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REVIEW ARTICLE

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2D and 3D patient's representation of simulated restorative esthetic outcomes using different computer-aided design software programs: A systematic review

Wenceslao Piedra-Cascón DDS, MS[1] | Joshua Fountain DDS[2] | Wael Att DDS, Dr Med Dent, PhD[3] | Marta Revilla-León DDS, MSD[4,5,6]

[1]Affiliate Faculty Graduate in Esthetic Dentistry Program, Complutense University of Madrid, Spain and Researcher at Revilla Research Center, Madrid, Spain

[2]Private Practice, Dallas, Texas, USA

[3]Professor and Chair Department of Prosthodontics, Tufts University School of Dental Medicine, Boston, Massachusetts, USA

[4]Assistant Professor and Assistant Program Director AEGD Residency, Comprehensive Dentistry Department, College of Dentistry, Texas A&M University, Dallas, Texas, USA

[5]Affiliate Faculty Graduate Prosthodontics, Restorative Dentistry Department, School of Dentistry, University of Washington, Seattle, Washington, USA

[6]Researcher at Revilla Research Center, Madrid, Spain

Correspondence
Dr. Marta Revilla-León DDS, MSD, Assistant Professor and Assistant Program Director AEGD Residency, Comprehensive Dentistry Department, College of Dentistry, Texas A&M University, 3302 Gaston Avenue, Room 713 Dallas, TX 75246, USA.
Email: revillaleon@tamu.edu

Abstract

Objective: To review the techniques and available 2D and 3D computer-aided design (CAD) software programs to perform a diagnostic waxing for restorative procedures when cone beam computed tomography is not indicated.

Overview: An electronic review was performed in Medline, Embase, and Scopus search engines. A manual search was also conducted. The articles evaluating methods to obtain a 2D or 3D patient's representation for restorative dental procedures were included. A total of 33 articles were included for full text review. CAD programs provide the capability to integrate facial features from 2D photographs or 3D facial scans and facilitate facially driven digital diagnostic waxing procedures. Diagnostic and design tools varied among the programs, and multiple technique descriptions were found. However, the literature evaluating the accuracy of virtual patients and the perception variations between the 2D and 3D dimensional representations is limited.

Conclusions: The integration of digital technologies into treatment planning procedures introduce variation into the conventional interfaces; however, the concepts remain the same. Further studies are needed to evaluate the accuracy of the virtual representations and the influence of the type of dimensional representation on the esthetic perceptions among dental professionals.

Clinical significance: The 2D and 3D CAD software programs facilitate the integration of facial features into digital diagnostic waxing procedures; however, the esthetic perception of the patient's virtual representation might vary among the different systems.

KEYWORDS

3D virtual patient, CAD-CAM, computational superimposition, diagnostic waxing, prosthodontics

1 | INTRODUCTION

The success of esthetic dental prostheses relies on adequate diagnoses and treatment planning procedures.[1-5] The development of digital technologies such as facial and intraoral scanners and computer-aided design (CAD) software programs have allowed the integration of the digitally-acquired patient information and the obtainment of a patient's virtual representation.[6-10]

Creating a patient's virtual representation includes two main procedures namely facial and intraoral digitizing procedures and the superimposition procedures of the patient's digital information using a CAD software program.[11-16] Additional digital information provided by different sources, such as cone beam computed tomography (CBCT), can be also integrated into the patient's virtual representation.[17-19] However, a CBCT might not be indicated in all treatment planning procedures.[6,10,19]

Multiple 2D and 3D dental and non-dental CAD software programs and superimposition workflows are available to elaborate a facially driven diagnostic waxing,[10] which might overwhelm dental professionals. The purpose of the present manuscript was to review the techniques and available 2D and 3D CAD programs to perform a facially driven diagnostic waxing for restorative procedures when a CBCT is not indicated.

An electronic review was performed in Medline/PubMed, Embase, and Scopus search engines. A manual search was also conducted. The articles describing or evaluating methods to obtain a 2D or 3D patient's representation for restorative dental procedures using 2D photographs or 3D facial scans and intraoral digital scans or digitized diagnostic casts were included. The articles using either 2D or 3D CAD software programs were reviewed. The articles that used a CBCT for guiding the superimposition procedures were excluded.

The following MeSH terms, search terms, and their combinations were used in the search: ("dentistry" OR "dental") AND ("patient representation" OR "[MeSH] computer simulation" OR "[MeSH] computerized model") AND ("digital AND patient" OR "virtual AND patient" OR "virtual AND patient AND representation") AND ("facial scan" OR "extraoral scan" OR "laboratory scan" OR "intraoral scan" OR "intraoral scanner" OR "digital scan" OR "superimposition procedures" OR "merging procedures" OR "CAD-CAM"). A total of 54 title and abstract articles from the electronic search engines and 17 articles selected from manual search were reviewed. All titles and abstracts were first assessed for the following inclusive criteria which included English written articles that described or reported 2D or 3D patient's representation for restorative dental procedures. A total of 33 articles were selected for final full-text review.

TABLE 1 Summary of the main 2D and 3D CAD software programs

Software program classification	Manufacturer	Software program
2D Non-dental CAD	Adobe	Photoshop
	Apple	Keynote
	Microsoft	PowerPoint
2D Dental CAD	3Shape	Smile Design
	ADN3D Bioetch SRL	Smile Cloud Biometrics www.smilecloud.com
	ADSD - Dr. Valerio Bini	Esthetic Digital Smile Design
	Dentsply-Sirona	CEREC Smile Design
	Digital Smile Design	DSD App
	EGS Solutions	Smile Design Software
	Exocad	Smile Creator
	Just Digital	Digital Smile System
	Nemotec	NemoSmile
	Planmeca	Romexis Smile Design
	Tasty Tech Ltd.	Smile Designer Pro
	Web Motion LTD	VisagiSMile
3D Dental CAD	3Shape	Dental Systems
	Dentalwings	DWOS
	Exocad	Exocad Matera
	Nemotec	NemoStudio, NemoDSD
	ZirkhonZhan	ZirkhonZhan Software
3D Non-dental CAD	Autodesk	Meshmixer
	The Blender Foundation	Blender - Scripts: 1. Open Dental MOD 2. Open Dental CAD 3. Blender for Dental (B4D)
	Vectra	Vectra
	Visual Computing Lab	MeshLab

1.1 | 2D Non-dental CAD programs

Non-dental CAD software programs include presentation software applications such as Keynote or PowerPoint programs [20-23] or photography editing programs such as Photoshop (Table 1).[24,25] As an advantage, these programs can be used in any personal computer or laptop facilitating easy dental professional access, require a relatively low economic investment, and are user friendly.

Previous authors have reported methods to integrate presentation or photography editing software programs for treatment planning purposes of dental rehabilitations.[22-26] The techniques described include facial and dento-facial analysis using patient's photographs, integration of tooth templates, and facilitation of a photorealistic simulation of the digital diagnostic waxing outcome on the patient's photograph.[22-26] Furthermore, the tooth size calibration on the photographs is achieved by using a digital ruler which is standardized by measuring the width of the central incisors on the conventional diagnostic stone casts of the patient (Figure 1).[22,23]

Coachman et al[22] described a technique to elaborate a diagnostic waxing using presentation software applications for a maxillary anterior esthetic rehabilitation. Authors introduced the term digital smile design term (DSD) where classical concepts were adapted to more modern digital tools.[22] The combination of digital and conventional

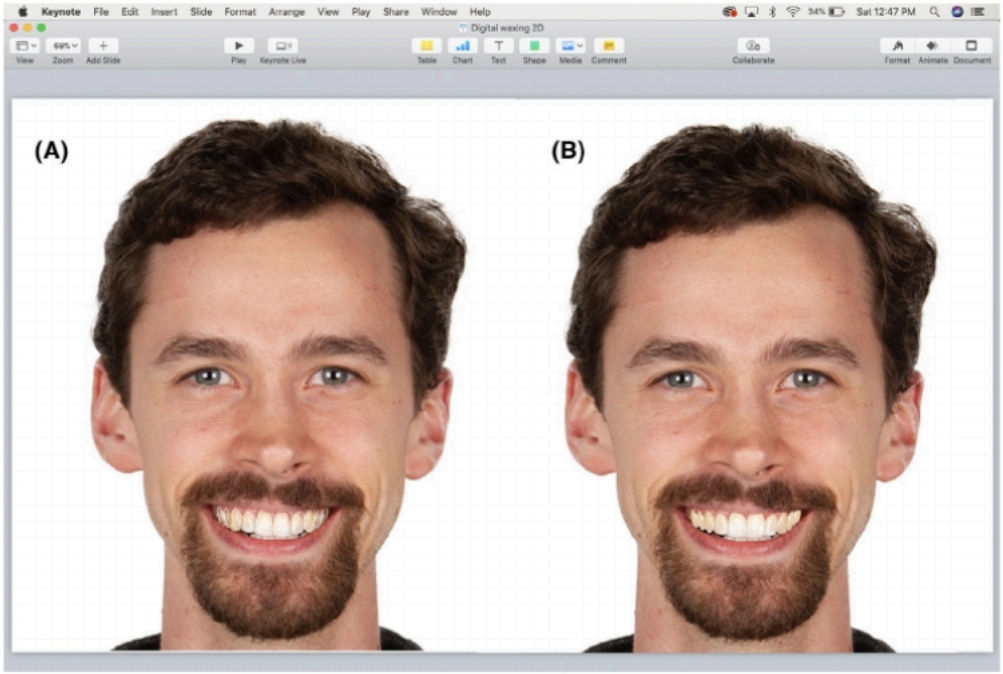

FIGURE 1 Diagnostic waxing simulation using a non-dental CAD software program (Keynote; Apple). (A) Tooth templates; (B) Photorealistic simulation outcome

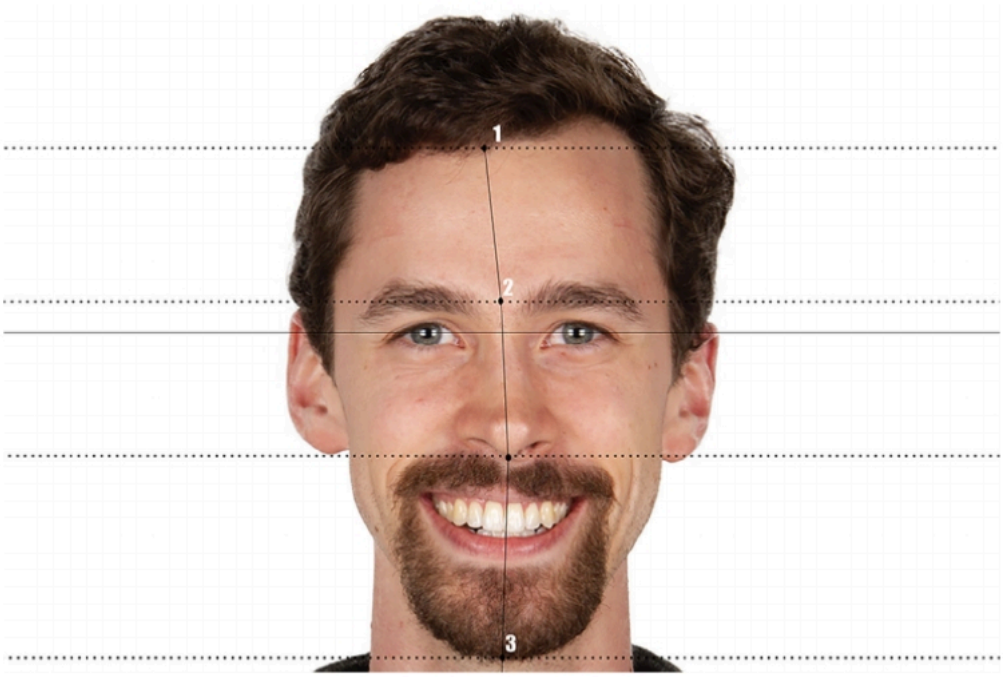

FIGURE 2 Curved facial midline concept with glabella (1), subnasal (2), and pogonion (3) landmarks

procedures facilitated the design of the diagnostic waxing into the patient's photographs, the transferring of the digital planning into the conventional diagnostic casts, and the conventional diagnostic waxing preparation. Subsequently, a diagnostic trial restoration is described to verify the outcome of the treatment planning procedures into the patient's mouth. Ultimately, ceramic veneers were performed on the maxillary anterior teeth.[22]

2D non-dental CAD procedures provide a communication tool between clinicians and dental technicians[22-26] and provide the capability of integrating the curved facial midline concept (Figure 2).[27] However, those 2D non-dental CAD programs only allow a 2D analysis of the facial and dento-facial features of the patient, require conventional impression procedures to obtain diagnostic conventional stone casts, involve manual size calibration procedures by transferring measurements obtained physically on the diagnostic stone casts to the software, and only provide the capability of exporting the simulation in a 2D forma0,t such as Joint Photographic Experts Group (JPEG) or Tagged Image File (TIFF) formats.

1.2 | 2D Dental CAD software

2D dental CAD software programs are specifically developed for dental professionals for use in private practice.[10] These programs aim to ease the elaboration of a facially driven digital diagnostic waxing in a 2-dimensional environment and simplify the creation of a photorealistic simulation of the diagnostic waxing outcome on the patient's photographs (Table 1).[10,28-30]

The step-by-step facially driven diagnostic waxing procedure is initiated with integration of the patient's photograph with the location of the vertical and horizontal facial line references which are used to orient the patient's head. Subsequently, the user can select multiple designing program tools to elaborate the diagnostic waxing such as proportion guides and tooth templates with different tooth shapes. One limitation of the 2D dental CAD programs is that the proportion guides and the vertical facial midline line cannot be customized; therefore, a curved facial midline cannot be implemented on those systems. Lastly, a photorealistic simulation of the diagnostic waxing outcome on the patient's photograph is generated (Figure 3).[10,28-30]

Previous authors have described the digital workflow to elaborate such 2D diagnostic waxing procedures integrated into patient's photographs for restorative treatment planning purposes.[28-30] Bini et al[28] reported the procedures using a dental software developed by the same author (Aesthetic Digital Smile Design; ADSD). Sharma et al[29] selected a 2D dental CAD program called VisagiSMile (Web Motion Ltd.) to elaborate a photorealistic simulation of the diagnostic waxing outcome on the patient's photographs in a 2D environment. Feraru et al[30] described a clinical case documentation where the diagnostic waxing procedures for an esthetic maxillary anterior rehabilitation was completed using the 2D CAD program, VisagiSMile.

Some of the 2D dental CAD software programs have incorporated further features such as the curved facial midline concept on the Digital Smile Design program[31] or a virtual cloud platform that incorporates artificial intelligence to provide a suggested tooth shape library based on the facial features of a patient, like on the Smile Cloud Biometrics program. As an advantage, the selected 2D tooth template can be downloaded as its correspondent natural tooth libraries in the standard tessellation language (STL) file format which can be imported into 3D CAD software programs to ease the diagnostic waxing procedures.

As a main limitation of the 2D CAD systems, the smile design is elaborated in a 2-dimensional format, using patient's photographs, without integrating the 3D virtual diagnostic casts of the patient.[10,28-30] Furthermore, 2D dental CAD programs do not allow software programming modifications and may also require an economic investment which includes an initial investment, renewal fees, and upgrades that allow for future development as the digital workflow improves.[10]

1.3 | 3D Dental CAD software

3D dental CAD software programs have been developed specifically for designing dental devices in a user-friendly workflow. However, these programs may require a significant economic investment and do not allow software programming modifications.

3D dental CAD software programs have the capability to import and merge the patient's digitized dentition by using an intraoral scanner or digitized conventional diagnostic stone casts by using a laboratory scanner and the 2D photographs or 3D facial scans files of the patient, creating a virtual patient.[6,10] Different protocols have been described to elaborate a facially driven diagnostic waxing depending on the file information format obtained namely 2D photographs or 3D facial scans using 3D dental CAD software programs (Table 2).[11,12,14-18,32-38]

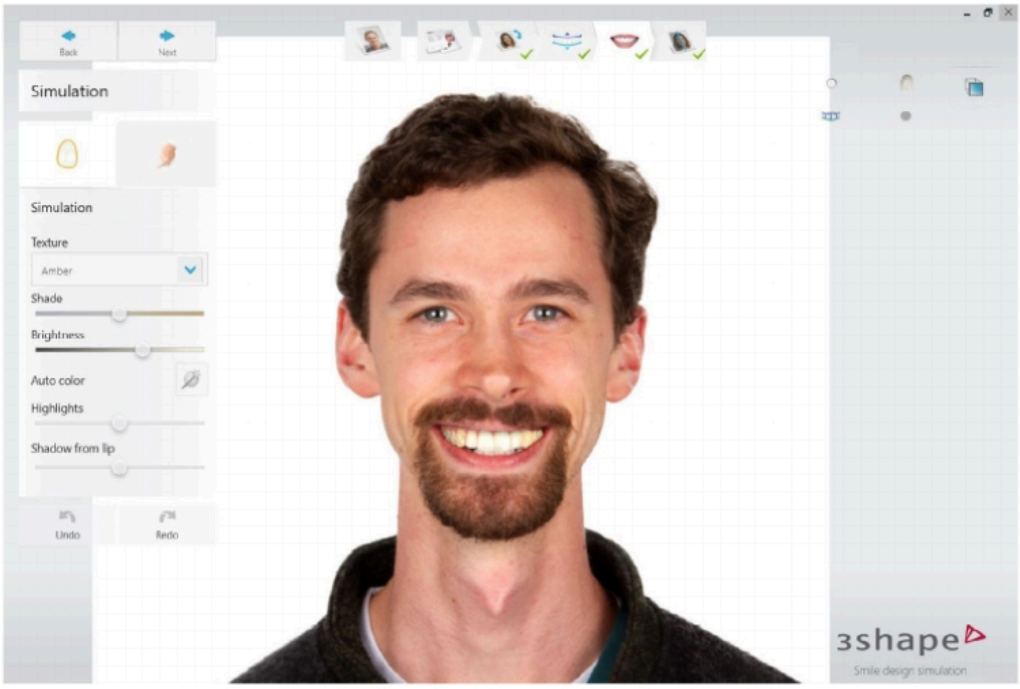

FIGURE 3 Diagnostic waxing simulation using a 2D dental CAD software program (Smile Design; 3Shape)

TABLE 2 Summary of dental literature describing techniques for virtual patient elaboration using 3D CAD software programs

Authors	Files merged	3D CAD Software used for superimposition procedures	Technique	Goal
Rangel et al[7] 2008	Digitized diagnostic casts 3D facial representation using a 3D stereophotogrammetrical camera	Maxilim software program, version 2.0.3 (Medicim NV, Mechelen, Belgium).	Iterative closest point algorithm	Technique description
Rosati et al[8] 2010	Digitized diagnostic casts 3D facial representation using a photogrammetry technique	Vectra software (Canfield Scientific, Fairfield, NJ)	Not described	Measure the accuracy and reliability of the 3D patient's virtual reconstruction
Katase et al[28] 2013	CBCT images converted into a STL file	Mimics; Materialize, Leuven, Belgium	Iterative closest point algorithm	Accuracy of face simulation for tooth arrangement preparation for complete denture fabrication
Joda et al[6] 2015	Intraoral digital scans Facial scans DICOM files of a CBCT	Not provided	Not described	Technique description
Cattoni et al[27] 2016	Intraoral digital scans 2D patient's photographs	Digital smile design (Digital Smile System Srl, Italy) 3D-Digital Smile System (EGS)	Iterative closest point algorithm	Milled diagnostic trial restorations Patient's satisfaction analysis
Hassan et al[11] 2017	Digitized diagnostic casts Facial scans	Priti-imaging software (Pritidenta GmbH, Leinfelden- Echterdingen, Germany) CAD software not provided	Iterative closest point algorithm	Design and manufacture milled immediate complete dentures
Hassan et al[17] 2017	Digitized diagnostic casts Facial scans	Priti-imaging (Pritidenta GmbH, Leinfelden- Echterdingen, Germany) CAD software not provided	Iterative closest point algorithm	Design and manufacture milled maxillary interim screw-retained implant-supported restorations
Coachman et al[35] 2017	Intraoral digital scans 2D patient's photographs	Digital Smile Design (DSD)	Iterative closest point algorithm	Technique description Diagnostic waxing elaboration, AM diagnostic waxing casts
Coachman et al[18] 2017	Intraoral digital scans 2D patient's photographs DICOM files of a CBCT	NemoDSD; Nemotec	Iterative closest point algorithm	Diagnostic waxing elaboration, implant planning, AM surgical guides, milled interim restorations
Revilla-Leon et al[12] 2018	Intraoral digital scans 2D patient's photographs	Dental Systems; 3Shape	Iterative closest point algorithm	Diagnostic waxing elaboration and silicone index design and manufacture for direct composite restorations
Cascón et al[13] 2018	DICOM files of a CBCT of hard and soft tissues converted into STL files. Facial scan through photogrammetry	Blender; The Blender Foundation Agisoft PhotoScan; Agisoft	Iterative closest point algorithm	Technique description Maxillary base plate and wax rim design and manufacture for a maxillary and mandibular complete-arch rehabilitation
Revilla-León et al[16] 2020	Intraoral digital scans Facial scans	Exocad Matera 2.4; Exocad	Iterative closest point algorithm extraoral and intraoral scan bodies	Diagnostic waxing elaboration and silicone index design and manufacture for direct composite restorations

Abbreviation: AM, additively manufactured.

3D dental CAD software programs allow a superimposition procedure to merge the 3D dentition with the 2D facial photographs using an iterative closest point (ICP) algorithm (Figure 4).[12,14-18,32,34-38] Similar to 2D CAD programs, facial feature analysis is guided by vertical and horizontal line references, tooth shape and proportion guides, and a photorealistic simulation of the diagnostic waxing outcome on the 2D patient's photograph.[12,14-18,32,34-38] However, as an advantage compared with the 2D CAD programs, the 3D dentition is used to elaborate the diagnostic waxing procedure which can be translated to the diagnostic trial restoration in the patient's mouth by additively manufacturing (AM) the diagnostic waxing cast,[34,35] milling the diagnostic trial restoration,[32] or AM the silicone index designed from the digital diagnostic waxing cast.[12,14-16,35-37]

A previous study compared patient satisfaction between the digitally designed pre-visualization simulation on the participant's photograph and the direct evaluation of the milled diagnostic trial restoration in 28 participants.[32] The virtual design of the additive

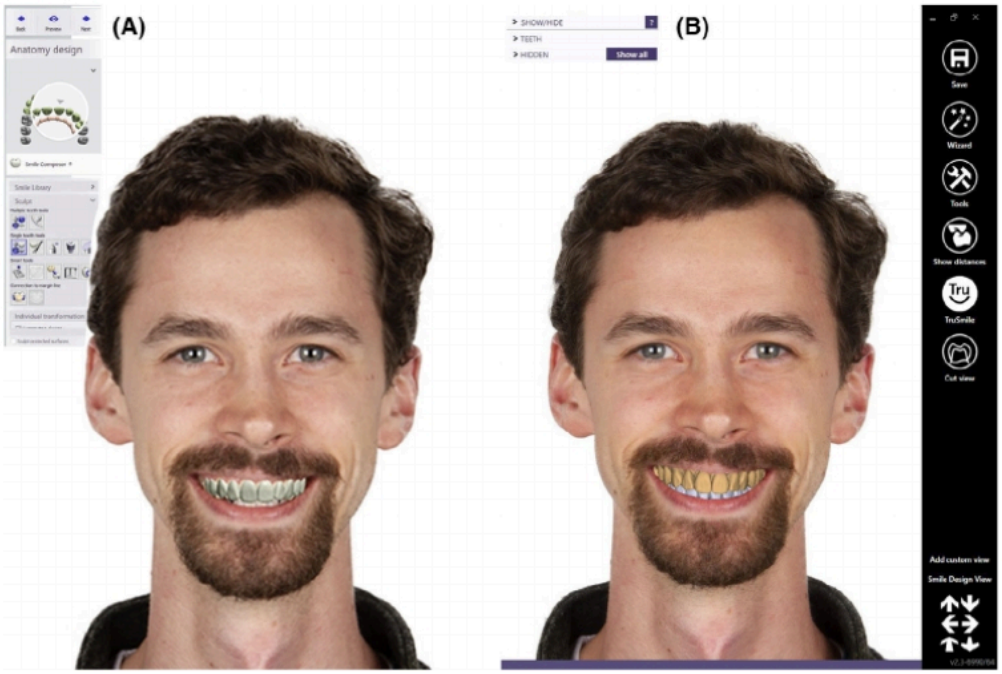

FIGURE 4 Diagnostic waxing elaborated using 3D dental CAD software programs integrating facial references with a 2D photograph. (A) Dental System; 3Shape, (B) Matera 2.4; Exocad

FIGURE 5 Diagnostic waxing elaborated using 3D dental CAD software programs integrating facial references with a facial scan. (A) Dental System; 3Shape. (B) Matera 2.4; Exocad

diagnostic trial restorations was completed in a 3D dental CAD software program (Digital smile system, DentalCAD; EGSolutions) merging the intraoral scan and the 2D full-face patient's photographs. The digital design was then manufactured into a milled diagnostic trial restoration. All of the participants graded both procedures as either "very effective" or "effective" approaches.[32]

A maxillary and mandibular implant-supported interim prostheses fabrication integrating a facially driven diagnostic waxing have been reported.[18] Authors merged patient's photographs and the digitized diagnostic stone casts using a 3D dental CAD software program (NemoDSD; Nemotec).[18] Furthermore, the CBCT of the patient was also merged for a prosthetically-driven implant planning procedure.

The workflow to elaborate a facially driven diagnostic waxing procedure using patient's photographs and intraoral digital scans in a 3D dental CAD software program (Dental Systems; 3Shape) has been also described in dental literature.[12,14,15] The authors transferred the diagnostic waxing into the patient's mouth by additively manufacturing a virtually designed silicone index for preparation of composite restorations and provisional restorations.[12,14,15]

In some 3D dental CAD programs, facial scans in STL, polygon file, and geometry definition file formats can also be imported.[11,16]

Dental literature has reported different techniques to superimpose intraoral digital scans or digitized diagnostic stone casts with the facial scans of the patient.[11,16,36-38] These techniques allowed the generation of the virtual patient when CBCT is not indicated (Figure 5).

A clinical study analyzed the viability of integrating facial scans and digitized definitive casts on the fabrication of immediate milled complete dentures.[11] Ten patients were engaged in the study.[11] All patients received the immediate dentures with satisfactory retention, stability, and esthetic outcomes. Similarly, in a posterior clinical study that involved 10 patients evaluated the feasibility of integrating facial scans and digitized definitive casts in the fabrication of implant-supported interim restorations.[17] Authors reported an esthetic outcome in 100% of the patients.[17]

A technique to superimpose patient's facial scans with maxillary and mandibular intraoral digital scans guided by extraoral and intraoral scan bodies and the iterative closest point algorithm in a 3D dental CAD software program (Matera 2.4; Exocad) has been reported.[16,36,37] Authors described the patient's 3D virtual representation for treatment planning of maxillary anterior esthetic rehabilitations including direct composite restorations and fiber-reinforce composite resin fixed dental prostheses. The digital diagnostic waxing was used to design and additively manufacture 3-piece[16,37] or 4-piece[36] silicone indices which aided transferring the diagnostic waxing into the patient's mouth.[16,36,37] After, the same technique has been described to treatment plan a complete-mouth rehabilitation accomplished with ultrathin CAD-CAM composite resin veneers for a patient with severe tooth wear.[38]

Dental literature analyzing esthetic perception disparities between the 2D and 3D patient representation among dental professionals and laypeople is scarce.[39,40] Previous authors concluded that differences in dimension significantly influenced the esthetic perception of the subjects, where the 3D facial simulations of particular dental discrepancies obtained higher esthetic ratings compared with the corresponding 2D simulations.[39] Therefore, esthetic discrepancies were detected to a lesser extent on the 3D visualizations. The same group of authors in a later study, evaluated the perception among the same population when rating the study participant's own 2D and 3D simulations of dental discrepancies.[40] Results showed that the classical acceptability ranges of dental discrepancies might not be followed when evaluating one's own simulation.[40]

1.4 | 3D Non-dental CAD software

3D non-dental CAD software includes non-dental, medical, non-medical, and open-source software programs that can be used to merge different 3D files.[7,8] Open-source programs are defined as programs liberally licensed to grant users the right to use, copy, study, change, and improve program design through the availability of its source code.[10,15,16]

In 2008, previous authors described a technique to superimpose the digitized diagnostic conventional stone casts with the 3D facial representation of the patient obtained by a 3D stereophotogrammetrical camera.[7] The digital files were merged using the iterative closest point algorithm in a 3D CAD program (Maxilim Software; Maxilim).[7]

Rosati et al[8] evaluated the accuracy of the 3D virtual representation obtained by superimposing the digitized diagnostic stone casts and 3D stereophotogrammetry facial scan in 11 subjects. The accuracy was evaluated by measuring linear distances from soft tissue to dental landmarks. The superimposition procedures obtained a mean error of 400 μm.

Open-source programs provide a variety of tools for measuring, analyzing, and modifying teeth libraries to perform a digital waxing. Open

FIGURE 6 Diagnostic waxing elaborated using 3D non-dental CAD software programs with an orthographic view.
(A) Meshmixer; Autodesk;
(B) Blender for dental 2.83; The Blender Foundation

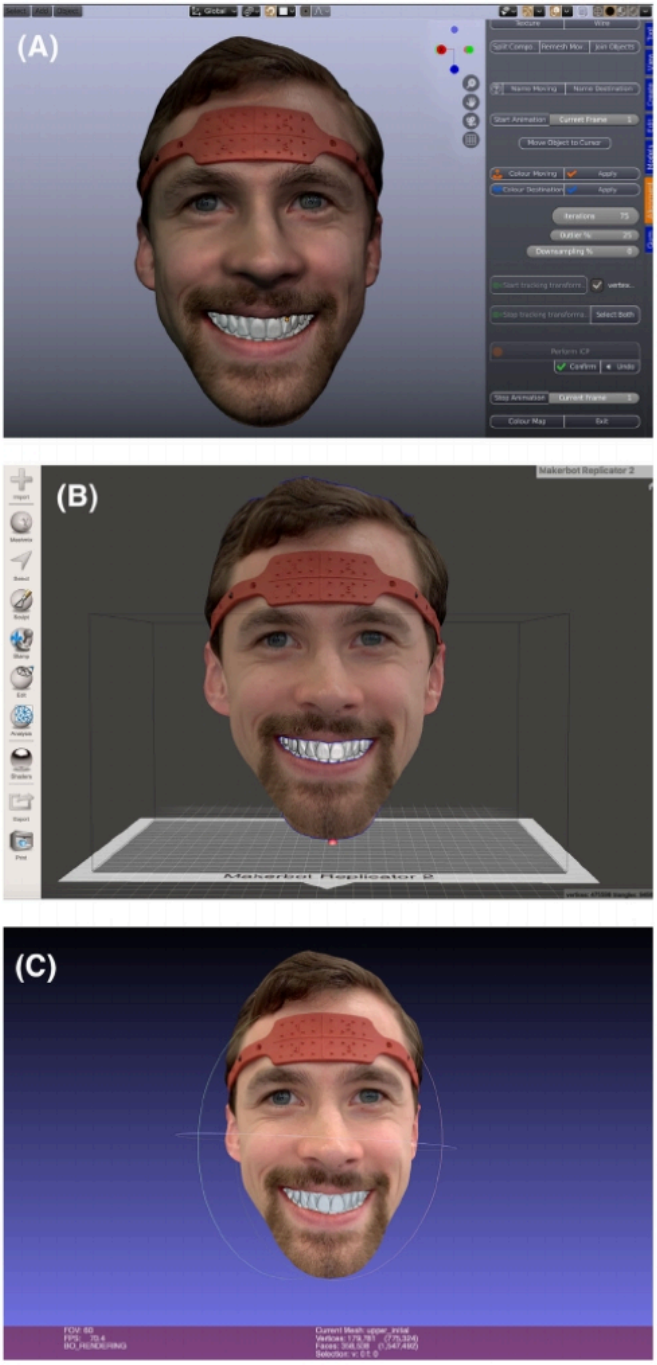

FIGURE 7 Diagnostic waxing elaborated using 3D non-dental CAD software programs with a perspective view. (A) Blender for dental 2.83; The Blender Foundation. (B) Meshmixer; Autodesk. (C) MeshLab; Visual Computing Lab

source programs offer flexibility in the designing process at a low-cost. As the main disadvantage, open-source programs do not guide the user into a step-by-step protocol, so the success of the virtual design relies on the knowledge and ability of the user.[10,15,16] Several different 3D CAD open-source software programs are available (Table 1).

An open-source CAD software program called Blender (The Blender Foundation) has recently incorporated different features for specific dental applications. The latest dental scripts incorporates the articulator tool, which allows importation of a 2D full face photograph or a facial scan and intraoral digital scans of the patient. The program permits merging of the photographs or facial scans and virtual diagnostic casts using the iterative point algorithm. Furthermore, the diagnostic casts can be mounted into a virtual articulator. A facially driven diagnostic waxing can then be prepared using the diagnostic and designing tools of the program (Figure 6).

Meshmixer (AutoDesk; CA, USA) is an open-source CAD software which can be used to analyze and edit 3D meshes. The program allows importation of different tooth libraries, which can be used for digital waxing purposes. Galibourg et al. described a dental technique to transfer the 2D teeth measurements and proportions of smile design to the 3D software to perform the digital diagnostic waxing over the intraoral scans of the patient.

Meshlab (Visual Computing Lab) is a mesh processing program which allows importation of all the 3D data sets of a patient along with alignment, cleaning, inspection, healing, and modification in order to visualize the final virtual patient rendering. However, this software does not allow creation of a virtual waxing by its 3D tools.

A technique to digitally design facially guided, baseplate and occlusal rims from the data obtained by the CBCT and facial scan of the patient using photogrammetry and a reverse engineering software (Agisoft PhotoScan, Agisoft) has been described.[13] The digital occlusal rims were additively manufactured to register the occlusal vertical dimension of an edentulous patient treatment planned to receive maxillary and mandibular fixed implant-supported rehabilitations.[13]

Lastly, 3D CAD open-source software programs have two possible visualization modes namely orthographic and perspective view, with the orthographic view being the most realistic (Figure 7). Furthermore, in both 3D dental and non-dental software programs, the 3D virtual representation is achieved in a computer screen which is a 2D visualization; therefore, the visualization is not a complete 3D representation.

2 | CONCLUSIONS

The integration of digital technologies into treatment planning procedures introduce variation into the conventional interfaces; however, the concepts remain the same. Further studies are needed to evaluate the accuracy of the 3D virtual representations and the influence of the type of dimensional representation on the esthetic perceptions among dental professionals.

DISCLOSURE

The authors did not have any conflict interest, financial or personal, in any of the materials described in this study.

ORCID

Wenceslao Piedra-Cascón https://orcid.org/0000-0002-2765-2207
Marta Revilla-León https://orcid.org/0000-0003-2854-1135

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