (A, B) Perio Analysis measurements determine the guide design. (C–E) Amount of gingivoplasty required. (F) The final design of the double guide. (G) Double guide printed and postprocessed

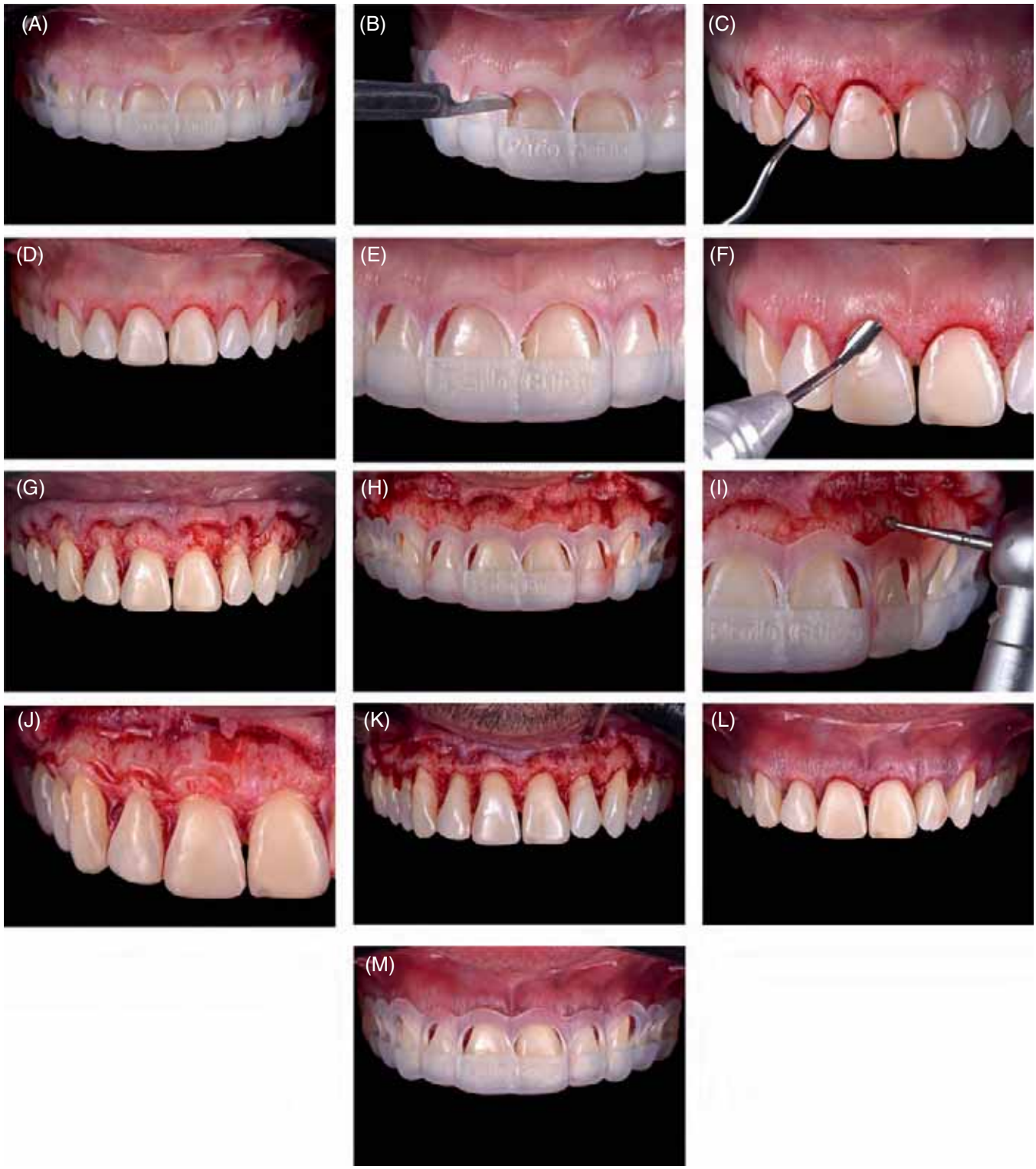

FIGURE 5 Surgical procedure with the double guide. (A) Evaluating the double guide fit on teeth and soft tissue. (B) Internal bevel incision performed with scalpel blade 15C perpendicular to the inner edge of the window of the guide, outlying the new gingival margin. (C) Soft tissue removal with a periodontal curette. (D, E) Upper arch after gingivectomy and confirmation through the guide. (F) Intrasulcular incision with an ophthalmologic scalpel blade. (G) Full-thickness mucoperiosteal flap elevated, note that the bone crest is mostly at the level of the CEJ. (H) Repositioning of the guide to perform the osteotomy. (I) Marking the osteotomy limit with spherical diamond bur according to the outer edge of the window of the guide. (J) Vertical bone level established. (K, L) osteotomy and osteoplasty finished and flap sutured. (M) Repositioning the guide and the comparison of planned and achieved gingival margin (quality control)

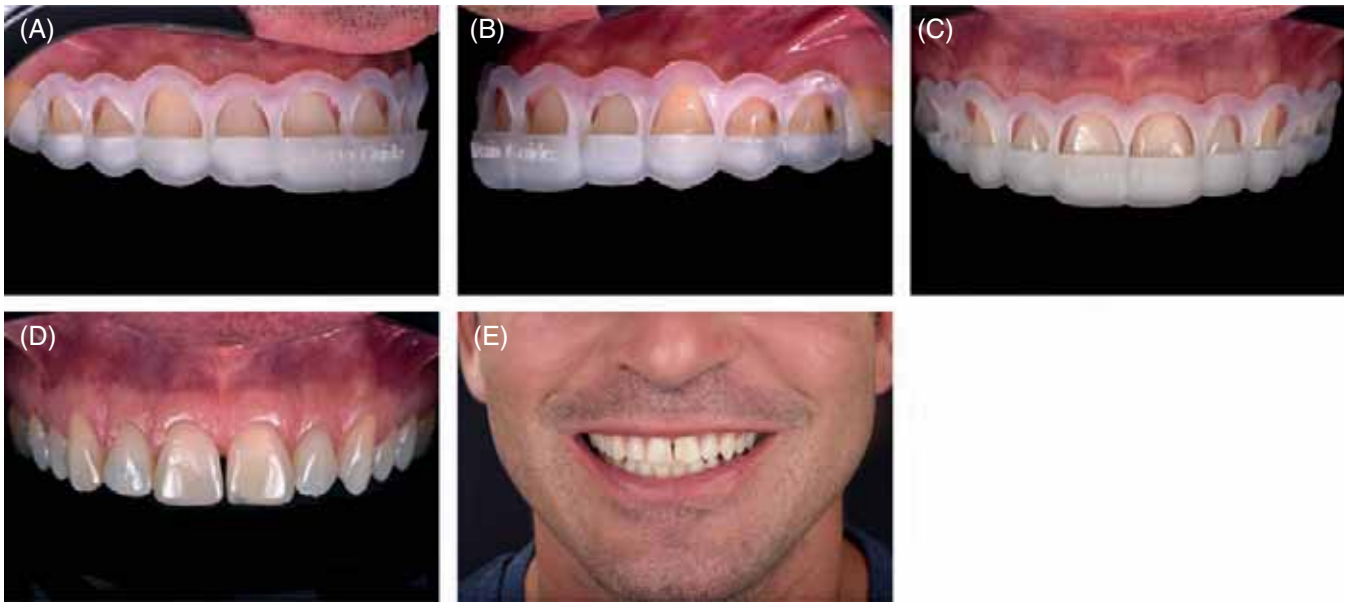

FIGURE 6 One-year follow-up. (A–C) Lateral and frontal view with repositioning of the guide confirming outcome obtained as planned (quality control). (D, E) Intraoral and extraoral view of the achieved gingival margin

concepts can assist treatments involving clinical crown lengthening in esthetic regions, promoting a digitally guided treatment, its integration with the face, with other interdisciplinary procedures, and leading the result closer to the initial planning.

2 | CASE REPORT

A 35-years old male patient was referred to the private dental office unsatisfied with the size of his teeth during smiling. After clinical and radiological examinations, photographs and intraoral scans were taken for data collection. A facially driven smile frame was designed using DSDApp (DSDApp LLC), which revealed the need for surgical crown lengthening to improve the smile appearance (Figure 1). Therefore, a cone-beam computed tomography (CBCT) exam with lip retractor was required for the Perio Analysis and surgical planning.[13] By superimposing the clinical data, a digital patient was created and a crown lengthening double guide was planned using the NemoStudio software (Nemotec, Madrid, Spain). The 3D simulations were presented to the patient, which accepted the treatment planning (Figure 2).

2.1 | Perio analysis and surgical planning

Taking the 2D facially driven smile frame as a reference, a 3D digital diagnostic wax-up was designed. The following distances were measured on CBCT images: bone crest to the gingival margin (pretreatment biological width); cement-enamel junction (CEJ) to the gingival margin; CEJ to the bone crest; gingival and bone thickness. When superimposing the digital diagnostic wax-up with the CBCT scan, the following measurements were obtained: the distance from the cervical margin of the wax-up to the gingival margin (determining the amount of soft tissue to be removed) and the distance from the cervical margin of the wax-up to the CEJ (determining if bone removal is required). Thus, this analysis allowed to determine the need for gingivoplasty associated with osteotomy and whether the osteotomy could be performed with a flapless approach, or would require flap elevation (Figure 3).

2.2 | Crown lengthening guide design and manufacturing

Based on esthetic and biological parameters, the double guide was designed to orientate the posttreatment position of bone and soft tissue (Figure 4). Therefore, a window was placed contouring the cervical margin of the waxed-up teeth, in which the inner edge guided the gingivoplasty and the outer edge guided the height of the bone crest. The distance between the inner and outer edge was determined by the periodontal phenotype. For cases of thin-scalloped periodontium (type A1), the distance from the bone crest to the gingival margin should be about 2.0 mm. For thick-scalloped periodontium (type A2) a distance of 3.0 mm should be observed. For a rather flat-thick periodontium (type B), this distance increases to 4.0 mm, which should be respected so that there is no relapse of the gingival margin.[14] After the guide was digitally designed, a motivational mock-up was tested intraorally and the guide was printed with a biocompatible resin, postprocessed, and sterilized (Figure 4).

2.3 | Crown lengthening surgical procedure

The surgical procedure is shown in Figure 5. According to the patient phenotype, a 3 mm biological width was determined by the Perio

Analysis measurements. After evaluating the double guide fit on teeth and soft tissue, the inner edge of the guide delimited the new gingival margin. Once the gingivectomy was performed and the flap elevated, the outer edge of the guide delimited the osteotomy limit. During every step, the repositioning of the guide was used to evaluate the soft and hard tissues limit, according to the planning.

2.4 | Digital quality control

After the healing period, the quality control was obtained by adapting the double guide to the teeth, revealing the planned and achieved gingival margin (Figure 6). In addition, after 1-year, intraoral scans were taken and the preand posttreatment exams were compared and stored in cloud data for future comparisons (Digital Quality Control).

3 | DISCUSSION

The main factors for the success in esthetic crown lengthening procedures include the achievement and maintenance of ideal gingival margin levels and architecture, which are influenced by biologic requirements.[15] The digitally obtained double guide provides proper soft and hard tissues management and, therefore, reduces the chances of under-or overcontouring of these tissues, facilitating predictability, reproducibility, and long-term pleasant outcomes.[1] In addition, optimal fit, ease fabrication, and time-efficient procedure have been reported among the advantages of the technique.[1]

The facially driven and biologically oriented planning associated with the 2D simulation and 3D guide design allows the clinician to propose and perform a less operator-dependent procedure because the decision of how much and which tissues should be removed is oriented by the Perio Analysis measurements. Hence, the digital visualization of the patient gingival phenotype and biological width is mandatory, which can be obtained with CBCT exam with lip retractor and intraoral scan.

Once the procedure is performed, the comparison between the planned and achieved outcomes is essential for the follow-up. Therefore, the Digital Quality Control is proposed to assess the maintenance of the gingival level and relapse of soft tissue.

The use of a digitally designed double guide for crown lengthening has been successfully reported elsewhere.[1,16–21] However, further studies should evaluate the accuracy of surgical guides for crown lengthening procedures and the influence of several factors such as scanner protocol and systems, guide errors or misfits, different resins, 3D printers, and software systems.[17,18] In addition, clinical trials are needed to validate and confirm the reliability and repeatability of this technique.[18,19]

4 | CONCLUSION

The double guide for surgical crown lengthening allows the proper management of hard and soft tissues for achieving a predefined goal based on biological requirements and facially driven planning. In addition, the digital quality control allows the follow-up compared with the preoperative condition and planned treatment plan.

ACKNOWLEDGMENTS AND DISCLOSURE

Christian Coachman is the founder and CEO of the DSD company. The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

No research data available

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How to cite this article: Coachman C, Valavanis K, Silveira FC, et al. The crown lengthening double guide and the digital Perio analysis. *J Esthet Restor Dent*. 2023;35(1):215-221. doi:10.1111/jerd.12920

Received: 29 September 2022 | Revised: 19 December 2022 | Accepted: 19 December 2022

DOI: 10.1111/jerd.13014

CLINICAL ARTICLE

WILEY

Copy–paste concept: Full digital approach in the management of gingival emergence profiles

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Abstract

Objective: Obtaining a perfect integration of a prosthetic rehabilitation on natural teeth and implantys in the esthetic zone requires a deep knowledge of the biological processes and a clear understanding of the characteristics of the restorative materials. Once the soft tissue profile has been created with the placement of a temporary prosthesis, the ability to accurately transfer information about the tissue profile and the contour of the restoration for the fabrication of the definitive crowns can be challenging.

Clinical Significance: This paper illustrate the copy paste full digital workflow, a simple protocol that allows to create definitive restorations by making an exact copy of the temporary prosthesis that has been placed in function in the patient's mouth.

KEYWORDS

digital quality control, digital workflow, emergence profile, intraoral scanning, restorative digital plan

1 | INTRODUCTION

The natural integration between the prosthetic restoration and the periodontal or peri-implant soft tissue has a key role in determine the esthetic result of the dental treatment. The creation of an harmonious profile of the restoration that contour the soft tissue around teeth and implants is of paramount importance for the final success, in particular in the esthetic area.[1,2]

The restorative dentist dedicates particular attention to the fabrication of the temporary prosthesis with the purpose of preserving, supporting, and sculpting the soft tissue while maintaining tissue health.[3,4] Once the soft tissue contour has been established and the ideal profile of the restoration has been identified, the critical part is the accurate transfer of those information to the dental technician.[5,6]

For many years, conventional impression techniques using elastomeric impression materials (polyvinylsiloxanes and polyethers) have been used in fixed prosthodontics for dental implants and natural teeth.[7]

On natural dentition, retraction cords or retraction paste have been placed into the sulcus to horizontally and vertically displace the marginal gingiva and allow the impression material to register the entire finish line of the tooth preparation. In implant dentistry, in order to prevent the natural collapse of the peri-implant mucosa after removing the temporary restoration, impression copings have been customized intra-orally or extra-orally and used with an open or close tray technique.[8]

In the last decade digital technologies have radically changed the way we routinely practice dentistry and new tools such as intra-oral scanners, 3D printers, and milling machines are often present in our practices.[9] Evolution in the dental industry has allow to significantly improve trueness and precision of intra-oral scans and the accuracy of printed models to such a level that full digital workflows are commonly used to fabricate definitive restorations on teeth and implants.[10]

The purpose of this paper was to describe full digital workflows to transfer the definitive emergence profile and angle for fixed restoration on dental implants and natural teeth.

2 | CLINICAL TECHNIQUE

The copy–paste full digital workflow in implant prosthesis.

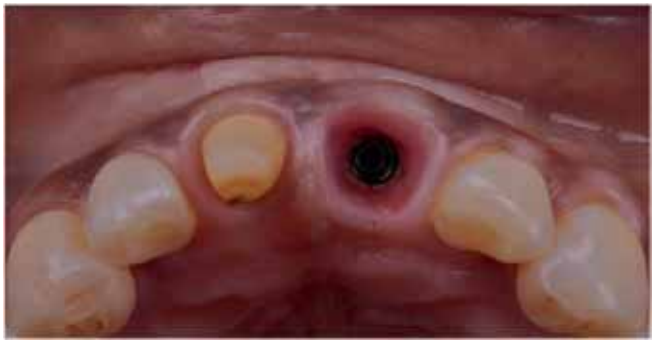

FIGURE 1 Occlusal view highlighting the periodontal and peri-implant soft tissue of the maxillary central incisors.

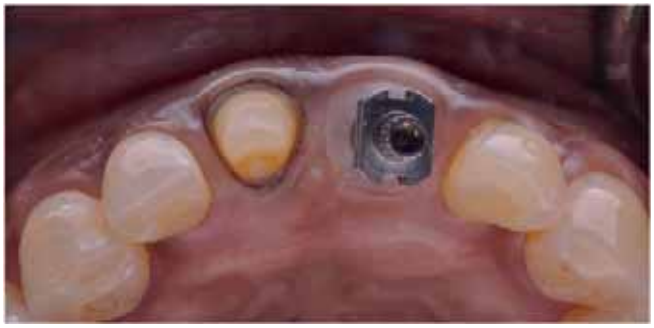

FIGURE 2 On the natural tooth a #000 retraction cord has been placed into the sulcus to horizontally and vertically displace the marginal gingiva, whether on the implant site an open tray impression coping has been customized extra-orally to support the peri-implant mucosa.

FIGURE 3 Occlusal view of the final prostheses. Note the profiles of the restorations that contour the soft tissue.

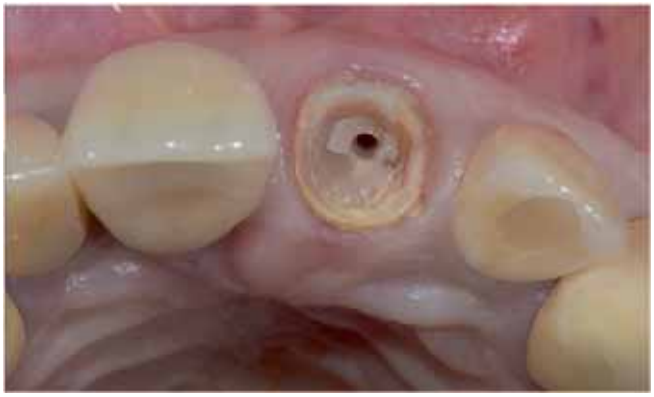

FIGURE 4 Maxillary left central incisor broken at gum line and judged non-restorable due to a palatal fracture.

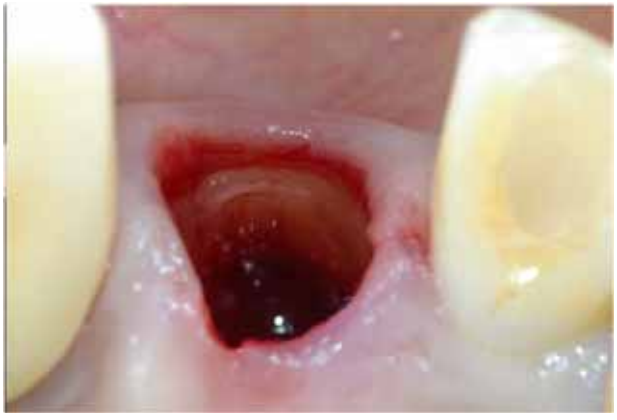

FIGURE 5 A partial extraction therapy approach was performed. The root was sectioned mesio-distally and a C-shape fragment of dentin was left facing the buccal site of the socket to maintain the supracrestal attached tissue. The coronal margin of the fragment was reduced until reaching the level of the facial bone crest.

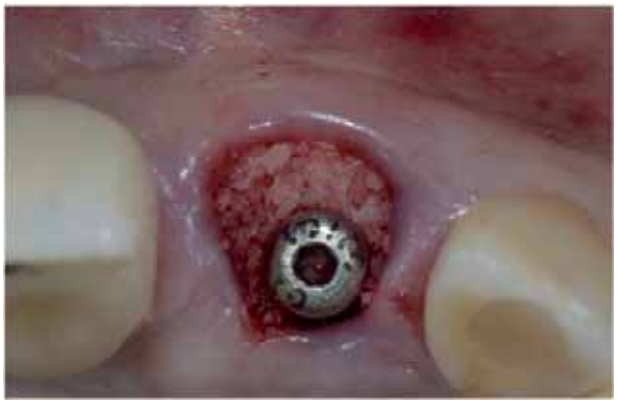

FIGURE 6 A tall and narrow healing abutment was placed and the marginal gap was filled with small-particle bone graft. The dual-zone bone grafting (i.e., placement of the bone graft in the gap between the implant and the labial bone plate, as well as in the zone above the implant-abutment junction) provides support and volume to the hard and soft tissues

A detailed treatment planning, precise 3D position of the implant and adequate soft tissue volume facilitate the achievement of a final natural esthetics.[11] A screw retained temporary prosthesis is commonly used to support and condition the soft tissues by generating an emergence profile that replicates and mimics the tissue architecture of the adjacent dentition.[12]

Significant amount of time is often required to optimize the morphology of the temporary restoration and waiting for tissue maturation, managing the critical and subcritical contour by adding or

trimming the acrylic material.[13] In order to fabricate the definitive restoration, all the information related to the prosthetic volume, the outline of the soft tissue and the clearance with the opposing arch need to be accurately transferred to the dental technician.[10–14]

One of the most popular technique included the use of a custom impression coping that will be embedded in a conventional impression taken with elastomeric materials.[15]

Afterwards, impression of the same arch with the restoration in place and the impression of the opposing dentition were taken (Figures 1–3).

The copy–paste full digital workflow allows to get those clinical information through the registration of six intraoral scans (Figures 4–10):

1. Scan of the arch with the temporary prosthesis in place
2. Scan of the opposing arch
3. Bite scan in maximum intercuspation
4. Scan of the arch without the temporary prosthesis
5. Scan of the scan body in high definition
6. Scan of the temporary restoration connected to an analogue chair-side

Scanning the arch without the temporary restoration in place do not provide accurate registration of the emergence profile due to the collapse of the soft tissue, but it is used to give information about the contact points of the adjacent teeth. The chair-side scan of the temporary restoration, on the other hand, allows to capture the subgingival component of the tissue outline. A CAD software combines all the scans and it generates a high-precision virtual model where the dental technician can identify the real profile of the soft tissue. If needed, a 3D printed model with removable gingival tissue can be fabricated and it can assist the technician during porcelain layering and finishing stages.

The copy–paste full digital workflow in natural dentition.

If one of the main aspect of fabricating implant prosthesis is the ability to transfer the tri-dimensional position of the implant and the orientation of the connection, the impression of natural dentition

FIGURE 7 Profile views of the screw-retained temporary prosthesis placed the day of surgery. The peri-implant tissue is adequately supported and it is in harmony with the soft tissue of the adjacent teeth

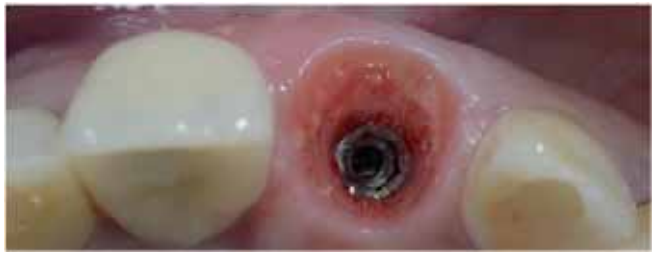

FIGURE 9 Occlusal view of the peri-implant soft tissue 5 months after the surgery. Note the excellent preservation of tissue volume and the proper balance between white and pink esthetics

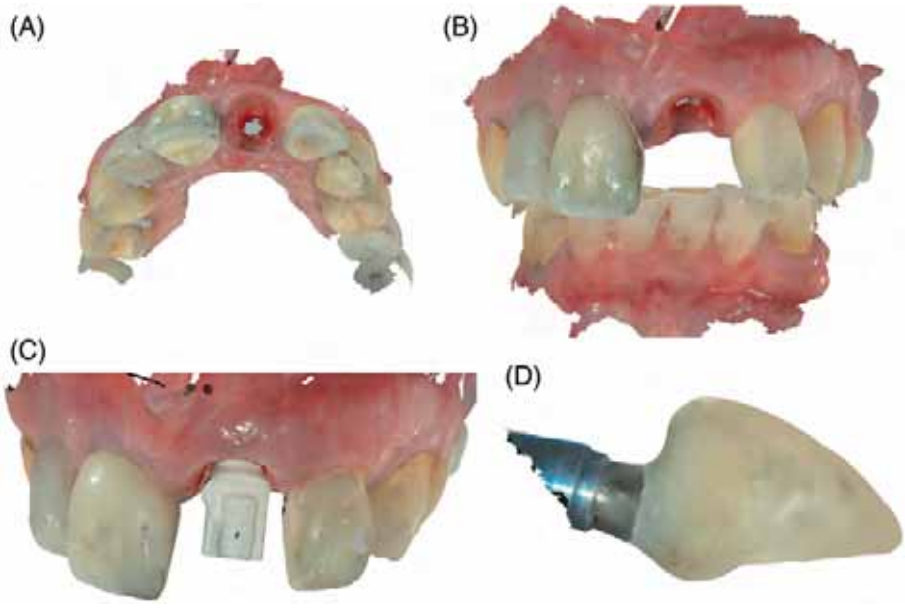

FIGURE 8 (a–d) Four of the six intraoral scans (scan of the soft tissue, bite scan, scan with the scan body and extraoral scan of the temporary prosthesis) that are included in the copy–paste full digital workflow for implant prosthesis

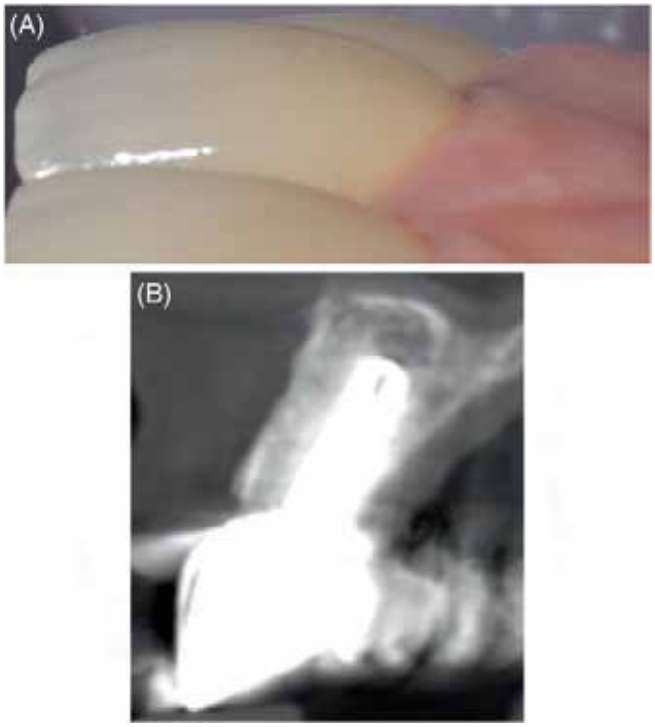

FIGURE 10 (a) Lateral view of the definitive prosthesis, showing the transition between the peri-implant soft tissue and the screw-retained zirconia crown (master ceramist Simone Maffei). (b) The CBCT taken 24 months after the surgery demonstrating the stability of the hard tissue

FIGURE 12 Each tooth received endodontic re-treatment, glass fiber post and composite direct core build up. The four abutments have been prepared with a vertical finish line and a temporary restoration have been placed

must register clearly the finish line of the teeth preparation. Mechanical means consisting of retraction cords and paste can be used to displace the soft tissue and allow the impression material or the light of an intra-oral scanner to capture the entire surfaces of the prepared teeth.[16]

The copy–paste full digital workflow on natural dentition consists of five different scans (Figures 11–20):

1. Scan of the arch with the temporary prosthesis in place
2. Scan of the opposing arch
3. Bite scan in maximum intercuspation

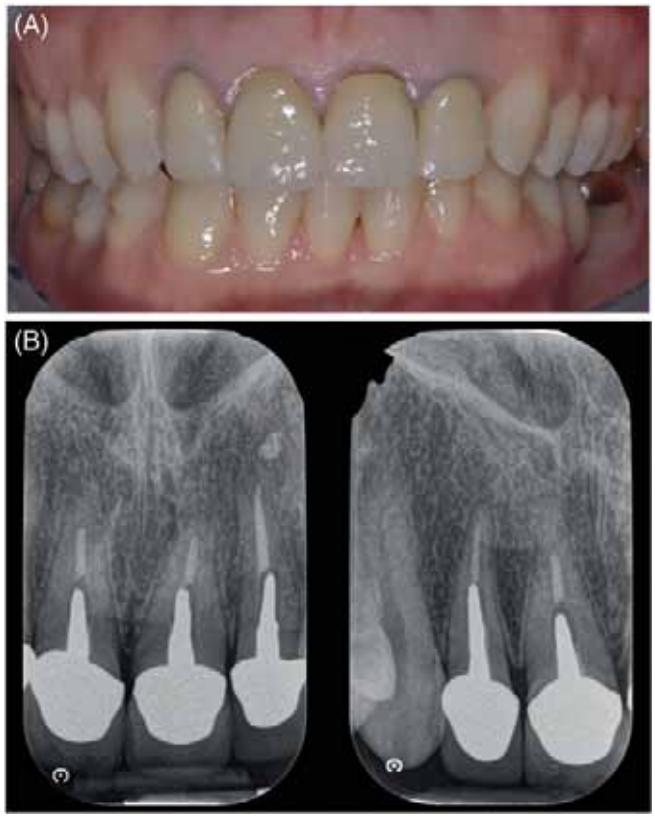

FIGURE 11 (a) A 41-year-old female patient presented at the first visit complaining about the esthetic of four metal-ceramic restorations, with discolorations at the gingival margin, altered tooth proportions and soft tissue asymmetries. (b) The peri-apical radiographs evidenced metal post and inadequate endodontic treatments

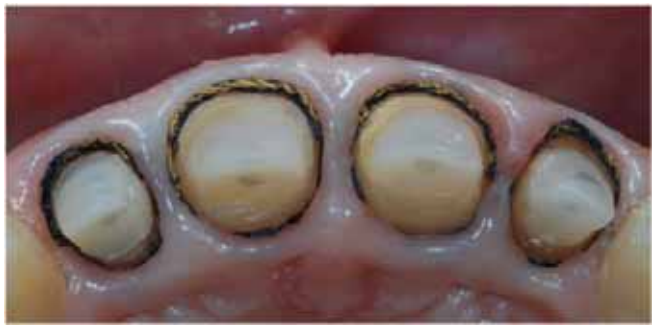

FIGURE 13 After the soft tissue maturation, the gingival phenotype was mapped with a periodontal probe to decide which diameter of retraction cord to use. Retraction cord #000 was placed first, followed by a #00 cord. The use of intra-oral scanner allows to register the impression of one tooth at the time, thus allowing to keep the retraction cord around the adjacent teeth until the last moment.

4. Scan of the teeth abutments
5. Scan of the temporary restoration chair-side

The dental technician will align the different files and recreate in a virtual environment (the CAD software) the clinical scenario that

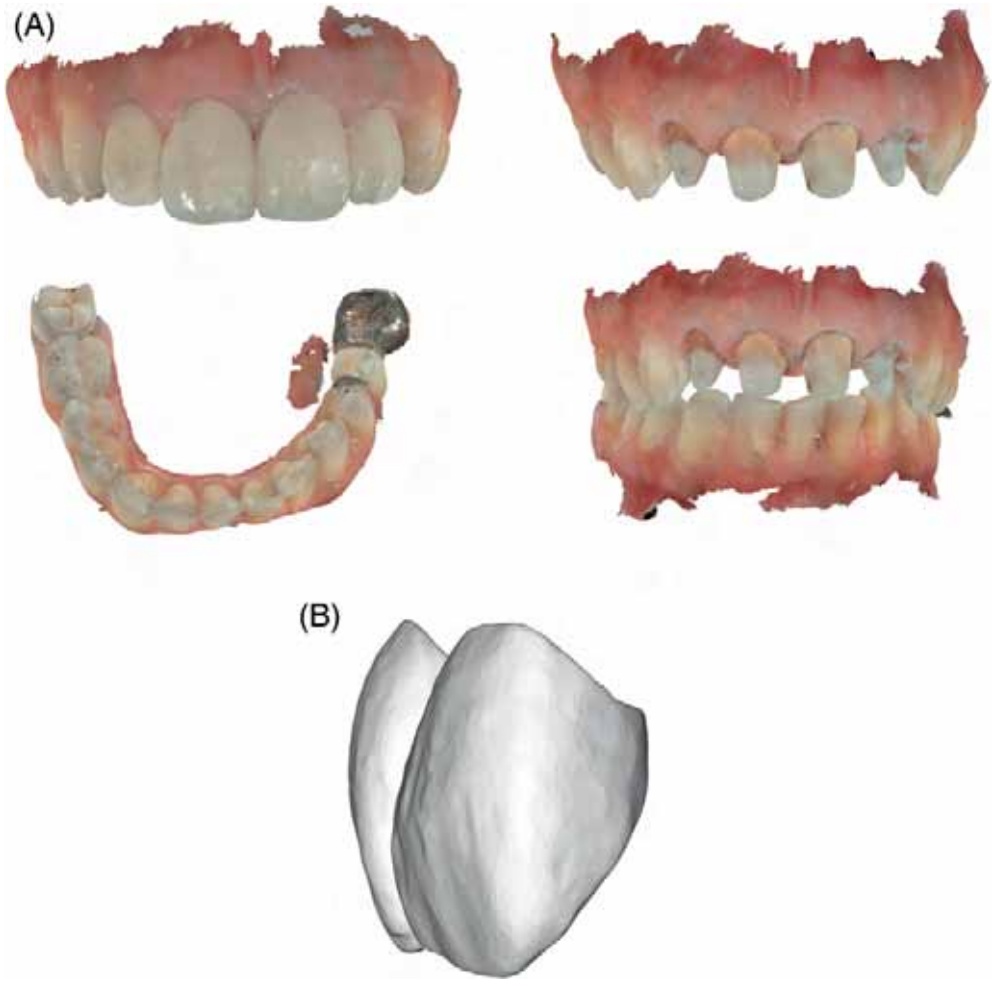

FIGURE 14 (a, b) The copy–paste full digital workflow on natural dentition includes five intra-oral scans (a) and one extra-oral scan of the existing temporary prosthesis (b). The extra-oral scan of the provisional crowns allows to register the supra gingival and sub gingival components of the restorations, capturing the profile of the crowns that have supported the soft tissue.

includes the soft tissue profile, the shape of the temporary restoration and the morphology of the abutments. Moreover, by setting different values of transparencies, he is able to visualize the position and the extension of the margins of the temporary prosthesis in relation to the gingival margin and the sulcus.

The definitive restoration is designed as an exact copy of the temporary prosthesis and it will contain all the information that have been tested clinically in terms of tissue support, esthetics, phonetics, and function.

3 | DISCUSSION

Nowadays, achieving and maintaining an harmonic soft tissue architecture and tissue stability in the long-term is of paramount importance for the esthetic outcome. The outline or the emergence profile of the restoration determines the natural transition between the prosthesis and the soft tissue with the purpose of achieving a natural integration between the white esthetics with the pink esthetics.[17,18]

In restorative dentistry, the function of the temporary prosthesis is not only to protect the teeth during the phases that precede the manufacturing and delivery of the final prosthesis. The temporary is used as a test drive to restore dento-facial esthetics and it must guarantee proper phonetics, tissue health and adequate masticatory function. Only when the temporary prosthesis has fulfilled all its functions is it possible to fabricate the definitive restoration, which in the ideal conditions should be the exact copy of the provisional, with the exception of the material with which it is made.[19]

The fundamental step in this process is the accurate transfer of all the information contained in the provisional to the dental technician. In this regards, digital technologies have radically changed the way we do dentistry, bringing several advantages for the clinician and the patient.[20]

The IOS can improve the communication between the dentist and the technician, eliminating stone models and reducing working time. Moreover, taking an intra-oral scan is faster than a conventional impression, resulting in improved patient comfort and experience.[10,21] Clinical studies and systematic reviews have also demonstrated that IOS are able to provide reliable outcomes when restoring natural teeth and dental implants.[22]

Despite the aforementioned advantages offered by digital dentistry, clinician should have the ability to formulate a correct treatment plan, to pursue precision in teeth preparation or in implant placement and have a clear understanding of the

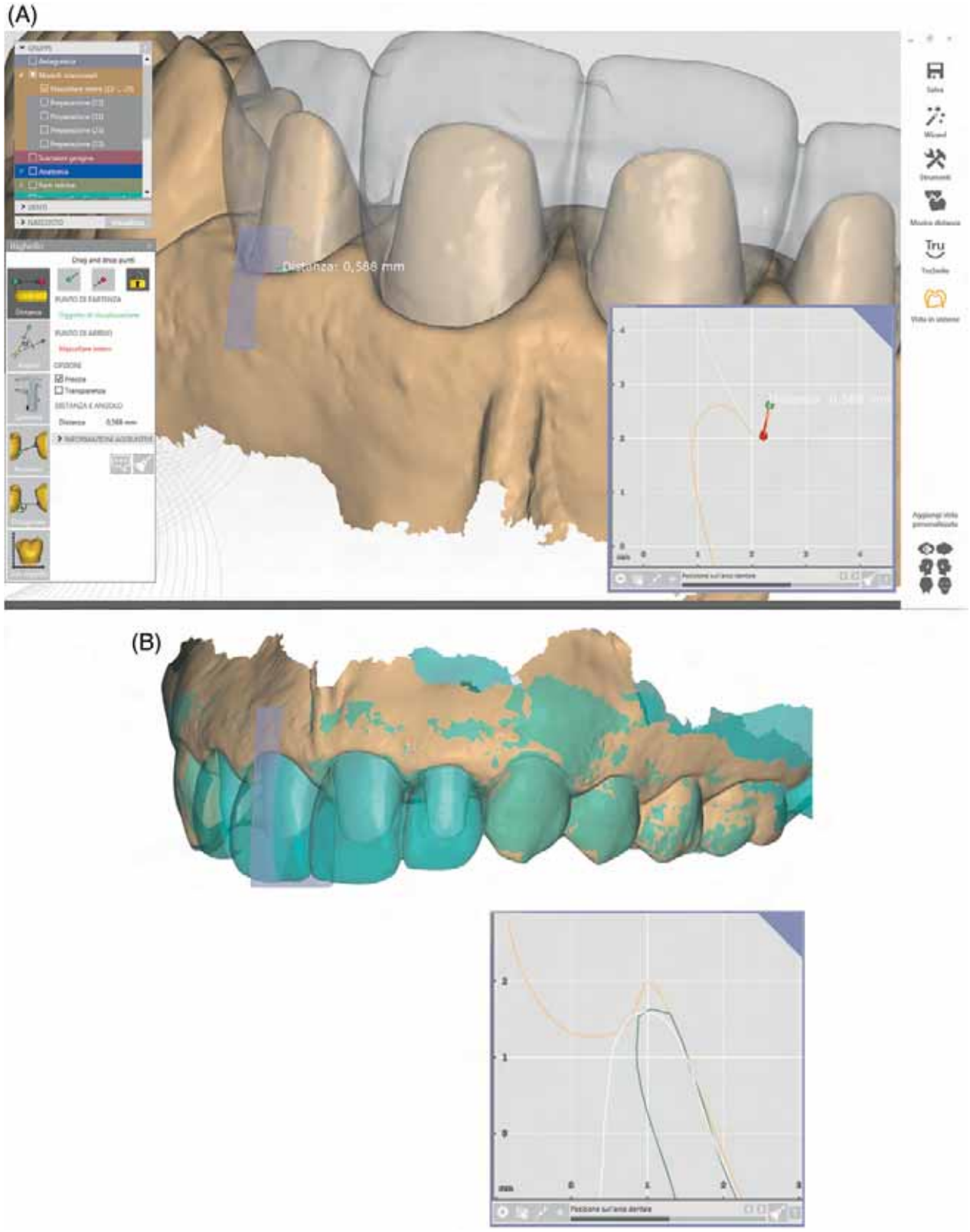

FIGURE 15 (a) After aligning the five scans into a CAD software and setting different level of transparencies, the dental technician is able to visualize the profiles of the soft tissue and the abutment (yellow line) and their relation with the temporary prosthesis (white line). It is also possible to measure the extension of the provisional crown inside the sulcus. (b) A different cross section showing the profile of the zirconia core (green line). Thanks to the copy–paste technique, the technician knows exactly where to extend the finish line of the zirconia crown in the apico-coronal direction as well as the thickness of the restoration in the sub-gingival and supra-gingival compartments.

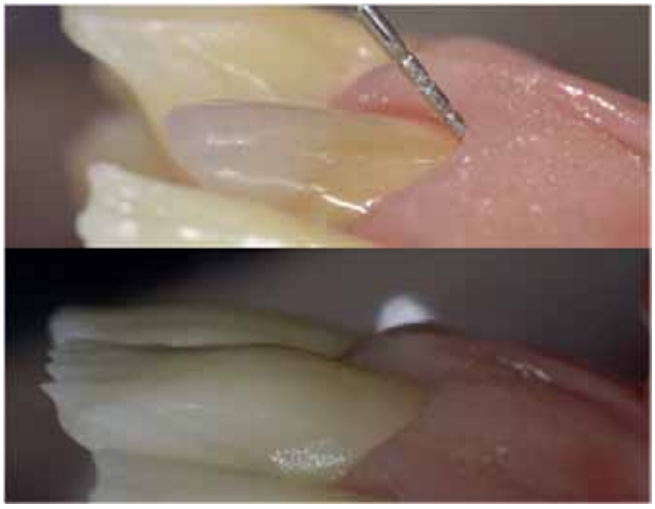

FIGURE 16 (a, b) During the framework try-in appointment the dentist checks the fit and the marginal accuracy of the zirconia core with the use of silicone paste. It is also possible to verify the occlusion of the monolithic portion against the opposing dentition

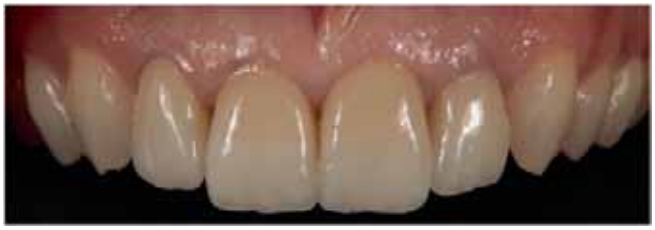

FIGURE 18 Frontal view of the four veneered zirconia crowns

biological principles and the characteristics of the restorative materials.[23]

Soft tissue management using temporary prosthesis has always been an artisan process that involved a fair amount of chair time and manual skills.[24] Before digital workflows were available, replicating the subgingival contour of the temporary prosthesis into the final restoration through a conventional workflows was associated with a variable degree of accuracy than relied on the quality of the impression and the ability of the dental technician to read that impression. The position of the gingival margin captured by the impression did not correspond to the real position of the tissue because of the displacement produced by the retraction cords. This implies that, in the traditional workflow for feather edge preparation, the clinician should always check the framework to identify any excessive compression of the prosthetic margins into the gingival sulcus.[25]

Using the copy–paste full digital workflow, the technician does not have to arbitrarily decide the emergence profile of the restoration or where to place its margins in apico-coronal direction (particularly with feather edge preparation), because by superimposing the different files and playing with the transparencies, he is able to visualize the volume occupied by the temporary prosthesis as well as the position of the soft tissue. At this point, the design of a zirconia core or a monolithic restoration is straightforward.

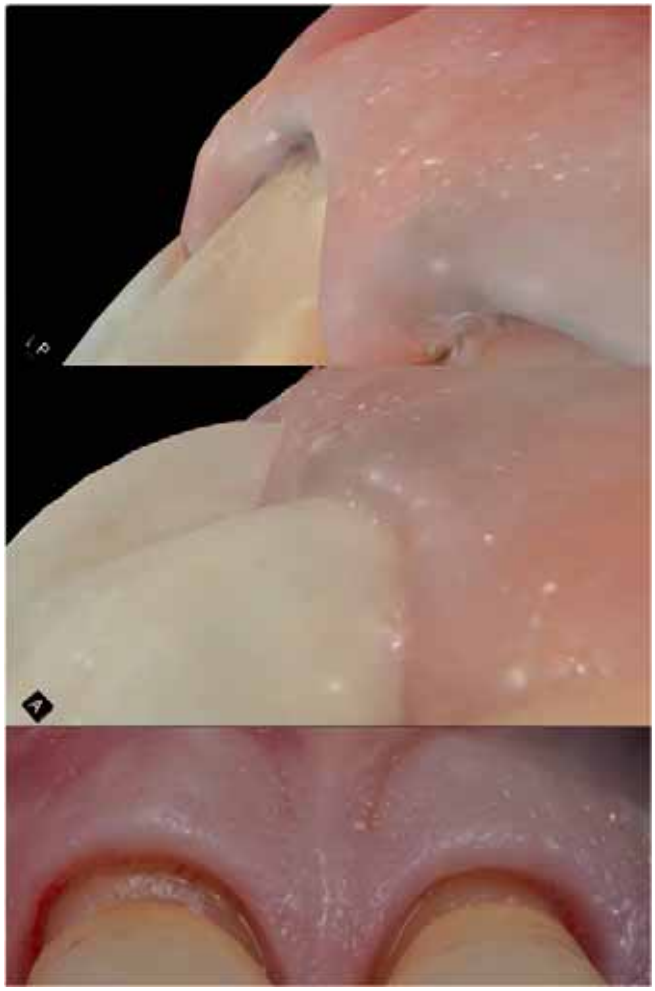

FIGURE 17 Soft tissue profile the day of the impression, with the temporary prosthesis in place and before delivering the definitive crowns. Not the stable contour of the soft tissue

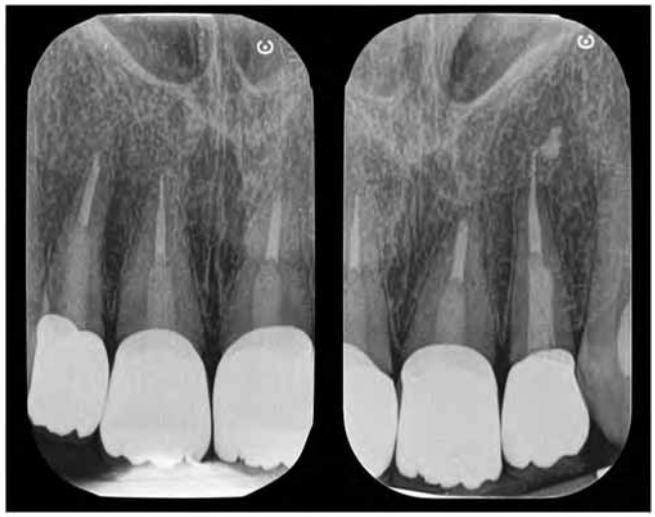

FIGURE 19 Peri-apical radiograph taken at 1 year recall

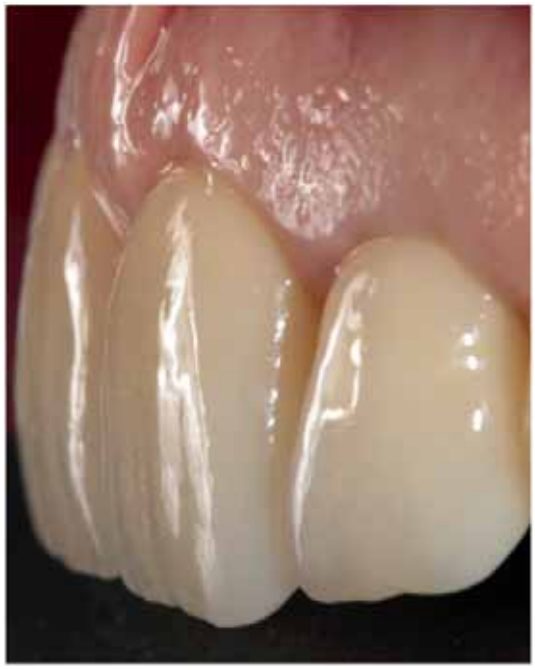

FIGURE 20 Detail of tissue stability 3 years after cementation (master ceramist Luca Dondi)

4 | CONCLUSIONS

The copy–paste full digital workflow simplifies the fabrication of the definitive prosthesis, allowing a precise replica of the emergence profile and angle of the temporary prosthesis. The dental technician can simply copy the morphology of the temporary prosthesis and the subgingival contour that has been established by the dentist and he will be able to fabricate a definitive prosthesis in few steps.

PATIENT CONSENT

All treated patients signed an informed consent to their treatments.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data sets used and analyzed during the current study are available from the corresponding author on reasonable request.

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How to cite this article: Agnini A, Romeo D, Giulia B, Tommaso W, Christian C, Agnini A. Copy–paste concept: Full digital approach in the management of gingival emergence profiles. *J Esthet Restor Dent*. 2023;35(1):222-229. doi:10.1111/jerd.13014

Received: 12 September 2022 | Revised: 30 October 2022 | Accepted: 31 October 2022

DOI: 10.1111/jerd.12985

REVIEW ARTICLE

WILEY

A guide for maximizing the accuracy of intraoral digital scans. Part 1: Operator factors

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Abstract

Objectives: To describe the factors related to the operator skills and decisions that influence the scanning accuracy of intraoral scanners (IOSs). A new classification for these factors is proposed to facilitate dental professionals' decision making when using IOSs and maximize the accuracy and reliability of intraoral digital scans.

Overview: Each IOS system is limited by the hardware and software characteristics of the selected device. The operator decisions that can influence the accuracy of IOSs include the scanning technology and system selection, scanning head size, calibration, scanning distance, exposure of the IOS to ambient temperature changes, ambient humidity, ambient lighting conditions, operator experience, scanning pattern, extension of the scan, cutting off, rescanning, and overlapping procedures.

Conclusions: The knowledge and understanding of the operator factors that impact scanning accuracy of IOSs is a fundamental element for maximizing the accuracy of IOSs and for successfully integrating IOSs in daily practices.

Clinical Significance: Operator skills and clinical decisions significantly impact intraoral scanning accuracy. Dental professionals must know and understand these influencing operator factors for maximizing the accuracy of IOSs.

KEYWORDS

accuracy, digital impressions, digital scans, esthetic dentistry, influencing factor, intraoral scanners, operator factors

1 | INTRODUCTION

Facially driven treatment planning procedures are a fundamental step to achieve esthetic rehabilitations.[1–3] When using a digital workflow, the 3-dimensional (3D) virtual patient can be created by integrating facial and intraoral digital scans, with or without incorporating cone beam computed tomography (CBCT) information.[4–8] Obtaining accurate intraoral digital scans is critical for acquiring accurate virtual patient representations and, consequently, improving the reliability of the clinical procedure. The more accurate the digitizing methods, the higher the accuracy of the virtual patient.[5,8,9]

Intraoral scanners (IOSs) are increasingly implemented in dental practices (Figure 1).[10] Regardless of the type of imaging technology employed by an IOS, all cameras require the projection of light that is recorded as individual images or video and compiled by the software after recognition of the points of interest (POI).[11] The multiple sets of points (or point clouds) generated through the optical sensors are subsequently registered (aligned with respect to each other) and are converted into a surface model represented as a triangle mesh.[11,12] Therefore, a mesh in a 3D scan refers to the way the surfaces are represented in the software via computer graphics. A mesh is a collection of vertices and triangles and includes information on how the vertices make up the triangles, and how the triangles are connected to

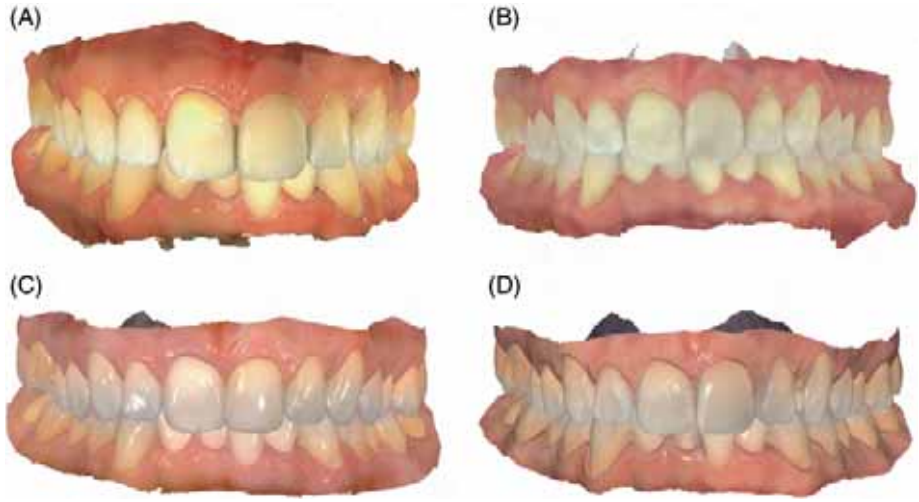

FIGURE 1 Esthetic intraoral digital scan visualizations in varying IOS software programs obtained in the same patient by using different IOSs. (A) Primescan; Dentsply Sirona. (B) iTero Element 5D; Align technologies. (C) Trios 4; 3Shape A/S. (D) i700 wireless; Medit. IOS, intraoral scanner.

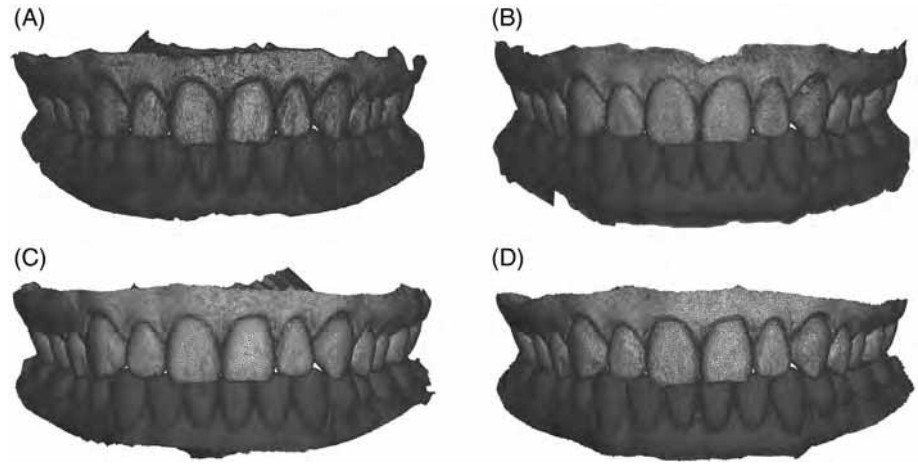

FIGURE 2 Representative mesh visualization of intraoral digital scans obtained in the same patient by using different IOSs. (A) Primescan; Dentsply Sirona. (B) iTero Element 5D; Align technologies. (C) Trios 4; 3Shape A/S. (D) i700 wireless; Medit. IOS, intraoral scanner.

each other (Figure 2).[12] Mesh density and quality discrepancies are present among the different IOSs.[13,14] Additionally, the algorithms employed by the IOS software programs can generate files of varying mesh densities. Higher density meshes usually produce more accurate analysis results or more surface detail reproduction.[12]

Accuracy is often the most important factor when assessing the quality of IOSs. Intraoral scanning accuracy is defined by trueness and precision.[15] Trueness measures how close the intraoral digital scan is to the real dimensions of the digitized intraoral tissues, while precision measures the reproducibility, or output consistency, of the intraoral digital scan obtained by using the same IOS system under the same scanning conditions.[15] Dental professionals should select IOS devices with high trueness and high precision values.

Multiple factors have been identified in the dental literature that can decrease the scanning accuracy of IOSs. Understanding and recognizing these influencing factors will increase the predictability and reliability of dental treatments completed by using digital workflows. These factors are related to either the operator or the patient. The objective of this first part of the manuscript is to describe a new classification of the factors related to the operator skills and decisions that significantly influence the scanning accuracy of IOSs systems. The goal of this classification is to simplify the understanding of the IOSs functionality, maximize the accuracy of the IOSs systems, and facilitate the integration of digital workflows in daily dental practices.

The operator factors are the dental professional skills and decisions that influence the scanning accuracy of IOSs (Figure 3). These operator factors include IOS technology and system selection, scanning head size, calibration, scanning distance, exposure of the IOS to ambient temperature changes, ambient humidity, ambient lighting conditions, operator experience, scanning pattern, extension of the scan, and cutting off, rescanning, and overlapping procedures.

1.1 | IOS TECHNOLOGY AND SYSTEM

The dental professional's first decision is to select an IOS system. There are multiple scanning technologies and IOSs systems available in the market (Table 1).[11] Each IOS system has the limitations determined by the hardware and software characteristics of the selected device. Different selection criteria have been described

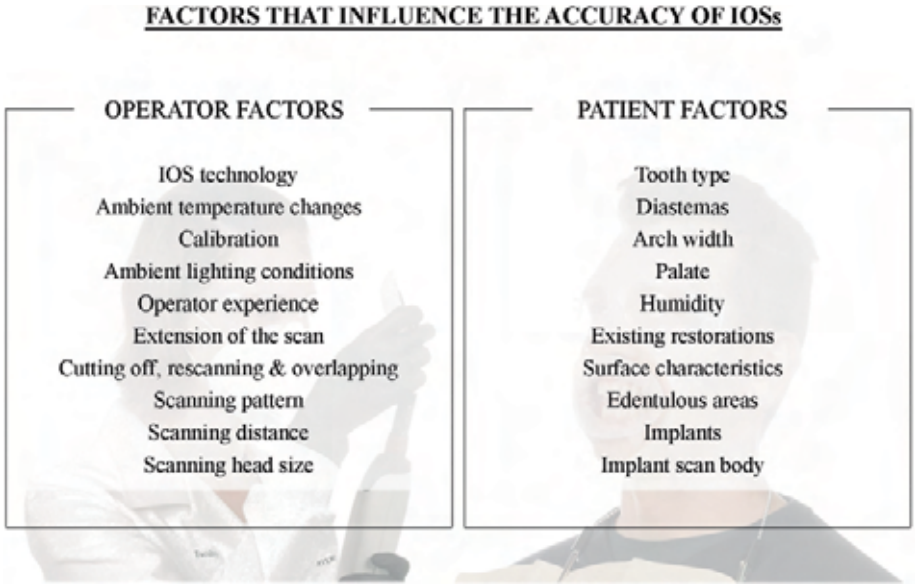

FIGURE 3 Factors related to the operator and patient that influence the scanning accuracy of IOSs systems. IOS, intraoral scanner.

TABLE 1 Available intraoral scanner systems

Manufacturer	Latest IOS
3Shape A/S	Trios 5
Align technologies	iTero Element 5D
Biotech Dental	WOW
Carestream	CS 3800
Condor	Condor IOS
Dental wings	Virtuo Vivo
Denterprise	QuickScan IOS
Dentsply Sirona	PrimeScan
Densys	Mia 3D IOS
E4D	Nevo
Eighteeth	Helios 600
GC America	Aadva IOS 200
Heron	Heron IOS
Intelliscan	Intelliscan IOS
Kavo	Kavo Xpro
Medit	I700 wireless
MyRay	3Di IOS
NewTom	NewTom IOS
Launca	Launca DL 206
Ormco	Lythos
Planmeca	Emerald S, PlanScan
Runyes	Runyes IOS
Seikowave health solutions	E-Vox
Shinning 3D	AoralScan
Suresmile	Oralscanner
Vatech	EZScan
Viz	Viz 3D IOS

Abbreviation: IOS, intraoral scanner.

for choosing an IOS including initial cost, monthly subscriptions expenses, scanning speed, wand size, ease of use, presence of a caries detection feature, software capabilities, wireless option, and manufacturer's support. However, dental professionals might want to balance these variables with the scanning accuracy of the IOS device which provides the reliability of the IOS system and, consequently, impacts the outcome of the manufacturing workflow of dental restorations.

Multiple studies have analyzed the accuracy of IOSs using in-vitro or clinical condition settings. However, research approaches should be distinguished between both methodologies. In laboratory studies, the ground truth or the reference model used to calculate accuracy values is known.[16–36] This means that the dimensions of the reference model are obtained by using the most accurate methods available today such as coordinate measurement machine (CMM) or an industrial scanner. On the other hand, in clinical conditions, the ground truth or the real dimensions of the patient's intraoral tissues being digitized are not known, and the reference model is obtained by using conventional techniques such as diagnostic stone casts.[16–36]

Variations in research methodologies among published studies compromises data comparison which makes it difficult to come to a clear conclusion. For in vitro conditions, the International Organization for Standardization (ISO) provides measurement method standards aiming to solve this issue within the last update completed in 2019 (ISO 20896-1:2019). However, the standardization of measurement methods in clinical settings is still needed.

Scanning accuracy discrepancies have been reported in the dental literature among the different scanning technologies and systems available based on the different clinical applications.[16–36] Independent of the scanning technology and IOSs system, IOSs provide a reliable digital impression alternative for acquiring virtual diagnostic casts with similar accuracy when compared with conventional impression

methods.[16–21,31] Clinical studies have evaluated the accuracy of IOSs for acquiring complete-arch intraoral digital scans, reporting a trueness mean value ranging from 73 to 433 μm and a precision mean value ranging from 80 to 199 μm.[16,19–21]

Complete digital workflows for fabricating tooth- and implant-supported crowns and short span fixed dental prostheses obtain similar marginal and internal discrepancies compared with conventional methods.[21–35] The challenge today remains to incorporate IOSs into complete digital workflows for fabricating complete dentures[29] and Kennedy Class I and II removable partial dentures.[30] Published studies have shown that intraoral digital scans can accurately digitized edentulous areas with firm attached tissue and mucosa, but capturing areas with mobile tissue by using an IOS is challenging, regardless of the scanning technology and system elected.[29,30,36–40] Therefore, for fabricating complete dentures or Kennedy Class I and II removable partial dentures, digitizing conventional impressions by using IOSs have been recommended.[29,30,36–40]

Similarly, complete-arch scans by using IOSs for fabricating complete-arch tooth- and implant-supported rehabilitations have shown contradictory results in the literature regarding reliability and accuracy.[31–35,41,42] Different techniques have been described to improve the scanning accuracy of complete-arch implant digital scans; however, due to the limited clinical data published, a systematic recommendation of complete-arch implant digital scans by using IOSs is difficult.[43–45]

Multiple published studies report discrepancies among the different IOSs depending on the clinical procedures tested.[17,28,41,46] Therefore, the selection of a specific IOS device would impact the accuracy of the intraoral digital scan for different clinical applications. Additionally, it is important to understand that not all available IOSs have been evaluated in those investigations. Therefore, the generalization of the studies' results should be done cautiously.

1.2 | SCANNING HEAD SIZE

Different scanning head sizes can be found among the various IOSs available in the market. Smaller head sizes are practical when acquiring intraoral digital scans with accessibility constraints such as patients with limited mouth opening. However, very few IOSs systems provide different scanning tip sizes for the same IOS device.

Limited studies have assessed the influence of scanning head sizes on the accuracy of intraoral digital scans.[47,48] These studies have reported higher intraoral scanning accuracy when employing larger scanning head sizes compared with smaller scanning head sizes.[47,48] This may be explained by the need to use a different scanning pattern when acquiring the intraoral digital scan due to the limited access or smaller scanning head, which might cause a different stitching process on the postprocessing procedures and result in a higher distortion. Additional studies are needed to further evaluate the impact of scanning head size on the scanning accuracy of different IOSs.

1.3 | IOS CALIBRATION

Except the iTero Element from Align Technologies and Trios 5 from 3Shape A/S IOSs that has integrated a self-calibration system,[12] all the IOSs require that the operator or dental professional calibrates the scanner. Additionally, a specific calibration device and protocol is provided by each IOS manufacturer (Figure 4). Although IOS software programs deliver alerts requiring the calibration of the system based on the time since the last calibration or the number of intraoral digital scans acquired since the latter calibration, dental professionals should probably include protocols in their practices to ensure daily IOS calibration before starting data collection procedures.[49]

1.4 | SCANNING DISTANCE

Scanning distance is the distance between the surface being scanned and the intraoral scanning tip, while scanning depth can be defined as the focal depth at which the scanner can capture reliable data. Recent studies have reported scanning accuracy discrepancies when the scanning distance is altered.[50,51] However, the optimal scanning distance and the focal depth of the scanner are determined by the hardware of the IOS selected. Each IOS manufacturer describes the optimal scanning distance for an appropriate handling of the system, as well as for optimizing the performance of the IOS. The understanding of the optimal scanning distance of the IOS selected will optimize the IOS performance and minimize the inadequate handling of the operator.

1.5 | AMBIENT TEMPERATURE CHANGES

Dental literature has recently identified ambient temperature changes as a variable that can influence intraoral scanning accuracy.[49] The exposure of an IOS to ambient temperature changes can easily occur in a dental practice, university, or dental institution between working and nonworking hours or even during the same day. These ambient temperature changes decalibrate the IOS and, subsequently, reduce its scanning accuracy.[49]

Revilla-León et al[49] assessed the influence of ambient temperature changes within the recommended operating ambient temperature ranges (15–30°C) on the accuracy of an IOS (Trios 4; 3Shape A/S). Results demonstrated that ambient temperature changes had a detrimental effect on the scanning accuracy of the IOS tested. In order to solve this problem, IOSs should probably be calibrated before starting each workday.

1.6 | AMBIENT HUMIDITY

Ambient humidity has been also identified as a factor that can decrease intraoral scanning accuracy.[52] In a laboratory study, Park et al[52] assessed the influence of varying simulated intraoral conditions on the scanning accuracy of two IOSs (Trios 3 from 3Spahe A/S and CS 3500 from Carestream). The authors attempted to replicate intraoral conditions by using a custom simulator in which ambient temperature, humidity, and lighting

FIGURE 4 (A) Examples of calibration devices provided by IOS's manufacturers for calibrating their systems. (B) Representative calibration protocol for an IOS (PrimeScan; Dentsply Sirona). IOS, intraoral scanner.

settings were controlled.[52] Two groups were created based on the conditions tested: group 1 (temperature ranged from 18–22°C, 40% humidity, and 262–272 -lux of ambient illumination) and group 2 (temperature ranged from 29–31°C, 100% humidity, and 173–197 -lux of ambient illumination).[52] No significant difference was found between the simulated intraoral conditions tested.[52] Further studies are still needed to determine if ambient humidity can impact intraoral scanning accuracy. Authors recommend calibrating IOSs to minimize the effect of ambient humidify on the IOS performance, except for iTero element from Align Technologies and Trios 5 from 3Shape A/S devices that has a self-calibration system.

1.7 | AMBIENT LIGHTING CONDITIONS

Ambient lighting conditions, or the intensity of the ambient light of the room in which the intraoral digital scan is acquired, has a significant impact on the scanning accuracy of IOSs in dentate patients (Figure 5).[13,20,53–57] Dental literature has revealed that the recommended lighting condition depends on the IOS selected (Table 2).[13,53–57] A luxmeter positioned at the patient's mouth is suggested for measuring the ambient light intensity at which the intraoral digital scan would be acquired (Figure 6).[13,20,54–56]

Although there is no universal optimal lighting condition that can maximize the accuracy of all IOSs, the majority of the IOSs perform better under 1000 lux ambient illumination conditions, known as room lighting conditions.[13,20,53–57] Achieving this ambient lighting condition requires turning off the dental chair light while leaving the room ceiling light on. It is important to understand that each room or operatory might have different ambient lighting intensities; therefore, the employment of a luxmeter to standardize ambient lighting conditions is recommended.

A recent publication has assessed the influence of five different ambient lighting conditions on the accuracy of seven IOSs when

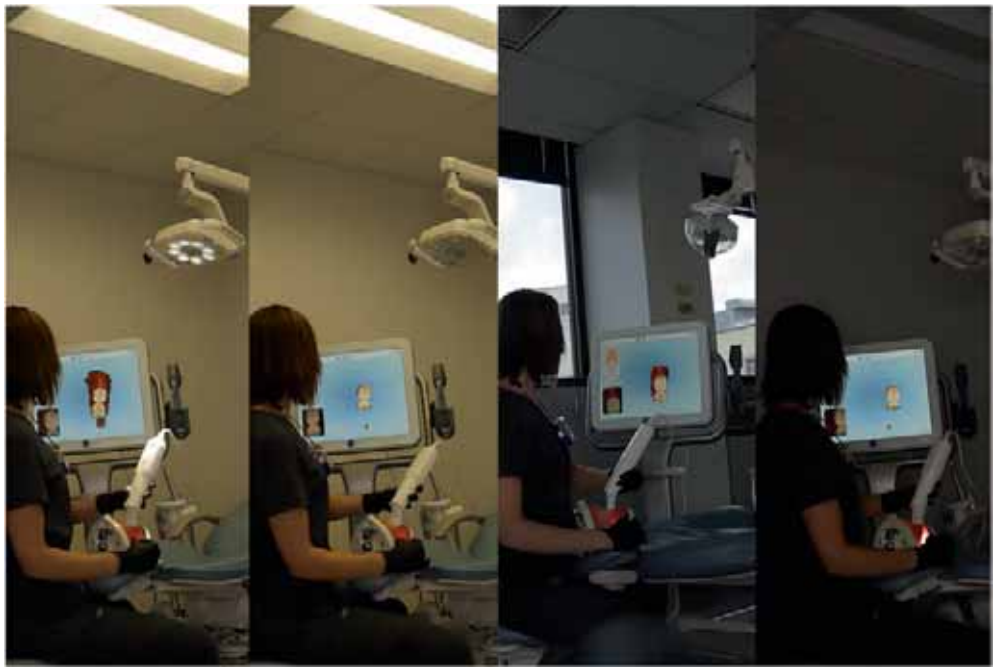

FIGURE 5 Varying ambient lighting conditions including chair light, ceiling light, natural window light, or no light

digitizing implant scan bodies.[58] Based on the results of this study, the optimal ambient lighting conditions for an IOS might be different when scanning teeth or implant scan bodies. Further studies are needed to assess the influence of ambient lighting conditions on the scanning accuracy of the various IOSs under different clinical conditions.

1.8 | OPERATOR EXPERIENCE

The previous handling experience of the operator acquiring intraoral digital scans has been identified as a factor that can impact the scanning accuracy of IOSs, where the greater the operator experience, the higher the accuracy of the intraoral digital scan.[59–62] However, this relationship seems to be stronger when using older generations of IOSs.[61] Additionally, operator experience reduces scanning time, improving the efficiency of the digital procedure.[59]

Undoubtedly, dental professionals require a learning period to effectively use IOSs while basic intraoral scanning concepts are learned. In 2021, a survey-based study performed by the Council of Scientific Affairs of the American Dental Association (ADA) revealed that 82% of the dental professionals surveyed received their IOS training by the manufacturer of the IOS purchased and 52% learned by doing.[10] As the technology matures and more studies are published, the data-related scanning accuracy of IOSs and its influencing factors are better described and identified. This scientific based advancement might accelerate the implementation of systematic teaching approaches in private and public educational dental institutions, but it may also provide the user with criteria to discern and evolve in the ocean of digital information, in which evidence-based learning will be more accreditive than anecdotal learning based on others' experience.

1.9 | SCANNING PATTERN

The scanning pattern or digitizing sequence performed when acquiring an intraoral digital scan significantly influenced the scanning accuracy of IOSs.[58,63–72] Therefore, if the scanning pattern is changed, the accuracy of the intraoral digital scan varies.[58,63–72] Generally, it is recommended to follow the scanning pattern recommended by the manufacturer of the IOS selected.

For acquiring intraoral digital scans in completely dentate patients, the scanning pattern is clearly described by the manufacturer of the IOS. For obtaining intraoral implant scans, the digitalization of the implant scan body is a fundamental procedure.[71] Dental literature has reported individualized scanning patterns for acquiring intraoral implant scans[73]; however, the literature assessing the optimal scanning pattern for capturing intraoral implant digital scans is scarce.[71] Similarly, few IOS manufacturers provide the recommended scanning protocol for extraorally digitizing complete dentures by using the IOS. Additionally, limited studies have assessed the influence on scanning accuracy of the scanning pattern for extraorally digitizing maxillary and mandibular complete dentures.[56]

In a clinical study, authors assessed the influence of the scanning pattern when digitizing the palate on the accuracy of the maxillary intraoral digital scan acquired by using an IOS (Trios 3 from 3Shape A/S).[72] Scanning accuracy discrepancies were observed between the two scanning patterns tested.[72]

Additionally, the scanning wand can be positioned with different orientations for acquiring the same scanning pattern. Oh et al[68] evaluated the influence of the rotation of the IOSs on their accuracy when performing complete-arch scans. Authors obtained better performance when the scanner head was positioned in a horizontal orientation throughout the scan when compared with rotations of scanner in a vertical direction.[68]

TABLE 2 Recommended ambient lighting condition based on the IOS system selected for acquiring intraoral digital scans.

Intraoral scanner; Manufacturer	Optimal ambient lighting conditions in dentate conditions	Optimal ambient lighting conditions digitizing implant scan bodies
Adva; GC America	1000 or 5000 Lux[39]	NA
CS 3600; Carestream	5000 Lux[39]	500 Lux[41]
CS 3700; Carestream	NA	100 Lux[41]
Emerald; Planmeca	Very inconsistent[39]	
i500; Medit	1000 Lux[40]	1000 Lux[41]
iTero Element; Align technologies	1000 Lux[34]	NA
iTero Element 5D; Align technologies	NA	100 Lux[41]
Omnicam; Dentsply Sirona	0 Lux[34] or 100 Lux[39]	NA
PrimeScan: Dentsply Sirona	NA	10,000 Lux[41]
Trios 3; 3Shape A/S	1000 Lux[34]	100 Lux[41]
Trios 4; 3Shape A/S	1000 Lux[34]	NA

Abbreviations: IOS, intraoral scanner; NA, not available.

FIGURE 6 Ambient light intensity should be measured at the patient's mouth by using a luxmeter.

1.10 | EXTENSION OF THE SCAN

Dental professionals should also decide the extension or length of the intraoral digital scan (i.e., half-arch or complete-arch scan) when manufacturing single restorations or short span rehabilitations. The extension of the intraoral digital scan can impact the accuracy of IOSs.[19,20,42,74,75] Previous studies have reported higher accuracy on half-arch scans when compared with complete-arch scans, which can justify the use of half-arch intraoral digital scans when manufacturing tooth- and implant-supported crowns and short span fixed dental prostheses.[19,20,42,74,75]

In an in-vitro study, authors compared the scanning accuracy of half- and complete-arch scans obtained by two IOSs.[74] Significant scanning accuracy discrepancies were reported based on the extension of the scan. For the Trios 3 IOS, in complete-arch scans a mean trueness ± precision value of 46.92 ± 20.79 μm was described, while for the half-arch scans a mean trueness ± precision value of 22.29 ± 14.12 μm was computed.[74] Similarly for the Primescan IOS, a mean trueness ± precision value of 28.73 ± 15.79 μm was measured for complete arch scans, while in the half-arch scans a mean trueness ± precision value of 18.91 ± 7.94 μm was computed.[74]

In a clinical study, Revilla-León et al[13] compared the scanning accuracy of half- and complete-arch scans obtained by an IOS (Trios 3). Authors reported higher accuracy on half-arch intraoral digital scans, when compared with complete-arch scans.[13] Kernen et al[19] evaluated the intraoral scanning accuracy of half- and complete-arch scans obtained in patients by using three different IOSs (True Definition, Trios 3, and Omnicam). For half-arch intraoral digital scans, authors reported a median trueness ± precision value of 47 ± 31 μm for the True Definition, 38 ± 23 μm for the Trios 2, and 45 ± 43 μm for the Omnicam. For complete-arch intraoral digital scans, results revealed a median trueness ± precision value of 433 ± 153 μm for the True Definition, 147 ± 80 μm for the Trios 2, and 198 ± 198 μm for the Omnicam.

1.11 | CUTTING-OFF, RESCANING, AND OVERLAPPING METHODS

Cutting off and rescanning procedures have been identified in the dental literature as factors that can decrease intraoral scanning accuracy.[76–79] Previous laboratory and clinical studies have demonstrated that rescanning mesh holes significantly decreases the accuracy of intraoral digital scans.[76–79] Furthermore, the higher the number and diameter of the mesh holes rescanned, the lower the accuracy.[78] To maximize the accuracy of the IOS selected when acquiring intraoral digital scans, it is recommended to obtain the scan without leaving mesh holes or missing information, so the operator does not have to rescan those areas.

TABLE 3 Summary of the operator factors that can impact the accuracy of intraoral scanners.

Factor	Description	Literature findings
IOS technology	Different IOS technologies: Active wavefront sampling, triangulation technique, confocal imaging method, and stereophotogrammetry	Scanning accuracy discrepancies have been reported in the dental literature among the different scanning technologies and systems available based on the different clinical applications.[16–36] Clinical studies have evaluated the accuracy of IOSs for acquiring complete-arch intraoral digital scans, reporting a trueness mean value ranging from 73 to 433 μm and a precision mean value ranging from 80 to 199 μm.[16,19–21]
Scanning head size	Dimensions of the scanning head of the IOS	Higher intraoral scanning accuracy have been reported when employing larger scanning head sizes compared with smaller scanning head sizes.[47,48]
Calibration	Calibration of the IOS	Except the iTero IOSs that has integrated a self-calibration system,[12] all the IOSs require that the operator or dental professional calibrates the scanner. Authors recommend calibrating the scanner daily.
Scanning distance	Scanning distance is the distance between the surface being scanned and the intraoral scanning tip	Scanning accuracy discrepancies have been reported when altering the optimal scanning distance which is based on the IOS hardware.[50,51]
Ambient temperature changes	Fluctuation of ambient temperature of the room where the IOS is located	Ambient temperature changes reduce the accuracy of IOSs.[49] In order to solve this uncalibration problem, IOS calibration is recommended daily
Ambient humidity	Humidity of the ambient	Ambient humidity has been also identified as a factor that can decrease intraoral scanning accuracy.[52] In order to solve this problem, IOS calibration is recommended daily
Ambient lighting conditions	Light intensity of the ambient lighting measured at the patient's mouth	Ambient lighting conditions have a significant impact on the scanning accuracy of IOSs.[13,20,53–57] The optimal lighting conditions reported is provided in Table 2.
Operator experience	Operator previous IOS handling time	The greater the operator experience, the higher the accuracy of the intraoral digital scan.[59–62] This relationship seems to be stronger when using older generations of IOSs.[61] Operator experience reduces scanning time, improving the efficiency of the digital procedure.[59]
Scanning pattern	Scanning path used to acquire an intraoral digital scan	Scanning pattern influences the accuracy of intraoral digital scans.[58,63–72] Generally, it is recommended to follow the scanning pattern recommended by the manufacturer of the IOS selected.
Extension of the scan	Length of the intraoral digital scan: half or complete-arch scans	The extension of the intraoral digital scan impacts the accuracy of IOSs.[19,20,42,74,75] Overall, half-arch scans have higher scanning accuracy than complete-arch scans.[19,20,42,74,75]
Cutting-off, rescanning, and overlapping	Rescanning mesh holes with or without allowing overlapping (further modification of the pre-existing scan)	Cutting off and rescanning procedures decrease intraoral scanning accuracy.[76–79] Authors recommend obtaining the scan without leaving mesh holes or missing information, so the operator does not have to rescan those areas.

Abbreviation: IOS, intraoral scanner.

When cutting-off and rescanning procedures are selected, some IOS software programs provide the capability to block any changes to the existing prescan and prevent overlapping, so that the mesh hole is rescanned to capture information, but the existing prescan is not further modified. In a clinical study, Revilla-León et al[77] obtained lower accuracy on the intraoral digital scans obtained using cutting off and rescanning procedures when overlapping was allowed. Therefore, cutting-off and rescanning procedures should be completed without allowing further modification of the preexisting intraoral digital scan to maximize scanning accuracy.[77]

In a recent study published in 2022, authors demonstrated that the impact of the cutting off and rescanning procedures on scanning accuracy varied depending on the IOS tested.[79] Two different IOS from the same manufacturer, Omnicam and Primescan systems, were assessed. The Primescan system was found to be more negatively impacted by these cutting off and rescanning procedures that its predecessor IOS device tested.[79] However, the studies analyzing the influence of cutting off and rescanning procedures are scarce. Studies are needed to further assess the impact of those scanning procedures on the accuracy of virtual casts, as well as its influence on the fit of the definitive restorations.

Recommended digital workflows for fabricating tooth- and implant-supported restorations include cutting off and rescanning procedures. First, a prescan is obtained which normally incorporates the interim restoration. Then the operator intentionally creates a mesh hole into the existing prescan in the interim restoration area. Finally, the mesh hole is rescanned to capture a tooth preparation or an implant scan body.

2 | CONCLUSIONS

Operator skills and decisions significantly influence intraoral scanning accuracy (Table 3). These influencing operator factors include scanning technology and system selection, scanning head size, calibration, scanning distance, exposure of the IOS to ambient temperature changes, ambient humidity, ambient lighting conditions, operator experience, scanning pattern, extension of the scan, and the use of cutting off, rescanning, and overlapping procedures. Dental professionals must know and understand these operator factors for maximizing the accuracy of IOSs and successfully integrating digital workflows in daily practices.

FUNDING INFORMATION

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

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How to cite this article: Revilla-León M, Kois DE, Kois JC. A guide for maximizing the accuracy of intraoral digital scans. Part 1: Operator factors. *J Esthet Restor Dent*. 2023;35(1): 230-240. doi:10.1111/jerd.12985

Received: 12 September 2022 | Revised: 31 October 2022 | Accepted: 14 November 2022

DOI: 10.1111/jerd.12993

REVIEW ARTICLE

WILEY

A guide for maximizing the accuracy of intraoral digital scans: Part 2—Patient factors

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Abstract

Objectives: To describe the factors related to patient intraoral conditions that impact the scanning accuracy of intraoral scanners (IOSs). A new classification for these influencing factors is proposed to facilitate dental professionals' decision-making and maximize the accuracy and reliability of intraoral digital scans.

Overview: Variables related to intraoral conditions of the patient that can influence the scanning accuracy of IOSs include tooth type, presence of interdental spaces, arch width variations, palate characteristics, wetness, existing restorations, characteristics of the surface being digitized, edentulous areas, interimplant distance, position, angulation, and depth of existing implants, and implant scan body selection.

Conclusions: The knowledge and understanding of the patient's intraoral conditions that can impact the scanning accuracy of IOSs is a fundamental element for maximizing the accuracy of IOSs.

Clinical Significance: The patient's intraoral conditions, or patient factors, can significantly impact intraoral scanning accuracy. Dental professionals must know and understand these influencing patient factors to maximize the accuracy of IOSs.

KEYWORDS

accuracy, digital impressions, digital scans, esthetic dentistry, influencing factor, intraoral scanners, operator factors

1 | INTRODUCTION

Intraoral scanners (IOSs) are being used more frequently in dental practices.[1] The identification of the different variables that can impact intraoral scanning accuracy is a fundamental element for optimizing the accuracy of IOSs and successfully implement IOSs in dental practices. The gross accuracy of IOSs can be reduced by inadequate skills and handling decisions from the operator, as well as by patient intraoral conditions.

Multiple factors have been identified in the dental literature that can decrease scanning accuracy of IOSs. Understanding and recognizing these influencing factors will increase the predictability and reliability of dental treatments completed by using digital workflows. These influencing factors are related to either the operator or the patient and can significantly impact the outcome of the intraoral scan. However, these influencing factors have not been previously classified as being either patient or operator elements that are present when acquiring an intraoral digital scan and that can significantly impact the outcome of the intraoral scan. The objective of this manuscript is to describe a new classification of the factors related to the patient's intraoral conditions that significantly influence the scanning accuracy of IOSs systems. The goal of this classification is to simplify the understanding of the IOSs functionality, maximize the accuracy of the IOSs systems, and facilitate the integration of digital workflows in daily dental practices.

Patient factors are defined as the patient's intraoral conditions that influence the scanning accuracy of IOSs (Figure 1). These patient factors include tooth type, presence of interdental spaces, arch width variations, palate characteristics, wetness, existing restorations,

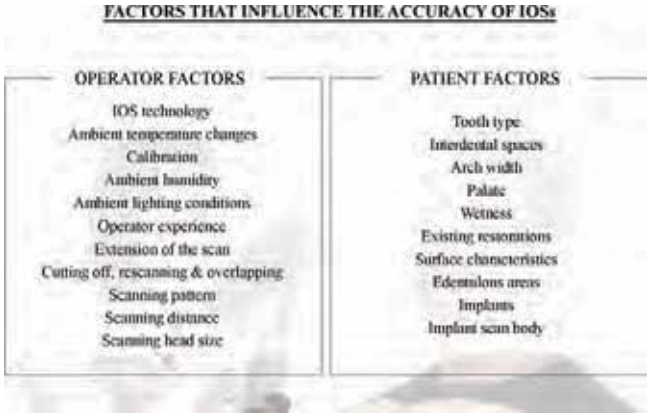

FIGURE 1 Factors related to the operator and patient that influence the scanning accuracy of IOSs systems. IOS, intraoral scanner

characteristics of the surface being digitized, edentulous areas, interimplant distance, the position, angulation, and depth of existing implants, and implant scan body selection. Although the intraoral conditions of the patient cannot be altered by the clinician, the systematic analysis of the patient's intraoral characteristics and the identification of the factors that can impact the accuracy of the intraoral digital scan would enhance the predictability and reliability of the digital procedure (Table 1).

2 | PATIENT FACTORS

2.1 | Tooth type

Tooth type has been recently identified as a factor that can influence intraoral scanning accuracy.[2] In an in vitro study, Son and Lee[2] evaluated the influence of the tooth type on the scanning accuracy of five different IOSs: CS 3500 and CS 3600 from Carestream, Trios 2 and Trios 3 from 3Shape A/S, and i500 from Medit. The results demonstrated scanning accuracy discrepancies among different tooth types: maxillary central and lateral incisor, canine, first and second premolar, and first and second molar.[2] Furthermore, for all the IOSs assessed, the more posterior the tooth, the lower the scanning accuracy computed.[2] This could be explained by the more complex anatomy of the posterior teeth compared with the anterior dentition, which might represent a more challenging geometry to digitize with IOSs. Moreover, all of the IOSs evaluated, except the i500 system, showed a horizontal displacement in the buccal direction as the scan moved posteriorly. In the i500 device, lateral displacements were shown in the lingual direction.[2] Additional laboratory and clinical studies are needed to further analyze the relationship between tooth type and the accuracy of IOSs.

2.2 | Interdental spaces

Publications in the dental literature assessing the influence of interdental space are uncommon.[3–9] In a laboratory study, the influence of 0-, 1-, 3-, and 5-mm of interdental space between the mandibular anterior teeth on the scanning accuracy of two IOSs (1st generation of the iTero system from Align Technology and the Trios 2 from 3Shape A/S) was measured.[3] Higher scanning discrepancies were obtained in the iTero system compared with the Trios 2 device, which might be explained by the generation discrepancies between the systems. For the Trios 2, when digitizing the mandibular cast without any interdental space, a mean trueness ± precision value of 32.32 ± 4.97 μm was reported; but when digitizing the cast with 5 mm of interdental space between the anterior teeth, a mean trueness ± precision value of 52.47 ± 16.83 μm was measured.[3] Therefore, a mean trueness discrepancy of 10 μm was computed between the best and worst values obtained.

Huang et al.[4] evaluated the effect of the distance between a tooth preparation and the adjacent teeth (1, 1.5, 2, 2.5, 3, and 3.5 mm) on the scanning accuracy of an IOS (CS 3600 from Carestream). For distances greater than 3.5 mm between the tooth preparation and the adjacent tooth, the scanning accuracy of the IOS tested was not affected.[4] When the distance between the abutment and the adjacent teeth was less than 3 mm, errors in the IOS evaluated differed depending on the direction of the scan with respect to the tooth preparation (buccal, lingual, mesial, and distal).[4] Furthermore, scan errors involving the margin scan area of the tooth preparation decreased as the distance between the tooth preparation and the adjacent teeth increased.[4]

Son et al.[5] study revealed that interproximal distance between the tooth preparation and adjacent tooth affected the scanning accuracy of an IOS (Primescan from Dentsply Sirona). Furthermore, as the interproximal distance increased, the trueness and precision values of the acquired scan increased, and the maximum positive deviation significantly decreased.[5]

Kim et al.[6] evaluated the influence of the presence of an adjacent tooth on the scanning accuracy of three IOSs (Primescan from Dentsply Sirona, Trios 3 from 3Shape A/S, and i500 from Medit) for a Class II inlay preparation. The presence of the adjacent tooth negatively affected the accuracy of all the IOSs assessed. The mean trueness and precision mean values decreased, and the maximum positive deviations increased compared to scans with no adjacent tooth.[6] Additionally, the absence of adjacent teeth increased the scanning accessibility.[6] The IOS software algorithm interpolates missing or uncertain data, which tends to smooth the surfaces and line angles in the scanned image and often leads to artificial bulges in the margins, which are presented as positive deviations.[6,7] Ferrari et al.[7] reported that artificial bulges on the margin and bridges between the preparation and adjacent teeth were frequently observed when the horizontal clearance was less than 0.5 mm.

The presence of diastemas or reduced space between tooth preparations and adjacent teeth creates difficult IOS accessibility, limits the scanning angle, and data acquisition procedures which can result in reduced scanning accuracy.[3–9] Further studies are required to assess the influence of varying space dimensions and locations on the scanning accuracy of the various available IOSs.

TABLE 1 Summary of the patient factors that can impact the accuracy of intraoral scanners

Factor	Description	Literature findings
Tooth type	Tooth type: maxillary central and lateral incisor, canine, first and second premolar, and first and second molar	Literature demonstrates scanning accuracy discrepancies among different tooth types.[2] Furthermore, the more posterior the tooth, the lower the intraoral scanning accuracy measured.[2]
Interdental spaces	Diastemas Space between a tooth preparation and the adjacent tooth	The presence of diastemas and/or reduced space between tooth preparations and adjacent teeth restrict IOS accessibility, limit the scanning angle, and difficult data acquisition procedures which can result in reduced scanning accuracy.[3–9]
Arch width	Arch width or intermolar distance	In general, the higher the intermolar width, the lower the intraoral scanning accuracy.[7,10,12]
Palate	Addition or not of the palate in the maxillary intraoral digital scan	Higher accuracy values have been reported when the palate is not included in the maxillary intraoral digital scan.[12]
Wetness	The presence of humidity on the intraoral tissues being digitized	Wetness difficult the digitizing procedure reducing intraoral scanning accuracy.[15,16]
Existing restorations	Presence of restorations on the teeth being scanned	Scanning accuracy discrepancies have been reported depending on the restorative materials being digitized, including material type, translucency, and surface finishing.[17–20]
Surface characteristics	Tooth preparation geometry including location of the pulpal and gingival floors, as well as position of the tooth preparation finish line	The characteristics of the surface being digitized can significantly reduce intraoral scanning accuracy.[8,9,26–35] Additionally, these discrepancies are different depending on the IOS technology and system selected.[8,9,26–35] • In general, the higher the complexity of a tooth preparation, the lower the scanning accuracy.[8,9,24,27,28] Sharp angles and uneven or rough surfaces are difficult to reproduce by using IOSs.[8,9,26–35] • Digitizing tooth preparations for full coverage restorations have demonstrated higher scanning accuracy values than scanning intra-coronal tooth preparations.[8,26,29] • The higher the occlusal convergence angle of the tooth preparation for a full coverage restoration, the higher the scanning accuracy values.[29] Similarly, the higher the divergence angle in intra-coronal tooth preparations, the higher the scanning accuracy values described.[29] • The most challenging area to acquire accurate tooth preparation geometric data is the axiogingival line angle.[30] • The higher the depth of the pulpal and gingival floors of a tooth preparation, the higher the discrepancy or lower scanning accuracy values.[33,35] • The more apically located the finish line of the tooth preparation, the more challenging to digitize and the lower the scanning accuracy values.[25,28,31]
Edentulous areas	Edentulous areas or spaces with missing teeth	Edentulous spaces present limited anatomical landmarks representing challenging surfaces for being digitized by using an IOS.[36–40] Different studies have revealed that IOSs can reproduce firm and attached mucosa with the same accuracy as conventional impression methods; however, registering mobile tissues are difficult independently of the IOS technology and system selected.[36–40]
Implants	Interimplant distance Implant position, angulation, and depth	Inconsistencies are present in the literature regarding the influence of interimplant distance, implant position in the dental arch, and implant angulation and depth on intraoral scanning accuracy.[36–47] • In general, scanning discrepancies increases as interimplant distance increases.[46,47] • The implant positioned in the dental arch at the end of the intraoral digital scan obtains significantly higher distortion than the contralateral implant.[45] • Contradictory results have been reported regarding the influence of implant angulation on intraoral scanning accuracy.[36–45] Some studies concluded that implant angulation decreased the scanning accuracy of IOSs,[36,39,41,42,45] while other studies have shown that implant angulation had no effect on intraoral scanning accuracy.[37] • Contradictory results have been reported regarding the influence of implant depth on the accuracy of IOSs. Overall, accuracy decreases as the implant depth increases.[39,40]
Implant scan body	Implant scan body design, geometry, and material	The restricted published data does not support a systematic recommendation for selecting an implant scan body design involving single or multiple implants.[53–60] Furthermore, there may be no implant scan body design that optimally performs for all the different IOSs available.[53–60]

Abbreviation: IOS, intraoral scanner.

2.3 | Arch width

Dental arch width variation has been identified as an intraoral patient condition that can impact intraoral scanning accuracy.[8,10–12] In 2020, an in vitro study measured the influence of different volumetric dimensions of maxillary casts on the scanning accuracy of three IOSs (CS 3600 from Carestream, Trios 3 from 3Shape A/S, and i500 from Medit).[10] The intermolar width tested ranged from 38.45 to 71.09 mm.[10] Results revealed that the scanning accuracy of the IOSs tested varied depending on the volumetric dimensions of the complete arch assessed.[9] Except for the i500, the higher the intermolar width, the higher the scanning discrepancies measured.[7] In the i500 system, the narrowest and broadest intermolar widths tested obtained the highest scanning discrepancies.[10]

In a clinical study, Gan et al.[12] assessed the influence of arch width on the accuracy of maxillary intraoral digital scans. Trueness scanning discrepancies were not found with variations in arch width; however, the scanning precision of the intraoral digital scans decreased with increased arch width.[12] Further in vitro and in vivo investigations are required for assessing the influence of arch widths on the scanning accuracy of IOSs.

2.4 | Palate

Few investigations have assessed the influence of digitizing the palate on the accuracy of the maxillary intraoral digital scans in completely dentate patients,[12,13] as well as in complete-arch implant digital scans in edentulous patients.[14]

A clinical study evaluated the influence of digitizing the palate and the palatal vault height (low, medium, or high) on the accuracy of maxillary intraoral digital scans.[12] Results showed higher trueness and precision mean values when the palate was not included in the maxillary intraoral digital scan.[12] Although the discrepancies were not statistically significant, the higher the palatal vault height, the higher the scanning accuracy discrepancies obtained.[12]

In an in vitro investigation, the influence of digitizing the palate on the accuracy of maxillary complete-arch implant digital scans was assessed by using an IOS (Trios; 3Shape A/S).[14] The generation of the system tested was not provided in the manuscript and the typodont tested included four dental implant analogs.[14] Results showed that the accuracy of digital scans of edentulous maxillary arch with four implants when the palate was stitched compared with unstitched was similar.[14] However, only a single IOS and scanning pattern was tested. Additionally, the ambient lighting conditions under which the intraoral scans were obtained is unknown. Additional investigations are required to further understand the influence of digitizing the palate on the accuracy of maxillary intraoral implant digital scans in different clinical conditions.

2.5 | Wetness

The presence of humidity on the surface being digitized can reduce intraoral scanning accuracy.[15,16] The light reflected from the wet tooth surface is refracted by the effect of water on the surface, which can reduce the performance of the IOSs.[16]

In a laboratory study, authors evaluated the influence of liquid on the surface being digitized (dry, presence of saliva or ultra-pure water, and blow-dried with a three- way syringe) on the scanning accuracy of complete-arch intraoral digital scans captured by using two IOSs (Trios 3 from 3Shape A/S and Primescan from Dentsply Sirona).[16] Humidity present on the digitized surface reduced the scanning accuracy of the IOSs tested.[16] Blow-drying the teeth with a three-way syringe effectively reduced the negative effects of the humidity of the surface being digitized on the accuracy values of the intraoral scan.[16]

2.6 | Existing restorations

The presence of restorations on the teeth being scanned can reduce intraoral scanning accuracy.[17–20] The reflectiveness characteristic discrepancies among the different restorative materials significantly influences the scanning performance of IOSs.[16–19] Scanning accuracy discrepancies have been reported depending on the restorative materials being digitized, including material type, translucency, and surface finishing.

Dutton et al.[17] evaluated the influence of different restorative materials on the scanning accuracy of various IOSs. A typodont with different materials (enamel, dentin, blue build up composite resin, amalgam, composite resin, lithium disilicate, zirconia, and gold) was digitized with eight IOSs (Omnicam and Primescan from Dentsply Sirona, i500 from Medit, iTero Element and iTero Element 2 from Align technologies, Emerald and Emerald S from Plamenca, and Trios 3 from 3Shape A/S). Results revealed significant scanning accuracy discrepancies among the different restorative materials independent of the IOS system used.[17] Furthermore, the different IOS systems tested presented scanning performance variations among the different materials tested.

Revilla-León et al.[19] assessed the influence of different interim (conventional poly-methyl methacrylate (PMMA), conventional bis-acryl composite resin, milled PMMA, and additively manufactured bis-acryl-based polymer) and definitive (milled gold, zirconia, lithium disilicate, hybrid ceramic, and composite resin) materials with two surface finishing protocols (polished and glazed) on the accuracy of an IOS (Trios 4 from 3Shape A/S). The data obtained demonstrated that the type and surface finishing of the different restorative dental materials tested influenced the trueness and precision of the IOS assessed.[19] Furthermore, the lowest trueness values were obtained when scanning high noble metal specimens, while the highest trueness values were measured when scanning conventional and milled PMMA and additively manufactured bis-acryl-based polymer polished specimens. Except for zirconia crowns, higher trueness values were obtained with the polished specimens when compared with glazed dental crowns.[19]

Digitizing a translucent restorative material or acquiring an intraoral digital scan in a patient with multiple existing restorations might be challenging by using an IOS.[17–20] Intraoral scanner powder may reduce the reflectiveness of the restoration, facilitate the

digitizing methods, and reduce the scanning time.[9,21–25] However, in order to maximize the digitizing method, a uniform and thin coat of intraoral scanning powder is suggested.[9,21–25]

2.7 | Surface characteristics

The characteristics of the surface being digitized that significantly influence intraoral scanning accuracy include tooth preparation geometry and tooth location, depth of the pulpal and gingival floors, and finish line location of the tooth preparation.[8,9,26–35] Additionally, these discrepancies measured among the different tooth preparation characteristics would be different depending on the IOS technology and system selected.[8,9,26–35]

Tooth preparation geometry is an important factor that can reduce intraoral scanning accuracy; therefore, clinicians should revise preparations carefully before acquiring an intraoral digital scan to reduce sharp angles and uneven or rough surfaces.[8,9,26–35] Kim et al.[27] studied the scanning accuracy of nine IOSs (Omnicam from Dentsply Sirona, CS 3500 from Carestream, E4D Dentist 1st generation from D4D Technologies, FastScan from IOS Technology, iTero 1st generation from Align technology, Trios 2 from 3Shape A/S, True Definition from 3M ESPE, Zfx IntraScan from Zfx GmbH, and PlanScan from Planmeca) for acquiring complete-arch intraoral digital scans with denture teeth having different tooth preparations. Results revealed accuracy variations on the qualitative features among IOSs tested in terms of polygon shapes, sharp edge reproducibility, and surface smoothness.[27]

Different studies have shown that the higher the complexity of a tooth preparation, the lower the scanning accuracy.[8,9,24,27,28] Furthermore, digitizing tooth preparations for full coverage restorations have demonstrated higher scanning accuracy values than scanning intra-coronal tooth preparations such as inlay preparations.[8,26,29] The higher the occlusal convergence angle of the tooth preparation for a full coverage restoration, the higher the scanning accuracy values reported.[29] Similarly, the higher the divergence angle in intra-coronal tooth preparations, the higher the scanning accuracy values described.[29]

Tooth preparations involving proximal surfaces are the most challenging to accurately scan by using an IOS.[8,24,30] Moreover, the visibility of undercut areas below the height of contour can be restricted and appeared as shadow regions which are difficult to accurately scan. Jin-Young Kim et al.[30] assessed the influence of varying intra-coronal tooth preparation geometries on the scanning trueness of six different IOSs (Omnicam from Dentsply Sirona, E4D from D4D Technologies, FastScan from IOS Technology, iTero from Align technology, Trios from 3Shape A/S, Zfx IntraScan from Zfx GmbH). The authors reported not only trueness discrepancies among the IOSs, and intra-coronal tooth preparation geometries tested, but also the scanning trueness was compromised when the tooth preparation presented a steep occlusal divergence and sharp line angles.[30] Additionally, for all the IOSs tested, the trueness decreased where two surfaces of the tooth preparation met. In particular, the most challenging area to acquire accurate geometric data was the axiogingival line angle.[30]

Tooth preparation location has been identified as a factor that can influence intraoral scanning accuracy, with posterior teeth obtaining lower scanning accuracy values compared with the anterior dentition.[9,34] Another preparation variable is the depth of the pulpal and gingival floors which can also reduce the accuracy of the digitizing procedure. The higher the depth of the pulpal and gingival floors of a tooth preparation, the higher the discrepancy or lower scanning accuracy values reported.[33,35]

The finish line location of a tooth preparation significantly affects the scanning accuracy values (Figure 2).[25,28,31] Therefore, the apico-coronal position of the tooth preparation finish line may impact the accuracy of the intraoral digital acquisition procedure. Gingival retraction is recommended to expose the tooth preparation finish line to facilitate the digitizing technique. A finish line located more gingivally is the harder to digitize and results in a larger number of scanning deficiencies.[25,28,31] Son et al.[31] assessed the influence of the location of the preparation finish line (supragingival, equigingival, and intracrevicular without and without using a retraction cord) on the scanning accuracy values of an IOS (i500 from Medit). The more apically located the finish line of the tooth preparation, the more challenging it was to accurately digitize, and the lower the scanning accuracy values obtained.[31] In particular, the lowest accuracy values were measured on margins at the equigingival and subgingival finish line locations.[31] Moreover, the use of a retraction cord on the intracrevicular finish line location improved the scanning accuracy mean values by a mean 63%.[31]

An important step when digitizing tooth preparations by using IOSs involves the determination in the scan of the tooth preparation (Figure 3). This step is a fundamental procedure to optimize the outcome of the intraoral digital scan. Based on the area selected, the IOS software program selectively reduces the mesh density of the scan, maintaining a high mesh density on the tooth preparation area and reducing the mesh density in the rest of the scan. This procedure reduces the weight of the intraoral digital scan file, facilitating the management of the file, and optimizing the efficiency of the system. In the best knowledge of the authors, there is no published study that evaluates this selective mesh reduction procedure on the accuracy of the definitive restoration.

2.8 | Edentulous spaces

Edentulous spaces or areas with missing teeth have been identified as a variable that can decrease intraoral scanning accuracy.[36–41] Edentulous spaces present limited anatomical landmarks representing challenging surfaces for being digitized by using an IOS.[36–40] Different studies have revealed that IOSs can reproduce firm and attached mucosa with the same accuracy as conventional impression methods; however, registering mobile tissues are difficult independently of the IOS technology and system selected.[36–40]

In an in vitro investigation, Waldecker et al. compared the scanning accuracy of partially and completely dentate maxillary typodonts captured by using three different IOSs (Omnicam and Primescan from Dentsply Sirona and Trios 4 from 3Shape A/S).[41] Results revealed that dental status affected scanning discrepancies, resulting in larger deviations in the partially edentulous maxilla compared with the completely dentate maxilla in all the IOSs tested.[41]

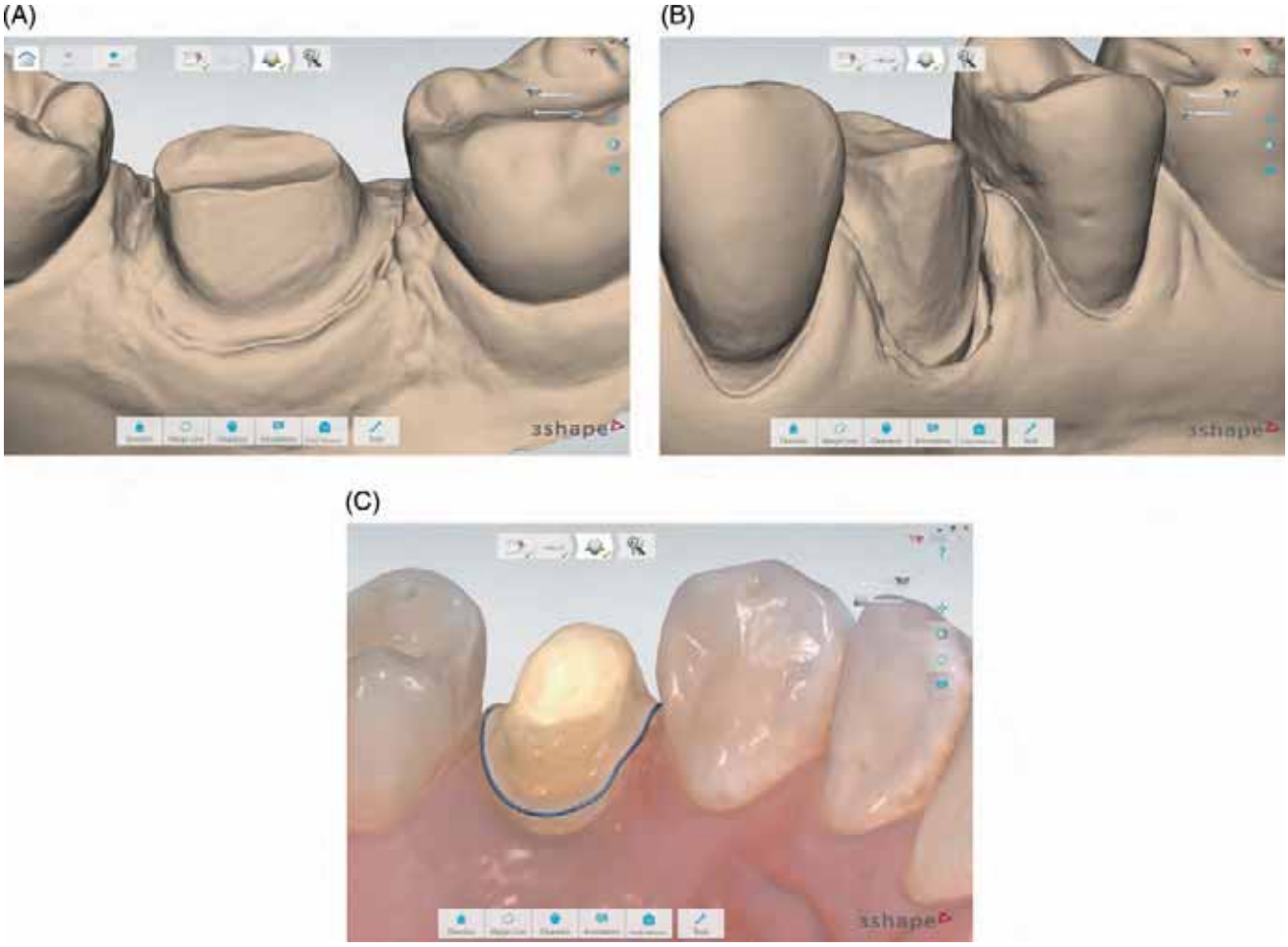

FIGURE 2 Intraoral digital scans that include a tooth preparation. (A) Inadequate finish line visibility of the tooth preparation. (B) Adequate digitalization of the finish line of the tooth preparation. (C) Finish line determination by using the tools of the IOS software program. IOS, intraoral scanner

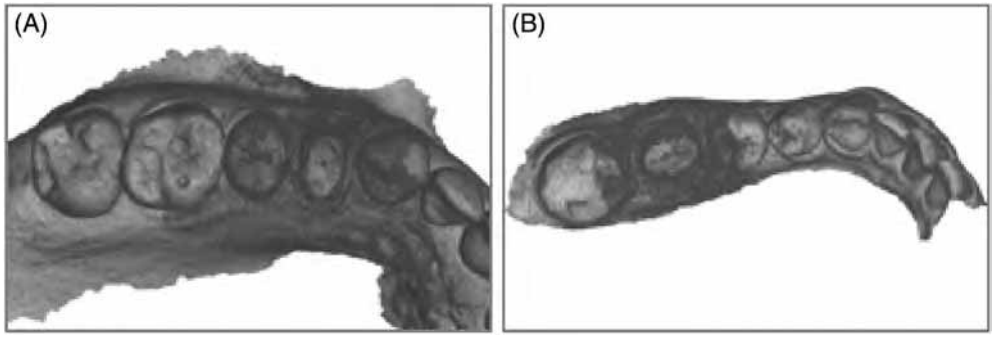

FIGURE 3 Representative intraoral digital scan with varying mesh density. Higher mesh density is located in the tooth preparation area. (A) Tooth preparation on a maxillary right first premolar. (B) Tooth preparation on a mandibular left first molar

2.9 | Interimplant distance, implant position, angulation, and depth

The distance between two adjacent implants, as well as implant position in the dental arch, implant angulation, and depth of the existing implants have been identified as variables that can decrease intraoral scanning accuracy.[41–52] However, inconsistencies are present in the dental literature regarding the influence of these variables on intraoral scanning accuracy.[41–52] Additional studies are needed to further assess the influence of implant related factors on scanning accuracy of IOSs. Photogrammetry systems provide a digital alternative to acquire the 3D position of the implants.[53–57]

A limited number of studies have analyzed the influence of the interimplant distance on intraoral scanning accuracy.[51,52] The results obtained

by these studies were mainly consistent with the expectation that errors would increase as scanning distance or interimplant distance increased.[51,52]

Regarding implant position in the dental arch, Gómez-Polo et al.[50] assessed the influence of the implant angulation and implant position on the scanning accuracy of complete-arch implant scans captured by using an IOS (Trios 3 from 3Shape A/S). Results demonstrated that the implant positioned in the dental arch at the end of the intraoral digital scan obtained significantly higher distortion than the contralateral implant.[50]

Contradictory results have been reported regarding the influence of implant angulation and depth on intraoral scanning accuracy.[41–50] Some studies have reported that implant angulation decreased the accuracy of the digital scans compared to the conventional impressions, or that implant angulation decreased the scanning accuracy of IOSs.[41,44,46,47,50] However, other studies have shown that implant angulation had no effect on intraoral scanning accuracy.[42]

Implant depth is related to clinical implant scan body height.[43–45] Studies have analyzed the influence of the implant depth on intraoral scanning accuracy with contradictory results reported.[43–45] In an in vitro study, Laohverapanich et al.[43] evaluated the influence of the implant depth (3, 6, and 9 mm) on the scanning accuracy of four IOSs (Omnicam from Dentsply Sirona, Trios 3 from 3Shape A/S, True Definition from 3 M ESPE, and DWIO from Dental Wings) when obtaining a half-arch scan on a partially edentulous cast with 1 implant scan body. The best accuracy values were obtained when implants had up to 6-mm depth.[43] Similarly, Sequeira et al.[45] evaluated the influence of the implant depth (7, 6, 3, and 0 mm) on the accuracy of half-arch implant digital scans acquired by using an IOSs (CS3600 from Carestream). The cast selected had a single implant scan body. These results demonstrated that the accuracy values decreased as the depth increased.[45]

In a laboratory study, Gómez-Polo et al.[44] assessed the influence of the implant depth and implant angulation on the accuracy of complete-arch implant digital scans captured by using an IOS (Trios 3 from 3Shape A/S) and found that implant angulation and clinical scan body height influenced scanning accuracy.[44] When implants were parallel, no significant difference was computed between the different clinical implant scan body heights tested. However, in angulated implants, the shortest clinical implant scan body height resulted in the lowest scanning accuracy measured.[44]

2.10 | Implant scan bodies

Limited published data is available to determine the optimal implant scan body geometry and material for maximizing the scanning accuracy of intraoral digital scans involving single or multiple implants.[58–65] Different scan body designs have been tested aiming to simplify the digitizing procedures and to increase intraoral scanning accuracy.[48,64,65] However, the restricted clinical data does not support a systematic recommendation for selecting an implant scan body design. Furthermore, there may be no implant scan body design that optimally performs for all the different IOSs available.

Additional variables that should also be considered include implant scan body manufacturing tolerance,[66] implant scan body position distortion caused by tightening torque,[60,67] and one-piece PEEK implant scan body wear due to multiple reuses.[68–70] Due to the limited available data, it is difficult to establish protocols based on the number of times that an implant scan body can be sterilized and reused. Implant scan bodies with the implant interface fabricated in metal might be preferrable when compared with the one-piece PEEK implant scan bodies.[68–70] A cautious practice might include following the manufacturer's recommendation regarding the number of times that an implant scan body can be reused without affecting its performance, as well as the manufacturer's suggested torque when placing the implant scan bodies.

3 | CONCLUSIONS

The knowledge and understanding of patient intraoral conditions that can impact the scanning accuracy of IOSs is a fundamental element for maximizing the accuracy of IOSs. Although the intraoral conditions of the patient cannot be altered by the clinician, the systematic analysis of the patient's intraoral characteristics and the identification of the factors that can impact the outcome of the intraoral digital scan would enhance the predictability and reliability of the digital procedure.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Research data not shared.

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How to cite this article: Revilla-León M, Kois DE, Kois JC. A guide for maximizing the accuracy of intraoral digital scans: Part 2—Patient factors. *J Esthet Restor Dent*. 2023;35(1): 241-249. doi:10.1111/jerd.12993

Received: 24 October 2022 | Revised: 13 December 2022 | Accepted: 14 December 2022

DOI: 10.1111/jerd.13004

REVIEW ARTICLE

WILEY

Digital workflow in implant prosthodontics: The critical aspects for reliable accuracy

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Abstract

Introduction: This paper is a comprehensive treaty about the variables that influence the transfer of the position of an implant to the laboratory when using a digital workflow.

Objective: The aim is to provide operators and manufacturers with a guide on how to improve certain aspects of the digital workflow specific to the fabrication of implant-supported restorations.

Overview: It addresses intraoral scanning issues and CAD software issues. In the former, the variables that play a part in the quality of the scan file are investigated: the implant scan body, the IOS and the operator. For the latter, instead, the focus is on those aspects that still today may create inaccuracies in the workflow and in the final product being fabricated: the identification of the specific implant placed in the patient and the generation of a virtual model with the representation of that implant platform correctly positioned in the three dimensions of space. Suggestions and recommendations are given to improve the control on the quality of the digital workflow's output.

Conclusion: In a digital workflow for the fabrication of an implant-supported restoration, the selection and use of the implant scan body, the use of an effective scan strategy and the appropriateness of the best fit function in the CAD software, that is, the procedure of superimposing the library of geometric shapes of the ISB linked to the implant with the shape acquired intraorally, are variables that can influence the positional precision of the FDP.

Clinical Significance: Fully understanding the importance of the information enclosed in the ISBs themselves can be crucial in the digital workflow. A proper ISB's selection, a correct scan of the ISB's shape and an accurate CAD superimposition of the ISB's library can lead the clinician to reduce the variables that affect the final result in daily practice.

KEYWORDS

best fit, cad-cam, digital workflow, implant scan body, intraoral scan

1 | INTRODUCTION

Intraoral scanners (IOS) are becoming more common among dental professionals (source: Key-Stone survey, Italy, https://www.key-stone.it/) and, as a consequence, their use for taking the impression of implants is increasing. Part of the reason is due to the marketing messages and claims being made by several companies that IOS's are devices which can capture accurate impressions more quickly and with increased ease compared to traditional impressions.

However, looking at the scans that dental laboratories and milling centers receive, it seems that many clinicians lack training and

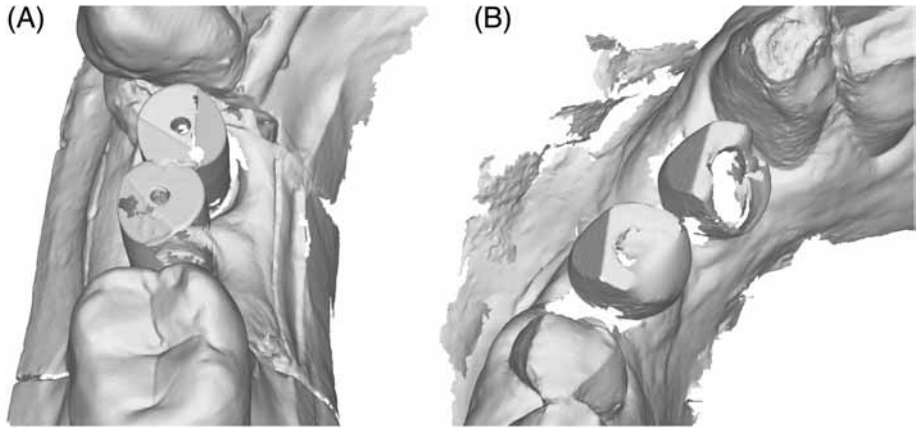


FIGURE 1 Sample scans commonly received by laboratories: (A) with doubling of the bevel of the ISB's scan area; (B) with a scan region that is insufficient to obtain a correct best-fit

knowledge about the variables that influence the accuracy of a digital impression for implant supported prostheses (Figure 1A,B). Indeed, there are many factors that the operator has to be aware of in order to perform an accurate implant impression which can then be used to fabricate a prosthesis that satisfies the requirements for placement in the oral cavity.

Several in vitro studies have investigated the accuracy of digital impressions of implants comparing them to conventional impression techniques demonstrating that, potentially, their accuracy can be clinically acceptable.[1–3] On the other hand, several papers have pointed out that the outcome can be influenced by the operator (i.e., experience and scanning strategy),[4] by the equipment (i.e., scanning technology and algorithm),[5] and clinical conditions (i.e., ambient light, saliva, dental materials in the oral cavity, amount of attached gingiva).[6]

In the digital workflow for the fabrication of an implant-supported prostheses, three phases or steps are required: the first is that of the intraoral scan which generates a file (usually, an .stl format), the second is the acquisition of the IOS file by a CAD software which then creates a virtual model and designs the restoration, and the third is the production of the restoration and, if indicated, of a 3-D model, utilizing a variety of technologies which span from subtractive to additive.

This article analyzes the clinical and technical variables only of the first and second steps. The aim is to make all involved in the process of the fabrication of an implant-supported prostheses (both operators and manufacturers) aware of potential pitfalls that may compromise the outcome and may require the repetition of the entire procedure.

2 | INTRAORAL SCANNING ISSUES

The accuracy of an intraoral scan of one or more implants depends on three main factors: the implant scan body selected, the intraoral scanner and the operator.[7]

2.1 | The influence of the implant scan body

According to Mitzumoto,[8] the scan body is defined as a "complex implant-positioning-transfer device." In the literature and in the marketing material, many names are found for this device besides implant scan body: scan abutment, scan flag, scan post, and scan peg. In this paper, we will refer to it as implant scan body (ISB).

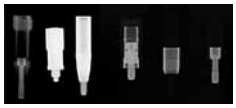
There is a profound difference between the ISB of a digital workflow and an impression coping used in the analog workflow. Both must engage the implant platform precisely, but, while the body of the latter can be modified if needed (such as reduced in height or narrowed in diameter in case of space constraints), the former cannot and should not be changed in any way. The only requirement of an analog impression coping is to be retained within the impression material that embraces it so that, when the implant or abutment analog is connected, it does not move or rotate. On the other hand, when matching the intraoral scan of an ISB with the library of shapes stored in the best fit function of the CAD softwares, the ISB's scan region should remain intact for a matter of superimposition. Some Authors[9,10] propose changes to the shape of the ISB to better adapt it to unfavorable clinical conditions that would prevent correct positioning in the fixture, such as situations in which the ISB makes contact with other ISBs or teeth present. Although this procedure allows the operator to still obtain a coupling with the implant library through best fit, later in the article it will be explained how this type of best fit may not be precise and may instead introduce positional errors of the virtual analog (see CAD issues below).[11]

Moreover, not all ISBs can be considered equal or comparable. They differ in many ways. They can be: metal, peek, plastic or a combination, 1-piece or 2-piece, single use or multiple use, screw-retained or snap on (friction grip), radiopaque or radiolucent, with a sand-blasted surface or a coated surface, tall or short, narrow or wide in diameter, simple or complex in geometry. Table 1 illustrates the main features of the ISBs available on the market indicating which should be avoided whenever possible.

2.2 | ISB materials and usage

ISBs are available in a variety of materials: metal (titanium, aluminum or stainless steel), PEEK (PolyEther-Ether-Ketone) or plastic. Even though they are more easily scanned than other materials,[12] the use of PEEK and plastic is discouraged since these materials tend to distort and wear due to the sterilization cycles, tightening of the screw,

TABLE 1 Main features of the ISBs available on the market and indications of critical aspects

Feature	Image	Which to avoid, if possible	Reason
ISB materials and usage			
Metal vs. PEEK or plastic		PEEK and plastic	May distort and wear and the consistency in their dimensions is lower than with full metal components.
1-piece vs. 2-piece		2-piece	May display variations in the assembly due to the variables when combining the parts or of the mechanical engagement.
Single use vs. multiple uses		Controversial	It depends on the material.
Screw-retained vs. friction fit (snap on)		Friction fit (snap on)	It may not be fully engaged (e.g., due to the interference of the periimplant tissues) without the awareness of the operator.
Radiopaque vs. radiolucent		Radiolucent materials	The correct seating cannot be checked with certainty.
ISB surfaces, dimensions and morphologies			
Coated vs. sandblasted surface		Controversial	There is no evidence to support the best surface treatment since it depends also on the IOS employed.
Height		Different than the neighboring structures, that is, short when next to teeth or tall next to edentulous spans	The component's height should be selected according to the clinical situation being scanned: it should be similar or close to the neighboring structures' height.
Diameter		Narrow with limited occlusal surface	If the occlusal surface is limited, it can be difficult to obtain a correct best fit in the CAD software.
Complex vs. simple scan region shape		Complex shapes (with undercuts or elaborated geometries)	It can be difficult to scan fully the component.

or biting on the component[13] (Figure 2). Furthermore, the tolerances in the consistency of their dimensions are much wider than for metal components.[14,15]

Thinking that in mechanics it is possible to produce consistent pieces according to the measurements of the technical project is utopic. Any piece produced will have a deviation from the actual measurements and its extent varies depending on the production method. Each manufacturer decides which is the range of acceptability (e.g., from + to − 30 μm) and whether the pieces just produced are checked and measured on a sample basis for each batch or piece by piece. This means that, at the end of the production process, from the same project, it is possible to have components on the market that may differ in size within the limits of this "acceptable" range. The ISB libraries in the CAD softwares, on the other hand, have a single dimension not subject to dimensional variations.

FIGURE 2 Wear of a PEEK ISB due to multiple uses

FIGURE 3 2-piece ISBs with a different height of the base due to incorrect assembly. Assuming that the right is the correct one, the use of the component on the left would lead to a vertical incongruity of the position of the analog and, subsequently, a possible under occlusion of the FDP

FIGURE 4 Friction fit (left) and screw-retained (center for an internal connection implant and right for an implant with an external hex) scan bodies

When we apply an ISB to the implants of a patient for taking a digital impression, potentially we could use components or scan bodies which are at the extremes of the tolerance range. A greater or lesser tolerance from the point of view of circumferential measurement, if uniform, does not cause inaccuracies in matching the scanned ISB with the library. This is because the best fit algorithm will still have a unique positioning since it is based on a mathematical average. On the contrary, variations in height can create different vertical positions of the virtual analog head. The use of these components would lead to a vertical incongruity of the position of the analog and, subsequently, a possible over or under occlusion of the FDP (e.g., if the ISB is +30 μm in height, the restoration will likely be under occluded by 30 μm).

The same reasoning applies to the engagement geometry (base): too wide or too narrow tolerances can cause an incorrect positioning in the vertical axis and in the rotational position.[16]

There are a number of manufacturers that sell 2-piece ISBs, often a metal base onto which a second piece (which can be of the same material or different) is either glued or engaged by friction. These scan abutments may display variations due to the assembly process or to incomplete seating of the top part (Figure 3). Therefore, these components can potentially generate a wider range of error since their variability is due to the sum of the tolerances of the two components.

Most manufacturers recommend to use the scan abutments only once to avoid the introduction of variables due to wear and tear in case of multiple uses, but this is controversial. As regards the nondisposable metal ISBs, the literature suggests a limited use of maximum 10 times, provided that there are no obvious signs of premature wear.[17] The clinician should, therefore, always inspect visually the components (preferentially, under magnification) prior to use and discard those that are no longer pristine.

The market offers dentists the opportunity to choose between two types of ISBs based on the method of engagement in the implant connection: screw-retention or friction fit (snap-on) (Figure 4). Even though a friction grip component (usually made of PEEK or plastic) may be quicker and apparently easier to apply, having a component held in position by means of a screw has the advantage of providing greater stability and, above all, of avoiding altogether the risk of partial dislodgment during the scanning procedure. Furthermore, one has to consider that, when two unlike materials are coupled by friction, the softer one will eventually wear (e.g., metal vs. metal wears less than PEEK vs. metal). As already mentioned, ISBs are subject to wear with multiple uses and those in PEEK and plastic in particular. For the aforementioned reasons, we do not recommend the use of snap-on scan bodies. In the absence of alternatives, they should at least be considered disposable.

On the other hand, due to the problem of mechanical tolerances in the production phase, screw-retained components for internal conical connections, even the metal ones, can have different degrees of

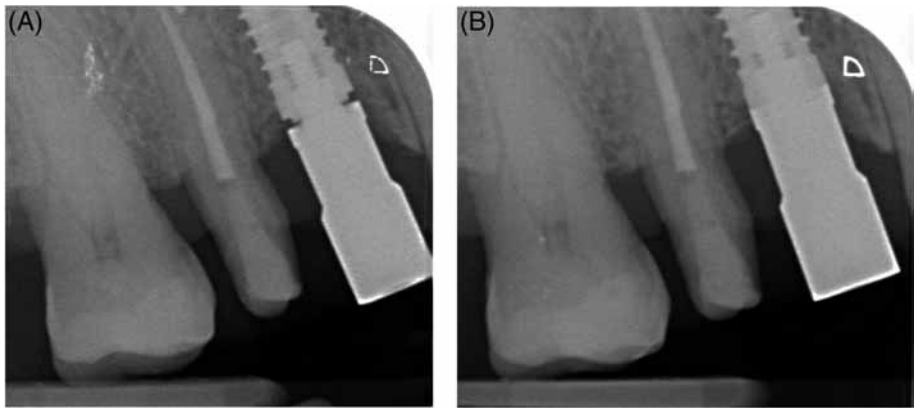


FIGURE 5 Radiographic examination should reveal improper vertical seating of the ISBs every time the interface is not visually inspectable. Only metal components allow the identification of the incorrect (A) or correct (B) adaptation to the implant platform. PEEK is a radiolucent material

adaptation. The clamping force of the prosthetic screw must be considered. While, on one hand, some authors recommend not to exceed 10 Ncm to avoid vertical displacement of the scan abutment, especially in conical connections,[18] there are manufacturers who recommend a torque of 30 Ncm.[19] Kim et al.[18] have shown that, if scan bodies in plastic material or PEEK are used, the vertical displacement at high torque values will be evident, because this screwing load creates a permanent deformation. Therefore, it is a good habit to torque ISBs at a defined value not superior to 10 Ncm through the use of calibrated screwdrivers.

Whenever the correct seating of the ISB on the fixture cannot be inspected directly, as in the case of an implant positioned at bone level or subcrestal, a radiographic examination should be performed. If the ISB is made of a radiopaque material, this verification can intercept improper vertical seating which will have significant negative repercussions on the prostheses' positional and occlusal features. All components made entirely of PEEK or radiolucent materials cannot benefit from this verification (Figure 5A,B).

FIGURE 6 Ceramized-like modification of the titanium dioxide sandblasted surface produced in a wet chemical process (left and center) compared with a common coating (right)

2.3 | ISB surfaces, dimensions and morphologies

An important aspect that impacts on the ease of the scanning procedure is the type of surface of the ISB. The surface should not be reflective. For this reason, metal ISBs are preferentially either sandblasted or coated. Despite this, some IOS have difficulties in obtaining the scan. PEEK, on the other hand, has a nonreflective surface because it is a semi-crystalline material, therefore opaque. There is research going on in the development of coatings which combine the advantages of an easily scannable surface with the durability and reliability of metal components (e.g., Plasma Electrolytic Oxidation by Thommen Medical, Switzerland, that is a ceramized-like modification of the titanium dioxide sandblasted surface produced in a wet chemical process) (Figure 6). At the moment, the main problem with the application of these coatings is the difficulty to guarantee consistency in distribution and thickness (Figure 7). Moreover, the coated layer can degrade or go away during the cleaning and sterilization.

Another important feature is the diameter. In partially edentulous patients, the diameter should be such as not to interfere with the

FIGURE 7 Nonhomogeneous coating distribution. This may cause improper alignment when using the best fit function in the CAD software

neighboring teeth (Figure 8) or scan abutments (Figure 9) and, at the same time, should provide enough space to capture the proximal surfaces of the teeth or of the scan abutments.

Some scan bodies have the fixation screw inside the body of the component itself, without the possibility of removing it (Figure 10). It can be accessed through a small occlusal hole, sufficient only for the passage of a thin-shank screwdriver. This solution responds to two desires: firstly, not losing a horizontal portion of the occlusal surface of the component (needed for an

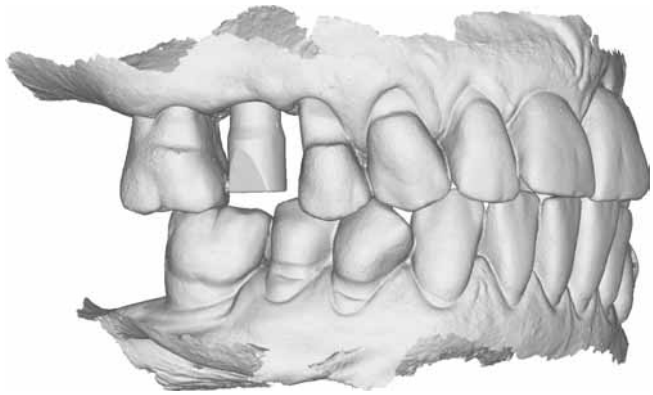


FIGURE 8 Even when there seems to be sufficient space, check that the ISB does not interfere with neighboring teeth. In this case, the ISB is contacting the mesial surface of the molar, thus not allowing the complete scan of that surface

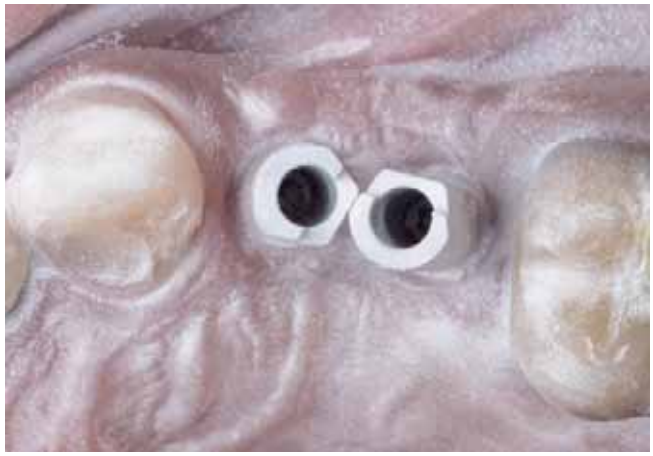


FIGURE 9 The ISB diameter and height should be such as not to interfere with the neighboring teeth or scan bodies. In this patient, the convergence of the implants does not allow the respective ISBs to be placed at the same time since they interfere with each other at the top. Either shorter ISBs should be employed or a double impression must be recorded

accurate best fit) like it occurs whenever the hole is large and the dimensions of the ISB are kept within certain limits for not interfering with the neighboring teeth in narrow spaces. Secondly, it allows the user not to lose the screw during insertion in the mouth and the sterilization processes. On the other hand, it is not possible to visually check the integrity of the prosthetic screw and, if damaged, replace it. Furthermore, it is necessary to reflect on how this component is produced. It is obvious that the screw must undergo an assembly process. As a matter of fact, even if visually it appears as a 1-piece, it has to be considered a 2-piece component with the possible variations to which this type of ISB is subject.

As far as the height is concerned, it should be as close as possible to the height of the neighboring teeth or scan abutments to facilitate the advancement of the scanner during the scan limiting as much as possible vertical excursions of the tip[20,21] (Figures 11 and 12). In fully edentulous patients, the height should be as low as possible. In both situations, the matching surface needs to be fully exposed and not partially covered by the soft tissues[22] (Figure 13).

The last meaningful feature to be discussed is shape. Simple shapes of the coupling geometry allow the operator to be faster and more precise in scanning the ISBs.[23] Ideally, a scan abutment should be read almost in its entirety in a single passage from the occlusal side. Only a simple ISB, linear in shape, free of undercuts and concavities, allows the operator, with simple movements, to capture and reach every portion of the geometric shape. This translates into shorter scanning time and a reduction in the possible errors that can occur when going over the same surfaces several times with the scanner.[23] Scan abutments that do not have bevels to determine the position and orientation of the implant fixture can complicate intraoral acquisition in the absence of other unique points of reference (such as stable teeth or attached gingiva), especially if they are very distant from each other (e.g., those for multi-unit abutments by Thommen Medical, Switzerland) (Figure 14A). The acquisition software may have difficulty to recognize the single scan body because it is completely identical to the others (Figure 14B,C). The presence of a bevel adds a distinctive element to each ISB which allows the scanner, during progression, to understand that it is not the same component since they will have different orientations.

2.4 | The influence of the IOS

The acquisition of the shape of a scan body may or may not be facilitated depending on the intraoral scanner used.[12,20,24] To start, the size of the acquisition window, called scan window, affects the amount of information detected in a single passage.[20,24] A large window will acquire more data faster, but, at the same time, the tip will be bigger and more cumbersome.[24] In situations where the scan bodies themselves, by position or shape, limit the access of the scanner, it is more difficult to perform linear and correct maneuvers to capture the shape of the component. Being able to choose smaller tips or using software features that vary the scan depth can give the clinician an advantage in such situations.[24]

Some of the early IOS contemplated the use of a powder in order to acquire the scan (e.g., True Definition, 3M, USA). The more recent models, instead, are marketed as "powder free." On the other hand, most of the IOS manufacturers recommend the application of a powder when the patient presents highly reflective surfaces (such as shiny metal FDPs) in order to opacify them. Titanium dioxide powders are available for this purpose. They are sprayed onto the surface and differ on the basis of whether or not they contain an adhesive.

The risk of powder application is that of creating a coating which may distort the shape of the object, as demonstrated in vitro by Dehurtevent et al.[25] This is particularly dangerous if the powder is applied to a scan abutment because it may modify its dimensions. Using a spray containing adhesive, if not correctly applied, will inevitably lead to the alteration of the shape of the ISB due to the thickness of the spray that is deposited on the surface. These

FIGURE 10 The access hole in the ISB on the left allows the screw to be removed. The ISB on the right, instead, has the fixation screw inside the body of the component itself, without the possibility of removing it. This offers a wider occlusal surface without increasing the component's overall diameter

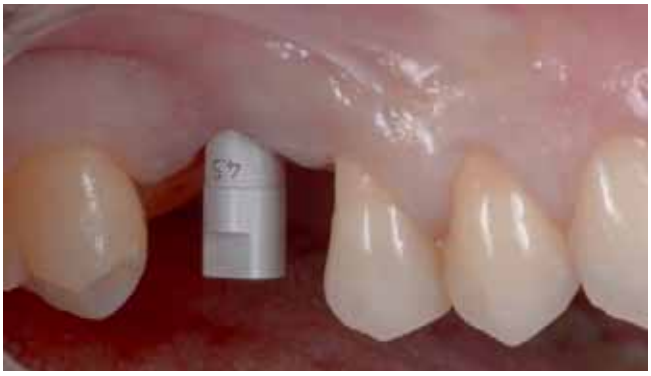


FIGURE 11 A correct height and diameter of the ISB facilitates and speeds up the IOS acquisition

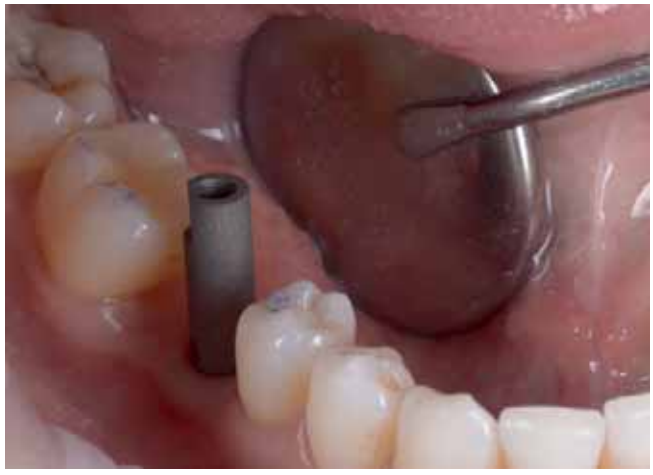


FIGURE 12 An excessive height of the ISB may interfere with the linear advancement of the intra-oral scanner, thus affecting the acquisition of a proper scan

sprays are easier to manipulate extra orally, for example in the lab, since the application can be made at the correct distance (e.g., 20 cm) to have a uniform diffusion and the object to be opacified can be rotated in any direction to be exposed to the spray. In the mouth, obviously we do not have the opportunity to do the same. Powders without adhesive are easier to apply and any excess dust can be easily removed by blowing air. However, the fact remains that it is a possible variable and source of distortion and there is no way to standardize the powdering procedure for each scan.[26]

2.5 | The influence of the operator

Many studies agree that the operator's experience affects the final quality of the scan.[4,27–29] Experience should not be interpreted as the number of scans performed, but as proper training and knowledge of the objectives to be achieved when taking impressions.[20]

The scanning strategy, that is how the scanner is positioned and moved across the arch, has been shown to affect profoundly the impression's accuracy and trueness.[30–32] It must be considered that the IOS is nothing more than a noncontact measuring instrument using optical technology. Any freehand measurement system is obviously subject to errors due to the operator's use and to the lack of measurable fixed references. A lab scanner, instead, has a plate whose size is known and onto which references are incorporated. It follows that a reading distortion can be more easily corrected by the processing algorithm of the final file.[33] In addition, the acquisition sequence is always the same since it is guided by a mechanized standard path. In contrast, the IOS operator represents the most relevant variable. Recent literature, therefore, has investigated the best scan path that, when applied faithfully, can minimize this variable.[30–32]

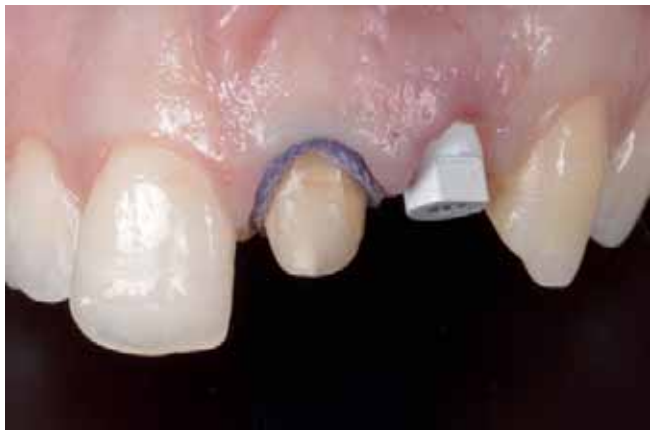


FIGURE 13 Whenever the soft tissue partially covers the ISB, it reduces the scan region for an effective best fit superimposition

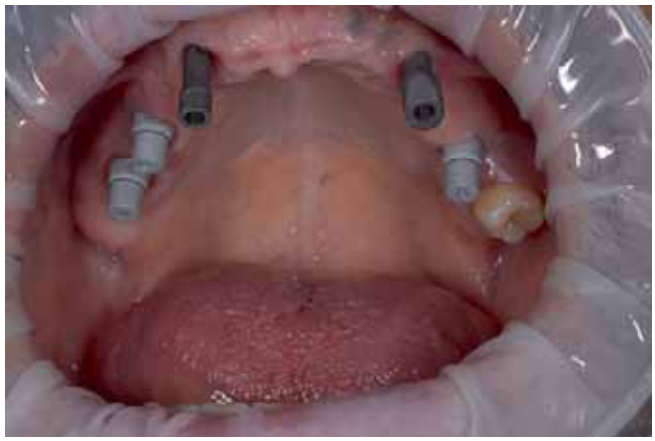


FIGURE 15 An effective lip and cheek retraction allows the operator to perform a correct scan thanks to the unimpeded movement of the scanner inside the mouth

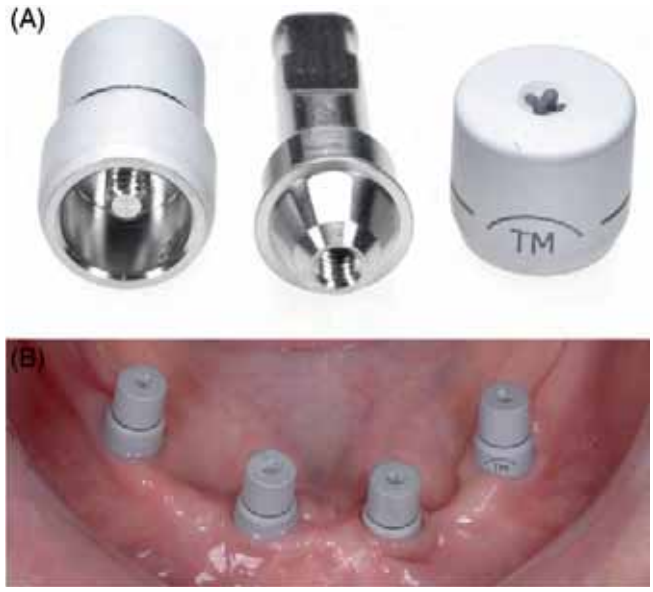


FIGURE 14 (A) ISBs for multi-unit abutments do not necessarily require an intaglio surface. (B) However, identical shapes of the ISBs without bevel make the acquisition difficult whenever the implants are far apart. (C) The operator's experience is crucial in order to obtain a proper scan, especially when the band of keratinized tissue is limited

In the absence of a scientifically validated scan strategy, we have relied on our experience that suggests to apply the following precautions which should be matter for future research projects:

- The IOS tip should be held close and parallel to the occlusal surface of the teeth or the gingiva in the edentulous spaces; although most of the IOS allow a contact scan, there are some devices that have a certain depth of field to respect. In this case, the advice is to try not to have oscillations outside the optimal working area.[20,33]
- It should not advance too quickly in order to facilitate stitching; a movement that is too rapid may create a poor and approximate acquisition of points.[20,24,33] On the other hand, dwelling too much on areas already correctly acquired can worsen the quality of the final mesh.[20] So, the advice is to scan the surfaces at their best, then move forward, avoiding to return several times in areas already fully scanned.
- The movements should be linear and not chaotic or random; a linear movement creates portions of surfaces on which new points are based for the progression. A random movement may not have these sure foundations to progress with the stitching of new surfaces.[20,24,33] Consequently, the acquired objects could incorporate distortions that are difficult to be appreciated once the mesh is created.
- The cheeks, lips and tongue should be kept away from the teeth through the use of appropriate devices and the field should be as dry as possible[34]; the visibility and accessibility of the operating field is a crucial factor. An effective lip and cheek retraction allows an ease of movement of the scanner inside the mouth, helping the operator to perform the correct scan (Figure 15). The assistant's role is to follow the dentist's movement by helping to keep the tongue away from the dental surfaces. He/she should, therefore, focus only on the patient. Instead, the dentist should only look at the progression of the acquisition on the monitor, avoiding as much as possible looking into the patient's mouth. A further important element is to dry the surfaces to be scanned in order to minimize the reflection that the scanning light will inevitably cause on saliva.
- In the case of a fully edentulous arch with little or no attached gingiva, the operator's experience and knowledge about the limits of the IOS are essential for the success of the scan. As a matter of fact, advancement on mobile and nonstable tissues without fixed references (such as teeth or a wide band of keratinized attached tissue) creates objective difficulties for the stitching process. There are, however, practical tricks in order to overcome them. Some authors have proposed special shapes of ISB with cantilevers (flag post)[35] or chains to be assembled and attached to the ISBs (e.g., Universal Scan Template, LaStruttura, Italy), or a customized over-scan body rings[36] or the use of liquid dam[37] to mimic replicate keratinized tissue when there is none. The concept behind all these solutions is to have fixed areas which can facilitate the stitching process.

3 | CAD ISSUES

Computer Aided Design (CAD) softwares have been undergoing continuous development over the past two decades to facilitate and automatise many functions. However, there are two aspects that still today may create inaccuracies in the workflow and in the final product being fabricated: the identification of the specific implant placed in the patient and the generation of a virtual model with the representation of that implant platform correctly positioned in the three dimensions of space.

3.1 | The pitfalls of implant platform recognition

At the moment, in the digital workflow, the information about the implants being captured by the IOS has to be entered in the prescription manually by the clinician or his/her staff. It is possible to use ISBs for different implant platform configurations and diameters with the identical scan area shape. Therefore, looking at the ISB in the digital impression, it is not possible to identify the implant type since the engaging portion is hidden (Figure 16A,B).

Not having a physical impression with the impression copings trapped that allow the operator to verify the correct choice of components, as in the case of the traditional workflow, he/she must rely exclusively on the information provided by the clinician in the lab prescription. In the event that a mistake has been made in communicating implant type, brand and platform diameter, the dental technician has no way to intercept it. The incongruity can only be found when the work is completed and the clinician attempts to insert it in the implant.

Therefore, incorporating in the ISB a serigraph of a bar code or QR code that automatically identifies the correct library to the CAD software is desirable since it eliminates human error (Figure 17).

3.2 | The pitfalls of the best fit function

Once the shape of the ISB has been acquired with the IOS, in the CAD software, the dental technician must position the virtual analog for the creation of the virtual working model. To do this, a known library of geometric shapes (linked to the implant) must be coupled or superimposed with the shape acquired intraorally, a procedure called best fit[8] (Figure 18). The word itself denotes the best possible fit based on the selected surfaces. The bevel allows the ISB to have a unique orientation in space to initiate this overlapping process. Then, an algorithm based on a weighted average between the known measurements of the library and the ISB measurements obtained by the scanner determines the best fit. The amount of surface available for the best fit can be decided and adjusted by a

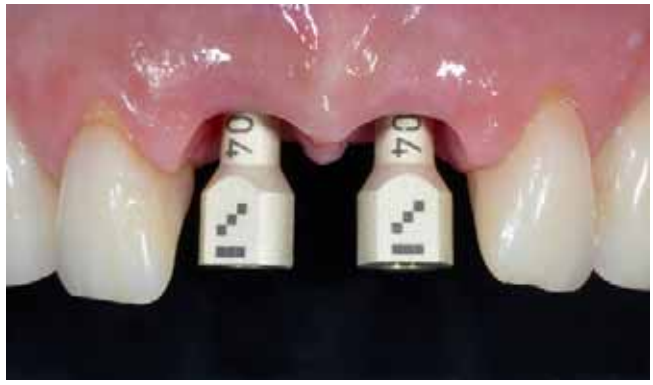


FIGURE 17 ISBs with a built-in QR code that automatically transfers the information and characteristics of the implant to the CAD software, thus eliminating a possible human error in selecting the correct prosthetic components

FIGURE 16 (A) ISBs with identical scan region shapes: it is not possible to identify the implant type from the top portion. (B) Only their engagement gives information about the different implant platforms, but this is not visible in the scan

special function in order to improve the overlap. Depending upon the area of best fit chosen, the position of the virtual analogue may change.

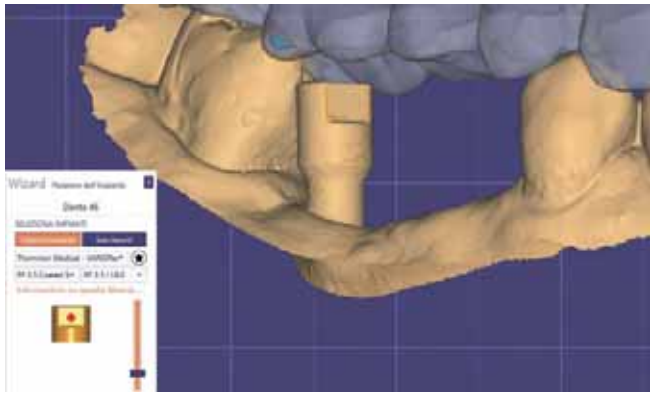


FIGURE 18 Rendering of the superimposition of the implant library and the scan body acquired by the IOS: in this view, the potential discrepancy between the two shapes cannot be appreciated

The best fit matching in the CAD softwares is an automatic process, but the operator can verify the correspondence of the two objects and how much they differ from each other by measuring the accuracy of the matching. As a matter of fact, blindly accepting the first best fit provided by the CAD software algorithm can result in an implant position that is not congruent with that of the patient. The authors, therefore, recommend the verification of the best fit during the CAD phase. This can be done in two ways:

- With a section view: the quality of the superimposition can be checked by making cuts that can highlight if and how much the library shape corresponds with the acquired ISB (Figure 19A).
- With a calibrated proportional color scale: enabling a function in the CAD software (i.e., by pressing the <CTRL> in EXOCAD, Align Technologies Inc., USA), the quality of the superimposition can be measured with a color scale (Figure 19B). The operator can improve that by cutting away the lower part of the geometry of the ISB library in the wizard window.

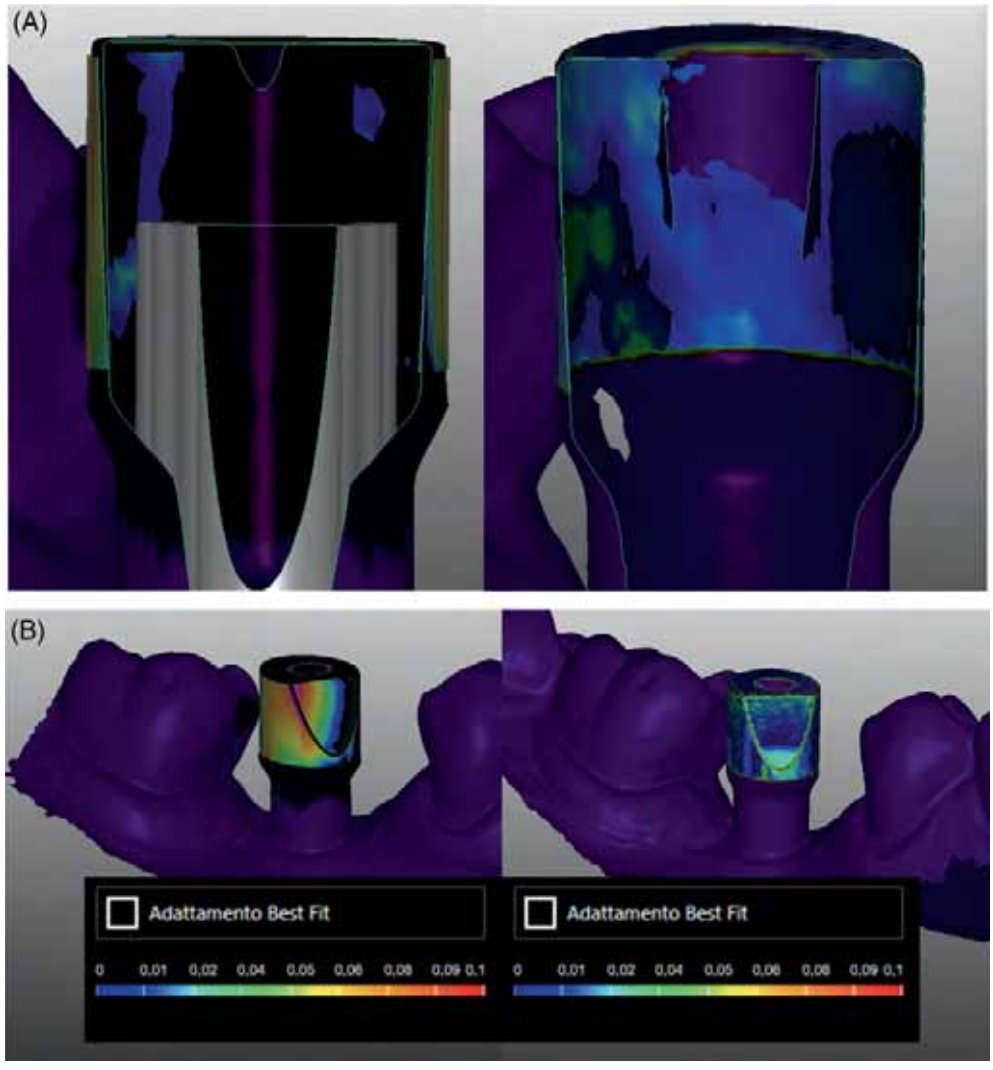


FIGURE 19 (A) Example of best fit verification using the section view in the CAD software. In the left side, the superimposition of the ISB's contours and the library contours shows a difference which demonstrates the fact that they do not coincide. In the right side, instead, the two contours coincide perfectly. (B) The same case in the view with a color scale measurement. In the left side, the gradient of colors is a demonstration of the lack of matching between IOS scan and library. The predominance of the blue color in the image on the right, instead, is a demonstration of a good superimposition

4 | CONCLUSIONS AND RECOMMENDATIONS

In a digital workflow for the fabrication of an implant-supported restoration, the selection and application of the implant scan body, the use of an effective scan strategy and the appropriateness of the best fit function are variables that can influence the positional precision of the FDP.

With so many manufacturers using different geometries and materials, probably to avoid patent infringement, it would be desirable to define a standard for ISBs. On the basis of what has been presented in this article, the following are the recommendations for the implant scan body of choice:

- 1-piece,
- screw-retained, with a clamping force not exceeding 10 Ncm,[18]
- metal (therefore, radiopaque),
- rough (sandblasted) or coated surface,
- same shape, but in different heights in relation to the clinical situation (dentate vs. edentulous),
- linear shape,[23] with minimum undercuts[23] and with as wide an occlusal surface as possible,
- with coding to identify automatically the implant platform underneath.

The operator's experience and knowledge of the limits of the IOS devices can contribute to improve the quality of the scans.[4,27–29] Appropriate scan strategies should be learnt while making sure that fixed references are always used to facilitate the stitching process.

As far as the best fit function is concerned, the operator should not blindly trust the best fit matching automatic function in CAD softwares.[8] He/she should instead verify the quality of the matching using the tools available (section view or the calibrated proportional color scale).

DISCLOSURE

Drs. Appiani and Noè do not have any financial interest in the companies whose materials are mentioned in this article. Dr. Gracis has no financial interest, but he is on the Scientific Advisory Board of Thommen Medical and 3Shape.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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How to cite this article: Gracis S, Appiani A, Noè G. Digital workflow in implant prosthodontics: The critical aspects for reliable accuracy. *J Esthet Restor Dent*. 2023;35(1):250-261. doi:10.1111/jerd.13004

Received: 13 October 2022 | Revised: 17 November 2022 | Accepted: 18 November 2022

DOI: 10.1111/jerd.12990

RESEARCH ARTICLE

WILEY

Design of customized soft tissue substitutes for anterior single-tooth and posterior double-tooth defects: An in vitro study

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Funding information
Gestlich Pharma; Geistlich Pharma AG

Abstract

Objective: This study aims to validate the standardized procedure for designing soft tissue substitutes (STS) adapted to optimally fit single-tooth defects in the anterior jaws and double-tooth defects in the posterior jaw and to compare mathematically modeled average shapes.

Materials and Methods: Casts from 35 patients with 17 single-tooth defects in anterior region and 21 double-tooth defects in posterior region were scanned. STS were designed and sectioned in 3D slices meshes. Thickness values were documented respecting mesial-distal and buccal-lingual orientations. Graphs were embedded into images, and hierarchical clustering was applied to group STS according to shape and thickness.

Results: STS clustered into two groups per defect type. For anterior single defects, STS ($n = 4$) were either a small and thin oval: 7 mm buccal-lingual, 4–5 mm mesial-distal direction and 1.1–1.5 mm thick or a larger oval ($n = 13$): 9 mm buccal-lingual, 5–7 mm mesial-distal and 1.6 m thick. For posterior double tooth defects, STS ($n = 10$) were either narrow, long and thick: 6–7 mm buccal-lingual, 16–20 mm mesial-distal and 2.2 thick or a wide, thinner rectangle ($n = 11$): 9–11 mm buccal-lingual, 12–14 mm mesial-distal and 1.1–1.5 mm thick.

Conclusions: The study validated the standardized digital method to design grafts for soft tissue volume augmentation and identified four average shapes for anterior single-tooth and posterior double-tooth soft tissue defects.

Clinical Significance: We developed and validated a standardized digital method to design an optimal geometrical shape of a soft tissue substitute for oral volume augmentation and combined it with mathematical modeling to identify average shapes for single-interior, and double-posterior tooth defects. The identified average shapes

This work was presented at the EAO Digital Days Conference in October 2021.

offer the possibility to produce better-fitted xenografts or synthetic STS blocks requiring minimal chair-side adaptation leading to reduced clinical time and patient discomfort and potentially improving soft tissue volume augmentation outcomes.

KEYWORDS
biomaterial, CAD, gingiva, graft substitutes, personalized medicine, soft tissue augmentation

1 | INTRODUCTION

Tooth loss, periodontal or systemic disease, trauma, or congenital disorders may cause various oral soft tissue volume defects and necessitate treatment to maintain functional mastication, speech, and esthetics. Remodeling and resorption of alveolar bone and soft tissue upon tooth extraction still represent a significant problem in restorative dentistry.[1,2] Prior to the placement of implant or tooth-borne restorations, soft tissue augmentation procedures are often required to improve final treatment outcomes.[3,4] An increase of soft tissue contours is indicated to stabilize and maintain peri-implant tissue health and improve functional and esthetic results,[5,6] particularly in the case of a thin gingiva biotype.[7,8]

Subepithelial connective tissue graft (CTG) remains the gold standard for soft tissue volume augmentation.[4,9,10] Although successful soft tissue regeneration can be achieved with autologous CTG transplantation,[11] several disadvantages still hinder this type of treatment. Infliction of the second wound, a limited amount of tissue that can be harvested, and prolonged pain[12–14] have prompted the quest for alternatives. Soft tissue substitute (STS) requirements for oral soft tissue augmentation comprise biocompatibility, volume and mechanical stability, biodegradability and tissue integration, secure handling, and low cost without compromised efficacy.[15] Different allogenic, xenogenic, and synthetic STS have been developed and produced to date,[16–18] and several have found their application in periodontal and peri-implant soft tissue regeneration.[19] While off-shelf soft tissue substitutes allow unlimited availability, reduce patient morbidity, and shorten intervention time, their clinical use remains limited. The primary issue remains the need for individual STS customization. STS are delivered as rectangular blocks of standardized dimensions and need to be tailored chair-side to fit each soft tissue defect. With the precision of trimming depending on the surgeon, the accuracy of the final shape remains suboptimal. Necessary STS preparation time results in the prolonged exposure of the defect site, thereby increasing the risk of infection, potentially compromising wound healing, and jeopardizing the final outcome. Hence, future STS should be produced in shapes that would better fit individual edentulous defects and be ready for immediate insertion or require minimal chair-side shape customization. The fabrication of STS based on the average shape of single-tooth or double-tooth defects would provide surgeons with an easier STS handling from preparation to subsequent insertion and suturing.

In our previous study, a standardized digital method was developed to design an optimal geometrical shape of STS for volume augmentation of the single-tooth posterior soft tissue defects and combined with mathematical modeling to identify average shapes.[20] To further validate this method, the current study aims to apply the same approach to design STS for single-tooth defects in the anterior and double-tooth defects in the posterior mandible and maxilla and to identify the average STS shapes.

2 | MATERIALS AND METHODS

2.1 | Defect scans

Conventional stone casts from 35 patients were collected: 17 scans of a single-tooth defect in the anterior region and 21 scans of double-tooth defects in the posterior region. The inclusion criterion was tooth extraction at least 6 months prior to taking the impressions and the presence of neighboring teeth. The exclusion criteria comprised patients suffering from osteoporosis, uncontrolled periodontitis, and uncontrolled diabetes. Ethical approval was not required for this in vitro study. The 35 casts with 37 defect sites were scanned with a laboratory CAD/CAM scanner following a standardized technical approach and software settings (Imetric4D; Courgenay; Switzerland), and STL files were generated (Figure 1A).

2.2 | Soft tissue substitute design

Design of an STS for the volume augmentation of single-tooth defects in the anterior region and double-tooth defects in the posterior region followed the previously established steps for single-tooth posterior defects.[20] Briefly, the STL file generated from the scanned cast was imported into the software 3Shape dental designer (Version19, 3Shape; Copenhagen; Denmark). The outline of the STS was designed based on the incision line (Figure 1B). The shape and the thickness of each STS were adapted to optimally fit the defect and in accordance with the desired final clinical outcome. Subsequently, the STL file of each STS (Figure 1C) was imported into GOM inspect (GOM; Braunschweig; Germany) for further analysis.

2.3 | Soft tissue substitute thickness measurements and clustering

GOM inspect was used to measure the thickness across each designed STS as described in our previous study.[20] Briefly, the occlusal plane was defined based on the mesial-incisal point of the central incisors (or lateral incisor in case the central incisors are missing) and

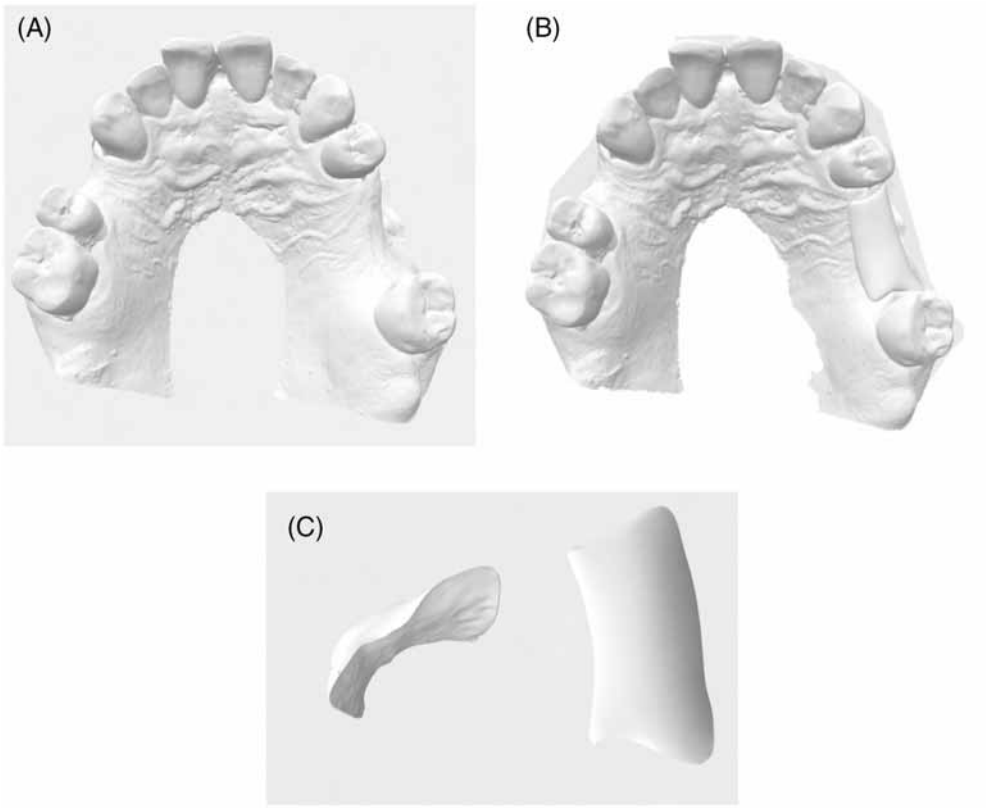

FIGURE 1 Design of the single soft tissue substitute (STS). Imprint stone casts harboring an anterior single-tooth or a posterior double-tooth defect (illustrated) were scanned with Imetric (A) and imported into the 3Shape software. The STS was outlined to optimally fit the defect, and the thickness was added manually as needed (B). The final STL file was extracted for further analysis (C)

the palatal (for maxilla) or buccal (for mandible) cusps of the second premolar in each quadrant. A mesial-distal plane was then drawn through the centers of the adjacent teeth and perpendicular to the occlusal plane, and a buccal-lingual plane was drawn perpendicularly to the occlusal plane and mesial-distal plane (Figure 2A).

The point zero (0,0,0) was defined at the cross of the outer surface of the STS, the mesial-distal plane and buccal-lingual plane. A lingual point was chosen at the cross of the buccal-lingual plane and the buccal margin of the STS, and the same approach was applied to define the buccal point. The top inner point was defined as a point at the cross-curve of the inner surface and buccal-lingual plane, most distant relative to the line connecting the lingual and buccal points. The connection of buccal, lingual and inner top points thus generated a reference circle. Radial sections at a 1 mm distance started from point zero and their number depended on the circumference of the circle (Figure 2B). To measure thickness in the mesial-distal direction, parallel sections were made from point (0,0,0) in the mesial—distal direction at 1 mm distance in the anterior single-tooth defect group and at 2 mm distance in the posterior double-tooth defect group (Figure 2C). Each STS thus resulted in a 3D mesh of slices where $x = 1$ mm, $y = 1$ or 2 mm and $z =$ thickness. Thickness values of each STS were documented in an excel chart with a coordinate system where the *X*-axis represented the buccal-lingual direction and the *Y*-axis the mesial-distal direction (Figure 2D). A scatter/bubble graph was generated for each STS, with the distribution of circles outlining the shape and dimension, and the circle diameter depicting the thickness of each 3D slice (Figure 2E). Scatter graphs were imported as images that were embedded with image embedder VGG-16 (Visual Geometry Group, University of Oxford) to allow image comparison. The complete-linkage hierarchical clustering analysis of STS images was performed to evaluate the similarity of shapes using Orange software (Version 3.24.1, Orange data mining toolbox in Python, Bioinformatics Lab, University of Ljubljana).

2.4 | Statistical analysis

Data were analyzed using the IBM SPSS Statistics 26.0 (IBM, New York, USA). To determine data distribution, the thickness values of all 3D slices for each STS were analyzed with the Shapiro–Wilk test. Across each STS, median values and 25% and 75% quartiles of the individual slice thickness were calculated from the excel charts for each shape group and expressed according to the STS orientation.

3 | RESULTS

Based on the defect region, 17 grafts were designed to fit into the anterior single-tooth defects and 21 designs into posterior double-tooth defects. A set of objective landmarks and standardized steps, established in our previous study,[20] were applied during the design and analysis processes.

In the anterior single-tooth group, 14 defects were in the maxilla and three in the mandible. The hierarchical clustering analysis of

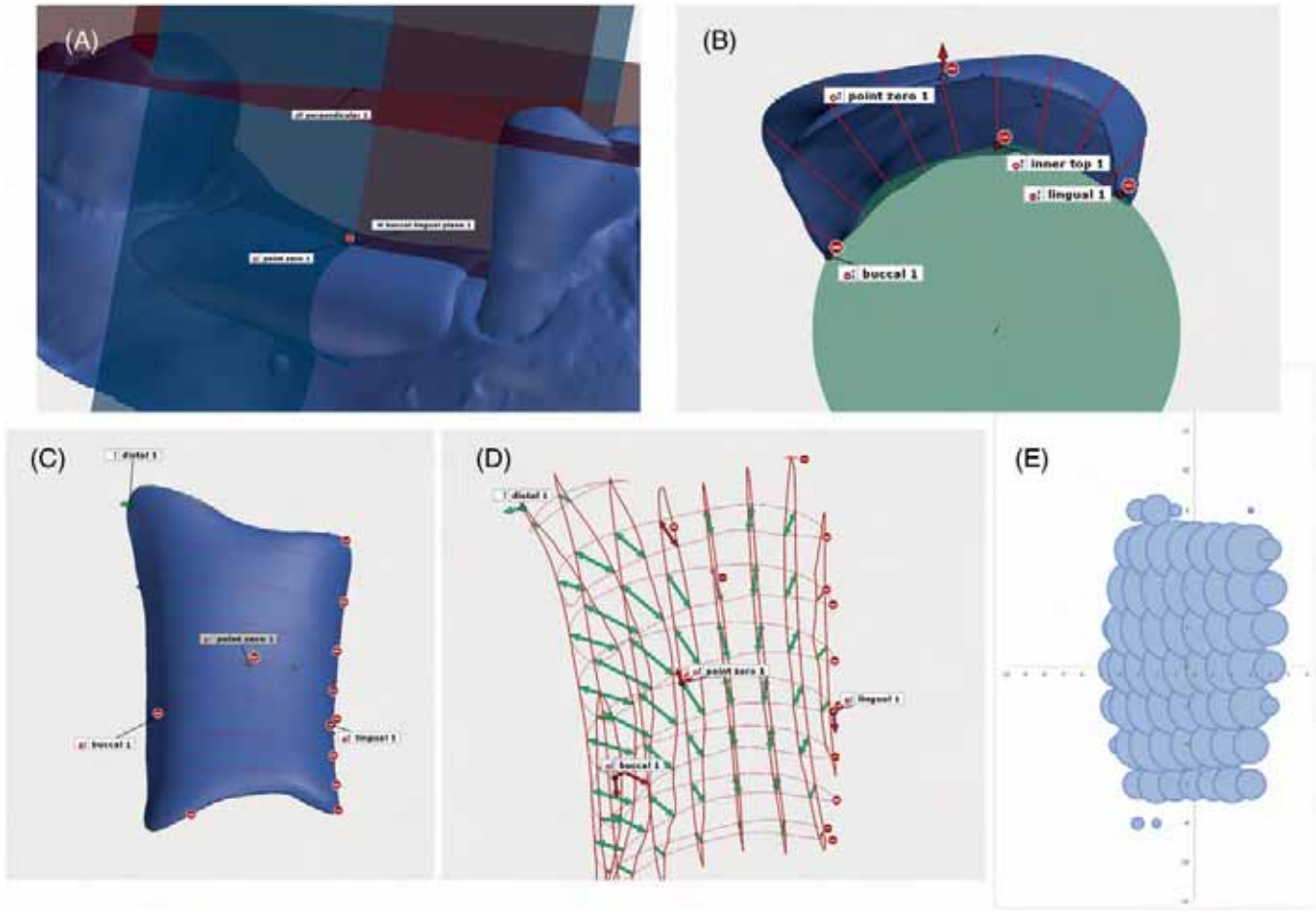

FIGURE 2 Standardized procedure to measure soft tissue substitute (STS) thickness. To section the STS into 3D slices where $x = 1$ mm, $y = 1$ mm and $z =$ thickness, three planes were defined in GOM Inspect: occlusal, mesial-distal and buccal-lingual plane (A). The circle was drawn to fit the inner side of the STS (B) and the radial sections were obtained at 1 mm distance (C). Parallel slicing in mesial-distal and buccal-lingual directions allowed partitioning of the entire STS into a mesh (D). In the mesial-distal direction, parallel sections were made from point (0,0,0) at 1 mm distance in the anterior single-tooth defect group and at 2 mm distance in the posterior double-tooth defect group

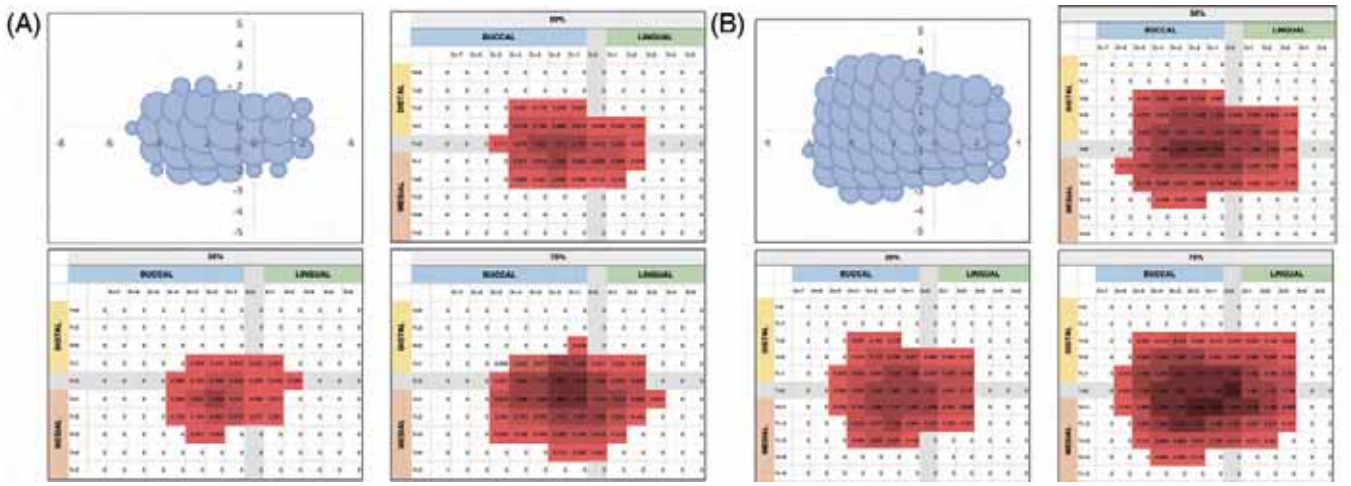

FIGURE 3 Scatter graph outlining the shape, median (50%), Q1 (25%) and Q3 (75%) values depicting thickness across graphs for anterior single-tooth group 1, $n = 4$ (A) and group 2, $n = 13$ (B). The intensity of red color corresponds to the thickness ranging from 0.001 mm (lightest shade) to 2.2 mm (darkest shade)

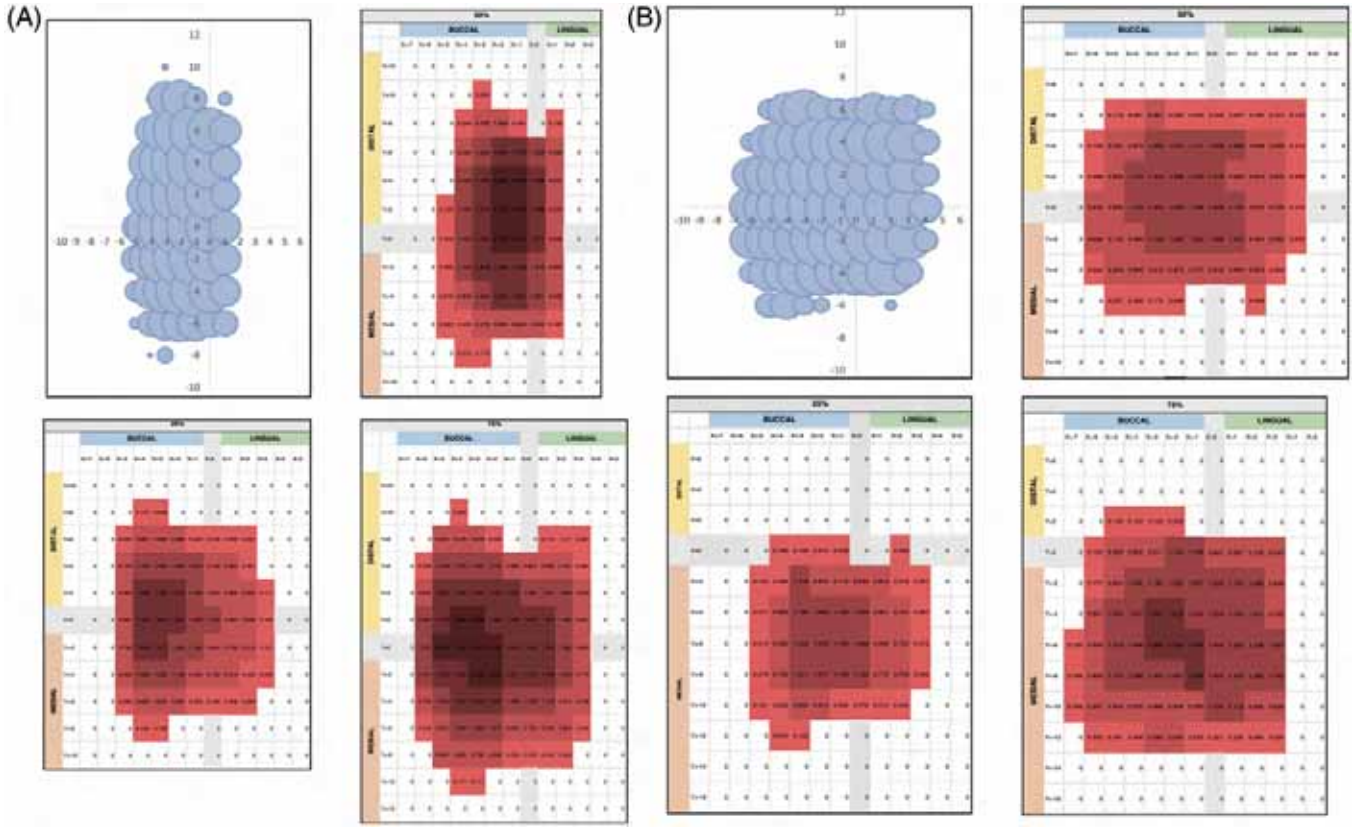

FIGURE 4 Scatter graph outlining the shape, median (50%), Q1 (25%) and Q3 (75%) values depicting thickness across graphs for posterior double-tooth group 1, $n = 10$ (A) and group 2, $n = 11$ (B). The intensity of red color corresponds to the thickness ranging from 0.02 mm (lightest shade) to 1.73 mm (darkest shade)

	anterior single	anterior single	posterior double	posterior double	posterior single	posterior single	posterior single
	group1	group2	group 1	group 2	mandible	maxilla group 1	maxilla group 2
sample number	4	13	10	11	9	13	11
mandible	2	1	10	3	9	0	0
maxilla	2	12	0	8	0	13	11
buccal/lingual (mm)	7	9	6-7	9-11	6-8	9-10	10-11
mesial/distal (mm)	4-5	5-7	16-20	12-14	5-10	7-9	4-7
maximum thickness (mm)	1.1-1.5	1.6	2.2	1.1-1.5	1.5-1.9	1.5-1.9	1.6
number of thickest points	4	3	6	21	10	12	2

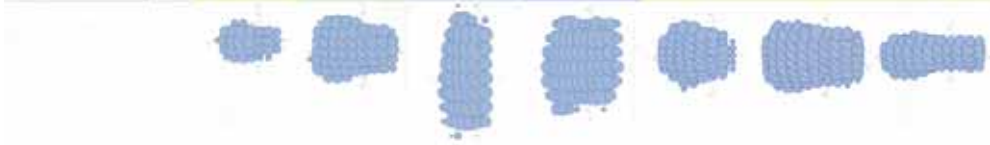

FIGURE 5 An overview of the soft tissue substitute shapes designed to fit average shape tooth defects in the jaws. Average shapes designed for anterior and posterior single-tooth and posterior double-tooth defects are depicted, including their size and thickness values

scatter graph images separated the STS shapes into two groups of 4 and 13. All designed STS had the highest thickness on the buccal side. The analysis of the median STS shape for group 1 ($n = 4$; 2 in mandible and two in maxilla) revealed an oval shape, with a length of 7 mm in buccal-lingual and 5 mm in mesial-distal direction (Figure 3A) The four thickest points resided in the center of the STS and ranged from 1.06 to 1.46 mm. The thickness gradually decreased from the center toward the edges until 0.005 mm. The highest 25% and 75% values in the center were 1.07 mm (1 point) and 1.52–1.86 mm (4 points), respectively. The median shape of group 2 ($n = 13$, 1 in mandible, 12 in maxilla) was also an oval, yet larger in both directions and thicker compared to group 1. The maximum length was 9 mm in a buccal-lingual and 7 mm in a mesial-distal direction (Figure 3B). The three thickest points of around 1.6 mm resided in the center of the STS and then gradually decreased toward the edges. The thickness gradually decreased toward the edges until 0.04 mm. The highest 25% and 75% values in the center were 1–1.3 mm (11 points) and 2.0–2.2 mm (3 points), respectively.

In the posterior double-tooth group, 8 defects were in the maxilla and 13 in the mandible. The hierarchical clustering analysis of scatter graph images separated the STS shapes into two groups of 10 and 11. All designed STS had the highest thickness on the buccal side. The median shape of group 1 ($n = 10$, all in the maxilla) was a long and narrow rectangle of 7 mm in the buccal-lingual

direction and extending to 20 mm in the mesial-distal direction (Figure 4A). The six median STS highest thickness points were around 2.15 mm in the center and then gradually decreased to the edges until 0.02 mm. The highest 25% and 75% quartiles values in the center were 1.57–1.80 mm (8 points) and 2.02–2.15 mm (8 points), respectively. The median shape of group 2 ($n = 11$; 3 in mandible and 8 in maxilla) was a thin and wide square, with 11 mm in buccal-lingual direction and 14 mm in mesial distal direction (Figure 5B). The median STS thickest points (21) ranged from 1.05–1.45 mm gradually decreasing toward the edges until 0.05 mm. The highest 25% and 75% values in the center were 1.02–1.29 mm (13 points) and 1.52–1.73 mm (6 points), respectively.

4 | DISCUSSION

A consensus on the best treatment modality for soft tissue volume augmentation with satisfactory long-term outcomes has not been reached. In the era of personalized medicine, soft tissue volume augmentation procedure still relies on tedious and inaccurate hand-shaping of subepithelial CTG or a xenogeneic matrix block. In our previous proof-of-concept study, a standardized procedure to digitally design individual STS and a mathematical modeling tool to obtain average STS adapted to optimally fit single-tooth soft tissue defects in the posterior jaw were developed.[20] In this study, the approach was validated by designing individual STS for single-tooth anterior and double-tooth posterior defects necessitating soft tissue volume augmentation. Based on the clustering of individual design images, the average shapes obtained for each defect type identified two distinct STS geometries in each group.

Restoration of partially or fully edentulous areas often requires bone and soft tissue augmentation. The stability of bone level has been correlated with the sufficient amount of soft tissue around implants,[6,21] and an influence on the final esthetic outcomes was demonstrated.[22,23] An ideally restored soft tissue should consist of a harmonious gingival margin, adequate papillae and follow a convex contour of the alveolar bone.[24] The optimal fit and rigid immobilization of any STS are essential for the initial oxygenation and nutrient supply through plasmatic diffusion until vascularization ensues.[25] Due to disadvantages the application of CTG presents, different allograft and xenograft substitutes have been developed and used in clinics, including collagen xenograft (porcine) matrices (Mucograft, Geistlich; Mucoderm, botiss biomaterials), collagen allograft matrix (Alloderm, BioHorizon), and reconstituted collagen matrix (Fibro-Gide, Geistlich).[26] Comparative reviews identified similar outcomes between Alloderm or Fibro-Gide and CTG yet the better performance of CTG compared to Mucograft.[23,27] Recent studies demonstrated similar buccal mucosal thickness between Fibro-Gide and subepithelial CTG after 3[28] and 5 years[29] as well as between Mucoderm and subepithelial CTG after 6 months.[30] Another recent study however reported inferior increase in the soft tissue profile in Fibro-Gide compared to subepithelial CTG after 1 year.[31] Despite promising performance of different STS, the circumvention of the second wound site, decreased surgical time, risk of infections and patient morbidity, these prefabricated STS blocks require time-consuming manual shape adaptation without possibility for standardization. Therefore, the production of individualized optimally fitting STS and/or—at the least—blocks corresponding to average defect shapes requiring minimal on-site customization and material waste would bring considerable clinical benefits.

A standardized approach to design individual STS and to mathematically define average shapes for the posterior mandible and maxilla defects has been developed.[20] Three different STS shapes have been identified, corresponding to the single-tooth defects in the posterior region. In the current study, to validate the approach, the procedure was applied to design STS for the defects resulting from single-tooth loss in the anterior region and double-tooth loss in the posterior region. All designs were made respecting the irregular defect shape, with the inner surface perfectly filling the lost volume and the outer surface corresponding to the desired ridge contour. Hierarchical clustering of the embedded individual STS images revealed two different shapes in each group. The anterior single-tooth defects in group 1 were an equal mixture of mandible and maxilla, while maxilla defect predominated in group 2 (92%). The posterior double-tooth defects in group 1 comprised solely mandibular defects while maxilla defects (73%) predominated in group 2. Thus, the application of image clustering demonstrated an efficient separation of shapes corresponding to the defect mainly in one jaw, that is, in accordance with their particular anatomical characteristics.

Similar to the single-tooth posterior defects and regardless of the size or position of the defects, the required main volume augmentation was always on the buccal side, in line with the more pronounced loss of the buccal tissues after tooth removal.[1,32] The thickest points corresponded to the standard thickness of subepithelial CTG (1–3 mm)[12,33,34] but not to the thick volume-stable yet highly porous substitute collagen block (6–8 mm).[28,35,36] Comparison of these shapes and their thicknesses with those identified for single-tooth posterior STS revealed four main average shape types (Figure 5): a small and thin STS (anterior single-tooth defect, group 1), large STS with the thickness of 1.5–1.9 mm (anterior single-tooth defect, group 2, and all posterior single-tooth defects), narrow and thick rectangle up to 2.2 mm (posterior single-tooth defects group 1), very large yet thinner rectangle of 1.1–1.5 mm (posterior single-tooth defects group 1). These data suggest that for the majority of single-tooth defects, one large STS could be produced and if necessary, minimally shaped to achieve most tissue volume augmentation on the buccal side where the major loss occurred.

The main limitation of the study is a limited number of samples. A larger number of STS for all types of defects should be analyzed to further validate the approach and to achieve a more reliable normalized data distribution. With the establishment of an entirely digital workflow, our method could be easily combined with intraoral scanning[37,38] and further accelerate soft tissue volume augmentation procedures. Additionally, for defects comprising alveolar bone and soft tissue, CBCT and intraoral scans could be combined, leading to a personalized augmentation of both hard and soft tissue volumes. Finally, the identified average shapes may lead to the production of better-

fitted xenograft or synthetic STS blocks requiring minimal chair-side adaptation to reduce clinical time and patient discomfort and potentially improve soft tissue volume augmentation outcomes. The currently ongoing laboratory study on animal jaws will test the easiness and the time needed for STS application and pave the way for a clinical trial.

5 | CONCLUSIONS

This study validated the standardized digital method to design the geometrical shape of STS to augment volume in anterior single-tooth and posterior double-tooth soft tissue defects. The STS design procedure together with mathematical modeling and the clustering algorithm is robust and reliable to be applied to different types of defects with the clustering results accurately differentiating the defect shapes.

ACKNOWLEDGMENT AND DISCLOSURE

This study was funded by Geistlich Pharma AG. Dr. Birgit Schäfer is employed by Geistlich Pharma AG. The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Sun Y, Strasding M, Liu X, et al. Design of customized soft tissue substitutes for anterior single-tooth and posterior double-tooth defects: An in vitro study. *J Esthet Restor Dent*. 2023;35(1):262-269. doi:10.1111/jerd.12990

Received: 29 December 2021 | Revised: 6 April 2022 | Accepted: 13 April 2022

DOI: 10.1111/jerd.12919

CLINICAL ARTICLE

WILEY

Restoratively guided orthodontic treatment: The pre-orthodontic bonding concept

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Abstract

Objective: Communication between the orthodontist and the restorative dentist has always been difficult due to the inability of the orthodontist to achieve the desired orthodontic goals with just words in a referral note.

Clinical Considerations: A better method of communication is for the restorative dentist to create the ideal tooth anatomy either before or during orthodontic treatment to direct the orthodontic tooth movement.

Conclusion: It is the purpose of this article to present a technique, which makes the pre-restorative orthodontic treatment both more accurate and more efficient.

Clinical Significance: It is very difficult for the orthodontist to move teeth into their correct positions when the teeth are anatomically incorrect due to attrition/erosion or due to developmental malformation. When the restorative dentist makes the teeth anatomically correct with either pre-orthodontic or intermediate orthodontic bonding, the orthodontist has the benefit of ideal tooth anatomy to finalize the tooth positions. This then allows the restorative dentist to create final restorations, which are ideal, both functionally and esthetically.

KEYWORDS
intermediate orthodontic bonding, orthodontic-restorative interface, orthodontic-restorative treatment planning, pre-orthodontic bonding, restoratively guided orthodontics

Communication between the orthodontist and the restorative dentist is essential when definitive restorative dentistry is required at the end of orthodontic treatment. Traditionally, this has been accomplished with a verbal or written referral to the orthodontist either requesting specific treatment, or more often, "do orthodontic treatment." This method of multidisciplinary communication and treatment commonly results in less than an ideal final outcome.

In recent years, there has been minimal information presented regarding the pre-orthodontic bonding technique.[1,2] However, the concept of creating an actual three dimensional "blueprint" in the patient's mouth to direct the orthodontic treatment is not a new idea. In 1997, Kokich and Spear[3] wrote a definitive article on communication between the orthodontist and the restorative dentist. They presented guidelines to assist clinicians in overcoming the difficulties associated with the old style of communication. These limitations included:

1. It is difficult for both the orthodontist and the restorative dentist to visualize the final restorative outcome, when the patient presents with missing teeth, microdontia, and/or attrition/erosion.
2. Orthodontists may not be aware of the restorative requirements of the eventual restorative treatment plan.
3. The restorative dentist may not know the orthodontic possibilities for treatment.
4. The orthodontist should never be in the position to make the final restorative decisions.
5. Without definitive treatment planning, it is impossible for the specialists (orthodontist, periodontist, and oral and maxillofacial

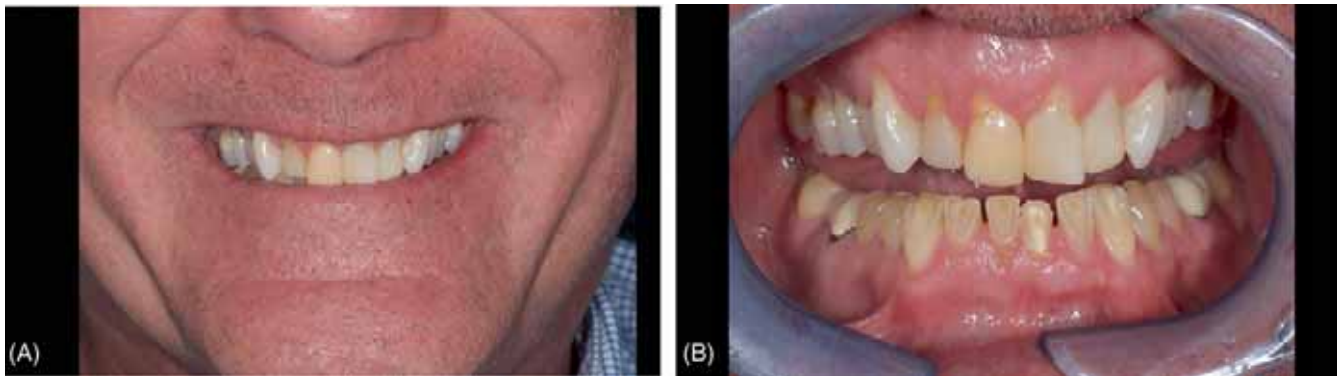


FIGURE 1 Pre-operative view.

FIGURE 2 After pre-orthodontic bonding.

FIGURE 3 After placement of orthodontic appliances.

surgeon) and the restorative dentist to create a sequenced treatment plan that maximizes efficiency.

These limitations are as relevant today as they were 25 years ago. In order to overcome these problems, Kokich and Spear[3] emphasized the importance of a diagnostic set-up/wax-up to aid in diagnosis and ultimately in the pre-orthodontic bonding, or the intermediate orthodontic bonding. They acknowledged the occasional need for this type of bonding on posterior teeth; however, their emphasis was on the anterior teeth. As these techniques have evolved, the authors propose a new guideline for this type of interdisciplinary treatment planning: Every tooth that will receive a restoration at the end of orthodontic treatment will receive an interim or definitive restoration either before or during orthodontic treatment.

The goal of this interim bonding is to make every tooth that will be restored at the completion of orthodontics, anatomically correct, in order to direct the precise positioning of the teeth with orthodontic treatment. When a small area of missing tooth structure must be replaced, that is, a cusp tip on a premolar, definitive composite bonding can be utilized. However, most of the worn teeth are restored with interim direct or indirect bonded restorations. Upon completion of the orthodontic treatment, the interim material is removed and the teeth are in the correct positions for definitive restorations. This almost universally allows the definitive restorations to be more conservative, because that which was lost due to attrition/erosion, becomes the occlusal/incisal reduction for the restorations, and minimal or no additional tooth structure is removed.

There are three reasons that a patient can present with short teeth: (1) microdontia, (2) incisal/occlusal attrition, and (3) altered passive eruption.[4] Restoring the ideal tooth size can be accomplished by

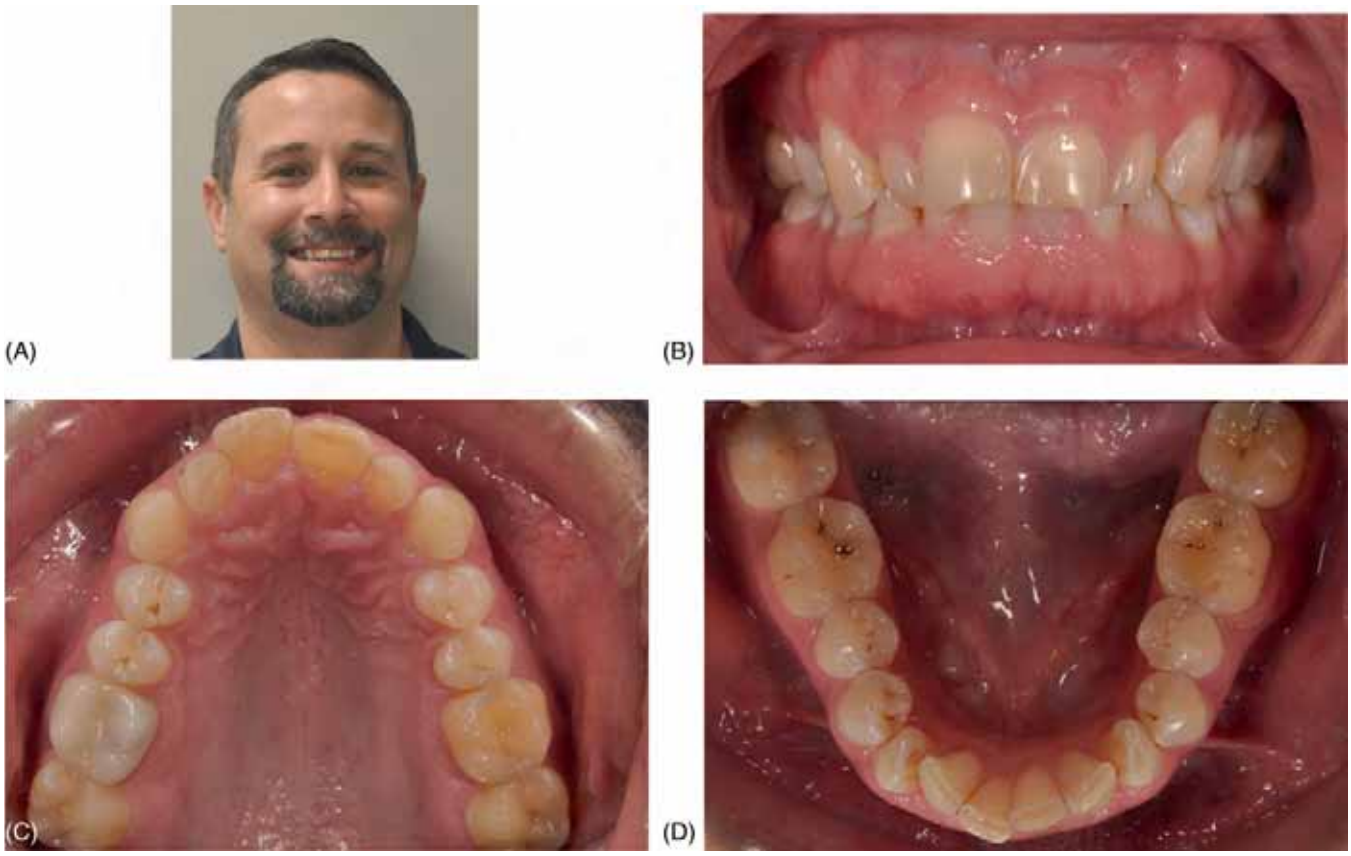


FIGURE 4 Pre-operative views.

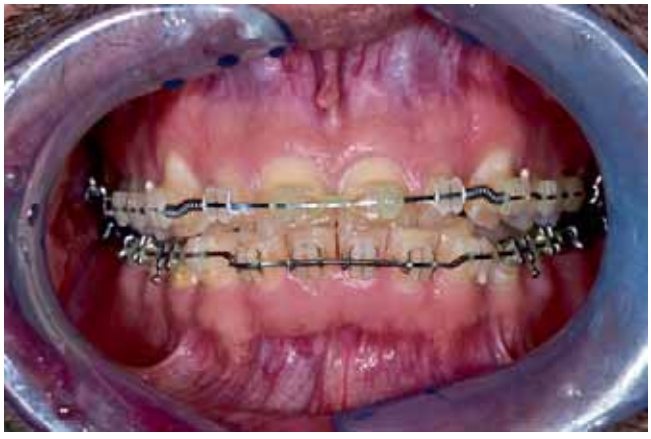


FIGURE 5 Clinical presentation at first appointment with author (BB) after 22 months in orthodontic treatment. There was no clinical end point for the orthodontic treatment.

FIGURE 6 Photograph used to communicate with the orthodontist the desired treatment goals.

increasing incisal/occlusal length restoratively, crown lengthening surgery, or a combination of both. Once the diagnosis is established, the sequenced treatment plan can be developed. The primary diagnosis associated with the worn dentition is dentoalveolar extrusion.[5] As teeth wear, they supererupt, bringing bone and soft tissue with them. This results in a curved gingival line in relation to horizon. In this circumstance the teeth, the soft tissue, and the underlying alveolar bone are all in the incorrect positions for restorative dentistry.

There are three primary strategies for restoring the worn dentition[5]: (1) functional crown lengthening, (2) restoring at an increased vertical dimension, and (3) orthodontic intrusion/flairing. Functional crown lengthening surgery is used primarily to increase clinical crown height to provide adequate retention and resistance form for restorations. The restorative disadvantages of functional crown lengthening include: (1) exposed roots, which must be restored, (2) open gingival embrasures, (3) triangular shaped crowns, (4) rolled gingival margins, and (5) increased crown to root ratio.

Restoring at an increased vertical dimension is the traditional prosthodontic approach used to restore the worn dentition. When there is generalized wear of both anterior and posterior teeth, a full mouth rehabilitation is an acceptable treatment. The disadvantages are that it requires a high skill level, is very expensive, and commonly requires significant removal of tooth structure. However, when there is significant wear of the anterior teeth and minimal wear in the posterior teeth, restoring at an increased vertical dimension is seldom indicated.

The third strategy for treating the worn dentition is orthodontic intrusion/flairing. During the process of attrition and erosion, the teeth move into positions that make orthodontic treatment and restorative dentistry very difficult. Without the incisal edges of anatomically correct maxillary incisors, or appropriate gingival margins, as in the case of dentoalveolar extrusion with wear, the orthodontist has no stable landmark for correct bracket placement. Idealizing the tooth positions orthodontically allows the restorative dentist to place anatomically correct restorations with minimal tooth preparation.

Traditionally, the diagnostic process in a rehabilitation starts with clinically determining the proposed incisal edge position of the maxillary anterior teeth and then creating that position by adding wax on the articulated casts. However, this is not the case with pre-orthodontic bonding. The goal of the pre-orthodontic diagnostic wax-up is to make the teeth anatomically correct using either digital or analog waxing. Therefore, the casts are not mounted and the purpose of the wax-up is to wax each arch independently and make the teeth anatomically correct. It is also important that the clinical crowns are an extension of the long axes of the teeth, so that the orthodontist can use the bonding to guide bracket placement and axial inclinations of the teeth. Evaluation of the gingival levels is equally important. The gingival levels may be corrected with either orthodontic intrusion/extrusion, crown lengthening surgery, or a combination of the two. The ultimate goal of the interdisciplinary treatment plan is for the teeth to be in the correct positions in the patients face, between the upper and lower lips.

For many years, the most traditional technique of diagnosing tooth positions occurred near the end of orthodontic treatment. It was termed "mock bonding" and was used primarily on the anterior teeth that had been intruded for restorative purposes. The orthodontist would contact the restorative dentist to say that the patient was near the end of orthodontic treatment and asked the dentist to do an evaluation before orthodontic appliances were removed. The restorative dentist would do a quick composite mock-up on several upper and lower anterior teeth to determine if they were in the correct positions to meet the treatment goals. The four primary goals are: (1) esthetically acceptable incisal edge position of maxillary anterior teeth, (2) space to make anatomically correct maxillary and mandibular anterior teeth, (3) coupled at an acceptable interincisal angle (130–135 degrees), and (4) with an acceptable antero-posterior occlusal plane with no step-up or step-down. Upon, completion of the mock-up, seldom were the teeth in the correct positions and the restorative dentist would ask the orthodontist to make tooth movements to idealize the tooth positions. Approximately 4–6 weeks later, the patient would return to the restorative dentist and go through the same process again. This was a very inefficient method of finishing a case and commonly the patient and orthodontist became frustrated and gave up before the ideal tooth positions had been finalized. Although, the authors no longer use this technique routinely, it is still required when a restorative dentist begins treatment on a new patient, near the end of orthodontic treatment.

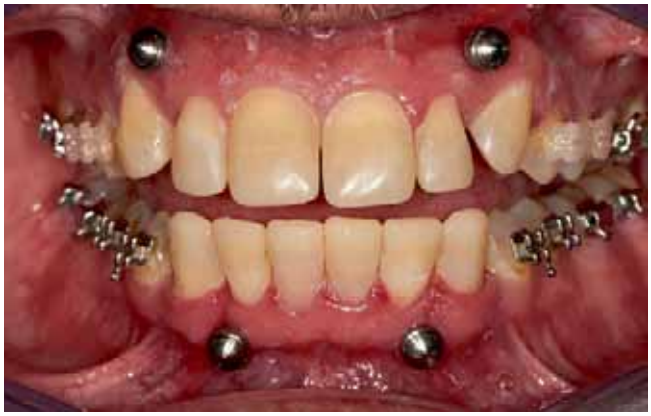
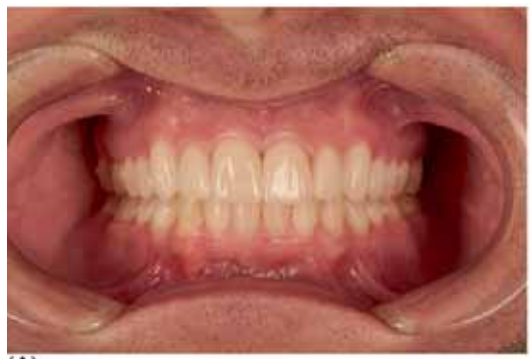


FIGURE 7 After intermediate orthodontic bonding and placement of TADs.



(A)

(B)

FIGURE 8 Post-operative views at completion of the restorative dentistry.

Currently the preferred techniques are pre-orthodontic bonding or intermediate orthodontic bonding. In pre-orthodontic bonding, the teeth are made anatomically correct with either direct and/or indirect interim restorations prior to the placement of orthodontic appliances (Figures 1–3). This is the most efficient and preferred method because it allows for correct positioning of the orthodontic brackets to achieve the ideal final tooth positions. However, there are some exceptions to pre-orthodontic bonding which require intermediate orthodontic bonding. (1) If a restorative dentist begins treatment on a new patient that is already in orthodontic treatment, intermediate bonding is required to direct the pre-restorative orthodontic treatment (Figures 4–8). (2) If the bonding is going to result in a very unesthetic outcome for the patient, then it is not done prior to placement of appliances. For example, pre-orthodontic bonding in a patient with either vertical maxillary excess or dentoalveolar extrusion with incisal edge wear of the maxillary anterior teeth will commonly result in teeth that are too low in the smile and will appear too long. In these circumstances, the maxillary anterior teeth will be intruded and as they are moved apically, intermediate composite bonding will be placed to direct the final orthodontic position of the teeth. (3) If there is inadequate proximal space to do pre-orthodontic bonding in the anterior teeth, the orthodontist must open spaces, and ideally create excess spacing. The appliances are removed and the intermediate bonding is accomplished so that the teeth have ideal height/width ratios. The orthodontic appliances are then replaced and the orthodontic treatment is completed. This is termed an "Orthodontic Holiday." (4) If there is significant crowding or rotation, initial orthodontic therapy is used to align the teeth prior to the intermediate orthodontic bonding. It is also important to remember that if a patient presents with altered passive eruption,[4] the esthetic crown lengthening surgery must be accomplished prior to the orthodontic bonding in order to create the correct height/width ratios in the diagnostic

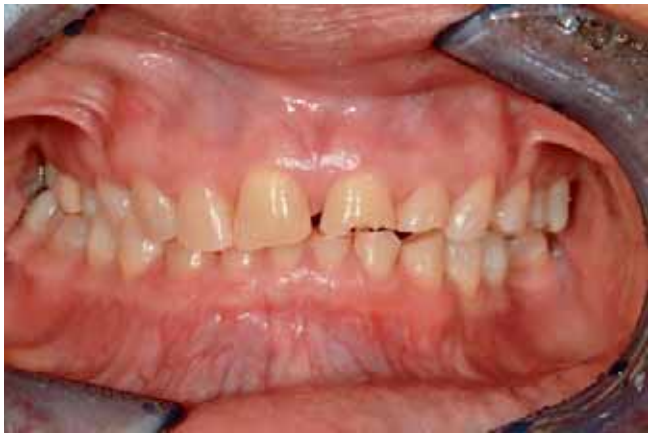


FIGURE 9 Pre-operative view in maximum intercuspal position.

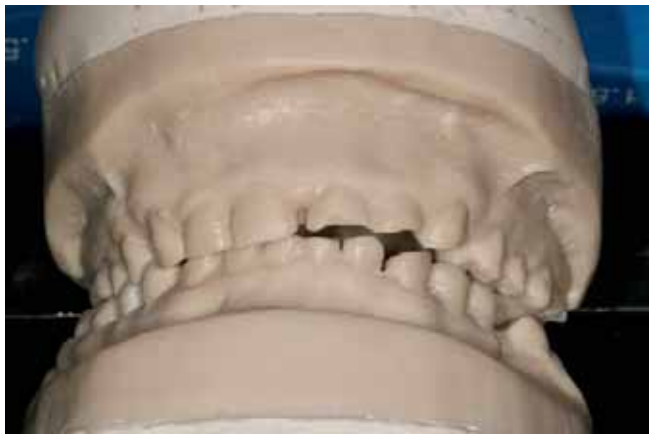


FIGURE 10 Mounted casts in a fully seated condylar position, which was obtained with a deprogrammer. Note the crossbite on the right side and the excessive overjet on the left side.

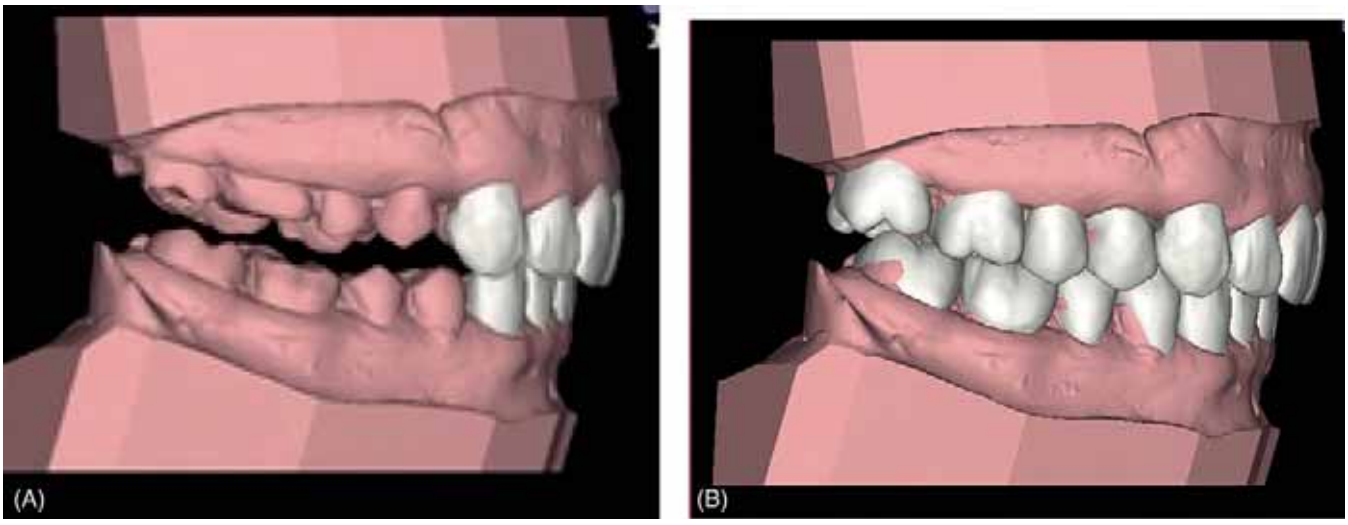


FIGURE 11 Digital wax-ups with and without posterior teeth. The clear matrix for the anterior direct bonding is made on the cast without the posterior wax-up.

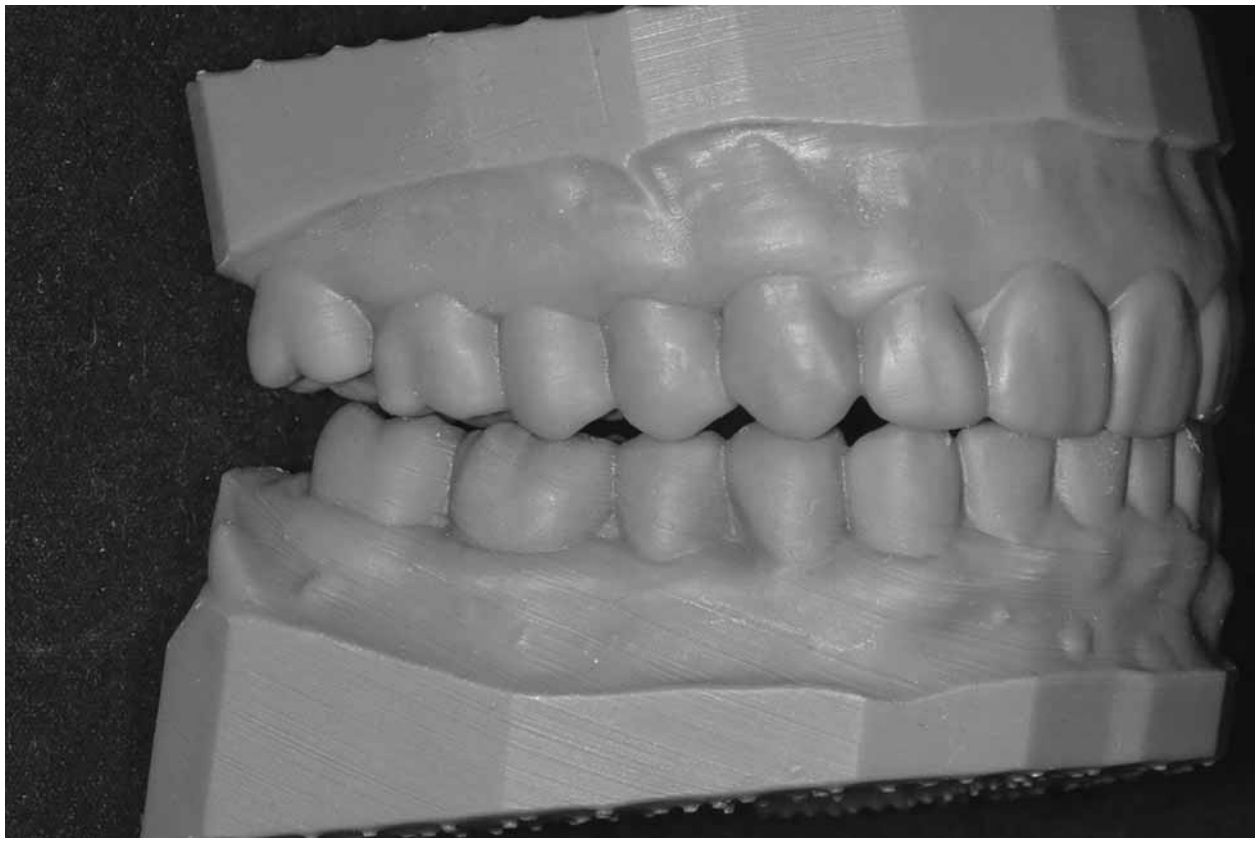


FIGURE 12 Printed casts of digital wax-up demonstrating lack of occlusal harmony.

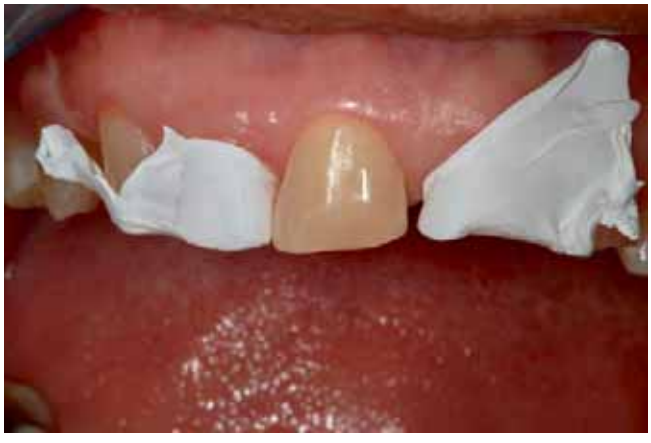


FIGURE 13 Tooth isolated with Teflon tape on adjacent teeth.

FIGURE 14 Tooth being etched with 35% phosphorous acid.

wax-up and composite restorations. Finally, aligner therapy creates a challenge because the pre-orthodontic bonding must be protected between the scanning of the case and the insertion of the aligners. The patient can wear interim clear retainers to protect the bonding during manufacture of the aligners. It is important that the patient understand this limitation during the initial case presentation. However, generally intermediate orthodontic bonding rather than pre-orthodontic bonding is used with aligner therapy, due to this limitation.

The first pre-orthodontic restorative step is to remove all existing crowns and restorations with questionable integrity. This allows the dentist to evaluate issues such as restorability, tooth vitality, retention and resistance form, and adequate space for the supracrestal attachment. Laboratory fabricated provisional crowns should be used and cemented or bonded with a permanent cement.

When planning the case, the occlusion should be evaluated in a stable condylar position (Figures 9 and 10). However, it is important for the restorative dentist to communicate with the laboratory

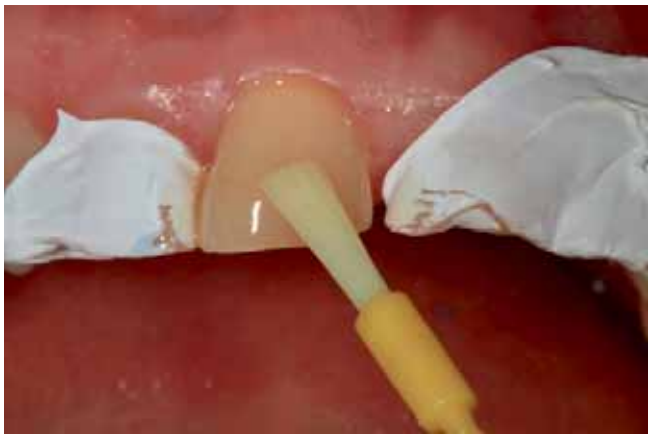


FIGURE 15 Bonding agent being placed on tooth.

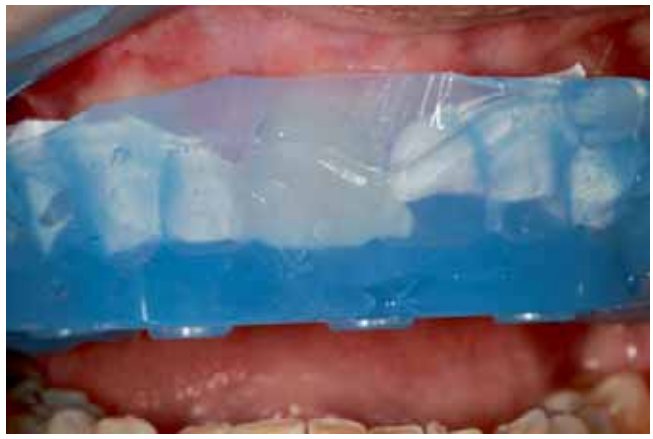


FIGURE 16 Heated composite placed in clear matrix and placed over prepared tooth.

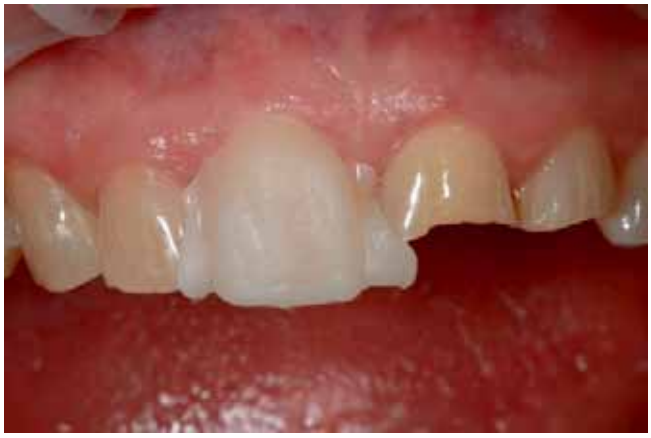


FIGURE 17 Composite restoration prior to finishing.

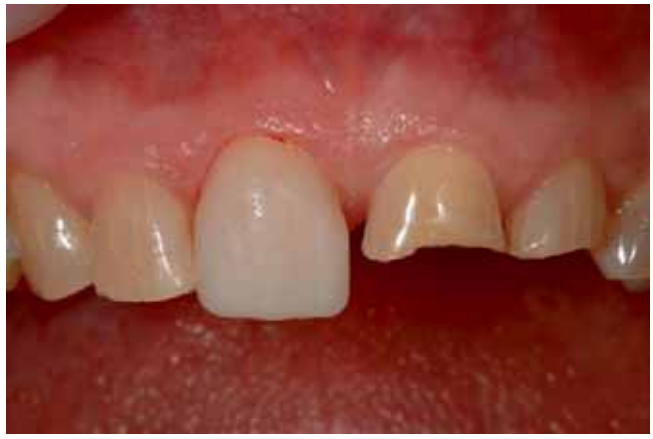


FIGURE 18 Finished and polished restoration.

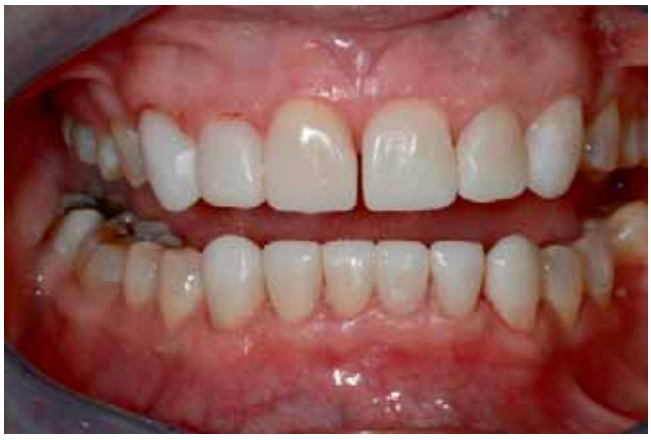


FIGURE 19 Completed direct pre-orthodontic bonding on maxillary and mandibular anterior teeth.

technician, because the wax-up is not done on mounted casts (Figure 11). The purpose of the wax-up is to give each tooth ideal incisal or occlusal anatomy, which is not dictated by the opposing teeth (Figure 12). Once the diagnostic wax-up is completed, a clear matrix is made for direct bonding of the anterior teeth on the cast with anterior diagnostic wax, but with none on the posterior teeth (Figure 11). The posterior bonding can be done with either a matrix and direct composite restorations, or indirectly with laboratory fabricated restorations. When direct bonding the anterior teeth, each tooth is bonded individually. Teflon tape is placed on the teeth adjacent to the tooth being bonded (Figure 13). The tooth is etched and the bonding agent is applied and light cured (Figures 14 and 15). Heated composite is placed in the clear matrix, taken to the mouth and light cured (Figure 16). The matrix is removed and the restoration is finished with finishing burs, discs, interproximal strips and polishers (Figures 17 and 18). The process is then repeated on the remaining anterior teeth (Figure 19). When small areas, that is, cusp tips, are being added to the posterior teeth, the same process, using a clear matrix, can be used. However, when larger areas of bonding are required, the placement of indirect restorations is more efficient. These restorations can be composite or PMMA and bonded with a dual cured resin cement (Figures 20 and 21).

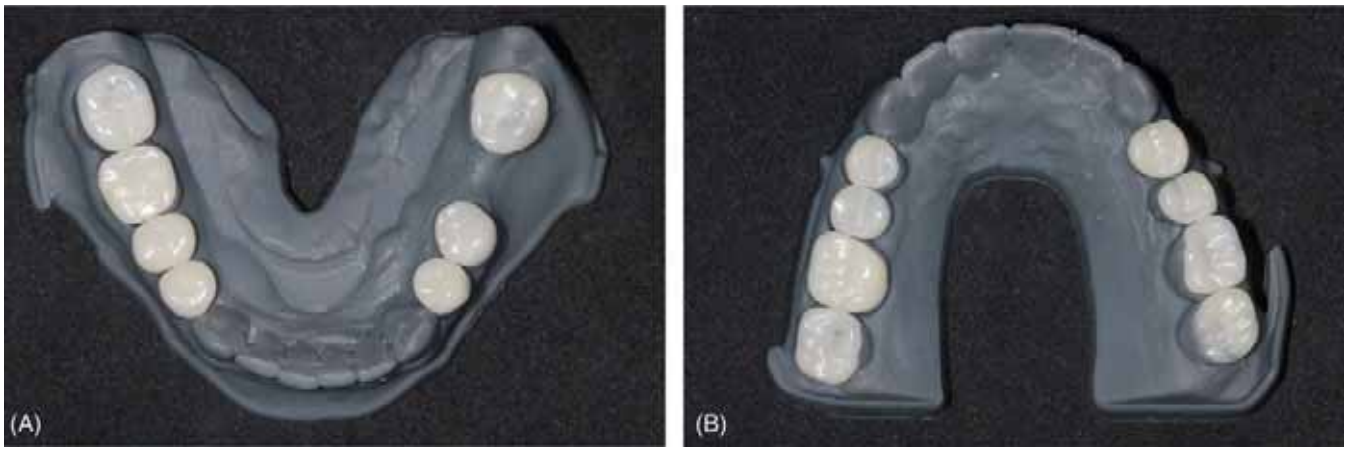


FIGURE 20 Indirect composite restorations for the posterior teeth.

FIGURE 21 Completed quadrant of indirect composite restorations bonded with a dual-cured resin cement.

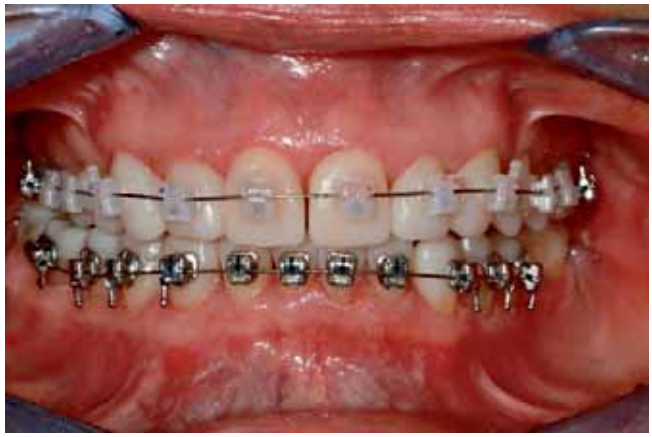


FIGURE 22 Orthodontic appliances are placed immediately or, as soon as possible, after the pre-orthodontic bonding.

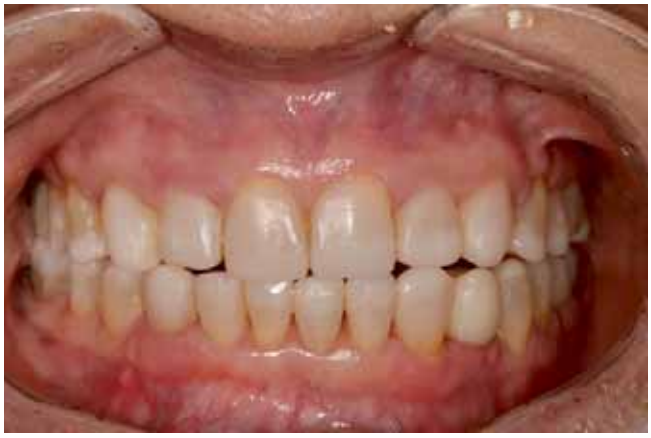


FIGURE 23 Post-operative view after 22 months of orthodontic treatment.

The bonding appointment should be coordinated with the orthodontic appointment for appliance placement. Once the pre-orthodontic bonding is completed, based on the diagnostic wax-up, the teeth will no longer be in a stable occlusion. Therefore, the orthodontic appliances should be placed as soon as possible after the pre-orthodontic bonding (Figure 22). The orthodontist then has two strategies to deal with the malocclusion created by the bonding. (1) Bite turbos can be placed on the lingual surfaces of the maxillary central incisors or canines. This not only takes care of the malocclusion created by the bonding, but also serves as a muscle deprogrammer. (2) Composite can be bonded to posterior teeth to give the patient a more balanced occlusion. At the completion of orthodontics, (Figure 23) the teeth are now in the ideal positions to receive conservative definitive restorations. Another advantage of this technique is the ability to stage the definitive restorative treatment over time. The interim bonded restorations can be replaced a sextant or quadrant at a time which allows the patient to receive a partial or full mouth rehabilitation over several years.

1 | CONCLUSION

It has been the purpose of this article to present a traditional, but updated approach to interdisciplinary treatment planning. In the concept of restoratively guided orthodontic treatment, pre-orthodontic

or intermediate orthodontic bonding is used to direct the orthodontic movement of the teeth into the precisely correct positions for the definitive restorative therapy.

DISCLOSURE

Dr. Norris reports a financial interest in the Norris 20/26 Orthodontic Bracket and Wire System. The other authors do not have any financial interest in companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in [repository name] at [DOI]. Yes

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How to cite this article: Robbins JW, Alvarez MG, Beckel BT, Norris RT, Caesar RR. Restoratively guided orthodontic treatment: The pre-orthodontic bonding concept. *J Esthet Restor Dent*. 2023;35(1):270-278. doi:10.1111/jerd.12919

Received: 15 October 2022 | Revised: 26 November 2022 | Accepted: 28 November 2022

DOI: 10.1111/jerd.12997

CLINICAL ARTICLE

WILEY

Orthodontic pretreatment with aligners for optimizing the result prior to fixed restorations in the esthetic zone

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Abstract

Objective: To show the benefit of a minor orthodontic pretreatment prior to fixed restorations in the esthetic zone in challenging situations.

Overview: Esthetic rehabilitations in complex situations need careful treatment planning and comprehensive interdisciplinary approach. Minor orthodontic pretreatments may transfer complex situations into straight forward situations. Typical indications are space opening in order to provide space for a restoration with anatomic proportion or corrections of the tooth axis.

Conclusion: This article presents three clinical cases that show how decision making can be facilitated by a functional and esthetic wax-up/mock-up workflow and how orthodontic pretreatment can contribute to a more functional, less invasive, and more esthetic outcome of restorative treatments in the esthetic zone.

Clinical Significance: Some complex cases in restorative dentistry can be transformed to straight forward cases with the help of minor orthodontic tooth movements.

KEYWORDS
aligner, dental implant, esthetic zone, orthodontic pretreatment, restorative dentistry

1 | INTRODUCTION

Restorative rehabilitations on Implants or teeth in the esthetic zone, especially in complex situations need careful treatment planning and comprehensive interdisciplinary approach.[1,2] Comprehensive facially derived treatment planning has become a standard in order to achieve predictable functional and esthetic results.[3–5] A diagnostic wax-up can enhance the predictability of the treatment by modeling the desired result in wax prior to treatment and to visualize the required procedures. It is critical to correlate the wax-up to the patient to avoid a result that appears optimal on the casts but does not correspond to the patient's smile.[6,7] Hence to check for feasibility and to plan the treatment under the participation of the patient.[8]

In addition, conscientious treatment planning is of utmost importance to identify the least invasive procedures possible and to identify risk factors and limitations.

Some clinical situations are complex and not straight forward cases. These situations may significantly benefit from minor orthodontic pretreatment in order to transfer a complex situation into a standard situation. A typical indication for these orthodontic pretreatments is space opening in order to provide space for a restoration with anatomic proportion, both on teeth or on implants.[9] Moreover, it may be required to open space between the apices of the roots of the adjacent teeth to provide space for safe implant placement.[10]

These minor orthodontic tooth movements can be accomplished with removable aligners[11] that align and improve the dentition. A recent comparative study assessed the outcome of orthodontic aligners versus fixed appliance treatment in young adults with mild malocclusions.[12] The results showed, that outcomes for treatment of mild malocclusions in adolescents showed equivalent effectiveness of clear aligners compared with fixed appliances, with significantly improved results for clear aligner treatment in terms of tooth alignment, occlusal relations, and overjet. Assessment of the number of appointments, number of emergency visits, and overall treatment time showed better outcomes for treatment with clear aligners.[12]

The aligners may lead to initial speech difficulties. However, most patients adapt quickly and speech returns to normal.[13] For effective

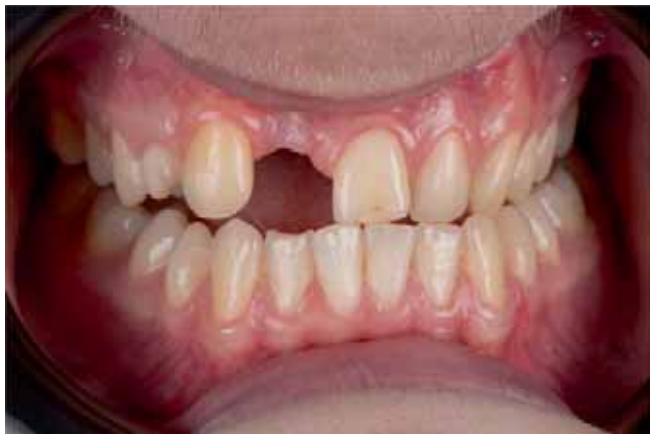

FIGURE 1 Initial situation caused by agenesis

FIGURE 2 Smile of the patient before treatment. Compromised overall esthetic appearance

three-dimensional tooth movements such as anterior root torque, rotation, mesio-distal movement and intrusion or extrusion, these aligners may require adhesive composite attachments,[14] that are tooth-colored and like the clear appliances itself almost not visible. As every dental treatment, aligner therapy needs a fundamental understanding of the basic principles of orthodontics and also has its limitations.[14,15]

This article presents three complex clinical cases of patients in need of fixed anterior restorations, who substantially benefited from a minor orthodontic pretreatment with aligners. These clinical cases demonstrate different aspects, such as diagnostics, comprehensive treatment planning, and interdisciplinary treatment with a focus on the benefits of a minor orthodontic pretreatment.

FIGURE 4 Wax-up according to esthetic analysis

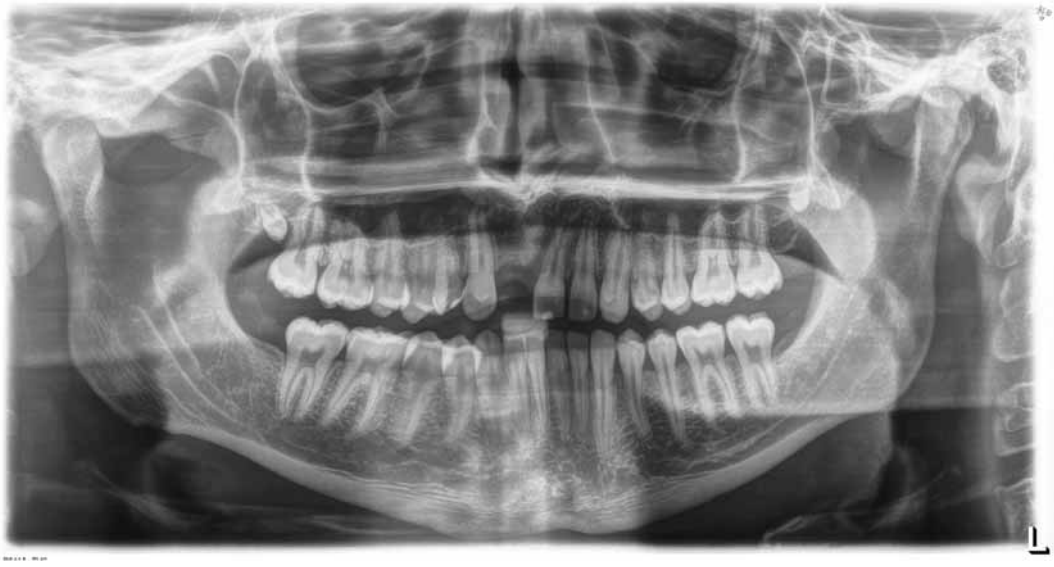

FIGURE 3 Panoramic radiograph before the treatment

2 | PRESENTATION OF CASES

2.1 | Case 1

A 18-year old male patient presented with congenitally missing right central and lateral incisors in the maxilla. The right canine was in the position of the lateral incisor and the canine of the first dentition in canine position (Figures 1–3). the mandibular anterior teeth showed crowding and the right lateral incisor showed a distinct grinding facet due to interaction with the antagonistic permanent canine. The patient asked for an esthetic rehabilitation.

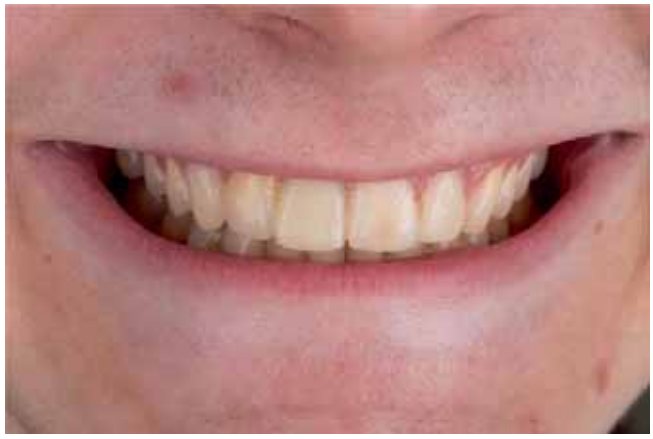

FIGURE 5 The mock-up helps to discuss the treatment goal with the patient

Besides the clinical evaluation, intra-oral scanning was performed, traditional impressions and photos were taken in order to perform facially derived treatment planning. A traditional wax-up was made to develop an idea of the ideal tooth proportions (Figure 4) and transferred to the mouth with a silicone index and a temporary resin material as a mock-up (Figure 5). The mock-up was accepted by the patient and served for defining the treatment goal, that was discussed with the multidisciplinary team. The final goal was to place an implant to replace the right central incisor and to reshape the anterior teeth with boned ceramic restoration in order to reestablish anatomical tooth proportions.

The models were placed into the articulator and the occlusion was checked for proper function. In dynamic occlusion with the mandible the wax-up simulation revealed an insufficient canine guidance and premature contacts on the planned implant crown and it's antagonist in protrusion (Figure 6).

It is well known, that the bite force on dental implant restorations is significantly higher because the mean threshold values for

FIGURE 6 Planning models mounted in the articulator. Wax-up interferes with lower incisors in dynamic occlusion (protusion) and shows insufficient canine guidance on the right side.

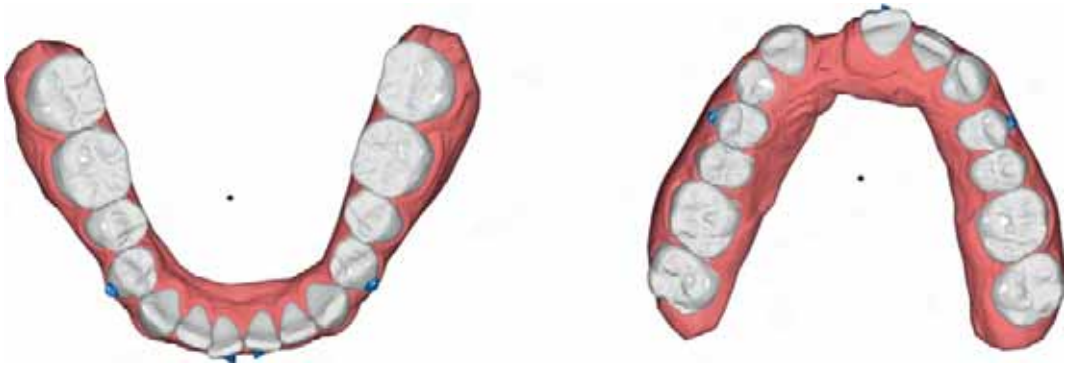

FIGURE 7 Scanned aches arch before treatment

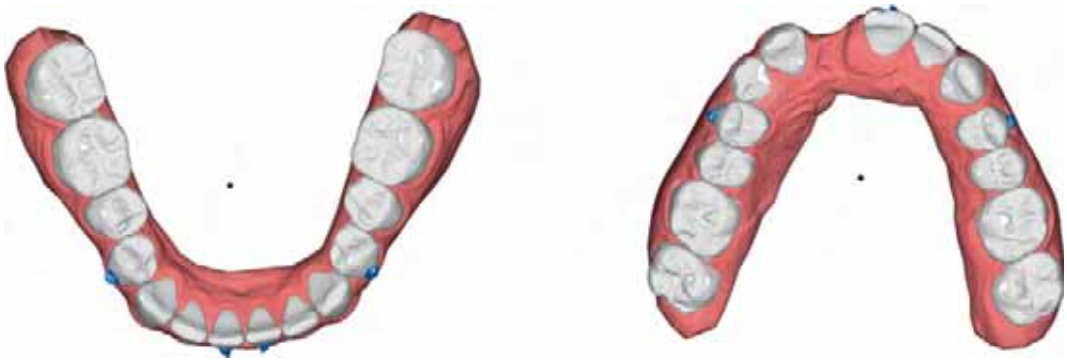

FIGURE 8 Simulation of orthodontic treatment goal

FIGURE 9 Anterior relation before the treatment (left) and simulation of treatment goal (right), necessary attachments marked blue

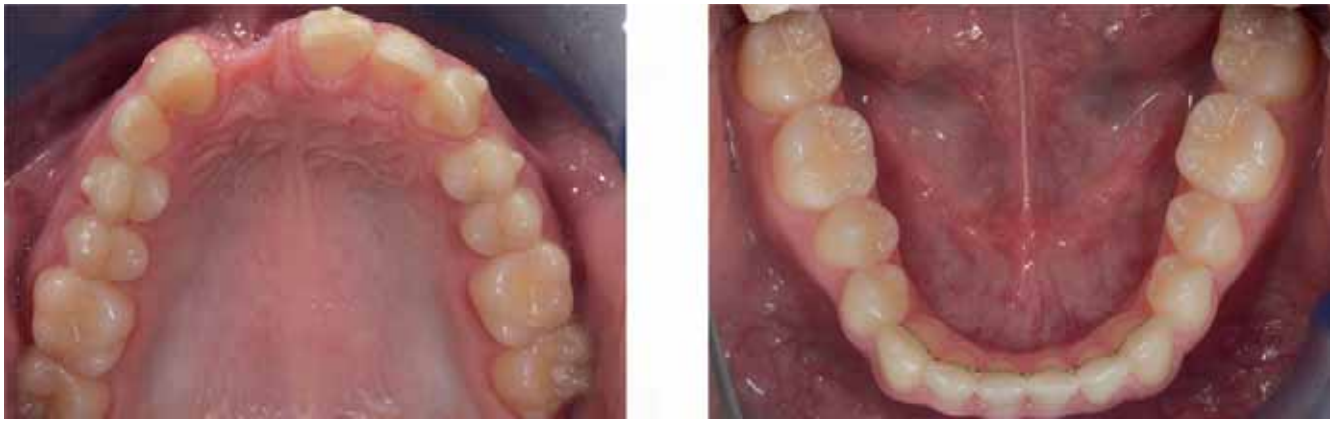

FIGURE 10 Clinical pictures of the aligned arches after orthodontic treatment providing a favorable starting situation for the restorative treatment to come (mandible: retainer in situ).

tactile perception for implants is 8.75 times higher than for teeth.[16] Therefore, fractures of the veneering porcelain are a common technical complication of implant supported fixed dental prosthesis that amounts up to 7.8%.[17] To eliminate the functional risk factors and to provide an equilibrated dynamic occlusion with a sufficient anterior guidance, an orthodontic pretreatment with aligners was digitally planned (Figures 7–9) and carried out. The desired tooth movements were accomplished with six aligners and four for refinement and took a total treatment time of 6 months and provided a favorable clinical situation for the restorative treatment with all-ceramic restoration on an implant and teeth (Figures 10–12).

The documentation of this case shows how a wax-up and mock-up can help to plan complex cases. Moreover, it depicts how minor orthodontics helped to transform the initial compromised situation to a standard situation providing better occlusal prerequisites for the restorative treatment to come.

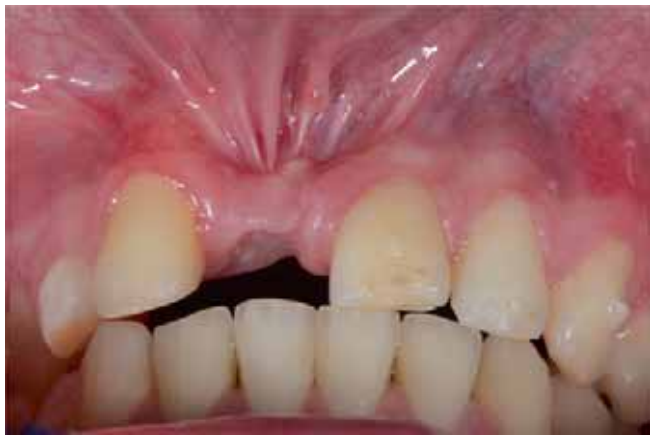

FIGURE 11 The anterior relation in protrusion after the orthodontic treatment shows favorable conditions for the further restorative treatment

2.2 | Case 2

A 19-years old male patient presented with two persisting teeth of the first dentition due to agenesis of the left central incisor in the maxilla and the left second premolar in the mandible. The persisting

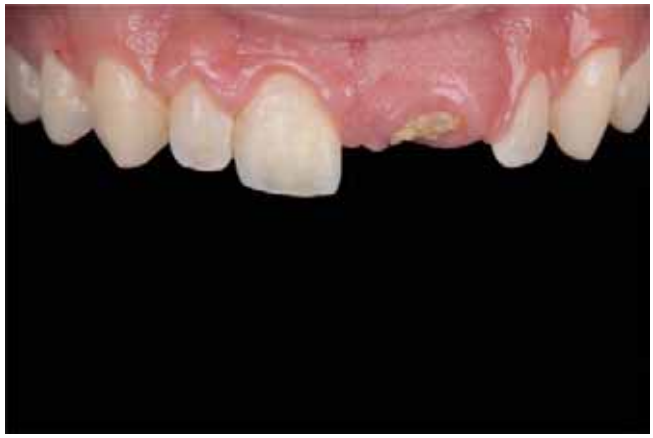

FIGURE 13 Initial intra oral view. Dysplastic left central incisor

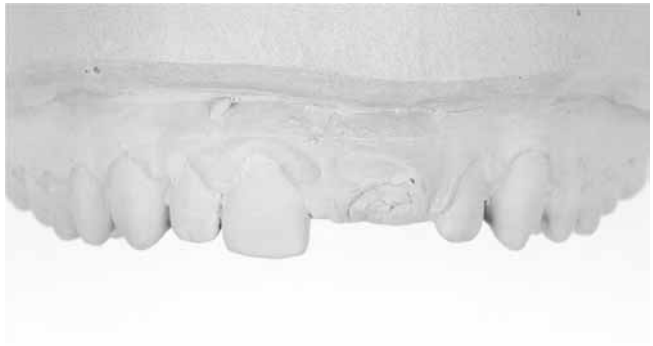

FIGURE 14 Study cast

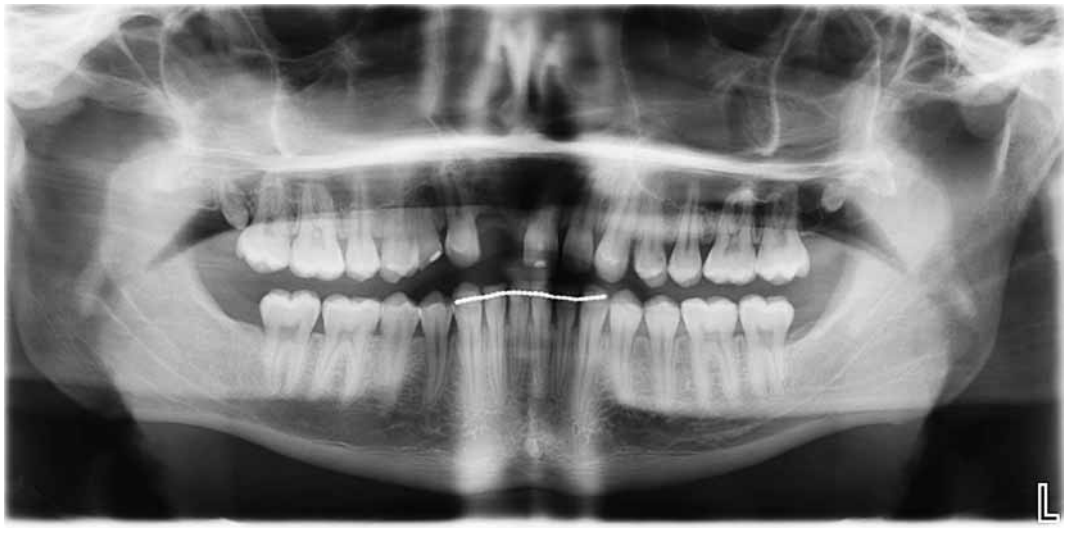

FIGURE 12 Panoramic radiograph after orthodontic treatment, before implant and restorative treatment

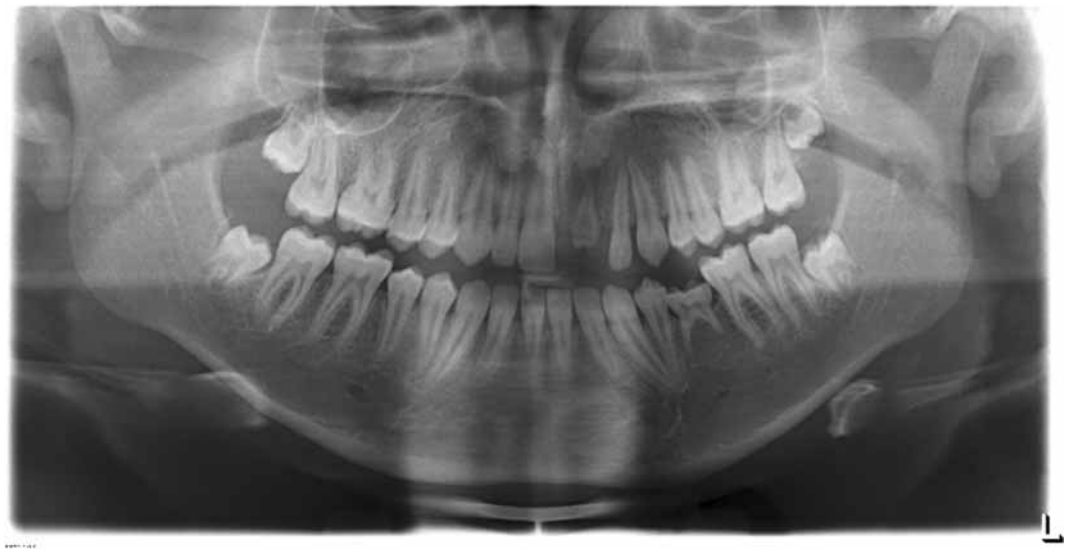

FIGURE 15 Panoramic view. Dysplastic left central incisor (or failing central of first dentition). Agenesis of the left second premolar in the mandible.

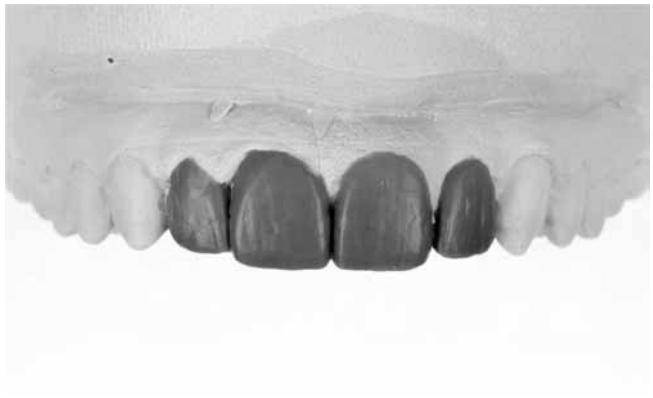

FIGURE 16 Wax-up with harmonic proportion

FIGURE 17 Occlusal view of the mock-up. Dimension of wax-up of central incisors (blue line) differ from clinical situation.

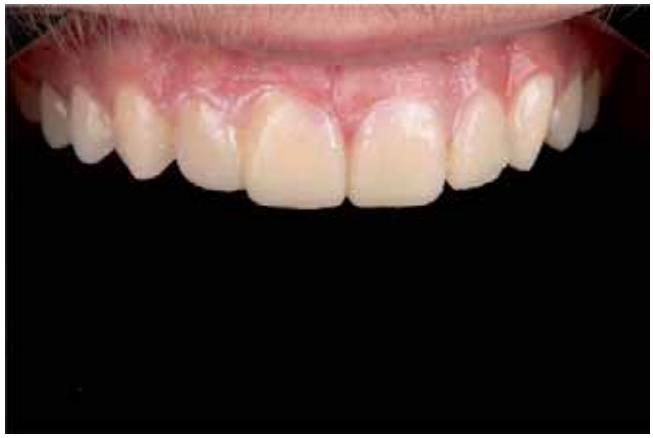

FIGURE 18 Transfer to the mouth as mock-up

FIGURE 19 Smile of patient with mock-up

left central in the maxilla was failing and infected (Figures 13–15). Oral hygiene had to be improved. An orthodontic treatment was already performed years ago alio loco, but without a clear final treatment goal. Now, the patient was looking for a final esthetic solution for the failing left central and the over-all situation.

This is a typical example for a clinical situation leaving an esthetic issue that cannot be solved with orthodontics alone, due to Bolton's

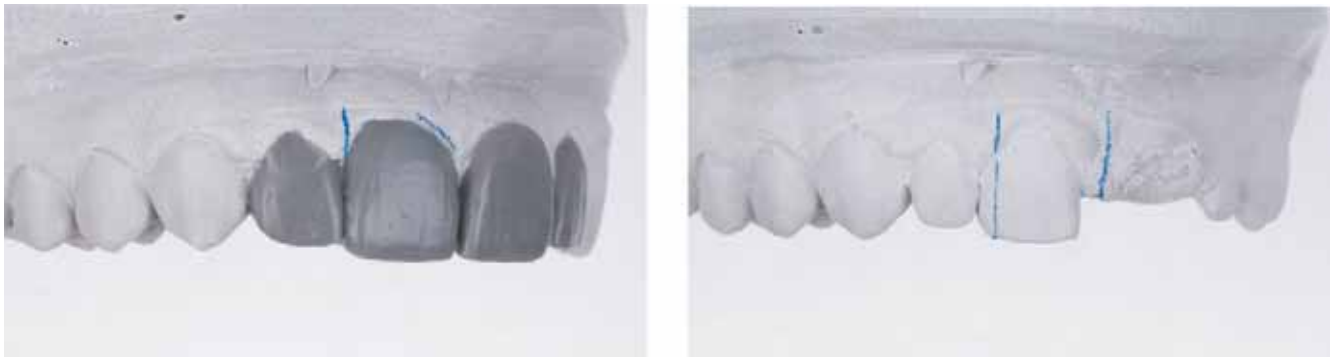

FIGURE 20 Comparison of wax-up with clinical situation. Tooth position does not correlate with planned position.

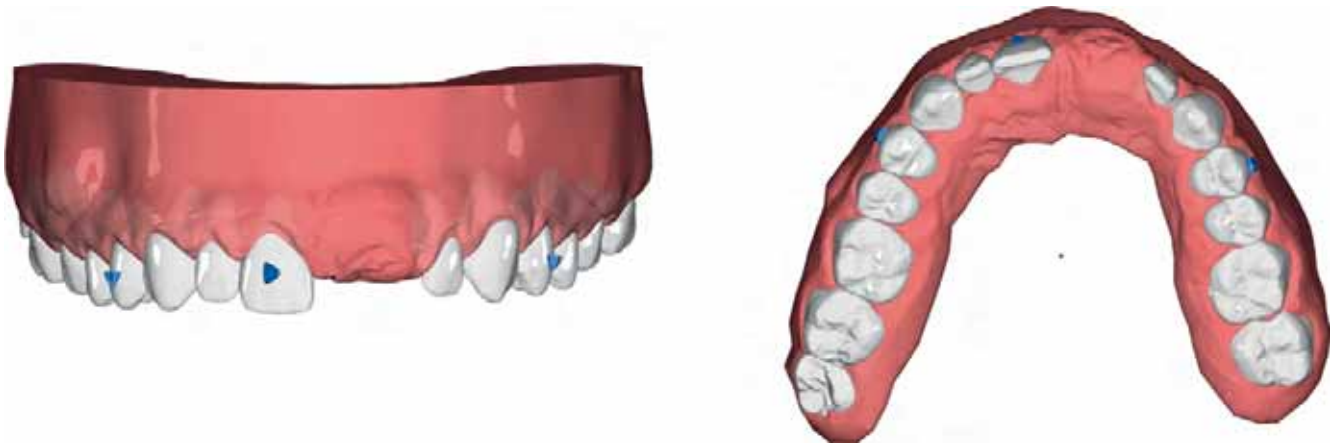

FIGURE 21 Simulation for orthodontic aligner treatment—initial situation. Attachments in blue

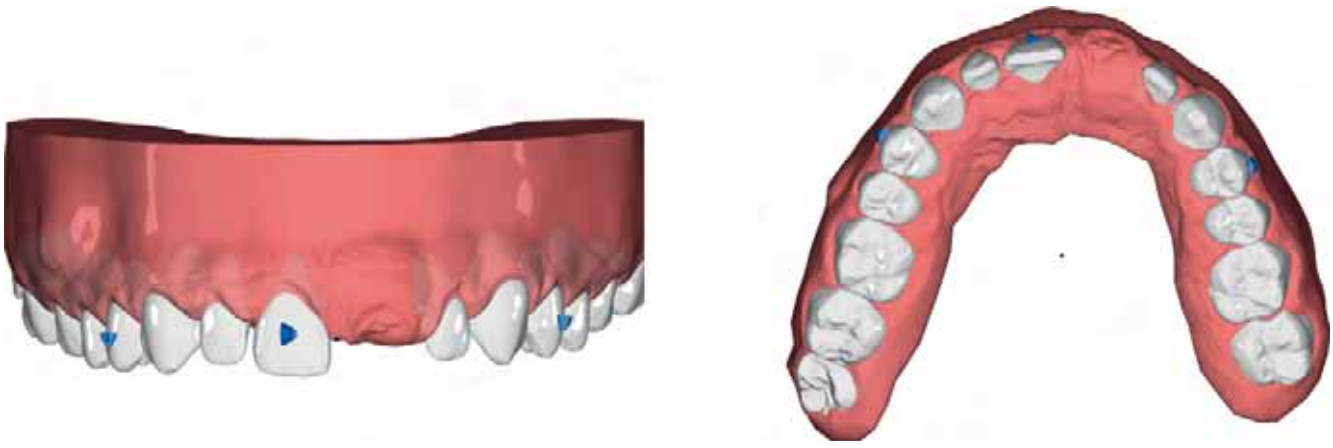

FIGURE 22 Simulation of planned ideal position of anterior teeth

discrepancy,[18] a disproportion between the size of the maxillary and mandibular anterior teeth. In these cases the remaining interdental gaps cannot be closed alone with orthodontics, but with additive techniques like composite or veneers.

A traditional wax-up was made to develop an idea of the ideal tooth proportions (Figures 16 and 17) and transferred to the mouth with a silicone index and a temporary resin material as a mock-up (Figures 18 and 19). The Evaluation of the study casts with and without wax-up showed, that the tooth positions did not correlate with planned position and a restorative treatment with veneers would raise the need for excessive removal of tooth substance for an ideal esthetic result (Figure 20). Therefore, intraoral scanning was

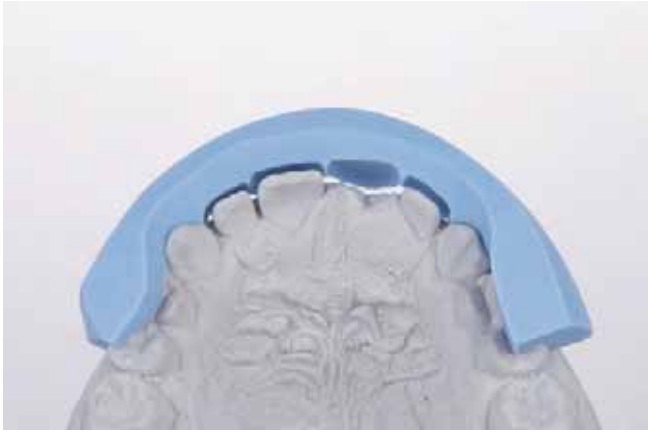

FIGURE 23 After aligner treatment. Reevaluation of the achieved tooth position and space in relation to wax-up with silicone index. Occlusal view.

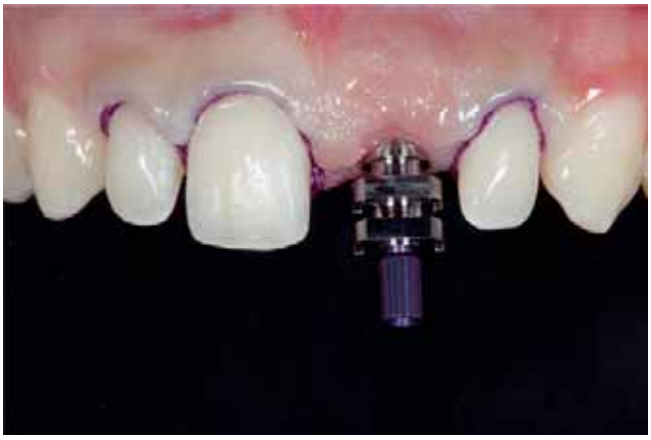

FIGURE 25 Situation prepared for impression taking of the implant and for nonprep veneers.

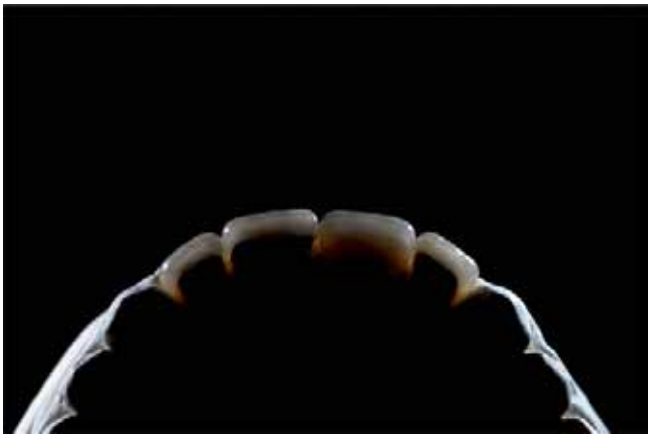

FIGURE 27 Occlusal view of master cast with final restorations showing light transmission and natural stratification.

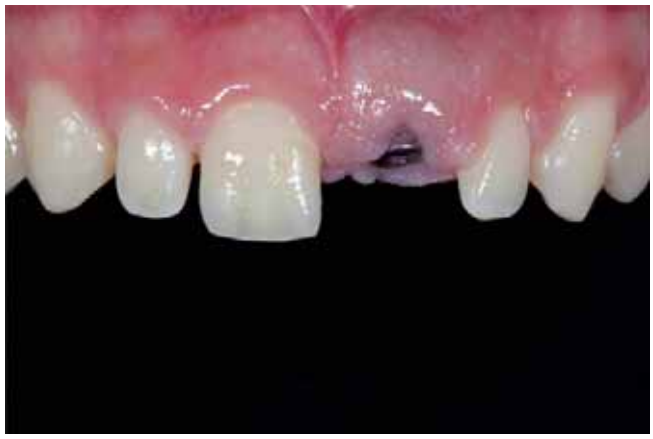

FIGURE 24 The situation after 12 weeks after implant placement

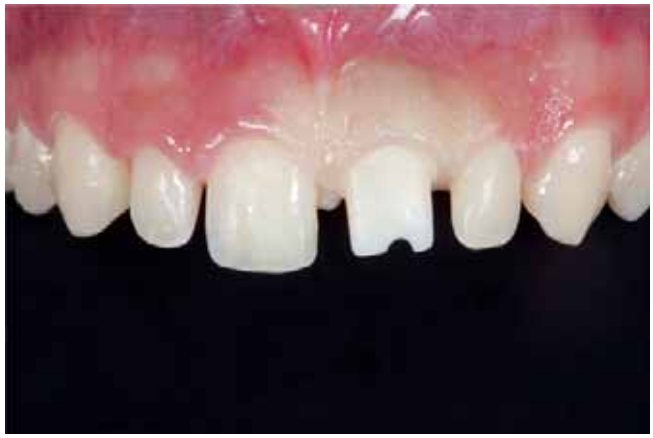

FIGURE 26 Try-in of the abutment, with moderate pressure to shape the emergence profile.

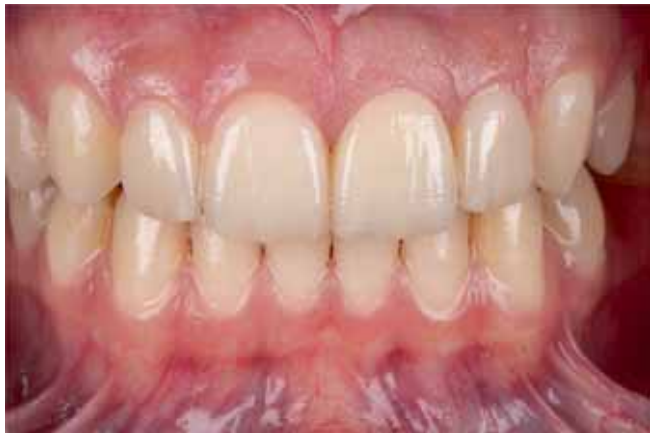

FIGURE 28 Placed restorations in occlusion with mandible

performed and a digital orthodontic simulation for an aligner treatment was made to plan preprosthetic orthodontic treatment to move the teeth into an ideal position for nonprep veneers for the right lateral and central and the left lateral incisor and an implant at position of the left central (Figures 21 and 22). Tooth alignment was performed with seven aligners plus three for refinement within a total treatment time of 4, 5 months. During the orthodontic treatment the patient's oral hygiene was successfully improved by instruction and professional cleaning.

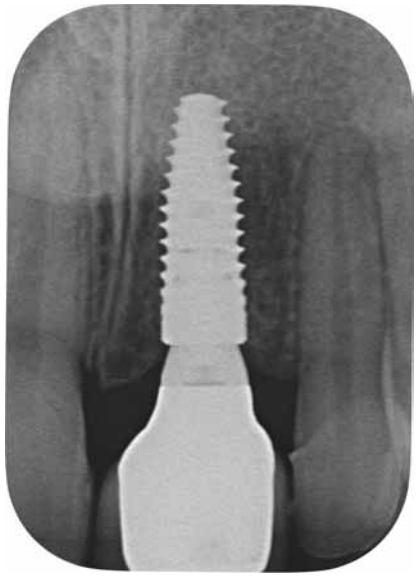

FIGURE 29 Periapical x-ray of the implant 6 months after placement

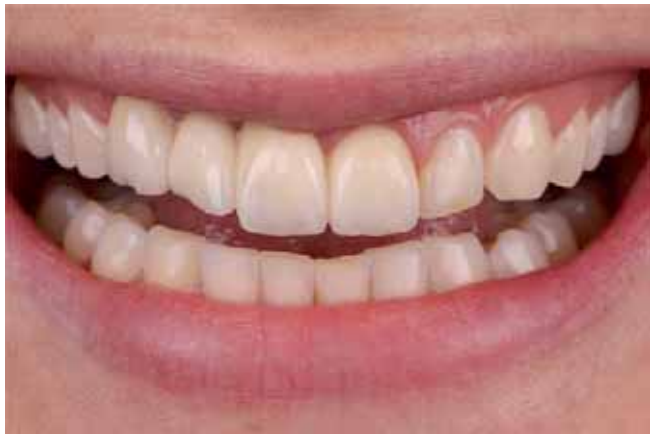

FIGURE 31 Smile of the patient before the treatment showing a compromised overall esthetic appearance

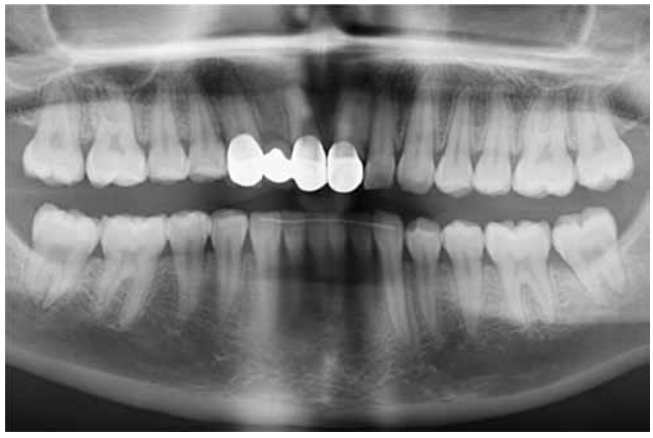

FIGURE 33 Panoramic X-ray before treatment

FIGURE 30 Smile of patient after treatment

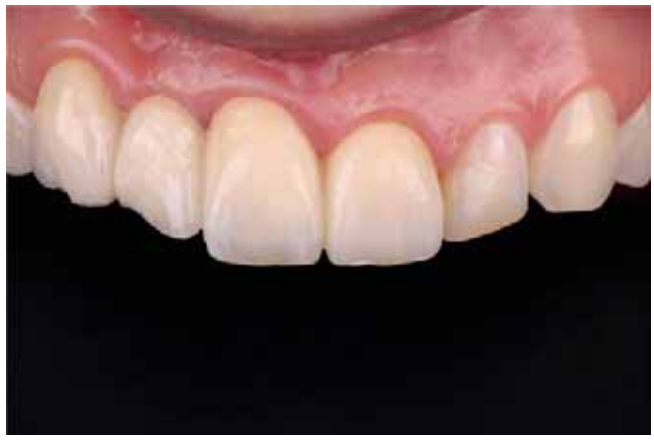

FIGURE 32 Intraoral view with of the old restoration and the soft-tissue situation

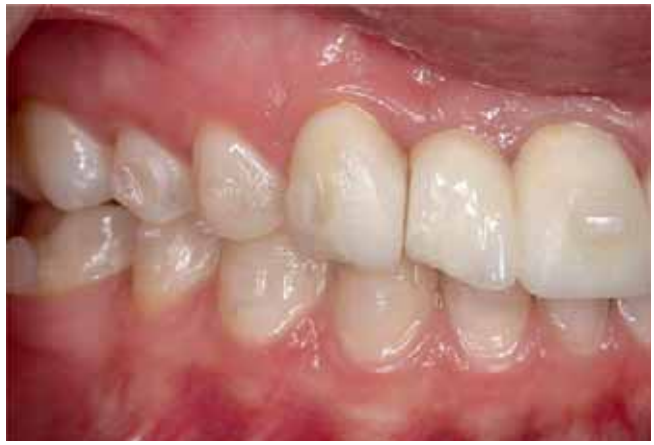

FIGURE 34 Separated bridge. Placed attachments for the aligner therapy

After successful tooth movement a reevaluation of the clinical situation was made with a set of new study casts. Silicone indexes of the initial wax-up that was approved with the mock-up, were used to

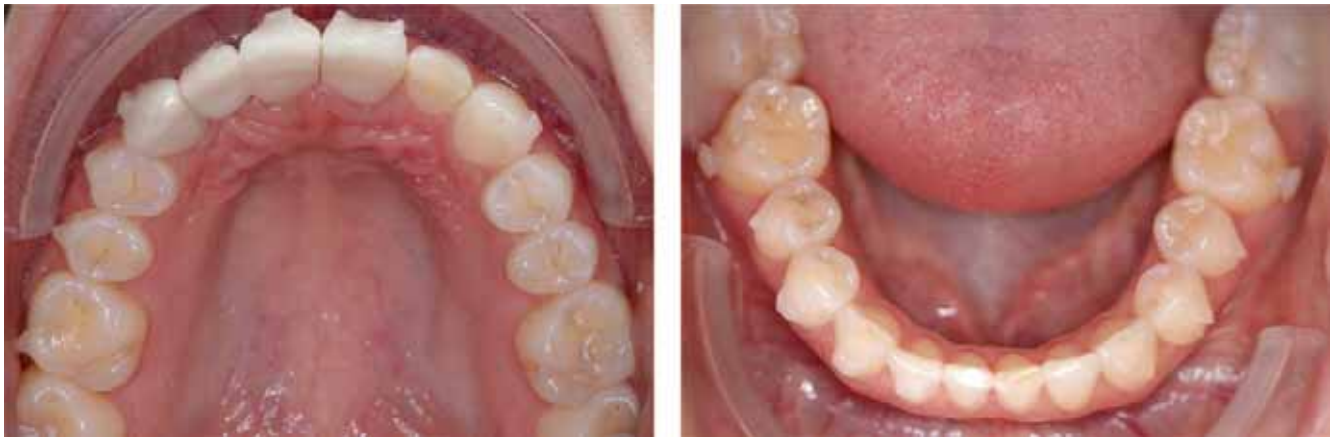

FIGURE 35 Arches after orthodontic treatment

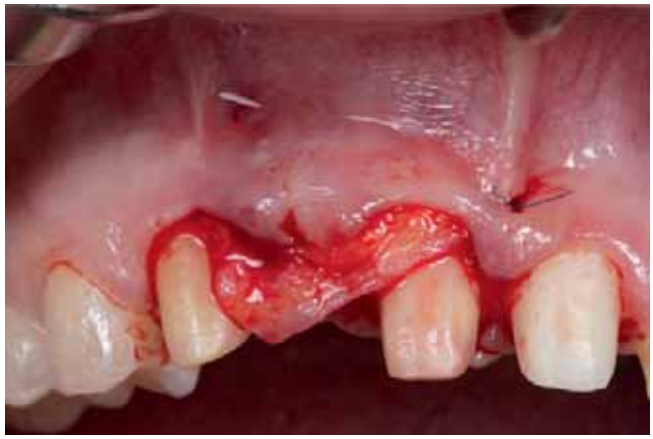

FIGURE 36 Connective tissue augmentation of the pontic site and facial soft tissue of the central incisor

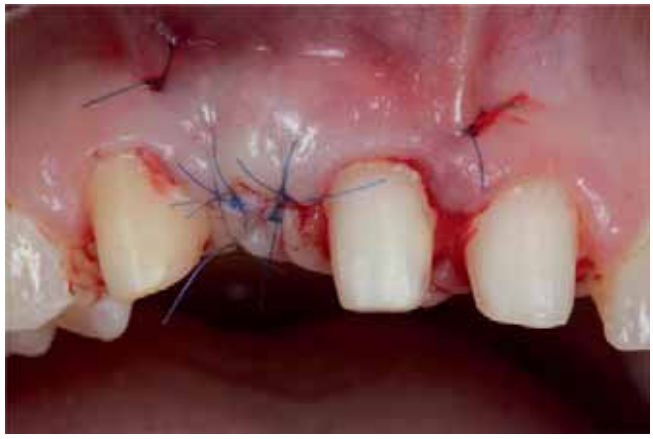

FIGURE 37 Site after perio-plastic surgery

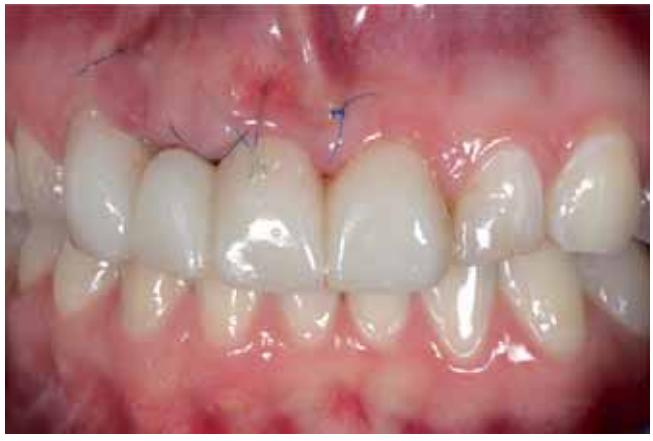

FIGURE 38 Healing of the site 1 week post-OP with transitional chair-side temporary restoration.

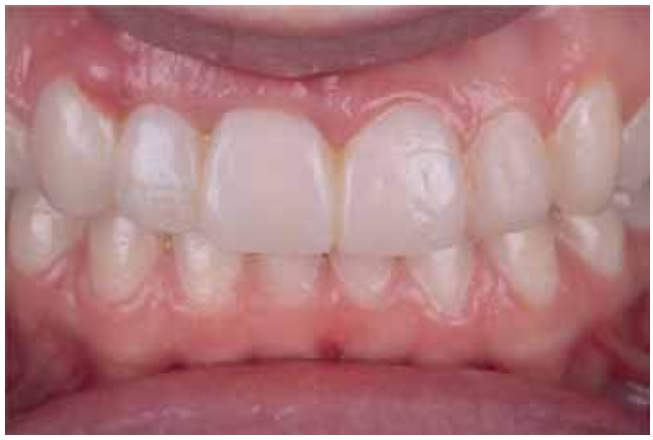

FIGURE 39 Long-term temporary

compare the accomplished new tooth position with the defined treatment goal (Figure 23). Meanwhile during the final phase of the orthodontic treatment, the failing central was extracted and the site was left for healing for 6 weeks. After healing, an implant (Bone Level Tapered, Straumann, Switzerland) was placed in a straight-forward procedure with a transgingival healing approach.[19] After successful healing of the implant (Figure 24) the restorative phase for nonprep veneers and an implant crown started (Figures 25–27).

After the patient approved the esthetic result, the restorations were adhesively cemented and the occlusion was adjusted (Figures 28–30). In

this case the orthodontic pretreatment allowed for a noninvasive restorative approach for the natural teeth and optimal space management for natural proportion of the restorations on the implant and teeth.

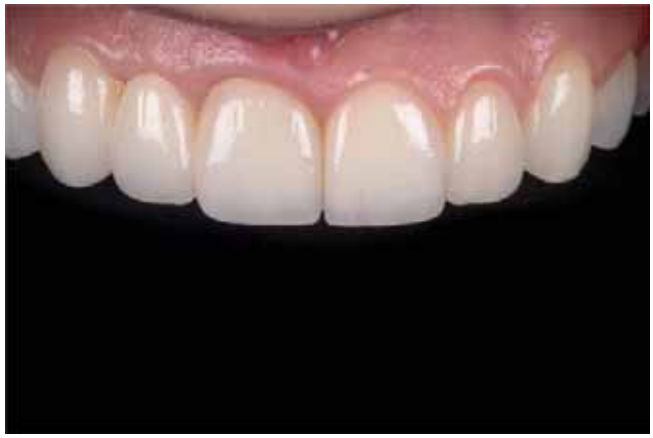

FIGURE 40 Final ceramic restorations (bridge, crown on left central, veneers on the left lateral and canine)

FIGURE 41 Smile of the patient after treatment

The patient and the patient's family were highly satisfied with the minimally invasive approach and the final result.

2.3 | Case 3

A 32-year old female patient presented with an old zirconia bridge from the right central to the right canine in order to replace the missing right lateral incisor. In addition, the left central incisor had a crown. The bridge showed significant ceramic chippings on the incisal edges. The soft tissue margins of the anterior dentition in the maxilla were asymmetrical, showing a deficit of papilla height and midfacial soft tissue recession at the abutment teeth of the bridge and the patient exposed the situation while talking and smiling due to a high smile line (Figures 31–33).

The patient received the restoration when she was 17 years old. Most likely, the bridge led to retention of the teeth, while the rest of the maxilla experienced further vertical facial growth over time.[20] This led to a vertical displacement of the periontal tissues of the abutment teeth of the bridge. Vertical facial growth is often a limitation in the treatment of young patients. Therefore, it is important to evaluate the completion of facial growths in these patients.[21] After careful treatment planning, the idea was to address the esthetic issues with orthodontic extrusion of the abutment teeth and soft tissue augmentation using perio-plastic surgery. In addition, the arches in maxilla and mandible had to be aligned. After a retention phase and periodontal healing with a temporary, new ceramic restorations were planned.

For the orthodontic aligner treatment, the bridge was carefully separated mesially to the canine using a rotating diamant disc and attachments were placed to allow for orthodontic extrusion (Figure 34). Extrusion of teeth has been described as an option to manage vertical deficits such as insufficient papilla in the esthetic zone.[22,23] The orthodontic treatment took 8 months and 24 aligners, because the combination of different three-dimensional movements was challenging. After seven aligners a new set of attachments had to be placed and a first refinement was done.

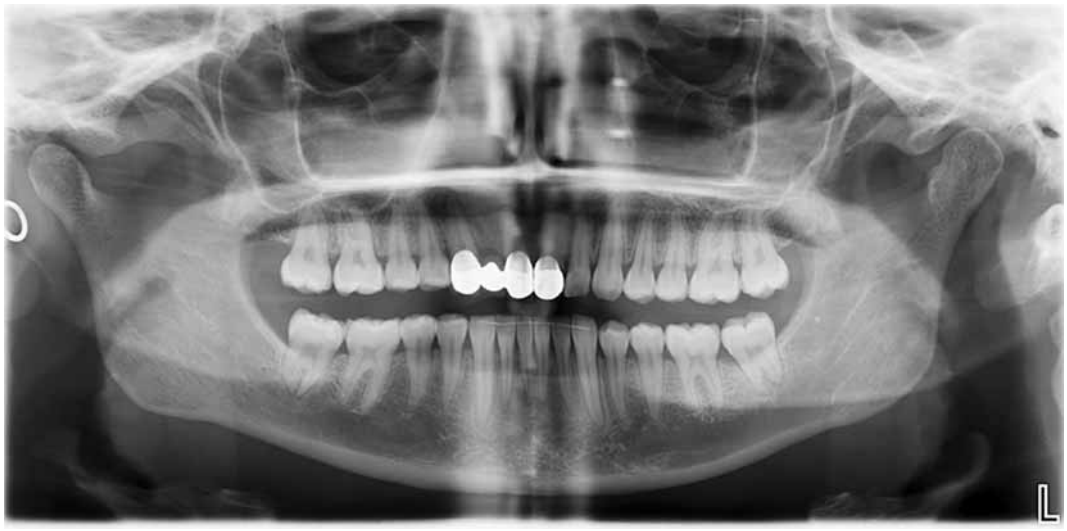

FIGURE 42 Panoramic view after the treatment

After 11 more aligners a second refinement with six aligners finalized the orthodontic tooth movement (Figure 35). Then, the pontic area was augmented with a connective tissue graft, that served for recession coverage at the right central incisor at the same time (Figures 36–38).

After healing of the site, a temporary restoration was placed for 3 months to provide retention of the extruded teeth and wait for soft-tissue maturation (Figure 39). Pontic sites that were augmented with connective tissue grafts have proofed to show good long-term volume stability after tissue maturation.[24] After the maturation phase the final all-ceramic were fabricated and the restorations were placed adhesively.

The final result showed a significant overall esthetic improvement and the patient was happy with the result. The orthodontic pretreatment was a key-element in solving the case by improving the position for the periodontal attachment through extrusion for this esthetically demanding patient (Figures 40–42).

3 | CONCLUSION

Some complex cases in restorative dentistry can be transformed to straight forward cases with the help of minor orthodontic tooth movements. Typical indications are space opening in order to provide space for a restoration with anatomic proportion or corrections of the tooth axis in order to open space between the apices of the roots of the adjacent teeth to provide space for safe implant placement. Moreover, minor orthodontic treatment with aligners can contribute to a more functional, less invasive, and more esthetic outcome of restorative treatments in the esthetic zone.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Happe A, Blender S, Luthardt RG. Orthodontic pretreatment with aligners for optimizing the result prior to fixed restorations in the esthetic zone. *J Esthet Restor Dent*. 2023;35(1):279-290. doi:10.1111/jerd.12997

Received: 19 October 2022 | Accepted: 17 November 2022

DOI: 10.1111/jerd.12994

CLINICAL ARTICLE

WILEY

Clinical advances in maxillary skeletal expansion and introduction of a new MARPE concept

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Abstract

Background: Transverse maxillary deficiency, typically characterized by the clinical manifestations of unilateral or bilateral crossbite, is a common orthodontic discrepancy. The primary goal of maxillary expansion should be to obtain a nearly maximum width increase in the basal bone of the constricted maxilla and to avoid the dental expansion of the anchor teeth. The introduction of miniscrew anchorage-supported rapid maxillary expansion (MARPE) devices has helped increase the feasibility of obtaining nonsurgical transverse correction in late adolescents and young adults with optimum orthopedic effects. However, the success rate of MARPE shows a negative correlation with age. Although MARPE offers an effective method for correcting a transverse skeletal deficiency, given the appliance cost and increased risk for complications, it could present challenges for adult patients and practitioners in daily practice.

Aims: In this article, current advances in maxillary skeletal expansion are summarized, and a new MARPE concept is introduced.

Conclusion: The new MARPE design offers several advantages to other existing methods: (1) it can be installed directly to the patient in the clinical setting with no additional laboratory waiting times. (2) It is purely a bone-borne appliance. (3) The appliance is designed to be placed in the thickest part of the anterior palate to maximize the cortical and trabecular bone support. (4) Allows for bicortical placement of the miniscrews with no perforations in the nasal floor. Finally, (5) offers an esthetic and minimalistic approach to maxillary skeletal expansion in late adolescent and adult patients.

KEYWORDS
adolescents, adults, bone-borne, MARPE, miniscrews

1 | INTRODUCTION AND BACKGROUND

The dental specialty for managing and correcting dental and skeletal abnormalities is referred to as "Orthodontics and Dentofacial Orthopedics" because orthodontists can influence jaw orientation via growth modification therapy. Changes to the facial skeleton via orthopedic applications are relatively slow and take time to be clinically relevant. However, the subject of "palatal expansion" is unique

compared to other orthopedic applications as it offers readily observable clinical and radiographic changes during and immediately after the completion of the procedure.

The practice of expanding the palate transversally via orthopedic forces brings about skeletal separation in the midpalatal suture and affects the entire circummaxillary suture network.[1] While pure skeletal expansion is highly desired with minimal dental and alveolar changes due to lateral forces exerted on the posterior teeth, buccal tipping of the anchor teeth and alveolar bending also occur during the orthopedic separation of the midpalatal suture.[2–6] Based on 7–9 mm of total screw expansion, the opening of the midpalatal suture varies from 1.5 to 4.3 mm anteriorly and 1.6 to 4.3 mm posteriorly.[4,7–9] According to a systematic review, the midpalatal suture opening is around 20%–50% of the total screw expansion.[1] Another report quantified the amount of skeletal expansion to be approximately 38%, while dental tipping and alveolar bending accounted for 49% and 13% of the total expansion, respectively.[10] Considering the highly variable response from midpalatal suture to expansion, it is evident that achieving a clinical outcome is not possible without dental side effects.

Regardless of their design, conventional palatal expanders cause significant buccal tipping of the posterior maxillary teeth.[5] However, it was shown that banded palatal expanders caused a more remarkable change in the axial inclinations of anchor teeth.[2,5,6] These reports led to the observation of an immediate decrease in buccal bone thickness and buccal marginal bone levels following palatal expansion. More often than not, these changes may not affect clinical practice (Figure 1). However, the main concern with reduced buccal bone width is the susceptibility of these areas to fenestrations, periodontal recession and the development of unesthetic gumlines in the long term. In addition to the side effects mentioned above, forces from palatal expanders may also result in volume loss, resorption, and thinning of the anchor teeth.[11,12] While it was shown elsewhere that changes in buccal bone thickness[13] might not suggest any clinically evident deleterious effects in the long term, some patients require a more than meticulous approach with palatal expansion because of their anatomic limitations (Figure 2).

Another factor to consider about conventional palatal expansion is the age of the individuals. For example, transverse skeletal discrepancy due to a constricted maxilla should ideally be treated in the late mixed dentition up until ages 15–18.[14] While separating the midpalatal suture is possible using palatal arches and removable appliances with lighter forces in younger children, 10–20 lbs of pressure is required in adolescents and teens as rapid palatal expansion is required. Accordingly, a high range of individual variability is observed as a response to heavy forces generated by palatal expansion.[1] Besides the maturity increase in the midpalatal suture over time, zygomaticomaxillary articulation and the pterygoid plates are the primary sources of increased resistance to palatal expansion (Figure 3). The more mature the individual gets, the more difficult it gets for the midpalatal suture to be separated by conventional palatal expansion devices. Therefore, bone-borne or miniscrew anchored rapid palatal expansion (MARPE) has been introduced in the orthodontic practice.[15–19] In bone-borne palatal expansion appliances, miniscrews replace the anchor teeth for providing support to the expansion forces generated by the expander. Accordingly, two (hybrid) or four miniscrews can be utilized in the design of MARPE appliances.

2 | EFFECTS OF MARPE IN THE ADOLESCENT POPULATION

The adolescence is when a child transitions to adulthood. It is a time of many physical, sexual, cognitive, social, and emotional developments. In the early years of adolescence (10–13 years), orthodontic patients are amenable to conventional rapid maxillary expansion. The maxillary sutures are still responsive to expansion and perhaps protraction. Proffit[14] argues that dental changes are much more pronounced after age 10 with conventional force application systems. Middle adolescence (14–17) is when clinicians start encountering a mixed response to conventional expansion. However, utilization of MARPE has changed the game quiet dramatically in this age group.

Clinical evaluation of MARPE applications in individuals within the postpubertal growth spurt stage yields impressive results. Figure 4 demonstrates initial and posttreatment photos of a 16-year-old male patient presenting with skeletal Class III, skeletal and dental anterior open bite, and maxillary transverse discrepancy. This patient was first treated with a hybrid MARPE design for maxillary transverse deficiency. The anterior palate offers a spacious area to insert the miniscrews, which replaced the need to extend the metal arms of the expansion device to the bicuspid region. Following the maxillary expansion protocol, the miniscrews were used for both the vertical

FIGURE 1 Cone-beam computed tomography scans before treatment (A) and after the completion of expansion and fixed appliance therapy (B) in a 13-year-old female patient. The patient finished the orthodontic treatment with palatal expansion and fixed appliance treatment with lesser buccal bone widths

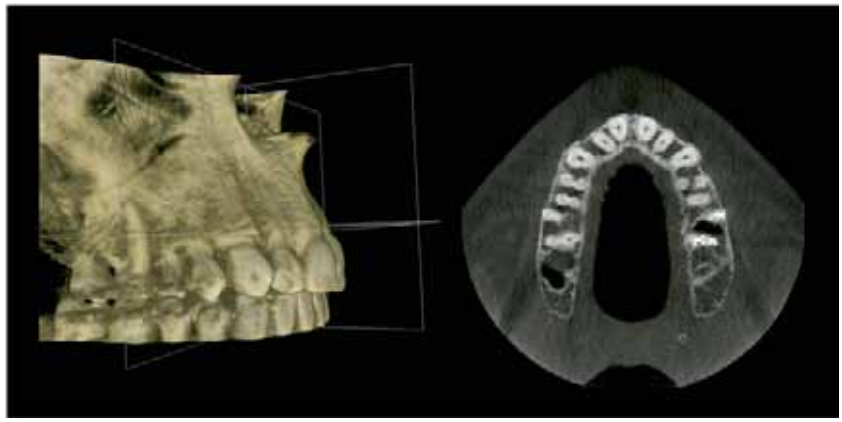

FIGURE 2 Three-dimensional volume rendering (A) and an axial slice obtained at the mid-root level of the maxillary first molar (B) of a cone-beam computed tomography scan of an orthodontic patient at the beginning of the treatment. This patient is not an ideal candidate for tooth-borne palatal expansion because of the lack of buccal bone covering the anchor teeth

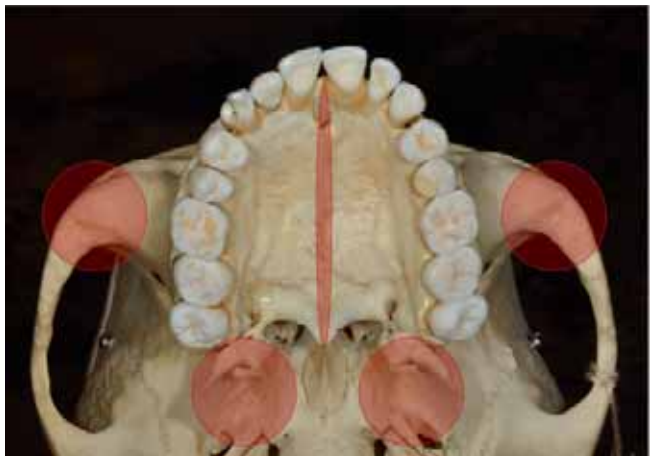

FIGURE 3 The main sources of increased resistance to palatal expansion are: the midpalatal suture, zygomaticomaxillary articulation, and the pterygoid plates

and A-P control of the molar anchorage during the Class III-elastic use. Accordingly, the mandibular arch was uprighted, and malocclusion was corrected.

In a prospective randomized clinical trial where a group of early to late adolescents was treated with four-miniscrew supported bone-borne MARPE (age: 13.8, SD: 1.3) and conventional tooth-borne Hyrax (age: 13.8, SD: 1.2) appliances, MARPE increased the extent of skeletal changes in the range of 1.5–2.8 times that of tooth-borne expansion.[20] Accordingly, the buccal bone width preservation with MARPE was more remarkable due to a substantial increase in the transverse width of the basal bone. It is interesting to note that maxillary first premolar and first molar teeth in the conventional RME group demonstrated buccal crown tipping. In contrast they demonstrated an opposite average inclination change in the bone-borne group (Figure 5). The uprighting of the maxillary first premolar and first molars in the bone-borne group could be explained by the absence of a buccal force acting on the crowns and the increased apical separation of the maxillary suture close to the nasal floor.

Another prospective randomized clinical trial[21] with a slightly increased age range (from 12 to 18) reported similar findings for the four-miniscrew supported MARPE compared to a conventional Hyrax appliance. Although both groups produced similar dental expansion of maxillary first molars, the ratios of skeletal-to-screw expansion and skeletal-to-dental expansion were nearly twofold greater in the MARPE group than in the Hyrax group. As mentioned earlier, clinicians usually face challenges and a mixed response from the midpalatal suture to conventional expansion in this age group. It was not surprising to see in Jia et al.'s[21] prospective clinical trial that four patients (two male patients: 15.8 and 17.0 years; and female patients: 16.3 and 17.0 years) showed no separation of the midpalatal suture in the conventional Hyrax group. Similar to the trial with a younger average age group, the success rate of midpalatal suture opening 100% in the MARPE group.

It is evident from clinical trials and experience that MARPE could reduce the tipping of the maxillary posterior anchor teeth and related buccal alveolar height loss. In addition, sutural separation seems to yield virtually absolute results from age 12 to 19. These results indicate that MARPE is a better alternative for patients with maxillary skeletal deficiency during the post-pubertal growth spurt stage than conventional expansion appliances. Based on the clinical experience and available data, MARPE should be utilized toward the end of that age spectrum and when miniscrews could serve other correctional purposes for the malocclusion.

3 | EFFECTS OF MARPE IN THE ADULT POPULATION

World Health Organization's definition of adolescence ends with age 19. MARPE showed promising clinical findings in young adults when employed as a non-surgical treatment alternative.[22,23] However, due to the inherent limitations of the mechanical aspects of miniscrews[22] and biological patient-related limitations, absolute success may not be possible in adult patients because the outcome of midpalatal suture separation becomes more complex to predict as the age increases. For instance, while the combined success rate of suture separation for individuals that are between 15 and 29 is slightly above 80%, it declines to 20% from 30 to 37 years.[24]

Between 19 and 29 is an interesting group because of the increased chances that skeletal expansion would succeed. In this age

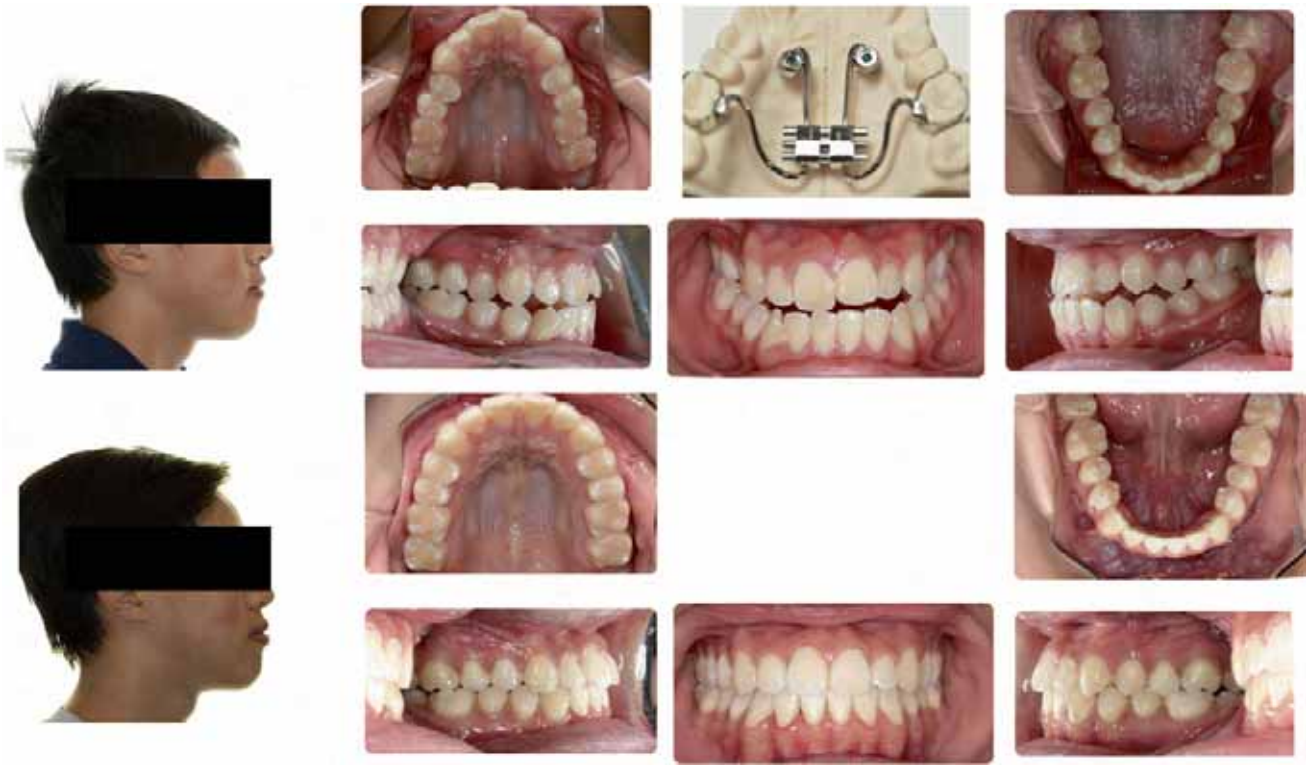

FIGURE 4 Pre- and posttreatment treatment photos of a 16-year-old male patient treated with a hybrid MARPE appliance. Two miniscrews placed in the anterior palate were used to design a hybrid MARPE appliance. Upon the completion or MARPE, a palatal bar supported with the miniscrews was designed to hold the expansion and stabilize the maxillary arch and the teeth for the remainder of the treatment

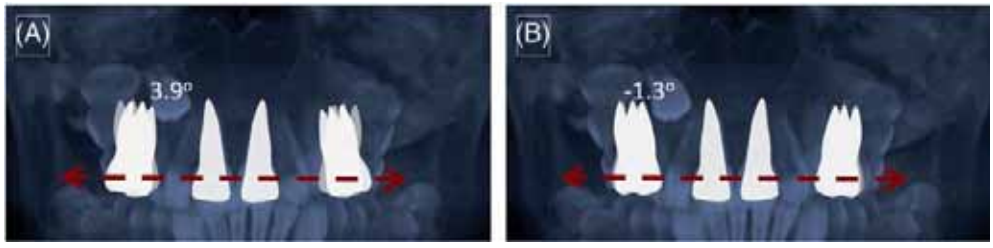

FIGURE 5 Schematic representation of inclination changes in maxillary molars after expansion with (A) conventional maxillary expansion appliances, and (B) MARPE in adolescents. Red line represents the transverse expansion vector. The first molars tip buccally with an average of 3.9-degree following conventional expansion. With MARPE, the first molars incline lingually and show an average of (−) 1.3-degree of uprighting

group, there are some patients that even a hybrid expander could be deemed successful. However, others do not respond to the same design (Figure 6). This mixed response to the application may seem frustrating. However, it is vital to communicate effectively with the patients and let them know about the possibility of failure. Most clinicians make careful patient selections, and when it is deemed that the midpalatal suture is not responding to the treatment, they change their expansion protocol to slow expansion to camouflage the transverse deficiency dentally. For instance, the clinical expansion protocol could start at two turns a day until a successful split is obtained in the midpalatal suture. If successful, the rate could be slowed down to 1 turn/a per day. If not successful, a slow expansion protocol of 1–2 turns/a week should provide adequate dentoalveolar expansion in cases where it may be indicated and will not harm the periodontal support.

Attempts were made to correlate the success of MARPE with chronological age,[24–27] midpalatal suture maturation stage,[24–27] midpalatal suture density ratio,[27,28] the maturation of cervical vertebrae, and some other morphologic variables.[26] Unfortunately, none of these reports were able to indicate a reliable parameter that can predict absolute success with MARPE other than a negative correlation with chronological age.[24] Also, it is essential to note that complications are significantly associated with increasing age.[29] Although MARPE offers an effective method for correcting the transverse skeletal deficiency, given the cost and increased risk of complications in older patients, it

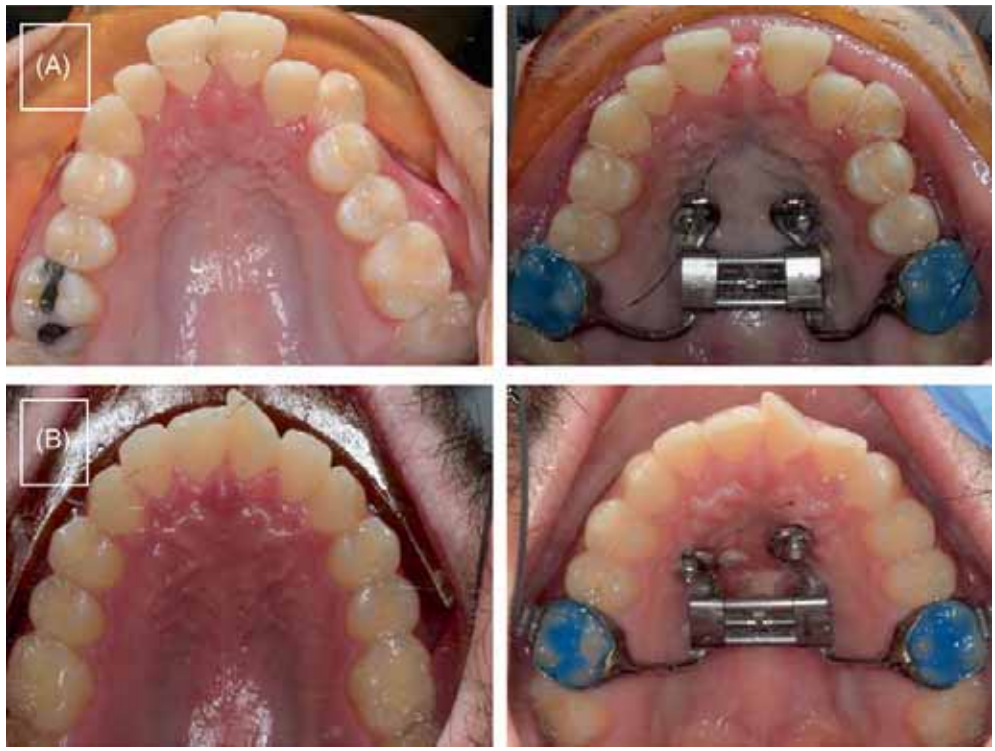

FIGURE 6 (A) Successful maxillary skeletal application in a young adult with a hybrid MARPE. (B) Another young adult in the same age not responding to MARPE

could present challenges for the patients and the practitioners in the practice setting. Therefore, it is a worthwhile topic to investigate and make clinically relevant innovations.

4 | A NEW CONCEPT FOR BONE-BORNE MARPE

Traditionally, tooth-borne palatal expanders are designed to be supported by four anchor teeth. As indicated before, MARPE appliances may include two (Hybrid) or four miniscrews to replace the anchor teeth. MARPE designs supported with four-miniscrews may also have additional tooth-borne support, such as a palatal bar connecting the maxillary right and left first molars.

Adding a transpalatal bar inevitably transforms the appliance design into a combination of a tooth- and bone-borne expander. In a study where pure bone-borne MARPE (supported with only four miniscrews) was compared to the tooth- and bone-borne combination MARPE (four-miniscrews and a palatal bar between the first molars) 100% success was achieved in midpalatal suture separation. However, the bone-borne appliance caused a significantly more significant skeletal width increase, fewer dental side effects, and less buccal bone reduction than the combination MSE appliance.[30]

Depending on where and how the miniscrews are inserted, it is possible to use longer miniscrews and obtain bicortical anchorage, including the palate and the nasal floor. While it may be argued that obtaining bicortical anchorage is not associated with success,[24] bicortical anchorage could reduce the lateral drift of the miniscrews when subjected to heavy forces.

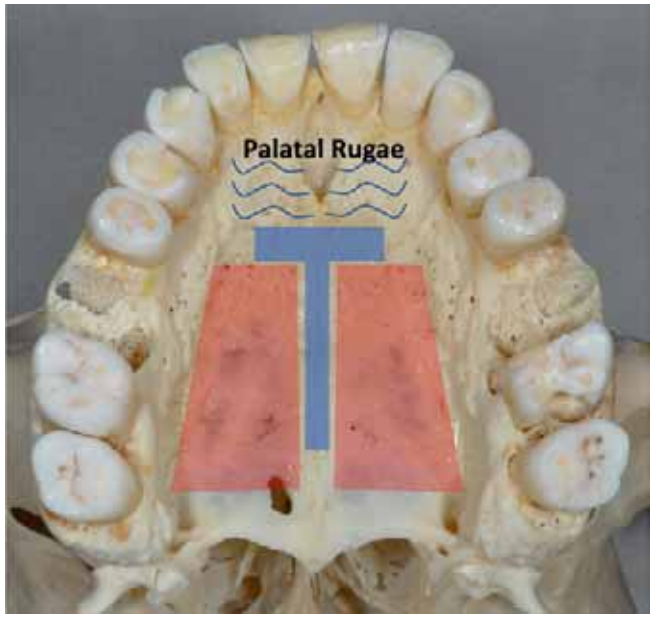

FIGURE 7 The "T zone": redrawn from Wilmes et al.[32]

In general, the anterior palate offers an outstanding amount and quality of bone, particularly an area distal to the third rugae extending medially toward the bicuspids and over the midpalatal suture posteriorly. Clinicians refer to this area (Figure 7) as the "T-zone."[31,32] Extensive research has been done in the anterior palate region and confirmed the presence of adequate quality bone for miniscrew placement.[33–38] When viewed from the profile, that is, looking at a cephalometric radiograph, maxillary bone tapers from anterior to posteriorly. Therefore,

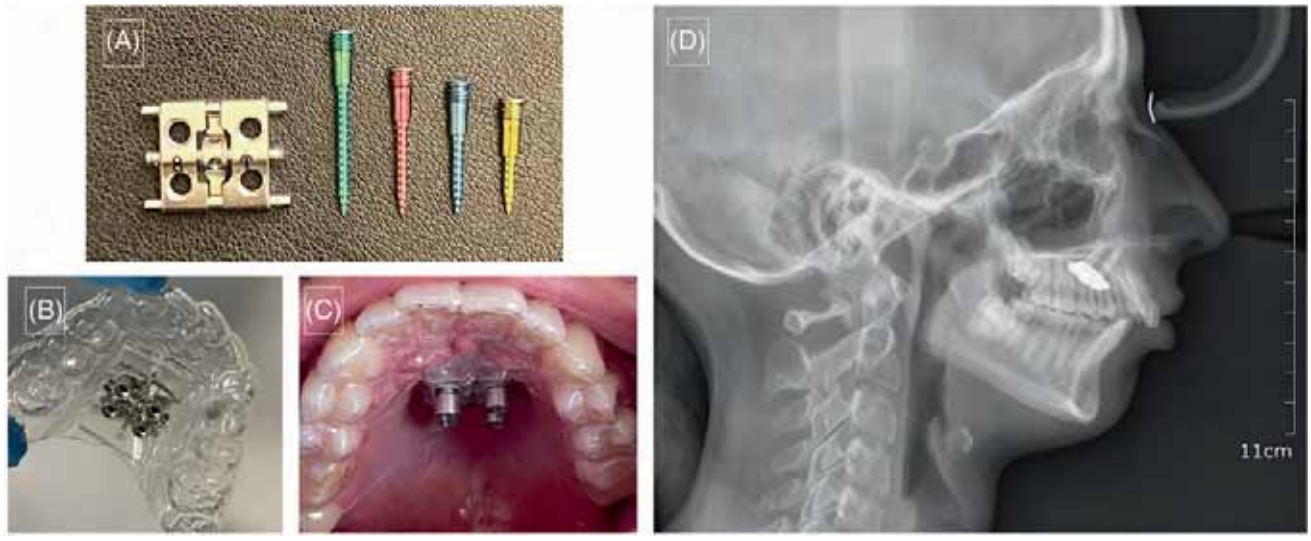

FIGURE 8 (A) Principal components of the UxL system: the bone-borne expander screw and the miniscrews. (B) Transfer template made out of thermoplastic material. (C) Transfer template seated in the mouth with guiding tubes installed for predrilling. (D) Bone-borne MARPE appliance installed with miniscrews

placing miniscrews outside the T-zone may be problematic for achieving adequate bone support and may, therefore, cause pronounced dislocation in the miniscrew positions. From an ergonomic point of view, it makes sense to host all four miniscrews within the anterior palate—hosted within a reasonable amount of cortical and trabecular support. Within this framework, a new MARPE concept was designed to position the expansion screw directly on the incline of the anterior palate.

In our reconceptualized MARPE design (Unite by Locking, UxL System), laboratory work is minimized significantly in addition to all the anatomic advantages of miniscrew placement. The square-shaped expansion screw consists of a turnbuckle screw and four mini holes to accommodate the insertion of miniscrews (Figure 8A). There is no need to weld or solder any other pieces to the expansion screw. The mini holes on each corner of the expansion screw are compatible with guiding tubes, predrilling burs, and the miniscrews that are used to fix the appliance on the palatal bone.

Before the appliance insertion process, minimal laboratory preparation is needed. The clinician decides on the exact positioning of the appliance using the rugae anatomy and considering the position of maxillary incisor roots. The expansion screw should be positioned slightly distal to the third rugae and parallel to the palate's anterior incline. Three-dimensional digital or plaster dental models can be used to arrange the position of the expander and fabricate a transfer template (Figure 8B) using thermoplastic materials or 3D printing.

After the expansion device is positioned parallel to the curvature in the anterior palate during the laboratory preparation, the mini holes are used to tighten the guiding tubes on the expander. Guiding tubes are used (Figure 8C) during the predrilling stage, and their purpose is to ascertain a perpendicular insertion into the cortical bone in that area. After the pilot holes are drilled, guiding tubes can be removed, and miniscrews can be inserted.

The miniscrews are cylindrical and tapered and have a diameter of 2 mm and an effective drilling length of 6.0–14.0 mm (Figure 8A). The total length of the screws range between 13 and 21 mm. Pretreatment cephalogram or cone-beam CT may be used to evaluate the bone height and thickness when selecting the appropriate length miniscrews. Usually, longer miniscrews are required in the anterior, and shorter miniscrews are used in the posterior that will engage in both the oral and nasal cortical bone layer of the palate (Figure 8D). Careful planning is the key to obtaining bicortical anchorage and eliminating the need to use the same size long miniscrews. Using the same size long miniscrews, especially toward the posterior palate, could cause miniscrews to penetrate through the nasal floor and result in unwanted complications. Following the drilling stage, miniscrews are inserted into the bone using a manual driver. Once fully inserted, the miniscrew heads are specifically designed to thread through the expander holes and lock them in place. The locking of the miniscrews in the expander holes provides a fail-safe mechanism in case miniscrews become loose.

Once the expansion screw is installed in place using four miniscrews (bone-borne), there is no need for additional laboratory or clinical preparation. The device is ready for activation. Activation may start by turning the screw twice a day (0.5 mm/day) for the first week until a diastema is observed between the central incisors. Following occurrence of a maxillary midline diastema or radiographically confirming the split in the midpalatal suture, activation should be switched to one turn a day (0.25 mm/day) protocol for two more weeks. Usually, the activation is completed by 28 turns (7 mm total expansion). It is good to remember that each turn (1/4 activation) of the UxL expansion screw provides about 0.25 mm expansion. Therefore, the maximum expansion range to be expected from the turnbuckle screw is 8 mm.

Figure 9 displays the pre- and post-expansion clinical photographs of two young adults at the end of the 3-week expansion protocol. Both patients demonstrated a successful midpalatal suture expansion with harmonious symmetry between the right and left

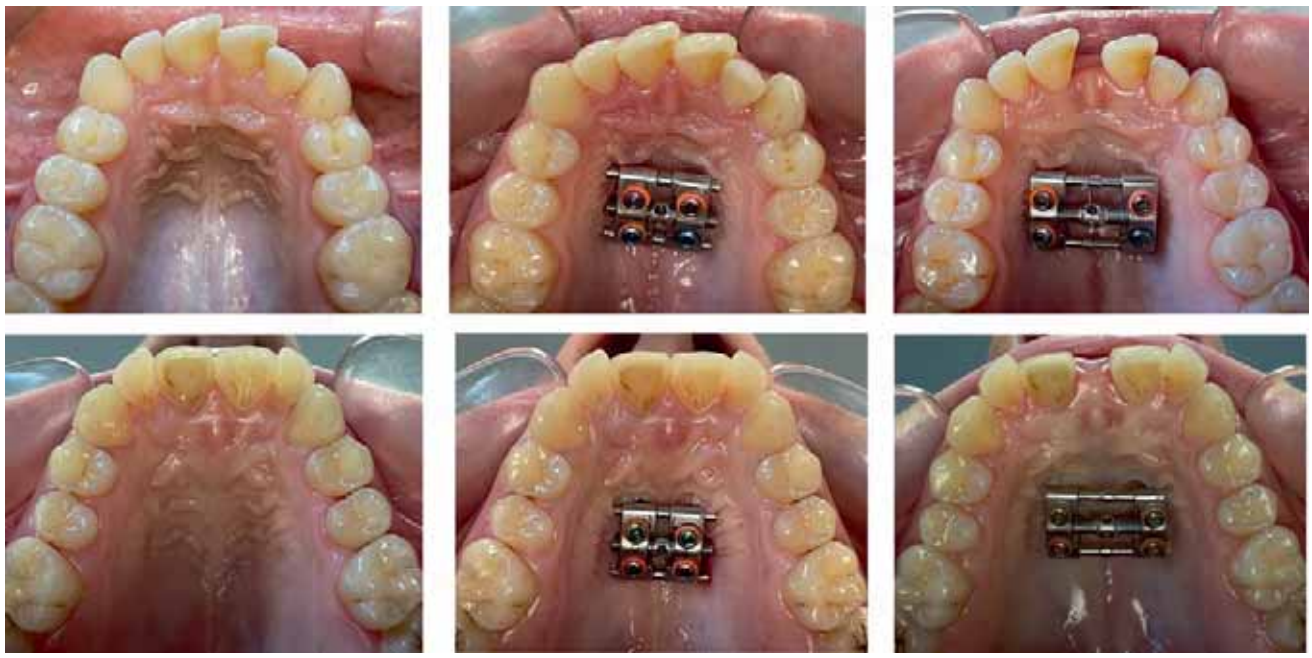

FIGURE 9 Pretreatment, pre-expansion and postexpansion clinical photographs of two adult patients treated with the new MARPE appliance (UxL system)

sides. Miniscrews were stable throughout the expansion process, and no complications were observed.

The installation of the expander appliance in the most convenient anatomic area of the palate at one clinical appointment, with no additional laboratory fabrication time, makes the appliance a perfect choice for adult patients. In essence, the UxL system is a bone-borne, non-surgical, and minimally invasive alternative for maxillary skeletal expansion in adults. While the initial clinical trials with this new MARPE concept yield promising results, its overall skeletal and dental effects should be compared and contrasted with other MARPE designs. Furthermore, there is a need to evaluate the appliance in individuals older than 30 years old to collect data on whether the utilization of bicortical anchorage in the anterior palate could expand the clinical limits of skeletal MARPE in adult patients.

5 | CONCLUSIONS

Miniscrew anchorage-supported rapid palatal expansion (MARPE) devices are associated with a high success rate in maxillary skeletal expansion in late adolescents and young adults. In addition to increased chances of midpalatal suture opening, lesser dental side effects and more pronounced orthopedic response have already clarified the scope of maxillary skeletal expansion. However, from an academic perspective, it is still an enigma to predict the reaction of midpalatal suture to MARPE in older individuals. Advances in the field enable us to make changes to the design of appliances while providing maximum bony support, as it was explained in this report. However, the time-related biological variation of the suture needs to be interpreted carefully. At the same time, well-controlled clinical studies are required to provide better opportunities to explore the newly introduced MARPE concept.

DISCLOSURE

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

Research data not shared.

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How to cite this article: Akyalcin S, Alev Y. Clinical advances in maxillary skeletal expansion and introduction of a new MARPE concept. *J Esthet Restor Dent*. 2023;35(1):291-298. doi:10.1111/jerd.12994

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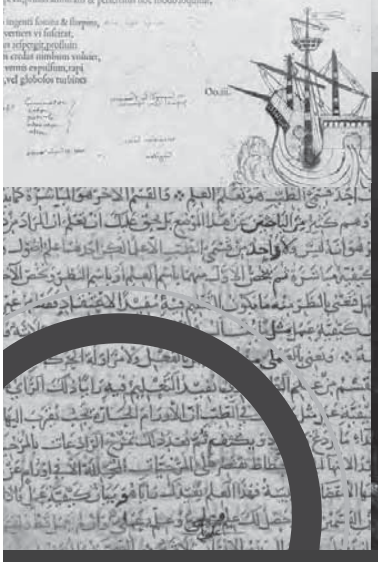

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