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ERD Journal of Esthetic and Restorative Dentistry VOLUME 28 | ISSUE S1 | 2016

EDITORIAL

S3 Digitally Enhanced Esthetic Dentistry – From Treatment Planning to Quality Control

> Christian Coachman, DDS, CDT, Rade D. Paravina, DDS, MS, PhD

RESEARCH ARTICLES

- S5 Color Correlations among Six Types of Permanent Anterior Teeth Yong-Keun Lee, DDS, PhD
- S14 Time Course of Potassium Nitrate Penetration into the Pulp Cavity and the Effect of Penetration Levels on Tooth Whitening Efficacy

So Ran Kwon, DDS, MS, PhD, MS, Deborah V. Dawson, ScM, PhD, Philip W. Wertz, PhD

S23 Susceptibility to Coffee Staining during Enamel Remineralization Following the In-Office Bleaching Technique: An In Situ Assessment

> Aline Akemi Mori, DDS, MSc, Fernanda Ferruzzi Lima, DDS, MSc, Ana Raquel Benetti, DDS, MSc, PhD, Raquel Sano Suga Terada, DDS, MSc, PhD, Mitsue Fujimaki, DDS, MSc, PhD, Renata Correa Pascotto, DDS, MSc, PhD

S32 Comparison of Contrast Ratio, Translucency Parameter, and Flexural Strength of Traditional and "Augmented Translucency" Zirconia for CEREC CAD/ CAM System

Alessandro Vichi, DDS, PhD,

Maurizio Sedda, DDS, PhD, Riccardo Fabian Fonzar, DDS, Michele Carrabba, DDS, PhD, Marco Ferrari, MD, DDS, PhD

S40 Gloss and Stain Resistance of Ceramic-Polymer CAD/CAM Restorative Blocks

> Nathaniel C. Lawson, DMD, PhD, John O. Burgess, MS, DDS

S46 Shade Correspondence, Color, and Translucency Differences between Human Dentine and a CAD/CAM Hybrid Ceramic System

> Ioana-Sofia Pop-Ciutrila, DDS, PhD, Diana Dudea, DDS, PhD, Mândra Eugenia Badea, DDS, PhD, Mărioara Moldovan, PhD, Sanda Ileana Cîmpean, DDS, PhD, Razvan Ghinea, PhD

S56 Spectrophotometric Analysis of the Influence of Metal Alloy Choice, Opaque Thickness, and Repeated Firing on the Shade of Metal Ceramic Restorations

> Khaled Q. Al Hamad, BDS, MSc, MRDRCSEd, FDSRCSEd, Mohammad M. Qadan, BDS, MSc, Ahed M. Alwahadni, BDS, MDSc, PhD

S68 Optical Dental Whitening Efficacy of Blue Covarine Toothpaste in Teeth Stained by Different Colors

Morgana Oliveira, DDS, Eduardo Fernández, PhD(c), DDS, Janaína Bortolatto, PhD, DDS, Osmir Oliveira Junior, PhD, DDS, Matheus Bandeca, PhD, DDS, Sharukh Khajotia, PhD, DDS, Fernando Florez, PhD, DDS

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DIGITALLY ENHANCED ESTHETIC DENTISTRY – FROM TREATMENT PLANNING TO QUALITY CONTROL

Digital aids complement a number of traditional dental procedures, with potential to enhance esthetic outcomes and create healthy, natural, beautiful and confident smiles. Digital technology is becoming a multi-use conceptual tool for dental treatment planning to strengthen diagnostics, improve communication/education, and enhance predictability of treatments.

Having no biological and functional problems is not sufficient for dental patients anymore. They desire beautiful smiles that are integrated with their physical characteristics and the emotional aspects. Dentistry has evolved further to meet highly esthetic demands and expectations of patients – the treatments are becoming more precise, delicate, minimally invasive, comfortable and faster. In achieving this, we must go beyond the boundaries of traditional dentistry and acquire a set of artistic/communication skills and vision, and this is where technology can play a pivotal role.

In view of the abovementioned, some of potential benefits of digital dentistry include the following: improvement of treatment planning and "smile design" process, transforming the patient into a co-author of his/her own new smile; development of effective communication protocol that facilitates interdisciplinary dentistry; increase of the perceived value of a dental treatment and consequently its acceptance through better education and motivation; and generating efficient and predictable clinical procedures and the final outcome similar to initial project presented to the patient.

The digital "smile design" workflow typically starts with specific videos of the patient that will allow the development of a "Facially Guided Smile Frame" that will suggest the ideal 3D position of the upper jaw (teeth and gingiva) according to lips and face in motion. The initial 2D frame can be translated into interdisciplinary software platform, allowing the team to use this digital tool to improve the decision-making process during treatment planning phase and perform the treatment according to this plan. This process decreases the amount of intra-oral adjustments and also works as an educational tool to improve the communication between dentists, specialists and patient.

New technologies brought a number of potential benefits and, to certain extent, a paradigm shift, changing the way we do traditional procedures. These include:

- 1. Dynamic dentofacial analysis, which provides the advantages of analyzing the smile in motion for better smile design/face integration, treatment planning decisions and communication with patient.
- 2. Taking photos from videos (snap shots) instead of taking photos directly from the patient multiplies the amount of moments captured.
- 3. Simplified documentation with smart phones.
- 4. Digital Ruler, a simple tool to make measurements on photos utilizing PowerPoint and/or Keynote.
- Visualizing the esthetic potential and developing a 3D understanding of the case by creating a simple 2D smile frame over three photos in specific angles of the patient.
- Online asynchronous communication protocol. Combining popular software (slide presentation software + dropbox/cloud sharing + whatsapp/ messaging app) to make treatment planning and interdisciplinary communication possible on a daily basis with no excess time or the need for live meeting.

EDITORIAL

- Buccal wax-up concept. Linking the facially guided smile design and functional treatment plan to generate simple and minimally invasive facially guided treatment plan.
- 8. Digital wax-up software enables connection between 2D and 3D.
- 9. Complete digital workflow. Connecting the facially guided digital wax-up to 3D orthodontic and orthognathic software, guided surgery and CAD/CAM software. Digitally designed models, guides, appliances, components and restorations complement traditional (sometimes) unpredictable procedures.
- 10. Interdisciplinary dental software platform can be used by different specialties for making timely clinical decisions.
- 11. Natural looking anterior monolithic CAD/CAM restoration. Bringing natural morphology and texture to CAD/CAM systems. Creating natural morphology and texture without handmade wax-ups and/or layering.
- 12. Digital quality control procedure after orthodontic treatment, crown lengthening, direct composites, wax-ups and indirect restorations, or in between procedures.

Technology is changing our profession for better and the future of digitally enhanced esthetic dentistry appears to be bright and exciting. We should not fear the evidence–based changes, but instead, we should embrace and take advantage of them. However, the basic principles of high quality dentistry remain pretty much the same and dental professionals would still have to invest in their traditional training in order to get into position to benefit from the advances in digital dentistry.

The editorial on digital dentistry blends well with this digital-only issue on color and appearance. It is our

pleasure to acknowledge the support we received from Harald Heymann, the editor in chief of Journal of the Esthetic and Restorative Dentistry and Mrs. Betty Cates of the editorial office, and Tom Pierson of Wiley and the publishing team. We would also like to thank our peer reviewers for their support and diligence: Judit Borbely, Razvan Ghinea, Joshua Kristiansen, William M. Johnston, Robert J. Kelly, Gerard Kugel, Yong-Keun Lee, Joe C. Ontiveros, John M. Powers, and Alvin G. Wee.

We thank all the authors who submitted their manuscripts to our journal. Papers published in this issue report on: color comparison among different types of teeth; tooth staining and whitening;, translucency and gloss of CAD/CAM restorative materials and compatibility of their optical properties with human dentine; and influence of various factors on color of metal ceramic restorations. We are looking forward to keep receiving your manuscripts. We will do our best to publish the best clinical and in vitro research.

Christian Coachman, DDS, CDT*

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Color Correlations among SixTypes of Permanent AnteriorTeeth

YONG-KEUN LEE, DDS, PhD*

ABSTRACT

Statement of Problem: When multiple teeth are missing, the color for missing teeth should be estimated based on the color of remaining teeth.

Purpose: The purpose was to determine the strength of color correlations among six types of permanent anterior teeth.

Methods: Color of I2 anterior teeth was measured by Shade Vision System for 47 volunteers. The color coordinates in each type of teeth such as maxillary central incisor (MXI), lateral incisor (MX2), and canine (MX3), and mandibular central incisor (MDI), lateral incisor (MD2), and canine (MD3) were determined. Correlations and differences among the corresponding color coordinates of each type of teeth were determined.

Results: Compared with MXI, the differences were in the range of -3.2 to -6.5 in L^* , 0.5 to 2.7 in a^* , -0.7 to 7.5 in b^* , and the color difference (ΔE^*_{ab}) was 4.5 to 10.3. The color difference by ΔE_{00} formula was 3.1–6.7. Although the color coordinates were different by tooth type, they generally showed correlations (p < 0.001).

Conclusions: For the color estimation of missing MXI, the color coordinates of MDI were the strongest predictors. In case of missing MX3, L^* and a^* of MD3 and b^* of MXI were the strongest predictors for each corresponding coordinates.

CLINICAL SIGNIFICANCE

The color for missing teeth, especially for maxillary central incisor and maxillary and mandibular canines, could be estimated based on those of the same type teeth on the opposing arch. These results should be applied for clinical color selection for missing teeth.

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INTRODUCTION

Knowledge on the human teeth color and its distribution is critical for dental shade matching.¹ Light scattering and absorption within enamel and dentine give rise to the intrinsic tooth color, and the properties of dentine can play a major role in determining the overall tooth color since enamel is relatively translucent.² Factors influencing the tooth color may include genetic, congenital, metabolic, chemical, infectious and environmental.³ The shade and appearance of tooth is a complex phenomenon because many factors such as lighting conditions, translucency, opacity, light scattering, gloss, and the human eye and brain influence the overall perception of the tooth color.³ The optical properties of human teeth are also influenced by their external configuration. Tooth dimension, shape and surface structure generate light reflection patterns, which influence the overall tooth color. Knowing that the amounts of reflected and absorbed lights depend on the thickness and translucency of tooth structure, it is evident that the thickness of enamel and dentine affects the tooth color.⁴ Inherited diseases may influence the thickness of enamel, or the mineral and organic contents of enamel, and therefore, can affect tooth color.⁵

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Variations in enamel thickness by tooth type were determined.^{6,7}

The application of color science has permitted the measurement of tooth color in an objective way.⁸ Indeed, many investigations determined the human teeth color.^{2,9,10} These investigations reported broad ranges in the Commision Internationale de l'Eclairage (CIE) color coordinates such as L^* , a^* and b^* values.^{2,8} These broad ranges were most likely due to the differences in measurement methods. For example, the color coordinates based on small-window colorimeter or spectrophotometer deviated significantly from those determined using a spectroradiometer.⁹ Despite these issues, colorimeters have been shown to be highly sensitive for the tooth color measurements.^{3,11,12} For an adequate color reproduction in dental restorations, it is also valuable to quantify the color distributions within each tooth.⁴ Each tooth does not have a single uniform color, and the middle region appears to represent the tooth color best.¹³ Color of human teeth showed gradation from cervical to incisal region,¹ and both reddish and yellowish hues tended to increase from incisal to cervical region.¹⁴

Although the CIELAB color difference formula (ΔE^*_{ab}) is widely used in dentistry,⁸ new color difference formulae are being developed to make a single-number shade pass/fail equation for evaluating the small to medium color differences. The CIEDE2000 color difference formula (ΔE_{00}) based on the CIELAB, which includes not only lightness, chroma, and hue weighting functions, but also an interactive term between chroma and hue differences for improving the performance for blue colors and a scaling factor for the CIELAB *a*^{*} scale for improving the performance for gray colors, was introduced.^{15,16} The formula has been officially adopted as the new CIE color difference equation.

Achieving natural looking restoration is one of the most challenging aspects in dentistry, and also the shade matching of restorations with natural dentition is a difficult task.¹⁷ Shade matching is an important step in the esthetic restoration of the missing or discolored teeth, and shade guides are generally used for shade matching with neighboring teeth. We

normally use the color of neighboring teeth for shade matching and selection; however, there are times for example that all the maxillary incisors are missing. In these cases, the color for missing teeth should be estimated based on the color of remaining teeth. Although it had been supposed that teeth color might be estimated based on skin color, there was only moderate agreement between the skin color and tooth shade.¹⁸ As to the color variations of teeth by tooth type, a colorimetric examination of permanent anterior teeth showed that maxillary anterior teeth were generally yellower than mandibular anterior teeth. On average, canines showed lower lightness than their adiacent incisors.¹³ There was a relation in color between the maxillary incisors and canines due to the uniform distribution of enamel and dentine thicknesses in these teeth.¹⁹ The color relations among all types of primary teeth were evaluated.²⁰

As to the perceptible and acceptable color difference thresholds based on the CIELAB formula,⁸ varied values have been proposed. Values of $\Delta E^*_{ab} < 1$ were regarded as not appreciable by human eye, and values $1 < \Delta E^*_{ab} < 3.3$ were considered appreciable by skilled operators but considered clinically acceptable, whilst values of $\Delta E^*_{ab} > 3.3$ were considered appreciable even by nonskilled persons and for that reason clinically not acceptable.^{21–23} Color difference values (ΔE^*_{ab}) of 1, \leq 2, and >3.7 were considered to be perceptible,^{24,25} to represent a clinically acceptable difference,²⁶ and to be a mismatch by the US Public Health Service criteria,^{25,27,28} respectively. In recent studies, the perceptibility and acceptability thresholds for dental ceramics were determined using both of the CIEDE2000 and the CIELAB color difference formulae.^{29,30} The CIELAB 50:50% perceptibility threshold was $\Delta E^*_{ab} = 1.2$, whereas 50:50% acceptability threshold was $\Delta E^*_{ab} = 2.7$. Corresponding ΔE_{00} values were 0.8 and 1.8, respectively.³⁰

Previous studies on the color correlations among teeth types were restricted to semiquantitative hue, value and chroma scale,¹³ investigated only maxillary permanent anterior teeth,¹⁹ or investigated primary teeth.²⁰ Therefore, quantification of the color correlations among the six types of permanent anterior

teeth would provide broader insights for the color selection of multiple missing teeth. The working hypotheses were (1) the color coordinates of six types of permanent anterior teeth in the same person were significantly correlated and (2) the color difference with an arbitrary reference tooth (maxillary central incisor) was in the range of acceptable ($\Delta E^*_{ab} < 2.7$).³⁰ The purposes were to determine whether there were significant correlations in the color coordinates of six types of permanent anterior teeth, and to check the possibility of estimation of missing teeth color with the color of remaining teeth.

MATERIALS AND METHODS

Tooth Color Measurement

Color of anterior teeth in 47 volunteers was measured (number of teeth = 564). Approval was obtained from the institutional review board and informed consent was obtained from each volunteer. Through clinical examination, it was confirmed that they did not have caries, abraded lesions or restorations in any of the anterior teeth. Eight males and 39 females were included, and their mean age was 29.5 (\pm 5.2) and 29.0 (\pm 6.8), respectively.¹²

Color of 12 maxillary and mandibular anterior teeth was measured by Shade Vision System (X-rite, Grandville, MO, USA). This device is a clinical colorimeter that utilizes image-grabbing technology, and provides a colored contour map image of the tooth. It comprises a handheld measuring instrument that is used to scan the tooth surface together with a docking station linked to a computer and associated software.³¹ The accuracy of this device is less than 1/2 shade guide unit through Vita 3D-Master Shade Guide as presented by the manufacturer. To exclude the influence of direct sunlight, all the measurements were performed between 5 PM and 6 PM at a dental unit chair not receiving any direct sunlight, and one dentist measured the color using the same measurement protocol. Aperture head was contacted at the center of each tooth. Measurements were repeated three times.

Distributions of the CIE L^* , a^* and b^* coordinates of each type of teeth such as maxillary central incisor (MX1), lateral incisor (MX2) and canine (MX3), and mandibular central incisor (MD1), lateral incisor (MD2) and canine (MD3) were compared. It was concerned whether the color of the same type of teeth on the right and left sides might be different. Therefore, the starting data used in the color estimation were the mean values of the same type of teeth in the right and left sides in each person. As to the differences in the color coordinates between the right and left sides, absolute values (not negative values) were calculated because right or left side was not the concern of this study. The CIELAB color difference between the pair was calculated as: $\Delta E_{ab}^* = [(L_r^* - L_l^*)^2 + (a_r^* - a_l^*)^2 + (b_r^* - b_l^*)^2]^{1/2}, \text{ in }$ which subscript r and l indicate right- or left-sided tooth, respectively.⁸ Differences in the color coordinates and color compared with MX1 (color coordinate of each tooth-corresponding coordinate of MX1 in the same person) were calculated with the CIELAB formula,⁸ and color difference was also calculated with the CIEDE2000 formula.¹⁶

Statistical Analyses

Statistical analyses were performed under the α level of 0.05 with the Bonferroni correction.³² Significant differences between the corresponding color coordinates of each type of teeth with MX1 were determined with paired t-test (p < 0.003). Correlations among the corresponding color coordinates of each type of teeth were determined with a linear regression analysis (p < 0.001), and the Pearson correlation coefficient was calculated.

Color estimation was made supposing the missing both of the same type of teeth in the right and left sides. The other five types of teeth were supposed to remain. The predictability for the color coordinates of missing teeth based on the corresponding coordinates of other five types of teeth was estimated with a multiple regression analysis with a forward method (p < 0.001). To eliminate the impact of interrelated predictors, the predictor which showed the lower standardized partial



FIGURE I. Differences in the color coordinate and color between the right and left teeth in the same person.

TABLE I.	Distributions	of the mean	color coord	linates of
each type of	fteeth			

Tooth	CIE L*	CIE a*	CIE b*
MXI	78.0 (2.5)	3.8 (0.9)	16.4 (2.4)
MX2	74.8 (2.5)*	4.8 (I.I)*	18.4 (2.5)*
MX3	71.5 (2.4)*	6.4 (I.I)*	23.5 (2.4)*
MDI	73.5 (3.0)*	4.3 (0.9) [†]	I5.7 (2.2) [†]
MD2	73.7 (2.2)*	4.8 (0.9)*	18.7 (2.2)*
MD3	72.4 (2.1)*	6.0 (1.1)*	23.8 (2.2)*

MXI = maxillary central incisor; MX2 = lateral incisor;

MX3 = canine; and MDI = mandibular central incisor;

MD2 = lateral incisor, MD3 = canine

*Significantly different compared with that of MXI based on paired t-test (p < 0.003).

[†]Not different.

correlation coefficient (β) was not included in the regression when the tolerance between two influencing variables was lower than 0.30.³³

RESULTS

Differences (mean of absolute values) in the color coordinates and color between the same type of teeth on the right and left sides in the same person are presented in Figure 1. Each differently shaded bar



FIGURE 2. Difference in the color coordinates and color compared with the maxillary central incisor (MXI).

indicates the difference in each of the color coordinates (CIE L^* , a^* , and b^*) and color (ΔE^*_{ab}), and the total height of the stacked bar indicates the cumulative amounts of differences in color coordinates and color between the right- and left-sided teeth. The range of differences by tooth type for L^* was 1.2–2.7, that for a^* was 0.5–0.9, that for b^* was 1.0–1.9, and that for the color difference was in the range of 1.8 (SD; standard deviation: 1.0) in MD1 and 3.2 (2.1) in MD3.

Distributions of the mean color coordinates of each type of teeth are presented in Table 1. The values of MX1 for L* was 78.0, a* was 3.8 and b* was 16.4. These values shifted to 71.5, 6.4, and 23.5, respectively, in MX3. Based on paired t-test, all the three color coordinates showed significant differences compared with those of MX1 (p < 0.003), except for a^* and b^* value of MD1. Differences in the color coordinates and color compared with MX1 are presented in Figure 2. The difference in L^* compared with MX1 was in the range of -3.2 (SD: 2.2) in MX2 to -6.5 (2.0) in MX3. The difference in a^* was in the range of 0.5 (0.9) in MD1 to 2.7 (1.1) in MX3. The difference in b^* was in the range of -0.7(2.1) in MD1 to 7.5 (2.4) in MD3. The color difference (ΔE^*_{ab}) was in the range of 4.5 (2.6) in MX2 to 10.3 (2.4) in MX3. The color difference in the CIEDE2000 formula (ΔE_{00}) was 3.1 (1.7) in MX2, 6.7 (1.6) in MX3, 3.7 (1.5) in MD1, 3.8 (1.7) in MD2, and 6.0 (1.7) in MD3. The color difference values in two formulae showed similar trend by the tooth type.



FIGURE 3. Scatter plot of the CIE *L** values of upper central incisor (MX1) and lower central incisor (MD1). Blue line is regression equation.

Scatter plot between the L^* values of MX1 and MD1 is presented in Figure 3. They showed a significant correlation (p < 0.001), and the following regression equation was obtained: L^* of MD1 = 0.85 × L^* of MX1 + α (r = 0.71). Pearson correlation coefficients (r) between the corresponding color coordinates are listed in Table 2. Five pairs did not show significant correlations, but all other pairs showed correlations (p < 0.001).

Multiple regression results for the color coordinate estimation of missing teeth are listed in Table 3. For the color estimation of missing MX1, the corresponding color coordinates of MD1 were the strongest predictors followed by those of MX3. In case of missing MX3, L^* and a^* values of MD3 and b^* value of MX1 were the strongest predictors for each corresponding coordinates. In case of missing MD1, L* and b^* values of MD2 and a^* value of MD3 were the strongest predictors for each corresponding coordinates. In case of missing MD3, L^* and a^* values of MX3 and b^* value of MD2 were the strongest predictors. Therefore, missing color coordinates might be estimated based on the color of corresponding tooth on the opposing arch, not the neighboring teeth in the same arch, in several types of teeth.

DISCUSSION

The first working hypothesis that the color coordinates of teeth in the same person were significantly

TABLE 2. Pearson correlation coefficient (*r*) between the corresponding color coordinates

Tooth	Coordinate	MX2	MX3	MDI	MD2	MD3
MXI	CIE L*	0.62*	0.67	0.71	0.63	0.60
	CIE a*	0.46	0.48	0.53	NS^{\dagger}	0.51
	CIE b*	0.54	0.55	0.59	NS^{\dagger}	0.45
MX2	CIE L*		0.65	0.65	0.51	0.59
	CIE a*		0.46	0.56	0.52	0.52
	CIE b*		0.47	0.60	0.46	0.47
MX3	CIE L*			0.57	0.49	0.75
	CIE a*			0.46	NS^{\dagger}	0.79
	CIE b*			NS^{\dagger}	NS^{\dagger}	0.53
MDI	CIE L*				0.78	0.69
	CIE a*				0.71	0.72
	CIE b*				0.68	0.52
MD2	CIE L*					0.63
	CIE a*					0.67
	CIE b*					0.68
MXI = n	naxillary central i	ncisor; M	X2 = lat	eral incis	or;	

 $\begin{array}{l} \text{MX} = \text{maximary central incisor; } \text{MX} = \text{tateral incisor;} \\ \text{MX} = \text{canine; and } \text{MDI} = \text{mandibular central incisor;} \\ \text{MD2} = \text{lateral incisor; } \text{MD3} = \text{canine.} \\ \text{*Significant correlations were marked when } p \leq 0.001. \end{array}$

[†]No significant correlation.

correlated was partially accepted because the color coordinates of six types of anterior teeth were significantly correlated with the corresponding coordinates (p < 0.001) except for five pairs (Table 2). The second hypothesis that the color difference with an arbitrary reference teeth (MX1) was in the range of acceptable was rejected because the color difference was in the range of 4.5-10.3 (Figure 2), which was higher than the acceptable limit ($\Delta E^*_{ab} > 2.7$).³⁰ Since the color difference based on the ΔE_{00} formula was 3.1–6.7, these values were also higher than acceptable limit ($\Delta E_{00} > 1.8$).³⁰ The present results indicated that it would be better to use the color of opposing dentition for the color selection of missing teeth (incisors for incisors and canines for canines). For example, it might be better to use the mandibular

TABLE 3. Multiple regression results for the estimation of the CIE L^* , a^* , and b^* values of missing teeth using the values of remaining teeth

Tooth*	M issing [†]	Model [‡]	R§	lncluded predictors (β) [¶]
MXI	L*	I	0.71	MDI** ^{,††}
		2	0.78	MDI (0.49), MX3 (0.40)
	a*	I	0.53	MDI
	Ь*	I	0.59	MDI
		2	0.68	MDI (0.44), MX3 (0.37)
MX2	L*		0.65	MDI
		2	0.73	MDI (0.41), MX3 (0.41)
	a*		0.56	MDI
	b*	I	0.60	MDI
MX3	L*		0.75	MD3
		2	0.80	MD3 (0.54), MXI (0.35)
_	a*		0.79	MD3
	b*		0.55	MXI
MDI	L*		0.78	MD2
_		2	0.84	MD2 (0.61), MX2 (0.34)
	a*	I	0.72	MD3
		2	0.79	MD3 (0.44), MD2 (0.42)
	b*		0.68	MD2
MD2	L*		0.78	MDI
-	a*		0.71	MDI
	b*		0.68	MD3
		2	0.78	MD3 (0.45), MDI (0.44)
MD3	L*		0.75	MX3
		2	0.81	MX3 (0.53), MDI (0.38)

TABLE 3. Continued

Tooth*	Missing [†]	Model [‡]	R§	Included predictors $(\beta)^{ m I}$
	a*		0.79	MX3
		2	0.88	MX3 (0.58), MDI (0.46)
	b*	I	0.68	MD2
	_	2	0.77	MD2 (0.58), MX3 (0.37)

*This column indicates the supposed missing teeth. [†]This color coordinate was set as a dependent variable. And the independent variables were the corresponding coordinates of

other five types of teeth. [‡]Model indicates the number models by the included variables. [§]Multiple correlation coefficient. All of the significant *p*-values were lower than 0.001.

[¶]By the order of inclusion in the multiple linear model. Influencing tooth type (β =standardized partial correlation coefficient for each predictor). All of the significant *p*-values were lower than 0.001. **In any model with only I predictor, the *R* and β values were the same.

 $^{\dagger\dagger}\mbox{Bold}$ tooth type indicates the same type of teeth on the opposing arch.

incisors (opposing dentition) for maxillary incisors shade selection instead of using maxillary canines (neighboring teeth), which are shown in Figure 2 and Table 3. As the teeth position moved from central incisor to canine, L^* value decreased and b^* value increased in both of maxilla and mandible, which were the same in a previous report.¹⁸

As to the color estimation of missing teeth, for example MX1, the following regression equations might be used for the estimation of the color coordinates: L^* of MX1 = $0.40 \times L^*$ of MD1 + $0.41 \times L^*$ of MX3 + constant; a^* of MX1 = $0.41 \times a^*$ of MD1 + $0.25 \times a^*$ of MX3 + constant; and b^* of MX1 = $0.49 \times b^*$ of MD1 + $0.37 \times b^*$ of MX3 + constant. In these regressions, the *R* values were 0.53-0.78.

The color difference between the right and left teeth in the same person was lower than 2.7 in MX1, MX3, MD1, and MD2, and higher than 2.7 in MX2 and MD3 (Figure 1). The color difference values were acceptable or not-acceptable by tooth type.³⁰ As to the

correlations with the corresponding color coordinates of other types of teeth (Table 2), they showed significant correlations except two cases (r = 0.45 to 0.79, p < 0.001); therefore, though the values were different by tooth type, they generally showed significant correlations.

The relation of the CIE L^* , a^* and b^* values among permanent two maxillary incisors and canines was reported.¹⁹ As results, a significant correlation was found between central and lateral incisors for all the color coordinates in the middle region, while the mean L^* , a^* and b^* values of canine differed from those of central incisor (p < 0.01). Compared with the results of the present study, although central and lateral incisors showed significant differences in the color coordinates both in maxilla and mandible (Table 1), they showed significant correlations (Table 2). In the present study, the color of middle region of teeth was also measured because this resulted in accurate color determination and represented the color of teeth.^{13,34} It was reported that the type of teeth and the mesial and distal areas of teeth affected the repeatability and reproducibility of intraoral spectrophotometric measurements.³⁴ Therefore, these factors should have influenced the color values of the present study. Further investigations should be made.

Color of 20 primary teeth was determined to check the relationship among the color coordinates between each type of teeth.²⁰ The greatest color variation among teeth types in the maxilla was found, in order, between: (1) incisors and molars ($\Delta E^*_{ab} = 4.6$); (2) incisors and canines ($\Delta E^*_{ab} = 4.5$); and (3) canines and molars ($\Delta E^*_{ab} = 2.3$). Regarding the opposing arches, the greatest color variation, in order, was between the maxillary and mandibular: (1) molars ($\Delta E^*_{ab} = 3.5$); (2) incisors ($\Delta E^*_{ab} = 2.5$); and (3) canines ($\Delta E^*_{ab} = 0.9$).²² Compared with results of the present study, although permanent teeth were analyzed, the color difference (ΔE^*_{ab}) between MX1 and MX3 was 10.3 and MX1 and MD3 was 9.7, which were higher than those of the primary teeth.

As to the causal factors for the significant color correlations in the same person, varied factors could be considered. Differences in enamel and dentine thickness within a tooth can explain the color difference and relation within each tooth.^{1,4} Crosssections of human molar teeth were examined to quantify variation in enamel thickness and enameldentine junction (EDJ) shape.⁶ This study demonstrated that enamel thickness and EDJ shape varied among molars, between sexes and among populations. The pattern of variation in enamel thickness on the mesial and distal margins of the four maxillary permanent incisors was examined.³⁵ Enamel thicknesses of primary teeth were also measured.⁷ Crown sizes, which also reflect the difference in enamel and dentine thickness, of human teeth are sexually dimorphic, with male larger than female.³⁶ Further studies should be performed for these issues.

The limitations of the present study were as follows: (1) The spread of age and sex of volunteers was limited; therefore, subjects were not classified. Young adult permanent teeth were investigated in this study. (2) Outer configuration of each type of teeth should have influenced the measured color value. However, variations in the color coordinates (measurement error) by the type of teeth were not clarified. (3) The color coordinates were derived from one instrument in this study. Different color measuring devices may give different absolute values, and possibly different regression equations. Further study should be performed.

CONCLUSION

Based on the results of the present study, the color coordinates of the six types of anterior teeth in the same person were significantly correlated except for two pairs. Although the color differences of anterior teeth with the maxillary central incisors were higher than the perceptible limit, color of missing teeth can be estimated with the colors of adjacent teeth because the color coordinates showed significant correlations. The color coordinates for missing teeth, especially for maxillary central incisors and canines in both arches, could be estimated based on those of the same type teeth on the opposing arch.

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COLOR CORRELATIONS AMONG ANTERIOR TEETH Lee

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Time Course of Potassium Nitrate Penetration into the Pulp Cavity and the Effect of Penetration Levels on Tooth Whitening Efficacy

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ABSTRACT

Objectives: To establish time-course of potassium nitrate (PN) penetration into the pulp cavity, and determine whether PN pretreatment would affect whitening efficacy.

Materials and Methods: Extracted teeth (n = 100) were randomized into five groups of 20 specimens each. Relief ACP (Philips Oral Healthcare, Los Angeles, CA, USA) was applied for 0, 5, 15, 30, and 60 minutes for groups 15, respectively. A nitrate/nitrite assay kit was used for colorimetric detection of nitrate. Whitening was performed using a Zoom White Speed system (Philips Oral Healthcare) for 60 minutes. Tooth color was measured with a spectrophotometer at baseline (T₀), I-day post PN application (T₁), I-day post-whitening (T₂), and I-month post-whitening (T₃). Kruskal-Wallis test was used to assess group differences in PN penetration and tooth color change. *Results:* PN penetration differed among all groups except 2 and 3. There were no differences among groups for any baseline color parameters (p > 0.30). At T₂ there was no change relative to baseline for individual components L^* , a^* , and b^* . At T₃ and T₄ there was significant change relative to baseline for ΔL^* , Δb^* , and ΔE^* , for all groups.

CLINICAL SIGNIFICANCE

Postassium nitrate penetration into the pulp cavity occurred as early as 5 minutes after application, and pretreatment with potassium nitrate containing desensitizers did not adversely affect tooth whitening efficacy. (| Esthet Restor Dent 28:SI4–S22, 2016)

INTRODUCTION

Tooth whitening with the use of peroxide-based materials is a conservative and economic treatment option for improving the appearance of patients' smiles. It is the most common elective dental procedure with more than 1 million Americans whitening their teeth annually, and driving nearly \$600 million in revenues for dental offices.¹ The wide range of whitening techniques provided in the dental office and also over the counter reflects its high popularity. Despite the well-established efficacy of these techniques, they are commonly accompanied with tooth whitening induced sensitivity (TWIS). This adverse

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effect typically presents as a generalized and transient sensitivity to cold, but sometimes also as sharp shooting pain limited to a few teeth.^{2,3} Depending on the severity of TWIS, it can negatively affect patients' satisfaction with tooth whitening and diminish compliance in completing the whitening treatment.

Potassium nitrate (PN) is one of the most effective agents for the management of whitening induced sensitivity. It acts as a depolarizing agent, creating a period of inactivation in the nerve cells.^{4,5} This calming effect on the on the nerve receptors, which are located mainly in the inner dentin, requires that the PN penetrates the entire tooth. A recent study showed that PN could be detected in the pulp cavity following the application of PN-containing desensitizers and whitening formulations to the coronal surface for 30 minutes. This study implicated concentration of the applied PN as a determinant of the level of penetration. However, penetration may also be influenced by the viscosity of the material, as well as by other constituents of proprietary preparations.⁶

Current protocols for the management of TWIS include the application of PN-containing desensitizers, either before or after the whitening treatment, by wearing of a tray for 10–30 minutes.^{7,8} Manufacturers have also incorporated PN within their whitening formulations, with the intention of having the nerve-calming action occur concurrently with the whitening process. However, there is little evidence on which to base a rationale for the most appropriate application time and duration of the desensitizers. Furthermore, a recent clinical study suggested that PN pretreatment may negatively affect whitening efficacy.⁹

Although the use of PN is known to be effective in the prevention and treatment of TWIS, little is known about it is time course of penetration of specific tooth structures, the most appropriate duration of application, or the effect of PN penetration levels on the efficacy of tooth whitening. The current study addressed these questions by assessing the amount of PN that penetrated the pulp cavity over time, and by determining whether PN application prior to whitening affected tooth whitening efficacy with regard to changes in overall color, lightness, and chroma. The hypotheses of this study were that: (1) PN penetration into the tooth is time dependent, and (2) pretreatment with PN does not affect the efficacy of tooth whitening.

METHODS AND PROCEDURES

Recently extracted human molar teeth without any identifiers were obtained from the University of Iowa. This study was determined to be nonhuman subject research by the Institutional Review Board of the University of Iowa (IRB ID# 201407809).

Sample Selection and Preparation

Extracted human molar teeth (n = 100) were collected prior to the study and stored in 0.2% Thymol solution (Sigma-Aldrich, St. Louis, MO, USA) at 4°C. All teeth were inspected for developmental anomalies, caries, existing restorations, deep crack lines, or severe attrition and those with such defects were not used. For the selected samples, the roots were trimmed 3 mm apical to the cemento-enamel junction, the pulp was removed and a cavity was prepared, leaving a standardized wall of 2 mm thickness, which would retain 200 µL of phosphate buffer saline. The occlusal pit and fissures were sealed with flowable resin (Estelite flow, Tokuyama Corp. Tokyo, Japan) to prevent any leakage of the buffer out of the cavity. With the purpose of limiting the colorreading area and creating a standardized whitening area, a circular adhesive label 6 mm in diameter was applied to the center of the buccal surface. The remaining tooth was painted with gray nail varnish (Sally Hansen, New York, NY, USA), and the adhesive label was removed after drying, leaving a 6 mm diameter window on the tooth surface, as shown in Figure 1, which illustrates the experimental procedures of this study.

Potassium Nitrate Application Protocol by Group

Specimens were randomized into five groups of twenty specimens each. Relief ACP, a desensitizing gel containing 5.0% PN (Philips Oral Healthcare, Los Angeles, CA, USA), was quantified (80 μ L) and applied



FIGURE I. Flowchart of Experimental Procedures.

on the exposed window for 0, 5, 15, 30, and 60 minutes for groups 1–5, respectively. Throughout the application process, the pulp cavity was filled with 200 μ L phosphate buffer saline solution, to stabilize any PN that might diffuse into this area. Throughout the exposure, all teeth were kept in a closed humid chamber (General Glassblowing Co. Lab Apparatus, Richmond, CA, USA), at 37°C with 100% relative humidity.

Tooth Whitening and Color Measurement by Group

Instrumental color measurements were performed using a contact-type intraoral spectrophotometer (Vita Easyshade Compact Advanced, Vita Zahnfabrik, Bad Säckingen, Germany). The Easyshade was calibrated according to the manufacturer's instructions and placed perpendicularly on the exposed surface of the tooth specimens. Color measurements were taken at baseline (T_0), 1-day post PN application (T_1), 1-day post whitening (T_2) , and 1-month post whitening (T_3) in a color controlled lightening box (MM 4e GTI Mini Matcher, GTI Graphic Technology, Inc, Newburgh, NY, USA) at CIE D_{65} , a color temperature of 6,500 K and light intensity of \approx 1,200 lux. The color difference at various time intervals was measured as ΔE^* from the Commission Internationale de l'Eclairage,¹⁰ using the following equation: $\Delta E^* = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2}$.

For the tooth whitening procedure, a jig was fabricated by gently placing the lingual surface of each tooth into a polyvinyl siloxane putty impression material (Exaflex, GC America Inc., Alsip, IL, USA) at a 30° angle from the base. The 25% hydrogen peroxide whitening material (Zoom Chairside Whitening Gel, Philips Oral Healthcare, Los Angeles, CA, USA) was applied to the buccal window and replenished an additional three times for every 15 minutes each (total application time: 60 minutes). Light activation was performed using a light-emitting diode lamp (Zoom WhiteSpeed, Philips Oral Healthcare peak wavelength: 466 nm) set at high intensity (190 mw/cm²).

Colorimetric Assay of Nitrate/Nitrite

A Nitrate/nitrite assay kit (Sigma-Aldrich, St.Louis, MO, USA) composed of nitrate and nitrite standard solutions, buffer solution, nitrate reductase, enzyme co-factors, and Griess dyes was used for the colorimetric determination of nitrate in the samples. The standard solutions were mixed with the buffer solution to yield final concentration of 0, 25, 50, and 100 μ M of nitrite and nitrate/nitrite, to establish the calibration curves. The final nitrate concentration in the samples were obtained by subtracting the sum of nitrate/nitrite from the measured nitrite amount.⁶

Data Analysis

Group differences for the effect of time of application on PN penetration were assessed using a nonparametric Kruskal-Wallis test. All possible pairwise comparisons of treatment groups were made using the Tukey method as modified by Conover to adjust for multiple comparisons in conjunction with an overall 0.05 level of Type I error.¹¹ The Spearman rank correlation was used to assess whether there was a decreasing or increasing relationship between PN penetration and the duration of its application.

Color change was calculated as the color value at the later time minus that at the earlier time. As such, positive changes imply an increase in the color

Descriptors	Group I (0 MIN)	Group 2 (5 MIN)	Group 3 (15 MIN)	Group 4 (30 MIN)	Group 5 (60 MIN)
Mean	2.75	4.08	4.46	6.59	20.35
Std Dev	0.68	1.05	0.68	1.86	6.88
Median	2.87	4.04	4.53	6.18	19.70
Minimum	1.35	2.33	3.14	3.76	10.19
Maximum	3.79	6.85	6.00	12.20	34.24

TABLE I. Descriptors of nitrate penetration level (μ M) by group corresponding to duration of application

parameter of interest, and negative values imply a decrease. Whether there was a significant change in color between time points was assessed using the Wilcoxon signed rank test. Group differences were again assessed using the the Kruskal-Wallis test as described above for the assessment of the effect of time of potassium nitrate application nitrate. Further adjustment for multiple comparisons was made using the standard Bonferroni method in conjunction with an experiment-wise level of Type I error of 0.05.

RESULTS

1. Effect of Time of Application on Potassium Nitrate Penetration

Descriptors of PN penetration are given for each of the five treatment groups (Table 1), and the distributions of results for each length of time of application are depicted graphically by the box plots in Figure 2. The data provided strong evidence of differences in the distribution of PN penetration among the five treatment groups (p < 0.0001, Kruskal-Wallis test). After adjustment for multiple comparisons, the distributions of PN penetration values were found to differ significantly among groups, the only exceptions being Groups 2 and 3, which correspond to the application of PN for 5 and 15 minutes, respectively, and did not differ from one another. The mean and median of penetration increased with duration of application (Figure 2), exhibiting a strong and highly significant direct correlation between minutes of application and nitrate penetration (Spearman's rho = 0.90, *p* < 0.0001).



FIGURE 2. Box plots showing the distribution of potassium nitrate penetration resulting from the application of potassium nitrate for various lengths of time.

2. Group Comparisons of Measurements of Baseline Color

Based on the analysis of variance, the data provided no evidence of differences in mean among groups for any of the baseline color parameters (p > 0.30 in all instances). No evidence of nonconformance to model assumptions of normality and homoscedasticity was found.

3. Median Color Change Relative to Baseline Within Treatment Groups

Table 2 lists the medians of color change relative to baseline for each treatment group, as assessed using the Wilcoxon signed rank test. This table illustrates numerous instances of significant color change. Because of the large number of statistical evaluations

Color change*	Group I	Group 2	Group 3	Group 4	Group 5	p-value [§]
ΔL I-d PPN*	0.4	0.70 [†]	0.3	0.1	0.55 [†]	0.32
Δ a I-d PPN*	-0.1	0	-0.1	0	-0.2	0.7
∆b I-d PPN*	-0.65 [†]	-0.65 [†]	-0.25	-0.65 [†]	-0.45	0.55
∆EI-d PPN*	l.19 [‡]	l.49 [‡]	I.32 [‡]	I.29 [‡]	I.I6 [‡]	0.82
ΔLI-d PW*	3.70 [‡]	4.55 [‡]	3.25 [‡]	2.00 [‡]	2.80 [‡]	0.04 [§]
∆a I-d PW*	0.55 ⁺	0.3	0.75 [†]	I.05 [‡]	0.90 [‡]	0.01 [§]
∆b I-d PW*	-9.90 [‡]	-9.90 [‡]	- 10.20 [‡]	-10.45^{\ddagger}	-9.55 [‡]	0.85
ΔEI-d PW*	10.79 [‡]	11.09 [‡]	10.99 [‡]	11.14‡	10.84 [‡]	0.97
ΔLI-m PW*	3.30 [‡]	4.70 [‡]	4.26 [‡]	3.46 [‡]	3.76 [‡]	0.03 [§]
∆a I-m PW*	-0.40 [†]	-1.00^{\ddagger}	-0.66 [‡]	-0.36 [†]	-0.86 [‡]	0.12
∆b I-m PW*	— I3.65 [‡]	— I5.05 [‡]	— I3.5I‡	— I3.8I‡	— 14.96 [†]	0.23
ΔEI-m PW*	I3.85 [‡]	15.45 [‡]	4.6 [‡]	14.IO [‡]	15.43 [‡]	0.16

TABLE 2. Median values of color change relative to baseline for five treatment groups representing durations of 0, 5, 15, 30, and 60 minutes of potassium nitrate application. N = 20 within each treatment group

*PPN = Post Potassium Nitrate Application; PW = Post Whitening; Color change relative to baseline was calculated based on color measurements taken one day after PN application (I-d PPN), one day after whitening (I-d PW), and one month after whitening (I-m PW). $^{\dagger}p < 0.05$. Significance probability associated with the exact Wilcoxon signed rank test of the null hypothesis that median color change is equal to zero; marked values are less than the nominal value of 0.05 but not significant after Bonferroni adjustment for multiple comparisons. $^{\ddagger}p < 0.05/60 = 0.00083$. Significance probability associated with the exact Wilcoxon signed rank test of the null hypothesis that median color change

is significant after adjustment for 60 multiple comparisons based on the Bonferroni method and an overall 0.05 level of significance. p < 0.05. Significance probability associated with the Kruskal-Wallis test of the null hypothesis that the distribution of the color change of interest is

the same in the five treatment groups; marked values are less than the nominal value of 0.05. None of these results remained significant after adjustment for multiple comparisons.

that consider whether there was significant color change between pairs of time points within each group (12 color change variables \times 5 groups = 60 tests), significance probabilities (*p*-values) are annotated in Table 2, in terms of whether they were less than the nominal value of 0.05, or less than 0.00083. A *p*value < 0.00083 represents a result that is significant at the experiment-wise 0.05 level after Bonferroni adjustment for 60 tests.

At 1-day post PN application, there was little compelling evidence for change relative to baseline in the individual components L^* , a^* , and b^* . There was, however, evidence of modest overall color change (ΔE^*) for all five treatment groups, and in all cases this change remains significant after multiple comparisons adjustment. At 1-day post whitening, there was strong evidence of color change relative to baseline for ΔL^* , Δb^* , and ΔE^* , with significant indication of change in all five treatment groups after multiple comparisons adjustment. The same can be said of results at 1-month post-whitening.

4. Differences in Color Change Relative to Baseline Among the Five Treatment Groups

Table 2 lists the results of treatment group comparisons for each of the 12 color change variables relative to baseline and Figure 3 illustrates the results. Based on the Kruskal-Wallis test, the data (subjected to Bonferroni adjustment for multiple testing) provide no evidence of a difference among the five groups with regard to changes in color relative to baseline. Based on the 12 color change variables considered, the



FIGURE 3. Median values of overall color change (ΔE^*) relative to baseline for five treatment groups at I day after PN application (T₁), I day after whitening (T₂), and I month after whitening (T3).

significance probability associated with a given Kruskal-Wallis procedure (last column of Table 2) would be considered significant after adjustment for multiple testing if it was less than 0.05/12 = 0.0042; none of the *p*-values achieved this value.

DISCUSSION

The dental profession is challenged and invigorated by the goal of providing a tooth whitening treatment that is effective, safe, and sensitivity-free. Many studies have evaluated the efficacy of various whitening materials and regimens, and the results have been summarized in several reviews.^{12,13} However, even with the tremendous improvement of whitening materials, TWIS remains a central issue that needs to be addressed to meet patients' compliance and satisfaction with the treatment.

The dental literature includes abundant references to dentin hypersensitivity that has been described as pain associated with exposed dentin, typically in response to chemical, thermal, tactile, or osmotic stimuli that are not related to other forms of dental defect or disease.¹⁴ The mechanism underlying such pain is not fully understood. However, the most widely accepted explanation for dentin hypersensitivity is the hydrodynamic theory, which posits that stimulus-induced fluid flow in the dentinal tubules results in activation of intradental myelinated A- β and some A- δ fibers in the pulp/dentin border area.¹⁵ Therefore, management strategies to date have aimed mainly to prevent fluid flow in the dentinal tubules, using blocking agents such as strontium,¹⁶ arginine and calcium carbonate,¹⁷ stannous fluoride,¹⁸ calcium sodium phosphosilicate,¹⁹ casein derivatives,²⁰ and oxalates.²¹

Many authors have viewed TWIS as a form of dentin hypersensitivity.²² However, this condition differs markedly from TWIS. For example, in contrast to dentin hypersensitivity, TWIS can occur in the absence of a provoking stimulus, and it is not necessarily associated with exposed dentinal tubules.⁴ Furthermore, whereas dentin hypersensitivity has a peak prevalence in the third decade, TWIS is not associated with gender or age.²³ In view of these differences it has been postulated that TWIS does not arise through the hydrodynamic mechanism but rather as a consequence of peroxide penetration of the tooth structure, causing direct stimulation of a neuronal receptor.⁴ This theory also implies that management strategies for TWIS should be directed towards the use of potassium salts to reduce the excitability of the intradental nerves, rather than to tubule-occluding agents.

Our study evaluated two hypotheses. The first is that applying PN to the tooth surface would lead to its diffusion into the pulp cavity, the site of action, and that penetration levels are time dependent. As many hydrogen peroxide penetration studies have been performed,^{24–28} these findings were expected to provide foundational knowledge for comparing penetration of the tooth structure by peroxide and potassium nitrate. The results we obtained supported our first hypothesis. Specifically, PN penetration of the pulp cavity was time dependent, with the amount of nitrate measured increasing with the duration of application. This is in accordance with other studies that evaluated the penetration of the pulp cavity by hydrogen peroxide and found that it was time dependent.^{27,28} Notably, potassium nitrate could be detected in the pulp cavity as early as 5 minutes after application, which is similar to the earliest time at which hydrogen peroxide could be measured.^{27,28} This finding is notable, since it suggests that maximal

desensitizion/depolarization of the nerves can be achieved by a 5-minute application. The similarity in penetration times for hydrogen peroxide and PN penetration could potentially be explained by the fact that both have low molecular weights, i.e., 34.40 gram/ mol and 101.10 gram/mol, respectively. Additionally, the fact that both agents are water-soluble may facilitate their transport within the tooth.

Our second hypothesis, regarding the effect of PN pretreatment on whitening efficacy aimed to provide support on PN pretreatment prior to whitening. Based on the results, pretreatment with PN did not affect tooth whitening efficacy, measured as overall color change at 1 day and 1 month post whitening. This is in agreement with one set of studies, which found that pretreatment desensitizers based on fluoride, amorphous calcium phosphate, and potassium nitrate did not influence the efficacy of subsequent tooth whitening.^{29,30} However, another study has found the opposite. A clinical study reported that the use of a 5% PN desensitizer for 30 minutes prior to an in-office whitening session involving the application of a 28% hydrogen peroxide gel for 45 minutes and light activation reduced the severity of sensitivity experienced by the subjects. Notably, however, this group experienced significantly less color change in the teeth compared with the group that did not use the desensitizer pretreatment, as measured by an intraoral spectrophotometer.⁹ The authors did not discuss a possible reason for the decrease in tooth color change associated with PN pretreatment, and thus this outcome may warrant additional investigation. It is noteworthy to point out that the overall color change increased after 1 month implying that teeth got lighter and changed color over a period of 1 month. This is in agreement with other in vitro studies that showed similar trends of color improvement over a period of time. It has been postulated that incorporation of hydrogen peroxide was still active within the tooth for up to 1 month resulting in a lighter tooth color.^{31,32}

Our study used the most widely adopted color difference formula within dental research, derived from the CIE-L*a*b* system.¹⁰ The 50:50% perceptibility threshold of $\Delta E^* = 1$ and a 50:50% acceptability threshold of $\Delta E^* = 2.7$ was used to interpret tooth color change results.^{33,34} Notably, even in Group 1, which was not treated with PN, there was significant overall color change ($\Delta E^* = 1.19$) compared with baseline. This may be explained by the fact that removing the tooth out of the storage medium and proceeding with the color measurements itself may cause subtle perceiveable color change due to various factors such as positioning errors, device repeatability and dehydration.^{35,36}

It is important to point out that this study was an in vitro study on extracted teeth that does not reflect the full dynamics of the oral environment, for example, the effects of saliva and the positive outward pulpal pressure associated with vital teeth. Furthermore, unlike natural teeth our study used teeth with intentionally enlarged pulp cavities to accommodate the buffer solution for assay purposes. Nevertheless, the results of our study provide guidance for innovations and modifications that could potentially be implemented in the future to create a whitening formulation that minimizes tooth sensitivity. Rather than incorporating the PN in the whitening gel, as is currently marketed in many whitening products, with respect to minimizing sensitivity associated with tooth whitening procedures it may be beneficial to use a two-step technique i.e., first applying PN and giving it time to penetrate into the pulp cavity, and then applying the peroxide-based whitening material. Future research on the efficacy of such an innovative approach may provide new avenues for formulating no-sensitivity whitening products.

CONCLUSION

Within the limitations of this study it can be concluded that PN penetration of the pulp cavity occurs as early as 5 minutes after application, and that penetration is highly time dependent. Pretreatment with PN did not adversely affect whitening efficacy.

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TIME COURSE OF POTASSIUM NITRATE PENETRATION INTO THE PULP CAVITY Kwon et al.

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Susceptibility to Coffee Staining during Enamel Remineralization Following the In-Office Bleaching Technique: An In Situ Assessment

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ABSTRACT

Purpose: To assess in situ the enamel mineralization level and susceptibility to coffee staining after in-office bleaching. **Materials and Methods:** Thirty-six human dental fragments assembled into intraoral devices were bleached with 35% hydrogen peroxide and treated as follows: (group 1) no contact with coffee; (group 2) immersion in a coffee solution for 30 minutes daily for 7 days, starting I week after bleaching; and (group 3) immersion in a coffee solution for 30 minutes daily for 14 days, starting immediately after bleaching. Enamel mineralization and color were assessed before bleaching (T1), immediately after bleaching (T2), and after 7 (T3) and 14 days (T4). The CIE whiteness index (W*) and closeness to white (ΔW^*) following bleaching and/or immersion in coffee were calculated. Data were analyzed with Friedman and Wilcoxon tests or Kruskal–Wallis and Mann–Whitney *U*-tests ($\alpha = 0.05$).

Results: Significant differences in the mineralization levels were observed as a function of time. No significant differences in W* were observed between groups, nor was W* significantly different at T3 and T4. Similar Δ W* was observed between groups after 7 or 14 days.

Conclusions: The mineral loss after in-office bleaching was progressively reversed by contact with saliva for 14 days. The whiteness index was not affected by contact with coffee during the remineralization period.

CLINICAL SIGNIFICANCE

The results of this in situ study suggest that the mineral loss caused by in-office dental bleaching is minimal and is partly compensated by remineralization due to contact with saliva. Additionally, whiteness was not affected by daily exposition to coffee during the enamel remineralization, which indicates that avoiding the consumption of coffee immediately following in-office bleaching is unnecessary.

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INTRODUCTION

Esthetic treatments have occupied an important place in modern dentistry, with dental bleaching being one of the most commonly performed esthetic procedures, either in office or at home.¹ The most frequently used bleaching agent for the in-office technique is 35% hydrogen peroxide. This is an agent with low molecular weight and free transit through the interprismatic spaces of enamel and throughout dentin, leading

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Although the technique for vital tooth bleaching has been widely studied during the last decades, several questions remain unanswered. Controversy among dentists concerning not only the bleaching procedure itself, but also the postoperative care instructions provided to patients still exists. One of these questions concerns the restrictions imposed to the ingestion of certain foods and drinks during and after bleaching, or the period of time that patients should avoid these substances to ensure long-term success of the treatment. To obtain increased color stability, some authors have suggested two to three in-office bleaching sessions, or even the association of in-office and at-home techniques.^{3,4}

Many authors have related the susceptibility to staining after bleaching to alterations caused by the bleaching agents to the dental enamel structure.^{5–11} These agents, often of acid nature, can dissolve the mineral content of the enamel, thus leading to loss of calcium and phosphate, and resulting in reduced crystal size and increased intercrystalline spaces within enamel.¹² During the dissolution process, the carbonate present in the structure of enamel may also be lost and expose the delicate protein structure surrounding the crystals.¹² In this condition, enamel is likely to become more susceptible to the penetration of staining substances. Nonetheless, remineralization of the affected structures is expected. Demineralization and remineralization phenomena are dynamic processes that constantly occur in the oral cavity due to the buffering action of saliva. In fact, remineralization after at-home¹³ and in-office¹⁴ bleaching has already been reported in previous studies. A period of 14 days in contact with saliva has been shown to be sufficient to preserve human enamel microhardness after at-home bleaching.¹³ In vitro, calcium loss of dental specimens immersed in water can be 2.5 times greater than specimens kept in the mouth, i.e., in situ.¹³ Due to the role of saliva in the remineralization process of bleached enamel, in situ or in vivo studies are necessary to obtain results that are more closely associated to the clinical reality.

Therefore, the objective of this in situ study was to analyze quantitatively the changes in enamel mineralization levels and the susceptibility to coffee staining of human dental fragments submitted to in-office dental bleaching.

MATERIALS AND METHODS

The experimental outline of this in situ study is illustrated in Figure 1. All procedures were performed after receiving the approval by the local research ethics committee (Certificado de Apresentação para



FIGURE 1. Flowchart illustrating the experimental outline. The specimens (A) were distributed (B) in three groups (N = 12). Nine specimens were fixed in each of the four intraoral devices in three rows of three specimens (C). Specimens in the row closest to the posterior palate (G3) were immersed in coffee 30 minutes daily, starting immediately after bleaching for 14 days (D). Specimens in the middle row (G2) were immersed in coffee during 7 days, starting from the second week after bleaching (E). Specimens in the row closest to the incisors (G1) were not immersed in coffee during the experiment (control). Measurements were recorded before (T1), and immediately after (T2) bleaching (BL), 7 days (T3), and 14 days (T4) after bleaching.

Apreciação Ética no. 0245.0.093.000-11). Four young volunteers (22–25 years) were selected according to the following inclusion criteria: normal salivary flow (≥0.2 mL/min), absence of caries and/or periodontal diseases, and presence of all natural teeth. Patients with orthodontic appliances, fixed or removable prostheses, gastric disorders, smokers, pregnant women, people making use of medicaments, or those who constantly ingested foods containing staining substances were excluded from the study. All the volunteers signed an informed consent prior to participating in the study.

Sample Preparation

Eighteen extracted sound permanent human premolars, obtained from a tooth bio bank, were used in the study. The teeth received prophylaxis with pumice and water and were sterilized in a 10% formaldehyde solution (pH 7) for 7 days.¹⁵ The middle third of the buccal and lingual surfaces of the teeth were sectioned with a diamond disk (12205, Extec Corp., Enfield, CT, USA) mounted on a cutting machine (Isomet 1000, Buehler, Lake Bluff, IL, USA). The 36 dental fragments (4 mm \times 4 mm \times 2 mm) were rinsed for 10 minutes under ultrasound vibration and kept in distilled water until use.

Alginate impressions (Jeltrate Dustless, Dentsply, York, PA, USA) of the maxillary arches of the volunteers were taken, and plaster models (Durone IV, Dentsply) were prepared. Polyvinyl siloxane blocks (Elite HD+, Zhermack Clinical, Badia Polesine, Rovigo, Italy) measuring $6 \text{ mm} \times 6 \text{ mm} \times 6 \text{ mm}$ were bonded to the palatal area of the plaster models with a cyanoacrylate-based glue (Super Bonder, Loctite, São Paulo, Brazil). The plaster models were then isolated and intraoral palatal devices were fabricated in clear acrylic resin (JET, Clássico Artigos Odontológicos Ltda., Campo Limpo Paulista, Brazil). Nine dental specimens were fixed with sticky wax (ASFER Indústria Química Ltda., São Caetano do Sul, Brazil) into the cavities left by the polyvinyl siloxane blocks forming three rows with three specimens each, in order for the enamel surfaces to coincide with that of the acrylic device (Figure 2). The dental fragments were placed in the intraoral devices in a randomized way (by drawing lots)



FIGURE 2. Intraoral device with dental specimens to be used intraorally by the participants of the study.

starting from the left to the right, and from the front to the back of the device. Specimens in the first row, closest to the incisors, were denominated group 1 (G1), specimens in the middle row group 2 (G2), whereas specimens in the back row, closest to the palate, group 3 (G3). There were a total of 12 specimens per group. This layout facilitated the immersion of specimens in G3 and G2 into the coffee solution (Figure 1).

Bleaching of the Dental Fragments

Bleaching of all dental fragments was performed outside the mouth in two sessions with an interval of 3 days between sessions. In each session, a 35% hydrogen peroxide gel (Lase Peroxide Sensy^{*}, DMC, São Carlos, Brazil) was applied according to the manufacturer's recommendations. A layer of approximately 1 mm of the gel was applied onto the specimens for 15 minutes. The bleaching agent was then removed with air-water spray for 30 seconds. The same procedure was repeated twice, totaling three applications in each session. Between sessions, the intraoral devices were used by the volunteers.

Immersion in Coffee

Soluble instant coffee (Nescafé[®], Nestlé, São Paulo, Brazil) was prepared by adding 50 mL of hot water to one spoonful of coffee, according to the recommendations from the manufacturer. The dental fragments in G1 were not immersed in coffee (control group). Volunteers initiated the immersion of specimens in G3 immediately after the second session of bleaching, whereas the immersion of the fragments in G2 only started 1 week after bleaching was completed. The dental fragments in the two experimental groups (G2 and G3) were immersed in coffee solution for 30 minutes daily in order to simulate the contact between the coffee pigments and the dental structures in 1 day.⁶ The dental fragments in G1 and in G2, when not immersed, were protected with a polyvinyl chloride film and adhesive tape, and kept above the level of the coffee solution. After immersion, each intraoral device was rinsed for 1 minute under running water and reinserted in the oral cavity.

Volunteers were instructed to use the intraoral device uninterruptedly (Figure 3), only removing it during meals, ingestion of drinks (except water), or brushing their teeth. Volunteers were also instructed to refrain from using mouthwashes during the entire experimental period, and to avoid the abusive consumption of acidic and staining foods. When outside the oral cavities, it was instructed that the intraoral devices should be wrapped in gauze imbibed in deionized water. Whereas the side in contact with the palate could be brushed with a dentifrice, the side containing the dental specimens could only be rinsed with water.



FIGURE 3. Intraoral device with dental specimens in the mouth of a volunteer.

Enamel Mineralization and Whiteness Assessments

Before any measurement was taken, the intraoral devices were worn by the participants for at least 48 hours. Enamel mineralization and color assessments were performed at four different moments: T1 – before bleaching, T2 – immediately after the second session of bleaching, T3 – 7 days after bleaching, and T4 – 14 days after bleaching (Figure 1).

Enamel mineralization assessments were performed using a laser fluorescence device coupled to a 2 mm in diameter type-B probe (DIAGNOdent^{*}, Kavo do Brasil Ind. Com. Ltda., Joinville, Brazil). According to DIAGNOdent[®] manufacturer's manual, display values between 0 and 10 are indicative of sound dental structure, whereas display values 11 or above indicate progressive mineral loss. Four consecutive measurements were performed in each specimen, and mean values were calculated. Color assessments were carried out with a clinical portable spectrophotometer (Easyshade^{*}, Vita-Zahnfabrik, Bad Säckingen, Germany) using the CIELAB system, where L^* is the luminance, while a^* and b^* represent the color coordinates on the red-green and blue-yellow axis, respectively. In each moment, color was measured three times, and the mean values for the L^* , a^* , and b^* were calculated.

All mineralization and color measurements were carried out by the same operator. To reduce the influence of the natural light, measurements were always performed under artificial light and in the same place. To standardize the measurements, templates in clear acrylic resin were fabricated to guide the tips of each device (Easyshade^{*} and DIAGNOdent^{*}) always in the same position and angle. The templates were fabricated with small windows compatible with the active tips of each respective device (5.5 mm in diameter for the spectrophotometer and 2.5 mm for the fluorescent laser). Calibration of each device was performed before each measurement according to the manufacturer's recommendations.

In order to quantify the whiteness before and after bleaching, the CIE recommended whiteness index

(WIC index) was used.¹⁶ The whiteness index (W*) is based on the distance of a color value from a nominal white point, represented in CIELAB color space as $L^* = 100$, $a^* = 0$, and $b^* = 0$, and defined according to the equation:

$$W^* = \left[(a^*)^2 + (b^*)^2 + (L^* - 100)^2 \right]^{1/2}$$

The nominal white point in the WIC index is equal to zero. Thus, the closer the W* is to zero, the closer it is to pure white. In this study, W* was calculated for each group (G1, G2, and G3) at each experimental period (T1, T2, T3, and T4).

Changes in the closeness to white (ΔW^*) following bleaching were calculated by subtracting W^* values obtained after treatment from those obtained at baseline, according to the equation:

$$\Delta W^* = W^*(treatment) - W^*(baseline)$$

In this study, ΔW^* was calculated by subtraction of W^* values at the periods: $\Delta W^*1 = T2-T1$, $\Delta W^*2 = T3-T1$, and $\Delta W^*3 = T4-T1$. A negative ΔW^* indicates color coordinates that are closer to pure white, and thus represents more favorable whiteness.

Statistical Analyses

Shapiro–Wilk test was used to verify the normality of data distribution. As some of the data presented asymmetric distribution (p < 0.05), nonparametric tests were used. Friedman and Wilcoxon post-hoc tests were used to verify differences in the level of mineralization and whiteness of dental fragments within the same group as a function of time. Kruskal–Wallis and Mann–Whitney U post-hoc tests were used to verify differences in the mineralization level and whiteness between groups at each experimental period. All statistical analyses were conducted with the SPSS Statistics software for Windows (IBM Corp., Armonk, NY, USA), version 21.0, with a level of significance of 5%.

RESULTS

Enamel Mineralization

Mineralization levels of the dental fragments are presented in Table 1. The level of mineralization within each group varied significantly as a function of time for all groups (Friedman test, p < 0.001). Mineral loss was greatest immediately after bleaching, (Wilcoxon

TABLE I. Median enamel mineralization levels (min. and max.) recorded by DIAGNOdent[®] for the three experimental groups at distinct periods

Period	Groups*					
	GI	G2	G3			
	Control No immersion in coffee	Immersion in coffee during 7 days following bleaching	Immersion in coffee during 14 days following bleaching			
ΤΙª	0.87 (0.00, 2.00)	0.89 (0.00, 4.00)	1.00 (0.00, 2.00)			
T2 ^d	5.00 (2.00, 7.00)	5.00 (2.00, 7.25)	4.00 (2.00, 6.25)			
T3 ^c	4.00 (1.00, 6.00)	3.87 (1.25, 5.25)	2.25 (2.00, 5.00)			
T4 ^b	2.37 (1.00, 5.00)	3.12 (1.00, 5.00)	2.00 (1.75, 4.00)			

*No significant differences were observed between groups (Kruskal–Wallis; p > 0.05).

Significant differences, represented by different superscript letters, were found between the investigated periods, within each group (Wilcoxon post-hoc test; p < 0.05).

post-hoc test, p < 0.05) but was progressively reversed after 7 and 14 days. No significant difference in the level of mineralization between groups was observed at any experimental period (Kruskal–Wallis test, p > 0.05).

Whiteness Index and Closeness to White

Significant differences for W* were detected at distinct periods within each group (Friedman test, p < 0.05), but no difference was found between groups (Kruskal–Wallis, p > 0.05). A significant decrease in W* values (i.e., whiter dental fragments) were observed from baseline (T1) to immediately after bleaching (T2), 7 days (T3), or 14 days (T3) after bleaching (Wilcoxon post-hoc test, p < 0.05). However, no significant changes in W* were observed between T3 and T4 (Table 2).

Changes in the closeness to white (ΔW^*) were observed within each group (Friedman test, p < 0.05) and between groups (Kruskal–Wallis test, p < 0.05). The ΔW^*1 (T2–T1) values were significantly higher when compared with ΔW^*2 (T3–T1), and ΔW^*3 (T4–T1) (Wilcoxon post-hoc test, p < 0.05), but no significant differences between ΔW^*2 and ΔW^*3 were observed (Wilcoxon post-hoc test, p > 0.05). The ΔW^*1 values for G2 and G3 were significantly higher than those registered for G1 (Mann–Whitney U post-hoc, p < 0.05). No further significant differences for ΔW^* in comparison to the control group were identified (Table 3).

DISCUSSION

Mineral loss, decreased surface microhardness, increased roughness, morphological alterations, and increased permeability have been reported as undesired effects of bleaching agents on the dental structures,^{17–22} a consequence of the acid nature of bleaching agents.¹² Not surprisingly, in this study the highest level of mineral loss occurred immediately after bleaching. However, the median values registered by DIAGNOdent[®] in the present study (Table 1) are compatible with those of sound teeth. Moreover, progressive enamel remineralization was observed after daily contact with saliva (Table 1). These results are in agreement with a previous in vitro study,²³ which demonstrated precipitates on dental surfaces immersed in natural saliva after bleaching with 35% hydrogen peroxide. The minimal enamel mineral loss after in-office bleaching with 35% hydrogen peroxide, and the progressive remineralization of enamel in contact with saliva, reinforce the hypothesis that bleaching can be considered safe for enamel.^{23,24}

The bleaching protocol employed in this study produced whiter dental fragments (Table 2). This was confirmed by the significant decrease in W* values (i.e., closer to zero) observed after bleaching (T2, T3, and T4) in comparison with unbleached specimens (T1). A color relapse was observed 7 days after bleaching (T3), but remained stable after 14 days (T4) (Table 2). A

W *	Groups [†]	Groups [†]					
	GI	G2	G3				
	Control No immersion in coffee	Immersion in coffee during 7 days following bleaching	Immersion in coffee during 14 days following bleaching				
₩* at TIª	38.04 (1.51)	38.24 (1.70)	35.92 (1.69)				
W* at T2°	29.06 (1.80)	34.02 (1.71)	31.30 (1.59)				
W* at T3⁵	31.90 (1.48)	34.16 (1.89)	32.16 (1.47)				
W* at T4 ^b	31.76 (1.36)	34.13 (1.91)	32.36 (1.43)				

TABLE 2. Whiteness index W* (adjusted mean and standard error) for each group at the investigated periods

[†]No significant differences were observed between groups (Kruskal–Wallis test; p > 0.05).

Significant differences for W^* , represented by different superscript letters, were identified between the investigated periods, within each group (Wilcoxon post-hoc test, p < 0.05).

Δ₩*	Groups					
	GI	G2	G3			
	Control No immersion in coffee	Immersion in coffee during 7 days following bleaching	Immersion in coffee during 14 days following bleaching			
$\Delta W^* \mid (T2-T1)^a$	-8.93 (1.26)	-3.94 (I.18) [†]	-4.13 (1.36) [†]			
ΔW* 2 (T3–TI) ^b	-6.04 (1.29)	-3.89 (1.13)	-3.23 (1.52)			
ΔW* 3 (T4–TT) ^b	-6.21 (1.24)	-3.81 (1.09)	-3.12 (1.46)			

TABLE 3. Closeness to pure white ΔW^* (adjusted mean differences and standard error) for each group at the investigated periods

[†]Significant differences between G2 versus the control group G1, and G3 versus the control group G1, for $\Delta W1^*$ were identified by Mann–Whitney U-test (p < 0.05).

Significant differences, represented by different superscript letters, were identified between ΔW^* 1, ΔW^* 2, and ΔW^* 3 within each group (Wilcoxon post-hoc test, p < 0.05).

possible explanation for this relapse is that measurements performed at T2 were obtained immediately after bleaching, when dehydration of the enamel may occur and most of the whitening effect is expected. Later at T3 and T4, the dental fragments were hydrated and remineralized in contact with the saliva. Both the whiteness index (W* at T3, W* at T4) and closeness to white (ΔW^* 2, ΔW^* 3) remained stable in the period between 7 and 14 days (Tables 2 and 3).

Moreover, whiteness and closeness to white were not significantly affected by contact with coffee. These results are in disagreement with a previous in vitro study, in which bovine specimens bleached with 16% carbamide peroxide and immersed daily in coffee for 3 weeks showed increased enamel staining.⁵ Another in vitro study also demonstrated that bleaching was less stable when dental fragments were exposed to coffee during at-home treatment using 16% carbamide peroxide gel 6 hours per day for 28 days.⁶ Nonetheless, the present results corroborate a previous in vitro study, which reported that contact with coffee for 30 and 150 minutes after bleaching sessions with 35% hydrogen peroxide did not, although contact with red wine did, increase the staining susceptibility of bleached enamel.⁷ This difference was justified by the fact that wine is a highly acidic beverage, which is capable of intensifying the demineralization of the enamel surface and increase its vulnerability to staining.⁷ This theory is supported by a recent in vitro study, in which high

enamel mineral loss, resulting from exposure to very acidic drinks between bleaching sessions, has resulted in increased staining susceptibility due to superficial alterations.⁸

Therefore, the minimal enamel mineral loss and partial remineralization observed after bleaching may explain in part the absence of coffee staining in the present study. According to these results, contact of bleached enamel with coffee did not adversely affect the whiteness of the dental specimens. Thus, avoiding contact with coffee to decrease enamel's susceptibility to staining seems to be unnecessary. Thus, this study provides scientific evidence for postoperative recommendations concerning the consumption of coffee immediately after in-office bleaching. This conclusion is further supported by a recent in vivo study, which demonstrated that exposure to coffee during bleaching does not seem to affect the degree of whitening.²⁵

Despite the great contribution provided by previous in vitro studies, specimens tested under these conditions lack the continuous contact with natural saliva. Although the testing variables can be controlled to a high level in in vitro models, it may be difficult to extrapolate their results to the clinical situation. In vivo studies, on the other hand, provide ideal clinical conditions, but it is difficult to control the testing variables. In situ models, such as the present one, allow for controlling the variables and testing them under the natural oral environment. Therefore, further studies using an in situ methodology, testing different types of staining substances, different contact periods, and associating acidic substances, are encouraged to strengthen the understanding and the level of evidence on this matter. The main implication of the results obtained in situ is that they closely reflect the dynamics of processes involved after bleaching of teeth,¹¹ not only regarding the remineralization process but also the susceptibility to staining. Additionally, the present study employed human teeth rather than nonhuman (usually bovine) teeth used in some of the previous studies.^{5–7,10} A limitation of this type of study, however, is the adherence of volunteers to the instructions given. Therefore, careful instructions and motivation were provided in order to ensure the required level of commitment from the participants.

CONCLUSIONS

Within the limitations of this study, it is possible to conclude the following:

- Minimal mineral loss following bleaching was observed in all dental fragments bleached with 35% hydrogen peroxide
- 2 The mineral loss was progressively reversed by contact with saliva
- 3 Contact with coffee did not influence the whiteness of bleached specimens

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Comparison of Contrast Ratio, Translucency Parameter, and Flexural Strength of Traditional and "Augmented Translucency" Zirconia for CEREC CAD/CAM System

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ABSTRACT

Purpose: Tetragonal zirconia polycrystals (TZP) can be used via CAD/CAM technique as metal replacement for fixed partial dentures. However, its intense white color and high opacity may represent an aesthetic limit. New TZPs with a claimed higher degree of translucency were recently marketed. The aim of the study was to investigate contrast ratio (CR), translucency parameter (TP), flexural strength (σ), Weibull characteristic strength (σ_0), and Weibull modulus (*m*) of three "traditional" (IPS e.max Zir-CAD, inCoris ZI, VITA In-Ceram YZ) and two "increased translucency" (inCoris TZI, VITA In-Ceram YZ HT) Y-TZPs.

Methods: For flexural strength, ISO 6872:2008 was followed. Bars (N=40) were cut from pre-sintered blocks. Dense-sintering, finishing, and polishing were performed in order to obtain specimens of $15 \times 4 \times 1.2$ mm. Samples were tested with three-point bending setup in a universal testing machine. For CR and TP, specimens (N=10) were cut perpendicularly to the long axis from pre-sintered blocks. After the dense-sintering, specimens were finished and polished in order to obtain tiles of $12 \times 15 \times 1$ mm. CR and TP were measured with a spectrophotometer equipped with an integrating sphere.

Results: No significant difference was found regarding flexural strength. A significant difference was found both for CR and TP among tested groups. VITA In-Ceram YZ HT and inCoris TZI showed the higher translucency. The difference was not statistically significant when compared with VITA In-Ceram YZ, and statistically significant when compared with IPS e.max Zir-CAD and inCoris ZI.

Conclusion: The new "augmented translucency" TZPs showed higher translucency and similar flexural strength than "traditional" TZPs.

CLINICAL SIGNIFICANCE

Monolithic zirconia use is partially restricted due to the zirconia low translucency. The new "augmented translucency" zirconia showed a modest but perceptible increase in translucency and a similar flexural resistance, thus increasing the clinically suitable thickness range with optimized aesthetic and resistance.

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INTRODUCTION

Yttria-stabilized (Y₂O₃) tetragonal zirconia polycrystals (Y-TZP) is considered one of the most versatile bioengineering ceramics due to its high hardness, toughness, corrosion resistance, low thermal conductivity, and biocompatibility.^{1–5} In dentistry, yttria-stabilized zirconia is currently used for the fabrication of either fixed partial denture frameworks, then veneered with traditional feldspathic porcelain, for monolithic crowns, implant abutments, and screwed-retained prosthesis substructures.^{6,7} Compared with other dental ceramics, zirconia has higher flexural strength, fracture toughness, and hardness, mainly derived from the mechanism called "transformation toughening."^{8,9} As a result of externally applied stresses, the tetragonal grains may transform into monoclinic forms, exhibiting a 4% volume expansion during the phase transformation, which creates compressive stresses believed to be responsible for partially shielding the crack tip from the far field stress and preventing crack propagation.^{8,10} Together with the mechanical performances, zirconia offers some aesthetic advantage over the traditional porcelain fused to metal restorations. The metal frame, in fact, differs from natural tissues as it is completely opaque, acting as a total barrier for light transmission, whereas zirconia is partially translucent. Nevertheless, Y-TZP is less translucent than natural tissues and other ceramic materials.¹¹ Translucency is one of the most important factors in matching the appearance of natural teeth with restorative materials.^{12,13} Translucency has been defined as the relative amount of light transmission or diffuse reflectance from a substrate surface through a turbid medium.¹⁴ The amount of light that is transmitted and reflected depends on the amount of crystals within the core matrix, their chemical nature, and the size of the particles compared with the incident light wavelength.¹⁵ Particles similar in size to the light wavelength have the greatest scattering effect.¹⁵ Both the chemical nature of the particles (leading to absorption) as well as the relative refractive index of the particles to the matrix affect the amount of scattering.

Most studies indicate that Y-TZP can be considered opaque at clinically relevant thickness.^{11,16,17}

Translucency of zirconia has been reported to be mainly related to grain size^{18–20} and density.^{20,21} Raising the sintering temperature leads to larger grain size and higher density, increasing translucency. Even the physical properties of zirconia depend on the size of the particles,^{2,22} and it has been reported that a larger grain size can lead to a drop of the mechanical performances.¹⁸

Recently, two Y-TZP materials for CEREC® CAD/CAM system with claimed increased translucency, Sirona inCoris TZI and VITA In-Ceram YZ HT were introduced into the market. In the present study, contrast ratio (CR), translucency parameter (TP), flexural strength (σ), Weibull characteristic strength (σ_0) , and Weibull modulus (m) of the two "augmented" translucency" and of three conventional Y-TZPs were investigated. The objective of the study was twofold: (1) The study ails to verify the manufacturer claim that the two newly introduced zirconia show a significant higher translucency than the traditional. The tested null hypothesis was that no statistically significant differences in translucency existed among the materials tested. (2) The study also aims to test if the claimed higher translucency of the new zirconia affects the mechanical properties. The formulated null hypothesis was that the materials do not exhibit significantly different flexural strengths.

MATERIALS AND METHODS

Three-Point Bending Test (3PBT)—Specimens Preparation

Five types of yttria-stabilized green-stage zirconium dioxide blocks marketed for CEREC[®] CAD/CAM system (Sirona Dental, Bensheim, Germany) were selected for this study (IPS e.max Zir-CAD, Ivoclar Vivadent AG, Schaan, Liechtenstein; inCoris ZI, Sirona Dental; inCoris TZI, Sirona Dental; In-Ceram YZ, VITA Zahnfabrik, Bad Sackingen, Germany; In-Ceram YZ HT, VITA—Table 1). Specimens were prepared according to ISO 6872:2008.²³ The blocks were fixed to a low-speed, water-cooled diamond saw (IsoMet Low Speed Saw, Buehler, Lake Bluff, IL, USA). With the use

Group	Material	Flexural strength Weibull statistics		Translucenc	Translucency				
		σ (MPa)	Sig	м	σ ₀ (MPa)	CR	Sig	ТР	Sig
I	lvoclar IPS e.max Zir-CAD	1157±100	а	13.6	1202	0.75±0.01	С	11.48±0.53	С
2	Sirona inCoris ZI	1160±108	а	12.3	1210	0.74 ± 0.02	b, c	12.64±0.93	b, c
3	Sirona inCoris TZI	1098±118	a	10.8	1150	$\textbf{0.68} \pm \textbf{0.01}$	a	14.05 ± 0.31	a
4	VITA In-Ceram YZ	1120±96	а	4.	1162	0.70±0.01	a, b	13.78±0.28	a, b
5	VITA In-Ceram YZ HT	1106±97	а	13.9	1133	$\textbf{0.68} \pm \textbf{0.01}$	a	$\textbf{14.44} \pm \textbf{0.34}$	a

TABLE I. Mean flexural strength, Weibull modulus, Weibull characteristic strength, translucent parameter (TP), and contrast ratio (CR)

The same significance letter indicates no statistically significant differences (p > 0.05) among the tested materials. Bold font indicates the "augmented translucency" Y-TZP (groups 3 and 5).

of a proprietary device, the blocks were first cut longitudinally and then turned 90° clockwise in order to obtain bar-shaped specimens. To perform an accurate cutting procedure, the speed was maintained below 250 rpm and no extra weight was put on the blocks. Cutting dimensions of the specimen were calculated to compensate the shrinkage induced by dense-sintering. Eight different blocks with five specimens per block were used for each of the five tested materials (N = 40)for a total of 200 specimens. Sintering was performed according to manufacturer instruction in a sintering furnace (ZYrcomat 6000 MS, VITA). After sintering, specimens were wet-finished with 600 grit paper until dimensions of 15 ± 0.2 mm length, 4 ± 0.2 mm width, and 1.2 ± 0.2 mm height were obtained. Specimens were then wet-polished with 1,200 and 2,400 grit paper. According to ISO 6872:2008,²³ a 45° edge chamfer was made at each major edge by keeping the specimens at 45° with the 1,200 grit paper disc with a metal rig. The "regeneration firing" was performed for each group in a furnace (Vacumat 6000M, VITA) after the finishing procedure, according to manufacturer instruction. A total of 100 specimens (N = 20) were obtained.

3PBT—Test Method

A 3PBT appliance was prepared. The tip and the supports were made in cobalt-HSS (high-speed steel) by using polished rollers 2.0 mm in diameter. The remaining part of the rig was milled from a stainless steel block (A.I.S.I. type 316). The span was set at

13.0 mm. Tests were performed in a universal testing machine (Triax 50, Controls, Milano, Italy) with a cross-head speed of 1 mm/minute. Specimens were tested dry at room temperature. The fracture load was recorded in N, and the flexural strength (σ) was calculated in MPa by using the following equation:

$$\sigma = \frac{3Pl}{2wb^2} \tag{1}$$

where P in the fracture load in N, l is the span (distance between the center of the supports) in mm, w is the width in mm, and b is the height in mm.

Data were tested to fit a normal distribution with the Kolmogorov–Smirnov test, and the homogeneity of variances was verified with the Levene's test. The one-way analysis of variance (ANOVA) was then performed. The level of significance was set at $\alpha = 0.05$. The statistical analyses were performed with the software PASW Statistic 18.0 (IBM Co, Armont, NY, USA).

The Weibull characteristic strength (σ_0) and the Weibull modulus (*m*) were calculated according to the following equation:

$$P_f = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{2}$$

where P_f is the probability of failure between 0 and 1, σ is the flexural strength in MPa, σ_0 is the Weibull

characteristic strength in MPa (the value at the 63.2% of the specimens fail), and *m* is the Weibull modulus.

CR and TP Measurement—Specimens Preparation

The blocks were fixed to a low-speed, water-cooled diamond saw (IsoMet Low Speed Saw, Buehler) and cut perpendicularly to the long axis. To perform an accurate cutting procedure, the speed was maintained below 250 rpm, and no extra weight was put on the blocks. Cutting measures were calculated to compensate the shrinkage induced by dense-sintering. For each tested material, five different blocks were used to produce 10 samples each, then finished with 600 grit silicon-carbide paper. Sintering was performed according to manufacturer instruction (ZYrcomat 6000 MS, VITA). All the specimens were wet-finished flat on a grinder/polisher with 1,200 grit silicon-carbide paper until the dimensions of $12 \text{ mm} \times 15 \text{ mm}$ and 1-mm thickness were obtained. A total of 50 specimens were produced. Specimens were ultrasonically cleaned in distilled water for 10 minutes before measurement procedure.

CR and TP Measurement—Test Method

The measurements were performed with a spectrophotometer (PSD1000, OceanOptics, Dunedin, FL, USA), equipped with an integrating sphere (ISP-REF, OceanOptics) with a 10-mm opening. The spectrophotometer was connected to a computer running color measurement software (OOILab 1.0, OceanOptics). D65 illumination and 10° standard observation angle were selected. Data were recorded both in CIEXYZ as well as in CIELab* colorimetric systems.

For CR, a quantitative measurement of translucency was made by comparing the reflectance of light "Y" in CIEXYZ colorimetric system (ratio of the intensity of reflected radiant flux to that of the incident radiant flux) through the test specimen over a backing with a high reflectance to that of low reflectance or high absorbance. Two measurements were made with the white reference backing (Y_W) and then the black backing (Y_B), resulting in a total of four measurements per specimen. The mean CR was calculated as $\mbox{CR} = \mbox{Y}_{B}/\mbox{Y}_{W}.^{24}$

For TP, CIELab^{*} colorimetric systems data were used instead. TP was calculated applying the formula $TP = [(L_B^* - L_W^*)^2 + (a_B^* - a_W^*)^2 + (b_B^* - b_W^*)^2]^{1/2}$, where the subscripts B and W refer to color coordinates over a black and a white background, respectively.²⁵

Since the pooled data of CR and TP did not pass the normality test, the use of one-way ANOVA was precluded to assess the significance of the dependent variables.

Since data distribution was not normal according to the Shapiro–Wilk test (p = 0.002 for CR and TP), two different Kruskal–Wallis ANOVA on ranks were applied, followed by the Dunn's multiple range test for post-hoc comparisons, whereas the level of significance was set at $\alpha = 0.05$. The correlation between CR and TP was investigated with the Pearson correlation test. The statistical analyses were performed with the software PASW Statistic 18.0.

RESULTS

The mean of flexural strength (σ), Weibull characteristic strength (σ_0), Weibull modulus (*m*), CR, and TP are reported in Table 1.

3PBT

The normality of data distribution was confirmed by one-sample Kolmogorov–Smirnov test (p = 0.053, two-tailed), and the homogeneity of variances was verified with Levene's test (p = 0.655). One-way ANOVA was performed, followed by Tukey's test for post-hoc comparison. No statistically significant difference among tested groups was recorded (p < 0.05). The power of the test was calculated to be 0.83.

The higher flexural strength was obtained by inCoris ZI (1160 \pm 108 MPa), followed by IPS e.max Zir-CAD (1157 \pm 100 MPa), In-Ceram YZ (1120 \pm 96 MPa), In-Ceram YZ HT (1106 \pm 97 MPa), and inCoris TZI
$(1098 \pm 118 \text{ MPa})$. Regarding the Weibull modulus, the higher value was obtained by In-Ceram YZ (14.1), followed by In-Ceram YZ HT (13.9), IPS e.max Zir-CAD (13.6), inCoris ZI (12.3), and inCoris TZI (10.8).

CR and TP

The result of the Kruskal–Wallis one-way ANOVA has shown a statistically significant difference among tested groups for both CR and TP (p < 0.001). Regarding the CR, In-Ceram YZ, In-Ceram YZ HT, and inCoris TZI obtained a statistically significant higher translucency than other tested materials. No differences were found between In-Ceram YZ and inCoris ZI. Sirona inCoris ZI and IPS e.max Zir-CAD obtained a statistically significant lower translucency. No differences in the levels of significance were found between CR and TP.

CR and TP have shown a statistically significant correlation (p < 0.001) with r = 0.945.

DISCUSSION

A statistically significant difference was found in translucency values between two of the three "traditional" and the two "augmented translucency" zirconia materials; thus, the first null hypothesis formulated is partially rejected. No statistically significant difference in flexural strengths was recorded. Hence, the second null hypothesis is accepted.

Translucency is an important parameter in matching the appearance of the natural tooth and was identified as one of the primary factor in controlling esthetics and a critical consideration in the selection of materials.¹² Translucency is generally measured with CR or TP. CR is the ratio of the reflectance of a specimen over a black backing to that over a white backing of a known reflectance, and is an estimate of opacity.²⁴ CR ranges from 0 to 1, with 0 corresponding to transparency (total translucency) and 1 corresponding to total opacity (no translucency). The TP is the difference in color (ΔE^*) between a uniform thickness of a material measured over white and black backing.²⁵ Although CR and TP for dental ceramics translucency measurement is matter of discussion,²⁶ at present they still represent a well-established parameter.^{27,28}

The Lamberts' law $T = e^{-\alpha x}$ identifies that the transmittance (*T*, a physical parameter representing the ability of light to pass through certain medium) decreases exponentially with increasing thickness (x). Therefore, thickness is a key factor relating to light transmittance. Few data are available on the translucency of different zirconia core materials at the required clinical thickness. In 2002, Heffernan and colleagues¹¹ investigated the translucency of various core materials, reporting glass-infiltrated zirconia-reinforced alumina (VITA In-Ceram ZIRCONIA) to have a CR of 1.00 at 0.5-mm thickness, which is a higher value than the ones obtained in the present study. The authors also found a significant difference among tested materials, and speculated that differences in translucency may be attributable to differences in crystal volume and the refractive index.¹¹ Chen and colleagues¹⁶ reported a relative translucency of 1.00 (totally opaque) for both VITA In-Ceram ZIRCONIA and Cercon base zirconia (dense-sintering zirconia). It should be considered that, even if the thickness of the specimens was the same for both studies, VITA In-Ceram ZIRCONIA is structurally different from Y-TZP zirconia as it is a glass-infiltrated material. Baldissara and colleagues¹⁷ measured the translucency of zirconia coping with the direct light transmission method and light flow (lux) as a unit of measure. In zirconia copings with a thickness from 0.3 to 0.6 mm, a relative amount of light passing through the material for all specimens was reported.¹⁷ The authors proposed that all the evaluated zirconia specimens may be consider translucent to a certain degree, although the quantity of transmitted light is not remarkable when compared with the value of the positive control flow (lithium-disilicate glass ceramic).¹⁷ This low amount of transmitted light, present but not remarkable, supported the definition of zirconia as "semi-translucent" core material.²⁹ Recently, Vichi and colleagues²⁷ proposed a clinical classification of the materials based on their CR. Sirona InCoris ZI and e.max Zir-CAD were classified as "low translucency" materials that comprise materials with CR ranging from 0.75 to 0.90. Sirona InCoris TZI and VITA In-Ceram YZ were instead classified as "medium translucency," which are materials with CR ranging from 0.50 to 0.75.

When comparing the CR of different materials, data should not be evaluated only from a statistically viewpoint, as the statistically significance parameter alone could not be representative of the clinical perception of translucency. Concerning CR, the mean minimal difference perceivable by the human eye was defined as the translucency perception threshold (TPT) by Liu and colleagues,³⁰ and it was found to be 0.07, but with significant variations according to the skill of the observer. Clinician with 10 years of shade-matching experience can have a TPT of 0.04, whereas dental students were in the range of 0.09. In the present study, the CR of In-Ceram YZ HT and inCoris TZI was 0.68 for both materials at 1-mm thickness. The differences in mean CR between the two "augmented translucency" zirconia and the three traditional materials ranged from 0.02 (versus In-Ceram YZ) to 0.06 (versus inCoris ZI) to 0.07 (versus IPS e.max Zir-CAD). These differences, even if statistically significant, from a translucency perception viewpoint were below or at the limit of the threshold (TPT). Besides the CR, the TP is also used to identify the translucency of dental materials.^{31–33} Recently, Barizon and colleagues³⁴ found a correlation between CR and TP, concluding that either CR or TP can be used to evaluate the relative translucency of ceramic systems. This is in agreement with the results obtained in the present study, where CR and TP obtained a strong correlation (0.945). Conversely for CR, for TP the limit of clinical acceptability has not yet been identified, and it is uncertain whether the differences reported could be clinically relevant, even if the correlation between CT and TP tentatively supports the same conclusions.

In clinical routine, zirconia is often colored by infiltration at green stage with specific coloring liquids. Some studies investigated the influence of coloring procedure on translucency of zirconia. Shaded zirconia was addressed to be partially translucent by Spyropoulou and colleagues³⁵ A mean CR between 0.877 and 0.880 was measured on 0.6-mm thickness shaded disks of NobelProcera zirconia, depending on the shade.³⁵ The authors concluded that the shaded zirconia is partially translucent, and varying the shade does not clinically affect the translucency. A TP similar to that of human dentine was also found in colored zirconia samples of IPS e.max Zir-CAD and LAVA Zirconia at 0.5-mm thickness.³² In the present study, it should be pointed out as possible limitation that the materials have been tested without any coloring system. This was preferred as different companies produce proprietary coloring liquids, and this could lead to a bias in the material evaluation both for optical test as well as for mechanical test. Further studies should be performed to better understand the variation in translucency for each of the zirconia tested in relationship with the use of coloring liquids in different shades.

A large role in the transparency of zirconia is played by density (porosity).³⁶ Pores larger than 50 nm cause significant scattering and thus reduction of light transmission ("pore scattering").³⁶ Using the technique of spark plasma sintering, Alaniz and colleagues¹ used nanocrystalline 8 mol% yttria-stabilized zirconia powder with a reported grain size of 50 nm to produce transparent specimens of different colors, according to the holding time at the final pressure and temperature. Specimens of amber brown, dark orange, and ruby-red colors were obtained, each one with high optical resolution.¹ The authors in the same paper proposed in fact that in high-density nanocrystalline zirconia, it is unlikely that pore diameter would be greater than grain size, and the use of <50-nm grain zirconia reduces the problem of light scattering.¹ The suggestion that pores can be the main factor that affects the translucency greatly was also proposed by Jiang and colleagues¹⁹ The authors demonstrated that using 40-nm powder instead of 90-nm powder improves the sintered density and reduces pores, reducing scattering. Sintering temperature also plays a primary role in determination of sintered density.³⁷ The authors have shown that the transmittance increases with the sintering temperature (from 1,350–1,500°C), and at the same temperature the transmittance of 40-nm powder was higher.³¹ With the increasing temperature, the zirconia crystal structure becomes more compact, whereas porosity, defect, and flaws decrease.19

From a clinical viewpoint, translucency is a key factor in material selection, but its evaluation should be flanked by flexural resistance evaluation. Lowering the thickness of the restoration would allow the material to be more translucent, thus more aesthetic, but at the same time less fracture resistant. Conversely, by increasing the thickness, the resistance of the material will be raised but the translucency will be decreased, limiting the aesthetic performances. Concerning monolithic zirconia, the use of which shows a fast-growing interest by clinicians, the minimal feasible thickness for clinical use, taking into account the clinical masticatory forces in terms of flexural resistance, could be considered at about 0.5 mm.³⁷ At the same time, with traditional zirconia, the opacity limits the aesthetic outcome of the material beyond about 0.75-mm thickness,²⁷ being this the thickness at which a traditional zirconia matches the opacity of dentin.^{27,38} Thus, with zirconia being prone to break below 0.5 mm and too opaque over about 0.75 mm, the interval $0.5 < ZrO_2 < 0.75$ mm could be considered a clinical range for the use of monolithic traditional zirconia combining resistance and aesthetic. Based on the results of the present study, the new augmented translucency zirconia showed similar flexural resistance with a slightly higher translucency; therefore, the range for combining optimal mechanical and aesthetic performance could be extended to about $0.5 < ZrO_2 < 1.0$ mm.

About veneered zirconia, an influence of the veneering technique on the translucency of zirconia-ceramic restoration has been reported.³⁹ Significantly different results in L*, a*, and b* parameters and total luminous transmittance have been observed when a zirconia core is veneered with heat-pressing or traditional condensing veneering ceramic.³⁹ However, the existing scientific literature shows a lack of information on this aspect, and the complexity of the optical interaction between the zirconia core and the veneering ceramic should be further investigated.

DISCLOSURE

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

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Gloss and Stain Resistance of Ceramic-Polymer CAD/CAM Restorative Blocks

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ABSTRACT

Objective: To evaluate the gloss and stain resistance of several new ceramic-polymer CAD/CAM blocks **Materials and Methods:** Specimens (4 mm) were sectioned from: Enamic (polymer-infused ceramic), LAVA Ultimate (nano-ceramic reinforced polymer), e.max (lithium disilicate), Paradigm C (porcelain), and Paradigm MZ100 (composite). Specimens were wet polished on a polishing wheel to either 320 grit silicon paper (un-polished, N=8) or 2000 grit silicon carbide papers followed by a 0.05 μ m alumina slurry (polished, N=8). Initial gloss and color (L*a*b*) values were measured. Specimens were stored in a staining solution at 37°C in darkness for 12 days (simulating 1 year). After storage, L*a*b* values re-measured. Change in color was reported as ΔE_{00} based on the CIEDE2000 formula. Gloss and ΔE_{00} were analyzed by two-way analysis of variance (ANOVA) (alpha=.05). Separate one-way ANOVA and Tukey post-hoc analyses were performed for both polish conditions and all materials. **Results:** Two-way ANOVA showed that factors material, polish and their interaction were significant for both gloss and ΔE_{00} (p < .01). Post-hoc analysis reveals that polished specimens had significantly less color change than un-polished specimens for Paradigm C and LAVA Ultimate. E.max had significantly higher gloss and less color change than all other materials.

Conclusion: The composition and polish of CAD/CAM materials affects gloss and stain resistance.

CLINICAL SIGNIFICANCE

Ceramic-polymer hybrid materials can achieve the high gloss required for esthetic restorations. These materials should be polished in order to minimize staining. If polished, all of the tested materials exhibited clinically acceptable color changes at I year of simulated staining.

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INTRODUCTION

With 15% of dentists now using CAD/CAM units, new materials have been developed specifically for compatibility with in-office milling devices.¹ The initial permanent restorative materials available for in-office CAD/CAM fabrication were feldspathic porcelains, glass ceramics, and polymer composites.² Lithium disilicate, a glass ceramic, has been the material of

choice for anterior full-contour restorations with in-office mills due to its superior esthetic and strength properties.³ Lithium disilicate crowns are fabricated in two steps. First, they are milled in a pre-sintered state. Next, they are heat treated in order to obtain their final strength.⁴ A new class of ceramic-polymer hybrid restorative materials has been introduced that can be fabricated in a single milling step without the need for heat treatment. The materials in this class include a

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polymer-infused ceramic (Enamic; VITA, Bad Säckingen, Germany) and a nano-ceramic reinforced polymer (LAVA Ultimate; 3M ESPE, St Paul, MN, USA). Essentially, Enamic is a feldspathic porcelain infused with resin polymer⁵ and LAVA Ultimate is a highly filled dental composite.⁶ The fracture strength of LAVA Ultimate has been found to be similar to lithium disilicate.^{7,8} Wear testing showed that LAVA Ultimate experienced slightly more material wear than lithium disilicate in one study⁹ and that both Enamic and LAVA Ultimate experienced equivalent wear as lithium disilicate in another.¹⁰ With mechanical properties similar or slightly inferior to lithium disilicate, ceramic-polymer hybrid materials are well suited for anterior restorations. Due to the highly esthetic demands for anterior fixed restorations, additional information about the optical and color properties of these materials is needed, particularly gloss and stain resistance.

The gloss of a dental material is a large factor in the esthetic appearance of the final restoration. Traditional composite materials show a greater gloss deterioration than ceramics.¹¹ As a result, the clinically evaluated esthetic stability of composites has been less than that of ceramics.¹² A recent study compared the gloss of Enamic and LAVA Ultimate to lithium disilicate before and after toothbrush wear.¹⁰ Although the ceramic-polymer blocks had similar gloss as the lithium disilicate prior to toothbrush abrasion, following toothbrushing, the resin-ceramics displayed lower gloss.

Previous studies have shown that polymer composites undergo clinically perceptible color change in staining solutions.^{13,14} Unlike glass ceramics, ceramic-polymer materials contain a polymer component, and a previous study concluded that Enamic and LAVA Ultimate had a higher color change in staining solution than lithium disilicate.¹⁵ A recent study concluded that LAVA Ultimate had less color stability than traditional laboratory processed composites.¹⁶ The authors speculated that staining of LAVA Ultimate was due to incomplete polymerization. The study did not evaluate Enamic or ceramic materials.

The purpose of this study is to compare the gloss and stain resistance of ceramic-polymer hybrid materials to ceramic and polymer materials traditionally used for CAD/CAM restorations. Additionally, the effect of surface polish will be compared. The null hypotheses are that: (1) there will be no difference in the gloss of polished or un-polished CAD/CAM materials and (2) there will be no difference in the stain resistance of polished or un-polished CAD/CAM materials.

MATERIALS AND METHODS

Specimen Preparation

Five materials were used in this study to represent various classes of CAD/CAM materials (Table 1). CAD/CAM blocks were sectioned into 4.3 ± 0.2 mm thick sections with a low speed sectioning saw. Lithium disilicate specimens were fired in a Programat CS Oven (Ivoclar Vivadent, Schaan, Liechtenstein) following the parameters of the manufacturer for crystallizing IPS e.max CAD (no glaze was used). Specimens (N=16 per material) were polished on a wet polishing wheel either with 320 grit silicon paper (N=8) or with a sequence of

Material	Manufacturer	Classification	Shade
Paradigm MZ100	3M ESPE	Composite	AI
Paradigm C	3M ESPE	Feldspathic porcelain	AI
LAVA Ultimate	3M ESPE	Nano-ceramic reinforced polymer	AI-LT
Enamic	VITA	Resin infiltrated ceramic	OMI—Translucent
IPS e.max CAD	Ivoclar Vivadent	Lithium disilicate	AI-LT

TABLE I. Materials used in this study

320, 400, 600, and 1200 grit silicon carbide grinding papers followed by a slurry of 0.05 μ m alumina powder (*N* = 8). Polishing to 320 grit represents adjustment with a diamond bur and polishing to 1,200 grit and alumina powder represents extra-oral polishing. All polishing was performed parallel to the straight edge of the specimen and repeated following a 90° rotation. Specimens were examined following polishing and if any stray scratches were present, the polishing procedure was repeated. After all polishing was complete, specimen thickness was confirmed to be 4.0 ± 0.1 mm or the specimen was remade.

Gloss and Color Measurement

Gloss measurements were recorded using a glossmeter (Novo-Curve, Rhopoint Instruments, East Sussex, UK) using 60° geometry. A positioning fixture made from impression material was used on the gloss meter to position each specimen and ensure repeatable measurements using the same specimen orientation used in polishing. The device was calibrated between materials and all ambient light was blocked by a black opaque lid. Two gloss unit (GU) values were recorded from each specimen and averaged.

Color measurements were recorded using L*a*b* values. Initial L*a*b* values were taken using a spectrophotometer (CM-700d; Konica Minolta, Ramsey, NJ, USA) against a white non-reflective background. Silicone fixtures for the spectrophotometer and a 1-second sampling delay were employed to minimize instrument vibrations during measurement. The device was run in specular component excluded mode with 10° geometry. Each sample was measured twice and the values were averaged together by the spectrophotometer.

Specimens were stored in a staining solution composed of 600 mL of cranberry juice, 3 black tea bags, and 50 mL instant coffee at 37°C in darkness for 12 days. This storage time was chosen to simulate 1 year of clinical service as 24 hours of staining in vitro corresponds to 1 month in vivo.¹⁷ After storage, specimens were cleaned in distilled water in an ultrasonic bath for 10 minutes. L*a*b* measurements were recorded exactly as described for pre-stain specimens. Stain resistance was measured using ΔE_{00} calculated with the CIEDE2000 color difference formula:^{18-20}

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{K_L S_L} \right)^2 + \left(\frac{\Delta C'}{K_C S_C} \right)^2 + \left(\frac{\Delta H'}{K_H S_H} \right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C} \right) \left(\frac{\Delta H'}{K_H S_H} \right) \right]^{1/2}$$

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ are differences in lightness, chroma, and hue; R_T (rotation function) accounts for the interaction between hue and chroma in the blue region; S_L , S_C , and S_H adjust for variation in the L*a*b* coordinate system; and K_L , K_C , and K_H correct for experimental conditions ($K_L = 1$, $K_C = 1$, $K_H = 1$ for this study).

Statistical Analysis

Gloss and ΔE_{00} were separately analyzed by two-way analysis of variance (ANOVA) (alpha = 0.05) to study the influence of the factors material and polish and the interaction between material and polish. As appropriate, separate *t*-tests, one-way ANOVAs, and Tukey post-hoc analyses were performed for both polish conditions (Bonferroni adjusted alpha = 0.025) and material type (Bonferroni adjusted alpha = 0.01).

RESULTS

The gloss and ΔE_{00} of both polished and un-polished samples are presented in Table 2. For both gloss and ΔE_{00} , the two-way ANOVA showed that factors material, polish, and their interaction were significant (p < .01). For gloss, separate one-way ANOVA and Tukey analysis of un-polished specimens showed that Paradigm MZ100 and Enamic had the lowest gloss whereas e.max had the highest gloss. For polished specimens, the Paradigm MZ100 material produced the lowest gloss and the e.max produced the highest gloss. All materials became significantly glossier following polishing. Separate one-way ANOVA and Tukey analysis for stain resistance of un-polished specimens

Material	Gloss of un-polished group (gloss units, mean ± SD)	Gloss of polished group (Gloss Units, mean ± SD)	Stain of un-polished group (ΔE_{00} , mean ± SD)	Stain of polished group (ΔE_{00} , mean ± SD)
e.max	57.2 ± 7.5^{d}	95.8±2.1°	0.18 ± 0.14^{a}	0.17 ± 0.08^{a}
Paradigm C	39.6±3.2°	89.3±1.1 ^d	1.23±.25 ^b	$0.58 \pm 0.34^{a,b}$
Enamic	2.3± .2ª	70.7±4.3 ^b	1.17±0.32 ^b	0.83 ± 0.4 ^{b,c}
LAVA Ultimate	30.5 ± 4.5 ^b	85.4±1.4°	2.76±1.19°	1.51±0.51 ^d
Paradigm	11.3 ± 3.3^{a}	42.3 ± 3.0^{a}	1.47±0.41 ^b	1.34±0.49 ^{c,d}

TABLE 2. Gloss and stain of un-polished and polished CAD/CAM restorative materials

Values with similar superscripts in each column represent statistically similar groups.

showed that LAVA Ultimate had the most color change whereas e.max had the least. For the polished specimens, e.max had significantly less color change than Paradigm MZ100, LAVA Ultimate, or Enamic. Post-hoc analysis reveals that polished specimens had significantly less color change than un-polished specimens for Paradigm *C* and LAVA Ultimate.

DISCUSSION

Both null hypotheses tested in this study were rejected; the gloss and stain resistance differed between materials and polishing condition. Polishing improved the gloss of all materials and improved the stain resistance for some materials (Paradigm C and LAVA Ultimate) but did not significantly affect others.

Gloss represent the amount of specular (mirror-like) reflection from a surface. A highly polished black reference glass is assigned a value of 100 GU whereas a completely non-reflective surface is assigned 0 GU.²¹ Gloss is determined by comparing the magnitude of incident light travelling toward a surface at a certain angle (in this case 60) to the magnitude travelling away from the surface at an equal and opposite angle. Therefore, gloss is affected by the index of refraction of a material and the topography of its surface. Index of refraction is a measure of the ability of a material to change the velocity and direction of incident light upon contact with its surface. It is dependent on the electrical excitability of atoms within the material, and has been shown to be higher for ceramic materials than carbon-based polymers.²² In this study, the two pure ceramic materials, e.max and Paradigm *C*, produced the highest gloss in the polished and un-polished state. The reflectivity of these ceramic surfaces is partially owing to their composition and the ability of their constituent atoms to retard advancing light.

The roughness of a material will also affect gloss as asperities on its surface will scatter light instead of reflecting it. All materials had improved gloss following polishing; however, the traditional composite material, Paradigm MZ100, achieved a much lower gloss than the other materials. Paradigm is a hybrid composite composed of filler particles ranging in size from 0.01 to 3.5 µm. In contrast, LAVA Ultimate is a composite filled with discrete and clustered nanoparticles on the size range of 5–20 nm. While polishing Paradigm MZ100, loss of micron-sized particles will leave surface irregularities larger than the wavelength of visible light (~400-800 nm), decreasing light reflectance and gloss. The nano-sized particles in LAVA Ultimate, however, are smaller than the wavelength of light so particle loss will not affect gloss.²³ A limitation of this study is that all gloss measurements were performed with a measurement angle of 60°; however, decreasing the measurement angle to 20° may have helped further discriminate the highly glossy specimens.

A previous study examined the gloss and gloss retention of Enamic, LAVA Ultimate, and e.max.¹⁰ That study found that all materials had gloss values 56–57 GU, but the specimens in were only polished to an equivalent of 1,200 grit silicon carbide paper, which may explain the lower gloss values than obtained in the current study. Their study also determined that gloss was significantly decreased following toothbrushing abrasion for Enamic and LAVA Ultimate but not e.max. As e.max was found to be over five times harder than Enamic and LAVA Ultimate, the surfaces of these hybrid materials were more easily abraded.

Stain resistance was measured with a three-dimensional color measurement system that consists of a lightness scale, L* and an opponent color axis for both redness-greenness, a*, and yellowness-blueness, b*.²⁴ The L*a*b* values were used to determine color changes in the specimens before and after staining using the CIEDE2000 formula. This formula is an update to the previous CIELAB color difference formula to adjust for the non-uniformity of the CIELAB space and differences in illuminating conditions. Additional modifications were also made to the formula to improve agreement with visual perception of neutral colors and a chroma/ hue interaction in the blue region.^{18–20} The CIEDE2000 formula provides a better fit with visually assessed acceptability and perceptibility of color differences in dental ceramics.^{25,26} A study by Ghinea and colleagues²⁵ determined that 50% of observers would accept a color difference of $\Delta E_{00} = 2.23$ under clinical conditions and that 50% of observers could detect a color difference of $\Delta E_{00} = 1.25$. Based on those parameters, only unpolished LAVA Ultimate had staining that would be clinically unacceptable (Figure 1) and only polished and



FIGURE I. Un-polished specimens before (top row) and after (bottom row) simulated staining (from left to right: e.max, Paradigm C, Enamic, LAVA Ultimate, Paradigm Z100).

unpolished LAVA Ultimate and Paradigm had perceptible staining. A trend in the results of stain resistance indicates that materials with polymer content have more staining the pure ceramic materials. Polymers uptake water and therefore may be more likely to absorb the pigments dissolved in the staining solution.²⁶

Other important optical factors to consider when selecting a restorative material are translucency and fluorescence. A previous study determined that LAVA Ultimate (1.2 mm thick) had a visible light transmission of 47.1% which is intermediate to a traditional composite (Paradigm MZ100, 45.5%) and a glass ceramic (Vita Mark II, 50.8%). Additionally, the LAVA Ultimate and Vita Mark II showed a higher fluorescence than the Paradigm Z100.²⁷ Another factor to consider when comparing ceramic and ceramic-polymer hybrid materials is that the latter group cannot be fired, eliminating the ability to apply a glaze. Glazed ceramics, however, have been shown to be less glossy than polished ceramics.²⁸

CONCLUSION

Once polished, ceramic-polymer hybrid materials are capable of achieving gloss much higher than a traditional composite material, but slightly less than pure ceramics. The hybrid materials showed less stain resistance than lithium disilicate. When polished, however, all materials showed clinically acceptable color change following 1 year of artificial staining.

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Shade Correspondence, Color, and Translucency Differences between Human Dentine and a CAD/CAM Hybrid Ceramic System

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ABSTRACT

Objective : To determine the shade correspondence between human dentine and two versions of a CAD/CAM hybrid ceramic system and to investigate color and translucency differences between these materials.

Materials and Methods: Twenty-four samples of different shades and opacities were fabricated from Vita Enamic CAD/CAM ceramic blocks. Human dentine samples were obtained from 73 extracted maxillary teeth. Color coordinates of all samples were measured using VitaEasyshade spectrophotometer. The translucency parameter (TP) and ΔE_{ab}^* and ΔE_{00} color differences, with respect to human dentine of anterior and posterior teeth, were calculated.

Results: Vita EnamicTranslucent was the best match for anterior teeth (>90% of cases) while Vita EnamicT 3M2 was the best option for the dentine samples of posterior teeth in 78.8% (ΔE_{ab}^*) and 54.5% (ΔE_{00}) of the cases. The smallest differences in translucency (Δ TP) with the dentine samples of anterior teeth were obtained for Vita EnamicT 3M2 (92.5%) and with those of posterior teeth for Vita Enamic HT IM2 (45.4%).

Conclusions : VITA EnamicTranslucent is the best option as color match for both anterior and posterior teeth dentine. In terms of translucency, VITA Enamic Translucent closely matched anterior teeth dentine while for posterior teeth, VITA Enamic HTwas the best option.

CLINICAL SIGNIFICANCE

The results of the present study could help clinicians in their decision of choosing a specific shade and translucency for their anterior or posterior esthetic restorations with hybrid ceramics.

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INTRODUCTION

In restorative dentistry, the aim of every clinician is to offer the patient a faithful imitation of the missing tooth structures. Complementary to the special attention given to the morphology, surface texture, and function of the reconstruction, a good matching between the color of the remained dental tissues and restoration is strongly required. In the process of assessment and reproduction of natural tooth color, it has been reported that the type of tooth, the optical properties, and the thickness of the missing structures have to be considered.¹ The final color of natural teeth is the result of the combination of enamel and dentine optical

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properties.² Similarly, shade perception of restorative materials is given by the interpenetration of light reflectivity, scattering, absorbtion, and transmittance phenomena taking place within the material aimed to duplicate the color appearance of natural teeth.³

The increased esthetic expectations of patients have led to the development of a variety of metal-free dental materials with different mechanical and optical properties, adapted to CAD/CAM technology. Their use, increasingly common in dental offices, has been constantly improved over the years.⁴ The two main classes of metal-free restorative materials are ceramics and resin-based composites. Selection criteria may be a challenge between the mechanical and the optical properties of the material. The increase of the esthetic parameters leads to decreasing in the crystalline content or filler particles of the material, which result in a reduced longevity and a greater translucency.⁵ However, computer-aided design and computer-aided manufacturing chairside system has been scientifically demonstrated to produce, in an easier and faster way, clinically adequate restorations with good long-term performance.^{4,6–11}

To overcome some of the disadvantages of both porcelains and resin-based composites, a new developed hybrid dental ceramic was offered as an alternative solution. This polymer-infiltrated-ceramicnetwork showed similar mechanical properties to the tooth double-layered structure.^{12,13} A recent microstructural characterization and evaluation of this material revealed a leucite-based ceramic network interconnected with an acrylate polymer network, combining features from both ceramics and highly filled resin-based composites.¹⁴ Nevertheless, little information is available on the optical behavior of this material compared to the color coordinates and translucency of hard dental structures. Awad et al.¹⁵ found that this type of hybrid-ceramic showed the lowest absolute translucency values compared to glass ceramics, feldspathic ceramics, and resin composites.

Translucency was considered one of the main factors contributing to the ability of a restorative material to mimic the natural appearance of the enamel and dentine.^{16,17} This optical parameter, situated between complete opacity and transparency,¹⁸ is influenced not only by the composition of the material^{19–22} but also by its thickness,^{20,21,23,24} shade,^{21,24,25} manufacturing technique, and illuminants.^{26,27} One method of assessment of the translucency of a material is the translucency parameter (TP). The TP is defined as the color difference of a material with precise given thickness on a black and white background.²⁸ TP was widely used in dental research showing differences between direct or indirect resin-based composites,^{29–31} ceramic materials with different chemical composition,^{20,32–34} translucent composites and human enamel,³⁵ zirconia ceramics and human or bovine dentine.³⁶

For clinical successful esthetic restorations, it is necessary to combine a proper translucency with an accurate color matching. In this sense, clinical spectrophotometers showed widely recognition due to their precise measurements, repeatability, and reproducibility,^{37–40} being a real aid in determining the values of CIE (Commission Internationale de l'Eclairage) $L^*a^*b^*$ color coordinates of a material.

The need of a perfect color match between the remained tooth structures and the desired restoration, led to the use in dental field of CIELAB (ΔE_{ab}^*), which represented the total Euclidean color difference between two points of the tridimensional CIELAB space. The larger the magnitude of color difference, the greater the value, suggesting a higher perceptibility of color difference by the human eye.^{41–43} Several investigations demonstrated that the more recently introduced CIEDE2000 (ΔE_{00}) color difference formula,⁴² currently recommended by CIE, incorporates specific corrections for nonuniformity of CIELAB color space, providing a higher degree of fit than CIELAB formula, for both color difference perceptibility and acceptability.⁴⁴

The purpose of this study was: (1) to determine the shade correspondence according to the frequency of best match based on the minimum color difference, between human dentine and a hybrid CAD/CAM processed ceramic in two different opacities: translucent (T) and high translucent (HT); (2) to evaluate, in terms of perceptibility and acceptability tolerances, the color variances between human dentine

and the two materials studied; and (3) to determine the differences in translucency among human dentine from anterior as well as posterior teeth and the two evaluated hybrid ceramics.

The null hypotheses against which we tested our study measurements assumed: (1) that there are no color differences among anterior and posterior human dentine and hybrid ceramics and (2) that the TP of hybrid ceramics did not differ from the corresponding values of human dentine.

MATERIALS AND METHOD

Preparation of Ceramic Samples and Human Dentine Specimens

A total of 24 square-shaped samples (14 mm \times 12 mm), distributed in 8 groups, 3 per group, were fabricated from HT (high translucent) and T (translucent) Vita Enamic (Vita Zahnfabrik, Bad Säckingen, Germany) hybrid dental ceramic ingots with the shades corresponding to 1M1, 1M2, 2M2, and 3M2 (Table 1) according to the Vita 3D-Master® shade guide (Vita Zahnfabrik, Bad Säckingen, Germany). Vita Enamic is composed from 86% (by weight) finestructure feldspar ceramic and 14% (by weight) polymer (Table 2). Hybrid dental ceramic samples of 2.1 mm thickness were obtained by cutting CAD/CAM blocks with a water-cooled diamond disk at low speed (150 rpm) in a precision saw machine (Isomet 1000, Buehler, Illinois, USA).

All samples were finished and polished by the same user on a grinder/polisher with wet 120-, 240-, 400-, 600-, 800-, and 1,200-grit silicon carbide paper. During the polishing process, the thickness of the samples was repeatedly evaluated until the final thickness of 2 ± 0.001 mm was achieved (Powerfix Profi+, OWIM Haiger, Germany).

Human dentine was obtained from 73 extracted teeth. Inclusion criteria were absence of caries, conservative or prosthetic restorations, cracks, and pathological discolorations. The teeth, extracted from orthodontic or periodontal reasons, were cleaned from debris under water jet and carefully visually inspected. After selection, they were divided in two sets, anterior (33 frontal and lateral maxillary incisors and 7 canines) and posterior (33 molars) teeth. All extracted teeth were preserved in distilled water at room temperature until their preparation and testing. A precision sectioning saw (Isomet 1000, Buehler, USA) was used to cut at low speed (250 rpm) under water cooling, dentine slices from the crowns of the teeth. First, the roots were manually cut away with a diamond disk and then embedded in a mass of transparent acrylic resin (Premacryl Plus, Spofa Dental, Warsaw, Poland). The resulted prisms were of 3.5 cm height and 3.0 cm in diameter. Incisors and canines were included with their labial surface toward the base of the prism, while molars had their occlusal surface toward the base of the prism. To ensure a perfect perpendicular position of the crown to the saw blade, all the prisms were fixed in a custom-made metal support adapted to the hard tissue microtome. Dentin slices of 2.1 mm thickness and 10 mm diameter surrounded by acrylic resin were obtained by removing through horizontal cutting the occlusal enamel for molars and the labial enamel for anterior maxillary teeth. One operator finished and polished manually, under constant pressure, all the samples with wet 400-, 600-, 800-, 1,000-, 1,500-, and 2,000-grit silicon-carbide paper (Klingspor Schleifsysteme Haiger, Germany). Finally, 2-mm thick specimens of superficial dentine, surrounded by a line of enamel, in the middle of a transparent mass of resin were obtained. Three short-term repeated measurements of thickness were performed with an electronic digital caliper (Powerfix Profi+, OWIM Neckarsulm, Germany).

Before color measurements, all the 24 ceramic disks, as well as the 73 dentine specimens were ultrasonically cleaned in distilled water for 10 minutes and dried under compressed air.

Color Measurements

A Vita Easyshade Compact[®] (Vita Zahnfabrik, Bad Sackingen, Germany) clinical spectrophotometer was used to measure CIE L^* , a^* , b^* color coordinates of both dentin specimens and hybrid dental ceramic materials against black ($L^* = 2$, $a^* = 1.1$, $b^* = -1.1$) and white ($L^* = 93.3$, $a^* = -1.1$, $b^* = 1.9$) backgrounds. Between the specimens and the background was interposed a sucrose solution

TABLE I. Tested hybrid ceramic materials

Material	Manufacturer	Classification	Number of samples	Shade	Batch #
Vita	Vita Zahnfabrik, Bad Säckingen,	Machinable ceramic	3	HT-IMI	47960
Enamic	Germany	by a polymer network	3	HT-IM2	53720
			3	HT -2M2	45810
			3	HT -3M2	43180
		_	3	T-IMI	44680
		_	3	T-IM2	34720
			3	T -2M2	40501
			3	T -3M2	48001

TABLE 2. Chemical composition of Vita Enamic

Ceramic network (oxides by weight)	Polymer network
SiO ₂ (58–63%)	Surface-modified
Al ₂ O ₃ (20-23%)	free from MMA
Na ₂ O (6–11%)	_
K ₂ O (4–6%)	_
B ₂ O ₃ (0.5–2%)	_
CaO(<1%)	-
TiO ₂ (<1%)	-

(n = 1.5 measured with a digital refractometer [Exacta Optech]). For each sample and background, three measurements without replacement were performed by the same operator and the results were averaged. The probe tip of the spectrophotometer was placed perpendicularly and in contact with the middle third of the labial surface for incisors and canines and with the center of molar dentin specimens. Prior to all measurements, the spectrophotometer underwent standard white point calibration according to the manufacturer's recommendations.

Color Differences

Color differences (ΔE) between the two sets of human dentine (anterior and posterior) and the ceramic

materials, were calculated using CIELAB (ΔE_{ab}^*) color difference formula^{41,42}:

$$\Delta E_{ab}^{*} = \sqrt{(\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}}$$
(1)

where ΔL^* , Δa^* , and Δb^* are the differences in the respective coordinates for a pair of samples; CIEDE2000 (ΔE_{00}) color difference formula, according to following equation^{42,44}:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C}\right) \left(\frac{\Delta H'}{K_H S_H}\right)}$$
(2)

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ are the differences in lightness, chroma, and hue for a pair of samples in CIEDE2000, and R_T 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 , S_H adjust the total color difference for variation in the location of the color difference pair in L', a', b'coordinates and the parametric factors K_L , K_C , K_H , are correction terms for experimental conditions. In the present study, the parametric factors of the CIEDE2000 color difference formula were set to 1.

To calculate using the CIEDE2000 color difference formula, discontinues due to mean hue computation and hue-

difference computation were taken into account, whereby both were pointed out and characterized by Sharma et al.⁴⁵

Color differences between the dentine samples and the ceramic materials (ΔE) were finally evaluated through comparisons with 50:50% perceptibility (PT) and 50:50% acceptability (AT) thresholds. The perceptibility thresholds considered in this study were 1.22 units (ΔE_{ab}^*) and 0.81 units (ΔE_{00}), while the acceptability thresholds considered in this study were 2.66 units (ΔE_{ab}^*) and 1.77 units (ΔE_{00}), as recently determined for dentistry using TSK Fuzzy Approximation.⁴¹

Translucency Parameter

TP values for both dental ceramics and dentine samples were calculated according to the following formula^{28,46}:

$$TP = \sqrt{\left(L_{B}^{*} - L_{W}^{*}\right)^{2} + \left(a_{B}^{*} - a_{W}^{*}\right)^{2} + \left(b_{B}^{*} - b_{W}^{*}\right)^{2}} \quad (3)$$

where subscript W refers to the color coordinates of a sample over the white background and subscript B to the color coordinates of the sample over the black background.

Differences in TP between the dentine samples and the ceramic materials were calculated as:

$$\Delta TP = |TP_D - TP_C| \tag{4}$$

where TP_D corresponded to the Translucency Parameter value of a dentine sample and TP_C corresponded to the Translucency Parameter value of a dental ceramic sample.

RESULTS

In Table 3 are presented the results for the frequency of best match (according to minimum color difference, computed with both ΔE_{ab}^* and ΔE_{00} color difference

formulas) between the two dental hybrid ceramic materials studied and the dentine samples of anterior and posterior teeth when measurements were performed against a black background. In terms of shade correspondence, for anterior teeth, according to the CIELAB color difference formula (ΔE_{ab}^*) the Vita Enamic T shade 3M2 was the best option in 52.5% of the cases, while when calculating with the CIEDE2000 color difference formula (ΔE_{00}), the best option for dentine samples of anterior teeth was Vita Enamic T shade 1M2 (42.5%). In the case of posterior teeth, independently of the color difference formula used, the best shade match was always Vita Enamic T shade 3M2 (78.8% for the ΔE_{ab}^* formula and 54.5% for the ΔE_{00} formula).

Shade correspondence in terms of frequency of best match (according to minimum color difference, computed with both ΔE_{ab}^* and ΔE_{00}) between the dental hybrid ceramic material studies and the dentine samples of anterior and posterior teeth when measurements were performed against a white background are presented in Table 4. The results obtained for the white background are similar with the results obtained for the black background. The highest frequency for anterior teeth was found for Vita Enamic T shade 3M2 (40.0%) when computation are performed with the CIELAB formula and for Vita Enamic T shade 1M2 (37.5%) when computations are performed with the CIEDE2000 color difference formula. In the case of the posterior teeth, the highest frequencies of best match were found, independently of the color difference formula used for computation, for Vita Enamic T shade 3M2 (93.9% for the ΔE_{ab}^* formula and 69.7% for the ΔE_{00} formula).

When compared with the perceptibility (PT) and acceptability (AT) thresholds, the minimum color differences between the dentine samples and the corresponding best match of hybrid ceramic material were in all situations higher than both the perceptibility and acceptability thresholds, independently on the color difference formula or the background used for color measurements and the type of tooth.

In terms of translucency, the material which presented the smallest difference in translucency (Δ TP) with the

Anterior teeth	Ceramic sample		нтімі	HT IM2	HT 2M2	HT 3M2	тімі	T IM2	T 2M2	T 3M2
	Frequency of best	ΔE^*_{ab}	0.0	0.0	0.0	2.5	5.0	27.5	12.5	52.5
	match (%)	ΔE_{00}	0.0	0.0	0.0	7.5	5.0	42.5	15.0	30.0
Posterior teeth	Ceramic sample		нт імі	HT IM2	HT 2M2	HT 3M2	тімі	T I M2	T 2M2	T 3M2
	Frequency of best	ΔE^*_{ab}	0.0	0.0	0.0	18.2	0.0	0.0	3.0	78.8
	match (%) —		0.0	0.0	0.0	42.4	0.0	3.0	0.0	54.5
Legend	Highest frequency			Second highest frequency Third highest frequency						

TABLE 3. Frequency of best match (%) of the two dental hybrid ceramic materials according to the minimum color difference $(\Delta E_{ab}^* \text{ and } \Delta E_{00})$ for measurements over black background

TABLE 4. Frequency of Best match of the two dental hybrid ceramic materials according to the minimum color difference $(\Delta E_{ab}^*$ and $\Delta E_{00})$ for measurements over white background

Anterior teeth	Ceramic sample		нтімі	HT IM2	HT 2M2	HT 3M2	тімі	T IM2	T 2M2	T 3M2
	Frequency of best	ΔE^*_{ab}	2.5	0.0	5.0	2.5	7.5	25.0	17.5	40.0
	match (%)	ΔE_{00}	5.0	2.5	2.5	12.5	5.0	37.5	5.0	30.0
Posterior teeth	Ceramic sample		нтімі	HT IM2	HT 2M2	HT 3M2	тімі	т ім2	T 2M2	T 3M2
	Frequency of best	ΔE^*_{ab}	0.0	0.0	0.0	0.0	0.0	3.0	3.0	93.9
	match (%) —		0.0	0.0	0.0	0.0	0.0	9.1	21.2	69.7
Legend	Highest frequency			Second highest frequency			Third highest frequency			

dentine samples of anterior teeth is Vita Enamic T shade 3M2 (92.5% of the cases) while for posterior teeth, the material which presented the smallest difference in translucency (Δ TP) was Vita Enamic HT shade 1M2 in 45.4% of the cases (Table 5).

DISCUSSION

Little information is available on the optical properties of human dentine derived from incisors, canines, and molars and on their relations with esthetic dental materials. Therefore, investigating the translucency and color differences between a new CAD/CAM hybrid ceramic and a large sample size of human dentine of anterior and posterior teeth can be beneficial in the prediction of the final clinical outcome of an esthetic restoration. The growing popularity of CAD/CAM metal-free materials milled in dental offices, suitable for minimally invasive restorations and with improved mechanical properties¹⁵ was the reason of choosing this type of material for the optical investigations of this study. As Vita Enamic is indicated for crowns, inalys/onlays, and veneers for anterior and posterior teeth, all the shades (besides bleaching shades) and both versions of translucent (T and HT) CAD/CAM blocks were investigated.

The first null hypothesis of the present study was rejected as important color differences were found among the samples of anterior and posterior human dentine and all the shades of the two hybrid ceramic investigated. Nevertheless, the material able to most properly match the color of human dentine, regardless the background used for color records was 3M2 T. For the dentine samples of anterior teeth, according to the minimum color difference, with CIELAB formula, 97.5% of the best matches over the black background

Anterior teeth	Ceramic sample	нт імі	HT IM2	HT 2M2	HT 3M2	тімі	T I M2	T 2M2	T 3M2
	Frequency of lowest ΔTP (%)	0.0%	0.0%	2.5%	2.5%	0.0%	2.5%	0.0%	92.5%
Posterior teeth	Ceramic sample	нт імі	HT IM2	HT 2M2	HT 3M2	тімі	T I M2	T 2M2	T 3M2
	Frequency of lowest △TP (%)	0.0%	45.4%	15.1%	3.0%	6.1%	6.1%	6.1%	18.2%
Legend:	Highest frequency			Second h	ighest freque	ncy	Third highest frequency		

TABLE 5. Frequency of lowest difference in translucency (Δ TP) between the two hybrid dental ceramic materials and dentine samples of anterior and posterior teeth

were obtained with VITA Enamic T, while with the CIEDE2000 formula, the best matches were obtained with VITA Enamic T in 92.5% of the cases (Table 3). When the measurements were performed over the white background, the frequency of best match between the dental hybrid ceramic and anterior dentine samples was 90% for 3M2 T when ΔE_{ab}^* formula was used and 77.5% for 3M2 T when ΔE_{00} formula was used (Table 4). In the case of posterior teeth, independently of the color difference formula or background used, Vita Enamic 3M2 T was the best match among the two materials studied. Within the limitation of this study (limited number of samples for human dentin) our results suggest that CAD/CAM T blocks with lower L values, but more chromatic, are more suitable for replacing dentine than HT blocks, which might better reproduce enamel characteristics. Further investigations on enamel and dentine specimens of different thicknesses are needed to reveal in what combinations of color and degree of translucency these hybrid ceramic materials can be used to substitute hard dental structures. Conversely, even though Vita Enamic was reported to have good clinical performances⁴⁷ its translucent characteristics were found less satisfactory when compared to glass or feldspathic ceramics.¹⁵

In terms of visual tolerance of color differences between two materials, several perceptibility and acceptability thresholds were established in dental literature.^{48–50} Perceptibility is defined as the smallest color difference that could be detected by the human eye. A 50:50% perceptibility threshold (PT) means that 50% of the observers will detect color difference between the restoration and the adjacent tooth, while 50% will not. In terms of acceptability, the color difference which is considered to be acceptable by 50% of normal observers under clinical conditions corresponds to a 50:50% acceptability threshold (AT).⁴¹ In the present study, the PT ($\Delta E_{ab}^* = 1.22$ and $\Delta E_{00} =$ 0.81) and AT ($\Delta E_{ab}^* = 2.66$ and $\Delta E_{00} = 1.77$) threshold levels recently established for dentistry in a prospective multicenter study were used.⁴¹

Considering the optical properties of anterior and posterior dentine samples and those of the material investigated in this study, none of the hybrid ceramic samples showed values below PT, regardless of their degree of translucency or shade. Consequently, there was no perfect, nondetectable match between dentine and Vita Enamic samples that would not be perceptible to average human observers. An explanation stand in the limited number of dentine samples that cannot cover the whole range of optical properties for the human dentine; moreover, human dentine does not have only one color, varying from one type of tooth to another and being influenced by age and pathological changes.^{1,51} In addition, the studied material is meant to replace not only dentine, but also enamel.

None of the best matches were below the AT, meaning that the studied hybrid ceramic samples are not clinically acceptable when they are compared to dentine originated from anterior or posterior teeth. Improved optical properties of this material are needed in order to keep the color differences at least below the AT, although it would be better to make them smaller than PT. It would be of great interest to extend this study with other materials (from other manufacturers) and/or with more shades, which might provide smaller color differences and a better color match; in addition, a comparison with enamel and enamel-dentine samples is also strongly required.

When assessing color and appearance in dentistry, results obtained with dark backgrounds tends to be more relevant as the oral cavity is black. In our study, in terms of best match according to minimum color difference, we found a good consensus between the results obtained when measurements were performed over black background and the results obtained over the white background. Furthermore, our results are in agreement with previous studies, which stated that translucency and background color significantly influence color difference between ceramic shades and that a darker background determines a higher ΔE .⁵² Also, it seems that the modifications introduced in the computations of the CIEDE2000 total color difference formula, led to a better distribution of the values, as in all cases the frequencies of best match are more evenly distributed when this latter formula is used.

The second null hypothesis of this study was also rejected because the TP of hybrid ceramics differed from the corresponding values of human dentine. Although spectroradiometers gained ground in the field of dental research, spectrophotometry remained the most frequently used method of color and translucency clinical measurements. The Vita Easyshade spectrophotometer is used in a large number of "in vivo" as well as in "in vitro" studies, providing reproducible and reliable measurements of all color coordinates.^{37,39,40} Nevertheless, this device is prone to edge loss effects when measuring translucent materials, leading to repeatable errors in its measurements.^{1,16,53}

According to our results, from four shades with 2 degrees of translucency, only one translucent shade (3M2 T) was found to have the smallest Δ TP with the dentine samples of anterior teeth (92.5% of the cases). For posterior teeth, VITA Enamic 1M2 HT was best match in translucency for 45.4% of the cases. This is not surprising as it was reported that human dentine of posterior teeth had higher absorption and

transmittance coefficients values than that of anterior teeth,¹ therefore, a greater translucency compared to incisors and canines dentine samples. Furthermore, the absorption coefficient of enamel is smaller than that of dentine⁵⁴ while the scattering and light reflectivity coefficients are greater.¹ These findings confirmed that the translucency of enamel is greater than that of dentine¹⁶ and suggest that, whenever esthetic restorations are wished, different degrees of translucency (HT or T) of the same material must be used for dentin and enamel layers.

CONCLUSIONS

Among the investigated opacities and shades of the hybrid ceramic, VITA Enamic Translucent is the best option as color match for both anterior (>90% of cases best match) and posterior (>80% of cases best match with ΔE_{ab}^* formula and >55% of cases best match with ΔE_{00} formula) teeth dentine.

In terms of translucency, VITA Enamic Translucent closely matched anterior teeth dentine in 95% of the cases while for posterior teeth, VITA Enamic High Translucent was best option for more than 60% of the dentine samples.

Within the limitations of this study, data recorded from spectrophotometric color measurements revealed that, the translucency and the color coordinates of the hybrid dental ceramic material investigated differed from those of human dentine of anterior and posterior teeth, with differences higher than both PT and AT in all of the cases.

DISCLOSURE

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

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Spectrophotometric Analysis of the Influence of Metal Alloy Choice, Opaque Thickness, and Repeated Firing on the Shade of Metal Ceramic Restorations

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ABSTRACT

Purpose: To determine the effect of type of base metal alloy, opaque thickness, and repeated firing on color of metal ceramic restorations.

Materials and Methods: Four nickel chromium and four cobalt chromium were selected with one noble alloy as a control. Ten discs (16 mm 0.5 mm) were prepared for each group. Color of specimens were measured using a spectrophotometer and were calculated using CIEDE2000 formula ($\Delta L'$, $\Delta C'$, $\Delta H'$, $\Delta E'$) between experimental groups and control at six stages of porcelain constructions: opaque 0.1 and 0.3 mm, dentine, enamel, glaze, and three times repeated firing. Shade A3 was used. One-way analysis of variance and Bonferroni multiple test were performed ($\alpha = 0.05$).

Results: Alloy type and stage showed statistical significance on total color and color parameter differences from the control and there was significant interaction between them (p < .05). Nidour alloy was the closest to control. Increase in $\Delta C'$ and a decrease in $\Delta H'$ and in a* and b* was the commonest in comparison with the control. However, $\Delta E'$ was below acceptability threshold for all alloys at all stages.

Conclusion: Despite the statistical significance, base metal alloys performed as good as noble metal control. Neither opaque thickness, nor repeated firing affected color variations from the control group. There was no obvious trend in the behavior of metal alloys at all stages. However, increase in chroma and a decrease in hue, with green blue shift, was the most common.

CLINICAL SIGNIFICANCE

Records of the effects of eight commonly used base metal alloys on the color of final shade of the metal-ceramic restorations, at various stages of ceramic buildup, have considerable value. (J Esthet Restor Dent 28:S56–S67, 2016)

INTRODUCTION

The final color of metal-ceramic restorations is influenced by its metal substructure, which may lead to clinical and laboratory consequences.^{1–7} It is also influenced by the type and thickness of ceramic,⁸ the number of firings,^{9–13} and opaque thickness.^{14–18} There are little colorimetric studies on base metal alloys despite being widely used.^{8,9,15} The reported studies primarily compared one or two different base metal alloys with precious alloys.^{2,3,6,19}

Brewer and colleagues² examined two alloys (high gold [Will-Ceram Y] and Pd-Ag [Will-Ceram W-1]) and two

Associate professor, Department of Prosthodontics, Faculty of Dentistry, Jordan University of Science and Technology, Irbid, Jordan [†]Master degree student, Department of Prosthodontics, Faculty of Dentistry, Jordan University of Science and Technology, Irbid, Jordan [‡]Professor, Department of Prosthodontics, Faculty of Dentistry, Jordan University of Science and Technology, Irbid, Jordan porcelain (Vita VMK-68 and Vita non-greening [VMK-68N] porcelain). Pd-Ag alloy with both types of porcelain had more b value (yellowish) and less L* value (darker) in comparison with high gold alloy. Pd-Ag alloy with conventional porcelain had less a* value (greenish) in comparison with high gold alloy. Both alloys had the same a* value with non-greening porcelain. The color variance was greatest at the first four steps but was very small at the final fabrication step.

Jacobs and colleagues³ used three metal alloys (gold-platinum-palladium, nickel-chromium, and high palladium) with three shades (Vita VMK-68, B1, A3, C4) and three different dentine porcelain thicknesses (0.5, 1.0, 1.5). Significant differences were reported in the hue between both the nickel-chromium and high palladium alloy and the gold-platinum-palladium alloy with A3 shade. The hue of gold-platinum-palladium alloy was shifted toward yellow-red more than the other two alloys. Shades B1 and C4 showed only small difference in hue, value, and chroma among the three different alloys. Visual assessment indicated that nickel-chromium alloy group was significantly different from both high palladium and gold-platinum-palladium alloys in all shades. All detected differences were more obvious with thinner layers of dentin porcelain.

Crispin and colleagues⁶ used five metal alloys (high gold, gold-palladium, nickel-chromium, palladium-silver, and palladium-copper-gallium alloy) and found that palladium-silver and nickel-chromium alloys caused significant color difference compared with the other three alloys. Gold-palladium and palladium-copper-gallium alloys performed as good as high-gold alloy in color stability.

Kourtis and colleagues¹⁹ investigated four metal alloys (Nickel-Chromium [Ni-Cr], Cobalt-Chromium [Co-Cr] alloy, Pd-rich noble, and a high noble Au-alloy) with two types of porcelain (Vita Omega and Ceramco Silver). Au-alloy and the Co-Cr alloy specimens had higher L* value (brighter) and lower a* value (green shift) with both porcelains than both Ni-Cr and Pd-rich alloys. The b* value where higher (yellow shift) for both the Au-alloy and Pd-rich alloys combined with both porcelains than the Ni-Cr and Cr-Co alloys. The vita porcelain showed higher L* values with all alloys compared with Ceramco specimens with the exception of the Pd alloy, where the difference was not statistically significant. However, the b* values where higher (red shift) with Ceramco porcelain than Vita porcelain specimens.

Stavridakis and colleagues²⁰ studied four high palladium alloys (Palladium-Copper-Gallium [Pd-Cu-Ga], Palladium-Gallium [Pd-Ga], Palladium-Silver [Pd-Ag], and Gold-Palladium alloy [Au-Pd] as control group), with 0.1 mm opaque porcelain thickness, with or without 0.9 mm dentine porcelain thickness.

The Pd-Ag alloy with only opaque porcelain did not exhibit significant color differences from the control group, whereas color differences for this alloy from the control group after the dentin porcelain and glazing firing cycles were found statistically but not clinically significant. The color difference between Pd-Ga alloys and the control Au-Pd alloy group were not statistically or clinically significant.

The reported studies showed that the color of metal ceramic restorations is influenced by its metal substructure. However, the effect of different types of alloys on color change or chromatic shift at the various stages of porcelain buildup is not clear.²¹

The majority of studies on color differences are quantified using Commission internationale de l'éclairage (CIELAB) color space and the associated color differences formulas. However, the quantitative assessment of color difference is of little value without the determination of the magnitude that is visually detected (perceptibility threshold) and the magnitude that is considered aesthetically an unacceptable alteration (acceptability threshold).²² Despite the ample literature on perceptibility and acceptability thresholds, there appears to be no consensus on these thresholds.

The aim of this study is to determine the possible effects of eight base metal alloys and also the effects of two opaque thicknesses and repeated firing on total color and color differences in comparison with noble gold-palladium alloy control group, investigated at all stages of ceramic buildup.

MATERIALS AND METHODS

Contacts were made with local dental laboratories by personal visits or phone calls in search of the most commonly used base metal alloys. Eight base metal alloys (four cobalt chromium and four nickel chromium) were selected in this study. One Au-Pd alloy was used as a control group (Table 1). Ten disc-shaped metal specimens were cast for each metal alloy. Round-shaped plastic patterns (Turkom-Cera®; LOT: Tc175F1-06; Turkom-Ceram Sdn. Bhd., Puchong, Selangor, Malaysia) were used to fabricate 16 mm in diameter and 0.5 mm in thickness metal specimens according to manufacturer's recommendations. Each metal sprue was sandblasted with 250-µm aluminum oxide (LOT: 81321, SandBlast; Sherra, Lemförd, Germany) and cut off by abrasive discs (Resista® Omega, Italy, LOT: 09872). Metal specimens were adjusted with tungsten carbide rotary cutting burs. Steam cleaning and degassing procedures were carried out according to manufacturer's recommendations. The thickness of metal specimens was controlled using manual micrometer. Opaque shade porcelain (A3)

(VMK 95, VITA Zahnfabrik, Bad Säckingen, Germany) was applied on the tested discs with a brush-on application technique. Two layers of opaque porcelain were fired accordingly. The first layer was applied as thin slurry and the second as a brush-on layer to obtain uniform coverage. The opaque porcelain was over built then corrected to 0.1 mm thickness using diamond rotary instrument. A second layer of opaque porcelain was applied to reach a total opaque thickness of 0.3 mm. Dentin porcelain was condensed to steam cleaned opaque porcelain that was lightly wet with distilled water and was built to a thickness of 0.7 mm. To simulate usual dental laboratory procedures, two firing cycles for the dentin porcelain were performed. Enamel porcelain buildup to a total metal ceramic thickness of 1.8 mm was performed using one firing cycle. Specimens were glazed and then were subjected to repeated firing three times.

The color of each specimen was measured with a spectrophotometer (VITA Compact EasyShade; VITA Zahnfabrik) at each stage of porcelain buildup (Table 2). This system captures the color coordinates using a D65 illuminant (color temperature 6,500° Kelvin; a mathematical construct equivalent to average daylight in the Northern Hemisphere) and a 2-degree viewing angle. The shade for each specimen was made three times, consecutively. The device was calibrated

LOT	Manufacturer	Code	Product name	Туре	Alloy groups
—	Adentatec GmbH, Germany	KN	System KN	Ni-Cr alloys	—
21/09	DFS Diamond GmbH, Germany	ND	Nidour		_
0088	—	PR	President		_
03344/1	Ugin' dentaire, France	UG	Ugirex		_
81304	SHERA GmbH & Co. KG, Germany	SD	Sheridium	Co-Cr alloys	Investigated base metal alloy
90062	SHERA GmbH & Co. KG, Germany	SH	Sherralloy E	_	_
876754	DeguDent GmbH, Germany	DC	Duceralloy C	_	_
043902	Megadental GmbH, Germany	MG	Maganium fm80	_	_
102342	Aurident INC. Fullerton. USA	XP	Auritex-XP	Au-Pd	Control group alloy
Au-Pd = gold-	palladium; Co-Cr=cobalt-chrome; Ni-Cr=ni	ickel-chrome.			

TABLE I. Brand name, code, LOT number, and manufacturer information for metal alloys

TABLE 2. Stages of porcelain buildup for color analysis of specimens

Stage number	Procedure
1	Opaque layer 0.1 mm thickness
2	Opaque layer 0.3 mm thickness
3	Dentine layer 0.7 mm thickness
4	Enamel layer 0.3 mm thickness
5	Glazing
6	Repeated firing (3 times)

according to the manufacturer's recommendations. The data were displayed in L*, a*, and b* values, according to the CIE (Commission International de l'Eclairage or International Commission on Illumination), where L* denotes lightness; a* denotes redness (positive +a*) or greenness (negative $-a^*$); and b* denotes yellowness (positive +b*) or blueness (negative $-b^*$).²³ The color difference ($\Delta E'$) between two objects was calculated using the equation:

$$\Delta E' = \left[\left(\frac{\Delta L'}{K_L S_L} \right)^2 + \left(\frac{\Delta C'}{K_C S_C} \right)^2 + \left(\frac{\Delta H'}{K_H S_H} \right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C} \right) \left(\frac{\Delta H'}{K_H S_H} \right) \right]^{1/2}$$

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ are the differences in lightness, chroma, and hue for a pair of samples in CIEDE2000, respectively, and R_T is a rotation function that accounts for the interaction between chroma and hue differences in the blue region. Weighting functions, S_L , S_C , S_H , adjust the total color difference for variation in the location of the color difference pair in L', a', b' coordinates and the parametric factors, K_L , K_C , K_H , are correction terms for experimental conditions.^{23–25}

The results were analyzed with statistical software (SPSS, PC, Version 18.0; SPSS, Inc, Chicago, IL, USA). Repeated measurements analysis of variance (ANOVA) was used to analyze the data (type of metal alloy, stage of ceramic buildup) for significant differences. The Bonferroni significant tests were used to perform multiple comparisons ($\alpha = 0.05$).

RESULTS

Means and standard deviations for $\Delta L'$, $\Delta C'$, $\Delta H'$, and $\Delta E'$ for all metal groups are presented in Table 3 for stages 1 to 3, and Table 4 for stages 4 to 6. Alloy groups were arranged in ascending order for each stage according to the $\Delta E'$ value. Metal alloy ND was the closest to the control group in all stages except stage 1 and 4. The average values of a*and b* for each alloy were analyzed and a summary of color shift in a* (red-green) and b* (yellow-blue) at each stage are presented in Table 5. ANOVA for alloy type and stage showed both factors to have significant effect on the results, and also showed significant interaction between alloy type and stage ($\alpha = 0.05$).

The alloy, which was the closest to the control group with the least $\Delta E'$ was used as a reference for the Bonferroni multiple comparison tests in each stage for $\Delta L'$, $\Delta C'$, $\Delta H'$, and $\Delta E'$. The results were presented in Tables 6 and 7. At stage 1 (0.1 mm opaque thickness), all alloys had more value (except ND), more chroma, and less hue. For $\Delta E'$, the results ranged from 1.15 for MG alloy to 2.08 for SH alloy (Table 3). Mean differences in comparison with MG alloy (the closest to control) showed significant differences for all other groups for $\Delta L'$, and only with ND and PR alloys for $\Delta C'$ and $\Delta H'$. Alloys ND, PR, and KN were significantly different from the MG alloy for $\Delta E'$ (Table 6).

At stage 2 (opaque porcelain 0.3 mm thickness), all alloys had less value except SH and UG alloys, more chroma except MG and KN alloys, and less hue except ND, MG, and KN alloys. The $\Delta E'$ values ranged from 0.73 (ND) to 1.74 (UG). Multiple comparisons for the mean differences with the ND alloy showed no significant difference except UG for $\Delta L'$, all other groups were significantly different except MG for $\Delta C'$, and KN, PR, DC, and MG for $\Delta H'$. Only UG, SD, and SH were significantly different from the ND alloy for $\Delta E'$ (Tables 3 and 6).

At stage 3 (dentine stage), alloys ND, DC, PR, and SD had less value whereas the rest had more value in comparison with the control group. All groups had

TABLE 3. Differences in lightness ($\Delta L'$), chroma ($\Delta C'$), hue ($\Delta H'$), and total color difference ($\Delta E'$) for a pair of samples in CIEDE2000, and standard deviations (SD) for stages I-3

Stage	Alloy*	ΔL'	SD	∆ C′	SD	Δ Η ′	SD	$\Delta E'$	SD
I	MG	0.46	0.39	1.08	0.47	-0.94	0.14	1.15	0.20
	PR	1.63	0.32	1.89	0.55	-1.40	0.27	2.06	0.20
	UG	1.70	0.34	0.55	0.45	-1.00	0.29	1.53	0.23
	KN	1.91	0.43	0.61	0.36	-1.16	0.25	1.73	0.26
	ND	-0.56	0.81	1.72	0.50	-1.33	0.28	1.72	0.30
	DC	1.71	0.55	0.50	0.26	-0.62	0.28	1.35	0.39
	SD	1.78	0.62	1.14	0.25	-0.79	0.26	I.58	0.41
	SH	2.64	0.73	1.27	0.46	-0.74	0.19	2.09	0.46
2	ND	-0.22	0.65	0.13	0.40	0.27	0.48	0.73	0.30
	MG	-0.19-	0.69	-0.65	0.45	0.31	0.44	0.83	0.34
	KN	-0.09-	0.50	-1.24	0.30	0.33	0.37	0.96	0.24
	DC	-0.10-	0.45	0.18	1.04	-0.33	0.81	0.98	0.40
	PR	-1.11-	0.58	0.29	0.24	-0.38	0.53	1.15	0.48
	SH	0.02	0.44	1.14	0.79	-1.20	0.45	1.43	0.46
	SD	-0.37-	0.89	1.42	0.71	-0.96	0.37	1.56	0.31
	UG	0.91	0.92	0.79	1.01	-1.29	0.42	1.74	0.46
3	ND	-0.65-	0.45	-0.24	0.49	-0.23	0.55	0.67	0.36
	UG	0.36	0.61	0.22	0.81	0.60	0.42	0.71	0.40
	KN	0.14	0.69	0.66	0.71	-0.22	0.57	0.72	0.24
	MG	0.24	0.78	0.10	0.72	0.56	0.42	0.79	0.24
	DC	-0.60-	0.84	0.51	0.85	.045	0.34	0.81	0.32
	PR	-0.31-	0.72	0.20	0.92	57	0.56	0.81	0.33
	SD	09-	0.75	0.51	0.81	0.80	0.45	0.86	0.37
	SH	.67	0.79	-0.33	0.81	0.38	0.36	0.86	0.31

*Alloys are arranged in ascending order according to Δ E00 values for each stage.

more chroma except ND and SH, and more hue except ND, KN, and PR. The least $\Delta E'$ was for ND alloy (0.67) and the most for SH (0.86). No statistical significance for the mean differences of $\Delta E'$ or $\Delta C'$ in comparison with ND alloy, while only SH for $\Delta L'$, and MG, SD, and

UG for $\Delta H'$ were significantly different from ND alloy at this stage (Tables 3 and 6).

At stage 4 (enamel stage), alloys DC, SD, KN, and PR had less value, while UG, MG, and PR had more

TABLE 4.	Differences in	lightness	(ΔĽ′),	chroma	(∆C′), I	hue (∆H	′), and tota	l color	difference	(ΔE')	for a	pair	of s	amples	in
CIEDE2000	, and standard	deviations	s (SD)	for stag	es 4–6										

Stage	Alloy*	Δ L ′	SD	∆ C′	SD	∆ H′	SD	∆E′	SD
4	SH	0.02	0.99	-0.27	0.95	-0.21	0.73	0.88	0.36
	DC	-0.08	0.91	-0.68	0.67	-0.86-	0.92	1.08	0.57
	UG	0.42	0.89	0.49	0.40	-0.89	0.96	1.13	0.50
	ND	0.21	1.11	-0.22	0.95	-1.18	0.44	1.22	0.47
	MG	0.71	0.90	0.54	0.62	-1.10	0.56	1.25	0.31
	SD	-0.67	0.94	-0.14	0.98	-1.96	0.52	1.78	0.41
	KN	-0.16	0.95	-1.14	0.50	2.19	0.56	1.93	0.33
	PR	-0.15	0.97	3.89	0.82	-0.53	0.52	1.96	0.28
5	ND	0.31	0.96	0.87	1.00	-0.52	0.65	1.01	0.34
	SH	-0.29	0.87	-0.18	0.95	0.66	0.94	1.04	0.45
	DC	-0.57	0.95	0.47	0.93	-0.02	0.99	1.05	0.39
	UG	-0.31	0.82	1.01	0.93	0.40	1.02	1.05	0.50
	KN	0.31	0.71	1.72	0.84	0.13	0.87	1.13	0.36
	PR	0.62	0.98	0.64	1.01	-0.55-	0.86	1.16	0.26
	MG	0.85	0.99	0.002	0.92	-1.32	0.45	1.39	0.39
	SD	-0.60	1.75	0.29	0.90	-1.09	0.61	1.45	0.61
6	ND	0.18	0.98	0.36	0.97	-0.89	0.71	1.09	0.41
	DC	1.33	0.72	0.53	0.75	-0.14	0.66	1.10	0.40
	SD	-0.03	0.86	1.44	0.85	-0.75	0.85	1.21	0.32
	SH	1.35	0.88	-0.42	0.88	-0.42	0.86	1.21	0.56
	KN	1.07	0.76	1.31	0.94	-0.77	0.62	1.28	0.40
	UG	1.52	0.73	0.40	0.79	-0.47	0.97	1.31	0.59
	MG	0.70	0.97	1.87	0.75	-0.91	0.50	1.34	0.47
	PR	1.77	0.92	2.09	1.06	-1.35	0.87	2.03	0.46

*Alloys are arranged in ascending order according to Δ E00 values for each stage.

chroma, and all groups had less hue except KN, in comparison with the control group. The $\Delta E'$ results ranged from 0.89 for SH to 1.96 for PR in comparison with the control. Only KN, PR, and SD had significant mean differences for $\Delta E'$ in comparison with SH alloy, which had the closest $\Delta E'$ to the control. The mean

difference with SH was significant for PR ($\Delta C'$), and also for KN and SD ($\Delta H'$). No significant difference was found for $\Delta L'$ (Tables 4 and 7).

At stage 5 (glazing stage), all groups had more value except SH, DC, and UG, and more chroma except SH,

Alloy	Туре	Stage I	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Nidour	Nickel-chrome	Green-blue	Green-blue	Green-yellow	Green-yellow	Green-blue	Green-blue
System KN		Green-blue	Red-yellow	Green-blue	Red-yellow	Green-blue	Green-blue
President		Green-blue	Green-blue	Green-blue	Green-blue	Green-blue	Green-blue
Ugrix		Green-blue	Green-blue	Red-blue	Green-blue	Red-blue	Green-blue
Sheridium	Cobalt-chrome	Green-blue	Green-blue	Red-blue	Green-yellow	Green-blue	Green-blue
Sheridium E		Green-blue	Green-blue	Red-yellow	Green-yellow	Red-blue	Green-yellow
Duracey C		Green-blue	Green-blue	Green-blue	Green-yellow	Green-blue	Green-blue
Maganium FM		Green-blue	Red-yellow	Red-blue	Green-blue	Green-yellow	Green-blue

TABLE 5. Color shift for each alloy according to a* values (green-red) and b* values (yellow-blue)

and less hue except SH, UG, and KN. The $\Delta E'$ ranged from 1.02 (ND) to 1.45 (SD). No significant differences were found for the mean differences in comparison with ND alloy for $\Delta E'$, $\Delta L'$, $\Delta C'$, and $\Delta H'$ (Tables 4 and 7).

At stage 6 (three times repeated firing stage), all groups had more value except SD, more chroma except SH, and less hue in comparison with the control group. The best $\Delta E'$ was for ND (1.09) and the worst for PR (2.03) There was no statistical significance for the mean difference with ND except for PR alloy for both $\Delta E'$ and $\Delta C'$, and also PR and UG for $\Delta L'$ (Tables 4 and 7).

DISCUSSION

Eight metal alloys were selected to represent the most common base metal alloys used in dental laboratories in Jordan. Shade A3 was selected in accordance with previous studies in this field.^{3,18} The Au-Pd alloy was selected as control group instead of high gold alloy; this alloy was reported to perform as good as high-gold alloys in terms of color.^{14,15,20}

CIEDE2000 formula was used in this study. In the majority of previous dental color studies, color differences were quantified using the formula ΔE_{ab} .²⁶ Recently, CIE recommended the use of the CIEDE2000 formula, which incorporates specific corrections for

non-uniformity of CIELAB space (weighting functions S_L , S_C , and S_H) and parameters accounting for the influence of illuminating and viewing conditions in color difference evaluations (parametric factors K_L , K_C , and K_H). In addition, an interactive term between chroma and hue differences for improving the performance of blue colors and a scaling factor for CIELAB a* scale for improving the performance of gray colors are introduced.^{23,24} Several studies compared the two formulas and found significant correlation between them.^{27–29} A linear correlation between them was reported, with ΔE_{00} values representing a 70% to 80% of the values of ΔE_{ab} . CIEDE2000 formula was reported to provide an improved correlation resulting in a more accurate clinical interpretation of color differences.^{24,29}

The clinical relevance of the results in this study depends on how much color change is considered perceptible and/or acceptable. In most studies on color, the author selects the perceptibility and/or acceptability thresholds with which to compare the results. The perceptibility threshold of 1 was reported in 54% of the literature.³⁰ The majority of these studies refer to three articles.^{31–33} The values for the acceptability threshold ranges from 2 to 4, one third of the literature refers to 3.7, and all refer to the same source.³⁴ Khashyar and colleagues³⁰ reported that "the literature that are referred to the most are mainly from the late 80's, which is remarkable because so many recent studies are still referring to a period of time well before the high

Stage	Alloy	Mean difference for ($\Delta L'$)	Mean difference for $(\Delta C')$	Mean difference for ($\Delta H'$)	Mean difference for (∆E′)
1	DC	-1.25*	0.58	-0.3	-0.20
	UG	-1.24*	0.53	0.06	-0.38
	SD	-1.32*	-0.64	-0.15	-0.43
_	ND	1.03*	-0.64*	0.39*	-0.57*
-	KN	-1.45*	0.47	0.23	-0.58*
-	PR	-1.17*	-0.80*	0.46*	-0.91*
-	SH	-2.18*	-0.19	-0.20	-0.93*
2	MG	-0.03	-0.60	-0.04	-0.10
_	KN	-0.13	-1.39*	-0.06	-0.24
_	DC	-0.12	-1.43*	0.60	-0.25
	PR	0.89	-1.54*	0.65	-0.42
	SH	-0.25	-2.39*	1.47*	-0.70*
_	SD	0.14	-2.68*	1.23*	-0.83*
	UG	-1.14*	-2.04*	1.56*	-1.02*
3	SH	-1.33*	0.09	-0.62	-0.05
_	SD	-0.57	-0.75	-1.04*	-0.05
_	DC	-0.05	-0.75	-0.28	0.001
	MG	-0.90	-0.34	-0.80*	0.02
	KN	80	-0.91	-0.02	0.08
	UG	-1.02	-0.47	-0.84*	0.10
	PR	-0.35	-0.44	0.33	0.14
*Statistically si	ignificant $(b < 05)$				

TABLE 6. Mean differences between each alloy and Maganium fm80 (the closest to the control) in stage 1 and Nidour (the closest to the control) in stages 2 and 3 for differences in lightness ($\Delta L'$), chroma ($\Delta C'$), hue ($\Delta H'$), and total color difference ($\Delta E'$)

aesthetic demands of the present society. One should expect the color thresholds in dentistry to reflect such clinical trends."

Ghinea and colleagues³⁵ did a study to determine the perceptibility and acceptability threshold for dental ceramics using CIEDE2000 and CIELAB _{ab} color difference formulas with a novel TSK fuzzy approximation. The authors reported 3.48 and 1.74 for the perceptibility and acceptability thresholds,

respectively, using CIELAB formula. As for the CIEDE2000 formula, the authors reported 1.25 and 2.23 for the perceptibility and acceptability thresholds, respectively.

Despite the fact that there is no consensus on these thresholds, the perceptibility threshold (PT = 1.25) and acceptability thresholds (AT = 2.23) reported by Ghinea and colleagues³⁵ were used for the purpose of discussing the results of color differences in this study. Analysis of

TABLE 7.	Mean differences	for each alloy with	Sherralloy E (the	closest to the c	control) in stage 4	and Nidour (the closest to the
control) in	stages 5 and 6 for	differences in light	ness (ΔL′), chroma	a (Δ C'), hue (Δ F	H′), and total color	difference (A	ΔE′)

Stage	Alloy	Mean difference for $(\Delta L')$	Mean difference for $(\Delta C')$	Mean difference for $(\Delta H')$	Mean difference for ($\Delta E'$)
4	DC	0.10	0.42	0.66	-0.20
	UG	-0.40	-0.75	0.68	-0.25
_	ND	-0.19	-0.05	0.98	-0.34
_	MG	-0.69	-0.80	0.90	-0.37
_	SD	0.69	-0.13	1.76*	-0.90*
_	KN	0.18	0.87	-2.40*	-1.05*
_	PR	0.16	-4.16*	0.33	-1.08*
5	SH	0.60	1.04	-1.18	-0.02
	DC	0.88	0.40	-0.5	-0.03
	UG	0.62	-0.15	-0.92	-0.04
	KN	-0.06	-0.86	-0.66	-0.11
	PR	-0.3	0.23	0.02	-0.14
	MG	-0.54	0.87	0.80	-0.37
	SD	0.91	0.58	0.57	-0.44
6	DC	-1.15	-0.17	-0.75	-0.01
_	SD	0.21	-1.08	-0.14	-0.12
	SH	-1.17	0.78	-0.47	-0.12
	KN	-0.89	-0.96	-0.12	-0.18
	UG	-1.34*	-0.042	-0.42	-0.2
	MG	-0.52	-1.51*	0.01	-0.25
	PR	-1.59*	-1.73*	0.45	-0.94*
*Statistically sig	nificant ($b < 05$)				

colorimetric data obtained from 0.1 mm opaque porcelain showed an increase in value and chroma and a decrease in hue for all alloys in comparison with the control. Further analysis showed decrease a^{*}, and b^{*} values for base metal alloys, which indicated a tendency to green-blue discoloration. Analysis of ΔE_{00} showed that MG alloy had $\Delta E'$ below the PT threshold while the rest of alloys were higher than PT and below AT. This means that the performance of base metal alloys were similar to the noble alloy at this stage of construction. Although 0.1 mm thickness of opaque porcelain could be useful for ceramo-metal restorations to leave enough space for body porcelain,¹⁰ the thickness of 0.3 mm opaque porcelain was recommended as the optimum thickness for gold alloys in terms of color.^{14,15,20} Other authors found that the use of base metal alloys shifted the color to yellow-green with negligible achromatic (L* value) change.^{15,17} The variability of these results with this study could be due to the use of different shades, porcelain brand, and metal alloys.

At stage 2, most alloys showed a decrease in $\Delta L'$ while kept the increase in $\Delta C'$. An improvement in total color difference with the control was evident as all alloys became below the PT except three alloys, which were still below the AP.

Two alloys (KN and MF) had yellow-red discoloration, one alloy had red-blue discoloration, and the remaining metal alloys had green-blue discoloration (Table 5). Despite the improvement in $\Delta E'$ for base alloys at this stage, the results showed that the performance of these alloys to be as good as the noble alloy.

The color differences at dentine stage for all base metal alloys showed that all became below the PT. All alloys (except ND) kept the increase in chroma, while the results for $\Delta L'$ and $\Delta H'$ were mixed. Some groups showed reddish color shift (SD, SH, UG, MF), and only SH showed yellowish shift (Table 5).

At the enamel stage, SD, KN, and PR had $\Delta E'$ between PT and AP, the rest were below PT. A decrease in chroma in comparison with the control was evident for all alloys except PR and MG. Also a decrease in $\Delta L'$ in comparison with the control occurred with four alloys. This meant that a decrease in value and chroma could be expected with some base metals after the enamel stage. All base metal alloys had green blue discoloration, except KN and DC which shifted to red yellow and green yellow respectively (Table 5). The effect of the glazing stage showed mixed results between the alloy groups with regard to the value, while it resulted in an increase in chroma in all alloys except SH. Only MG and SD were higher than PT and lower than AT, while the rest were below the PT. All groups had bluish color except MF, UG, and SH, which had reddish color shift while the rest were greenish (Table 5).

After the repeated firing stage, MG and PR values stayed between PT and AT, those for UG and KN were

increased above the PT but stayed below the AT. The rest stayed below PT. This meant that the performance of base metal alloys should not be different clinically from the control after the repeated firing. All groups had increased chroma except SH, and increased value except SD. Also, all alloys had decreased hue and had bluish-greenish color except SH, which had greenish yellowish color.

Several mechanisms had been proposed in dental literature by which various elements may react with the overlying porcelain, accounting for the discoloration.²¹ Bulk transfer involves the diffusion of an element from the interior of the alloy into the porcelain, whereas surface diffusion occurs when an element from the thin oxide layer on the alloy diffuses along the metal-ceramic interface and into the porcelain. The third mechanism of vapor deposition involves the elevated temperature vaporization of different component elements from the alloy composition and their subsequent deposition onto the porcelain surface, followed by diffusion into the interior of the porcelain which results in discoloration. At present, the relative importance of these three possible mechanisms for porcelain discoloration is unknown for the various metal-ceramic systems.

Several studies reported the existence of color changes resulting from the use of Ni-Cr and Co-Cr alloys. However, conclusions based on the clinical significance of these differences have varied.^{2,3,6,14,19,20} Records of the effects of eight commonly locally used base metal alloys on the color of final shade of the metal-ceramic restorations have considerable value. Differences in materials, techniques, color formula, and color matching thresholds make it difficult to compare results and draw clinically relevant conclusions.

There was no obvious trend in the behavior of the type of metal (Ni-Cr and Co-Cr) at the different stages of porcelain construction. However, an increase in chroma with greenish bluish color was the commonest in comparison with the control group. Base metal alloys performed favorably in comparison with the control group as all color differences at all stages were either below PT or below AT. After this quantitative assessment of the effect of different Ni-Cr and Co-Cr alloys on porcelain color, SEM/EDS examination of the interface is needed to explain the findings in this study.

Also, the effect on other brands of porcelain is a subject for further studies. At this stage, there is no consensus for dental researchers on the PT and AT thresholds. There is a need for prospective controlled studies to quantify color difference thresholds and to establish a gold standard for researchers.

CONCLUSIONS

Despite the statistical significance, base metal alloys performed favorably with regard to total color difference from the noble metal control group. Nidour was the closest to the control group at most stages of ceramic buildup. Neither the opaque thickness, nor the repeated firing had a clinical effect on color variation from the control group.

There was no obvious trend in the behavior of metal alloys at the various stages of ceramic buildup. However, a general increase in chroma and a decrease in hue, and also a shift to green blue was the most common in comparison with the control group. Shifting away from green blue toward red or yellow direction was most frequent during the dentin and enamel stages.

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Optical Dental Whitening Efficacy of Blue Covarine Toothpaste inTeeth Stained by Different Colors

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ABSTRACT

Objective: Evaluate the immediate and cumulative optical whitening efficacy of a blue covarine toothpaste. **Materials and Methods:** 180 bovine tooth specimens with similar shade ($\Delta E < 3.5$) were staining of different beverage: black tea(BT), green tea (GT), red wine (RW), orange soda (OS), and brazilian aĉai juice (AJ), and then submitted to tooth brushing with a blue covarine toothpaste (Op) or a control abrasive toothpaste (Ab). The whitening effect was evaluated at baseline (B), after staining (S), after I day (ID) and 7 days of cumulative use of toothpastes (7D). The color shade chances were assessment by Vita Easyshade reflectance spectroscope and the data of CIELab color coordinates (L*, a*, and b*), color difference (ΔE) and the whiteness index optimized (WIO), were analyzed by two-way mixed analysis of variance (ANOVA) for repeated measures and Bonferroni-corrected *t*-tests ($\alpha = 0.05$). **Results:** The analysis showed statistically significant differences before and after staining by colored beverages (p < 0.05), but no differences were found due to the action of toothpaste (p > 0.05), in the CIELab coordinates, ΔE and WIO index.

Conclusions: The use of toothpastes (Op or Ab) reduced the dental staining caused by different colored beverage, but the whitening effect of blue covarine toothpaste could not be confirmed (p > 0.05).

CLINICAL SIGNIFICANCE

Many professionals and patients have reported contradictory results after using the blue covarine toothpaste. This article demonstrates the limitations of this optical whitening toothpaste and guides professionals in the correct indication of this alternative to tooth whitening.

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INTRODUCTION

Frequent consumption of beverages containing high concentrations of organic pigments such as tea, coffee, and wine may lead to the severe discoloration of teeth.¹ The levels of tooth discoloration are often related with exposure frequency, oral hygiene

technique, enamel quality, presence of restorative materials and, most importantly, with certain physicochemical characteristics of pigments such as electric charge, molecular weight and size. Depending on the combination of these pigment-related factors, teeth may have their colors altered either by extrinsic discoloration (ED) or by intrinsic discoloration (ID).^{2,3}

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Daily oral hygiene with fluoride-containing toothpastes is the most common technique used to control ED.⁴ These toothpastes have in their formulation silica, calcium carbonate, and other types of particles that remove pigments from the surfaces of teeth by an abrasive action.^{4,5} A novel tooth whitening approach, based on the use of toothpastes containing blue covarine was reported in the literature. More recently, this minimally invasive and "optical" tooth whitening technique has been used in the treatment of both ED and ID as an alternative to conventional peroxide-based tooth bleaching techniques.^{6–10}

Studies investigating the efficacy of blue covarine containing toothpastes have reported that significant and immediate tooth whitening results were obtained after a single use of optical toothpastes. According to these studies, the tooth whitening results obtained using this novel technique persisted for periods over 8 hours after its use.¹⁰ In addition, their findings also indicated that the most significant color changes produced by the use of optical toothpastes were observed on the color parameters b* (yellowness) and WIO.^{7,10}

The main mechanism of action of these optical whitening toothpastes is based on the deposition of a blue covarine thin-film onto the surfaces of enamel. Depending on the quality and thickness of the film deposited, it will alter the natural colors of teeth from yellowish-brown to a more pleasing and aesthetic white-bluish color. However, limited information is currently available in the literature regarding the efficacy of optical whitening toothpastes in challenging aesthetic situations, where teeth discoloration results from aging, trauma, endodontic treatments or even from the incorporation of large amounts of organic pigments from the host's dietary habits. Therefore, the objective of this study was to assess the immediate and cumulative dental whitening efficacy of a toothpaste containing blue covarine on bovine teeth severely discolored by organic staining solutions. The null hypothesis tested in this study was that the toothpastes investigated would have similar tooth-whitening effects.

MATERIALS AND METHODS

The in vitro characterization of the optical whitening efficacy of a blue covarine toothpaste was performed using a randomized, controlled, double-blind experimental design (the operator responsible for measuring the color and the statistician) of repeated measurements.

The two independent variables were: (1) type of toothpaste: with optical whitening action (Op) versus abrasive action (Ab); and (2) staining solutions: no dye (ND—control), black tea (BT), green tea (GT), red wine (RW), orange soda (OS), and Brazilian açai pulp juice (AJ). The interaction of these variables resulted in the following groups: OpND and AbND comprised the control groups, and OpBT, AbBT, OpGT, AbGT, OpRW, AbRW, OpOS, AbOS, OpAJ, and AbAJ comprised the experimental groups (Figure 1). The effects of the interaction among these variables were studied at four time points (repeated measures): before staining (B), after staining (S), after a single application of toothpaste (1D), and after seven consecutive applications of toothpaste (7D).

The experimental design of this study has enabled us to assess two major effects: (1) Discoloration of teeth by distinct staining solutions, and (2) Immediate and cumulative tooth whitening results obtained with the use of an optical whitening toothpaste. Both effects were assessed by comparing the set of changes observed in each of the following color parameters: L* (lightness), a* (redness), b* (yellowness), ΔE (color difference), and WIO. The sample size (n = 15/group) was previously defined using the G* Power 3.1.7 software¹¹ considering an 80% statistical power and 95% confidence level ($\alpha = 0.05$).

Visual and spectrophotometric (Vita EasyShade Advance 4.0, Vivadent, Brea, USA; hand piece and calibration holder serial number: H25543)¹² analyses were performed to select a total of 180 bovine teeth based on color similarity ($\Delta E < 3.5$). Square-shaped specimens (area = 36 mm², thickness = 2 mm) obtained from the middle third of the buccal face of selected bovine teeth were obtained using a low-speed,

Code	Composition	Manufacturer		
Ор	Sorbitol, aqua, hydrated silica, PEG32, sodium lauryl sulfate, aroma, cellulose gum, sodium fluoride, trisodium phosphate, sodium saccharin, PVM/MA copolymer, mica, cl 74160, limonene	Closeup White Now Ice Cool Mint Unilever Brazil Industrial Ltda, Pernambuco - Brazil		
Ab	water, calcium carbonate, sorbitol, sodium lauryl sulfate, flavor, sodium silicate, cellulose gum, sodium bicarbonate, sodium saccharin, formaldehyde and sodium monofluorophosphate	Smile Super Refreshing, Colgate-Palmolive Company, São Paulo - Brazil		
вт	Leaves and stalks of Camellia sinensis (L.) Kuntze	Leão Fuze Chá Preto natural Coca Cola Company, Coca Cola Brazil - Brazil		
GT	Leaves of Camellia sinensis (L.) Kuntze	Leão Fuze Chá verde natural Coca Cola Company, Coca Cola Brazil - Brazil		
RW	Cabernet Sauvignon grapes with 12% alcoholic graduation	Marcus James Cabernet Sauvignon, Cooperative Winery Aurora, Bento Gonçalves, RS - Brazil		
OS	Carbonated water, sugar, orange juice, artificial synthetic flavoring, citric acid, sodium benzoate conservative, stabilizers acetate isobutyrate sucrose and sodium dioctyl sulfosuccinate and yellow artificial coloring twilight FCF	Fanta Orange Coca Cola Company, Coca Cola Brazil - Brazil		
AJ	Frozen pulp of the fruit of Euterpe oleraceade palm tree (Brazilian Açaí)	Medium açaí pulp Icefruit Food Ltda -Tatui, SP - Brazil		

FIGURE I. Code, composition, and manufacturer of products used as independents variables in this study.

water-cooled diamond saw (Isomet 4000, Buehler Ltd., Lake Bluff, USA). Then, sectioned specimens were randomly distributed among the experimental groups (previously described) using a random sequence that was electronically generated (https://www.random.org).

Staining of Specimens

All specimens, with the exception of the specimens that comprised our control group (ND), were submitted to four cycles of staining as proposed by Stookey et al.¹³, with modifications. Each staining cycle was composed of 4 hours of immersion in a staining solution (black tea [BT], green tea >, red wine [RW], orange soda [OS], and Brazilian açai pulp juice [AJ]) followed by a 1-hour air-drying period ($22 \pm 1^{\circ}$ C). After the completion of the staining process, specimens were washed in running water (5 minutes) before being stored in artificial saliva for 15 hours ($36 \pm 1^{\circ}$ C).

Toothpaste Application

Slurries of each one of the toothpastes investigated in this study were fabricated by mixing artificial saliva (Reativa—Homeopathy and Manipulation Pharmacy), water and the selected toothpaste (either optical or abrasive) in a 1:1:1 ratio. Then, slurry aliquots (10 mL at $36 \pm 1^{\circ}$ C) were individually applied over the surfaces of

the specimens immediately before subjecting the specimens to tooth brushing procedures in a semiautomated tooth brushing machine (MEV 2T—ODEME, Biotechnology, Joaçaba, Brazil) for 3,150 brushing cycles (150 strokes/minute, 3 minutes/day, 7 days, 200 g load).

Operator Calibration

The calibration of the operator was accomplished in a preliminary pilot study (data not shown). In that study, the operator assessed the natural colors of bovine teeth (n = 20) employing a subjective (visual analysis) and an objective method (reflectance spectroscopy) in a metamerism box (MAKO Industry and Commerce of Photographic Equipment Ltd., Rio Negro, Brazil) equipped with standardized light sources (DIN 6173, Mako CVB-D65 Daylight). The operator's calibration in the accurate determination of the natural colors of bovine teeth was confirmed by the interclass correlation coefficient test (ICC = 0.82).¹⁴

Spectrophotometer Calibration and Color Measurements

As described in the Vita EasyShade Advance spectrophotometer operation manual (page 9, Vivadent, Brea, USA), the unit requires an initial calibration step every time that the unit is turned on.

			Color parameter				
Effect	Variables	Statistic results	L*	a*	b*	ΔΕ	WIO
Interaction	TP*SB*TA	p value	0.07	0.02*	0.78	0.00*	0.00*
		CI 95%	(70.41–76.64)	(4.25–7.14)	(33.29–37.50)	(14.67–18.72)	(50.57–60.70)
		η^2_{P}	0.05	0.07	0.02	0.04	0.36
	TP*SB	p value	0.23	0.52	0.83	0.03*	0.00*
		CI 95%	(71.02–76.03)	(4.44–6.95)	(33.70–37.07)	(15.06–18.32)	(51.81–59.47)
		η^2_{P}	0.04	0.02	0.01	0.04	0.33
	TP*TA	p value	0.08	0.14	0.18	0.01*	0.00*
		CI 95%	(72.26–74.80)	(5.11–6.28)	(33.70–37.07)	(15.87–17.52)	(53.57–57.70)
		η^2_{P}	0.01	0.01	0.01	0.01	0.13
	SB*TA	p value	0.00*	0.00*	0.00*	0.00*	0.00*
		CI 95%	(71.33–75.73)	(4.67–6.72)	(33.90–36.88)	(15.26–18.13)	(52.05–59.22)
		η^2_{P}	0.65	0.75	0.76	0.48	0.51
Main effect	TP	þ value	0.16	0.43	0.05	0.03*	0.38
		CI 95%	(72.50–74.60)	(5.18–6.20)	(34.71–36.08)	(16.02–17.36)	(54.07–57.20)
		η^2_{P}	0.01	0	0.02	0.01	0.01
	SB	p value	0.00*	0.00*	0.00*	0.00*	0.00*
		CI 95%	(71.76–75.30)	(4.81–6.58)	(34.20–36.58)	(15.54–17.85)	(52.93–58.34)
		η^2_{P}	0.75	0.74	0.79	0.48	0.62
	TA	p value	0.00*	0.00*	0.00*	0.00*	0.00*
		CI 95%	(72.63–74.43)	(5.28–6.11)	(34.78–36.00)	(16.11-17.28)	(54.18–57.10)
		η^2_{P}	0.79	0.83	0.65	0.4	0.73

TABLE I. Statistical results of two-way ANOVA of repeated measurement for variables interaction and main effects

TP = toothpaste; SB = staining beverage; TA = time point of analysis.

*Statistically significant at p < 0.05; η^2_{p} = percentage of variance determined by the action of the variable under study (effect size).

The unit's calibration is performed automatically after the operator places the tip of the spectrophotometer (hand piece) in contact with the ceramic calibration block ($L^* = 87.5$, $a^* = 0$, and $b^* = 4.7$) located at the unit's base. All subsequent color measurements performed in this study, were carried out perpendicular to the specimens' surfaces and in contact mode. Unless otherwise specified, the data reported from the color measurements in this study are a true comparison between the color of the specimens, at a given time point, and the color of the ceramic calibration block. For this reason, independently of the step of color measurement considered, all data reported in this study will be different than zero.

Dental Bleaching Efficacy

The specimens' total color variation (ΔE),¹⁵ in each experimental step investigated (B, S, 1D, and 7D), was
the main parameter for determination of the tooth whitening efficacy attained with the use of traditional (Smile Super Refreshing, Colgate-Palmolive Company, São Paulo, Brazil) or optical (Closeup White Now Ice Cool Mint Unilever Brazil Industrial Ltd., Pernambuco, Brazil) toothpastes on severely discolored bovine teeth. The values of luminosity (L*), color variation in the green-red axis (a*), and in the yellow–blue axis (b*) recorded were utilized to calculate ΔE (equation (1)).¹⁵ Then, L*, a*, and b* values were transformed into Y, x, and y values using the color calculator resource available online (www.easyrgb.com/index. php?X=CALC). Thereafter, the whitening index optimized (WIO)¹⁶ was calculated using equation (2).

$$\Delta E = \sqrt{(L_i - L)^2 + (a_i - a)^2 + (b_i - b)^2}$$
(1)

$$WIO = Y + 1075.012(x_n - x) + 145.516(-y)$$
(2)

where (L_i, a_i, b_i) are the color coordinates of the initial reference, (x_n, y_n) are the chromaticity coordinates of the white reference, and (L, a, b, x, y) are the specimens' colors in each experimental step investigated.

Statistical Analysis

The interactions and main effects of the variables "type of toothpaste" and "staining solution" at four time points (B, S, 1D, and 7D) were analyzed using two-way mixed ANOVA for repeated measures and Bonferroni-corrected *t*-tests for the pairwise comparisons of interest. The dimension of the dental bleaching effect (η^2 p) was also determined and the statistical significance adopted for all analyzes was 5%. All statistical analyzes were performed using SPSS Statistics V19 (SPSS Inc., Chicago, USA).

RESULTS

The results of the two-way repeated measures ANOVA demonstrated statistically significant differences for the interaction between staining solution and time-point of color assessment (SB*TA) of all color parameters investigated in this study (Table 1). The main effects analysis indicated that the color changes observed are mainly due to the effect of the staining solutions (ND, BT, GT, RW, OS, and AJ) and the time-point (B, S, 1D, and 7D) color assessments. The whitening effects promoted by the use of the toothpaste containing bluecovarine was only observed when the ΔE index was considered, but the whitening effects observed had low practical value ($\eta^2_{\rm p} < 0.01$). This finding was corroborated by the analysis of the remaining color parameters investigated in which the whitening effect promoted by the use of the blue covarine toothpaste was similar (p > 0.05) to the whitening effect attained by the use of a conventional toothpaste.

In addition, the results of the color assessments performed on the specimens in the control group (ND) have demonstrated that independent of the color parameter considered (ΔE or WIO), type of toothpaste used (Op or Ab) or toothpaste application (1D or 7D), neither of the toothpastes investigated in this study were able to promote observable or measurable whitening effects due to the deposition of a blue covarine thin-film on the specimens' surfaces nor by an abrasive action (p > 0.05). The color variation observed in the specimens that were submitted to the staining process (BT, GT, RW, OS, and AJ) reveals that mechanical abrasion was the main effects of the toothpastes investigated (Figures 3 and 4).

DISCUSSION

Recently, the use of toothpastes with optical bleaching properties has been proposed as an alternative approach in the treatment of minor dental discolorations on vital teeth.^{7,8,10} Its mechanism of action is mainly based on the deposition of a blue covarine thin-film that is theoretically capable of altering the visual perception of the colors of teeth. Some manufacturers claim that the main advantages of optical toothpastes over traditional dental bleaching techniques is the achievement of immediate and significant tooth whitening results without the use of hydrogen peroxide, which has been previously



FIGURE 2. Comparison of the mean values and confidence interval (CI 95%) of the total color variation (ΔE), whiteness index optimezed (WIO), luminosity (L*), red–green (a*) and yellow–blue (b*) color coordenate registered before staining (B), after staining (S) and after use of abrasive toothpaste (Ab) or whitening toothpaste containing blue covarine (Op) for one day (ID) and seven consecutive days (7D), for the control groups (ND) expressed in arbitrary unit (au).

demonstrated to cause biological damage to dental tissues. $^{\rm 17-20}$

Previous papers have shown that the optical teeth whitening effects attained by the use of blue-covarine containing toothpastes were instantaneous, long lasting (over 8 hours), perceivable (visual analysis) and measurable (colorimetric analysis).^{8,10} However, there is no evidence in the literature to support the use of optical whitening toothpastes in cases of severe dental discolorations. Therefore, the objective of the present randomized, controlled, double blind in vitro study with repeated measures was the assessment of the tooth whitening efficacy of a toothpaste containing blue covarine.

The assessment of color change performed in this study has shown that independently of the beverage used to stain the specimens, significant color changes were observed in all experimental groups. The assessment of color change after one single application (1D), and after seven consecutive applications (7D), of the toothpaste containing blue covarine has shown that regardless of the color index considered, all experimental groups had significant color changes. Even though our findings demonstrate that significant changes were observed on all color parameters after one (1D) and seven (7D) applications of the toothpastes investigated (Figures 2-4), the tooth whitening effects achieved were not sufficiently strong to overcome severe discoloration. Further analysis of the evolution of color using the ΔE color parameter, has demonstrated that under the testing conditions and limitations of this study, the optical tooth whitening effects were very small or insignificant, and were not able to restore the specimens' initial colors. Our findings demonstrated that the blue covarine toothpaste (Op) had a whitening efficacy that was



FIGURE 3. Comparison of the mean values and confidence interval (CI 95%) of the total color variation (ΔE), registered before staining (B), after staining (S) and after use of abrasive toothpaste (Ab) or whitening toothpaste containing blue covarine (Op) for one day (ID) and seven consecutive days (7D) in function of the staining beverage used.

comparable to the efficacy of traditional toothpastes (Ab; p > 0.05).

The strong whitening effects observed on the specimens in the black tea group (BT) are isolated results and are not corroborated by the behavior of the remaining groups or by the overall statistical analysis performed in this study. However, it is possible that these results may demonstrate the impact of intrinsic characteristics of the pigments' molecules over the ability of an organic molecule to penetrate deeply into the specimens' crystalline structure. Assuming that this hypothesis holds valid, the results obtained for the specimens pertaining to BT clearly demonstrate that the presence of an optimized abrasive system composed of hydrated silica particles may help to efficiently remove ED from the surfaces of teeth, which in Figure 3 can be translated into ΔE values that were comparable to the baseline values.

Significant positive increases were observed for the color parameters L* and WIO, whereas significant reductions were observed in the color parameters a*,

b*, and ΔE . The combination of these results can be interpreted in terms of a significant reduction of the amount of pigments in the crystalline structure. Our statistical analysis indicated that "type of staining solution" and "time-point" were the main factors associated with significant color changes of the specimens. When ΔE is considered, 48% of the total color change can be attributed to the type of staining solution and 40% can be attributed to the time-point at which the color assessment was carried out.

These values increased to 62 and 73%, respectively, when the index WIO was the color parameter of choice (Table 1). In addition, our findings indicate that both traditional and optical toothpastes had similar tooth-whitening efficacies (p > 0.05). However, a statistically significant difference of 1% was observed between the ΔE values of both toothpastes investigated (p < 0.05), which from the clinical perspective is an insignificant or unperceivable color difference and therefore contradict previous findings.^{8,10} Our results are corroborated by the recent paper published by



FIGURE 4. Comparison of the mean values and confidence interval (CI 95%) of the whiteness index optimized (WIO), registered before staining (B), after staining (S) and after use of abrasive toothpaste (Ab) or whitening toothpaste containing blue covarine (Op) for one day (ID) and seven consecutive days (7D) in function of the staining beverage used.

Torres et al.²¹ who also evaluated the tooth-whitening efficacies of traditional and blue covarine containing toothpastes using bovine teeth and objective color measurements (spectrophotometer CM2600d, Minolta, Japan). Their results clearly demonstrated that the use of tooth-whitening toothpastes with exposure times two-times longer than the exposure times investigated in this study did not result in an increased toothwhitening efficacy.

The results of this study contradict the findings of Joiner et al. (2006) and Collins, Maeeni, and Platten (2008), who demonstrated in vitro and in vivo the obtainment of instantaneous dental bleaching results with the use of a toothpaste containing hydrated silica and blue covarine. We strongly believe that the difference in results could be attributed to methodological differences among the studies cited and this study. The optical whiteness effect from the use of toothpastes containing blue covarine was observed when the evaluation was performed by colorimetric or photographic method, using the WIO index as the color parameter. Other methodologies have failed to prove the optical whitening effects of blue covarine toothpastes. Among the limitations of this study we can highlight the absence of a control group where specimens would be subjected to the action of the bristles of the toothbrushing machine alone to demonstrate the effect of the use of toothpaste. In addition, the degradation of the pigments within the crystalline structure over the total assessment period (7 days) could have also overestimated the tooth whitening effects of the toothpastes investigated, and therefore could have masked their differences. The use of bovine teeth can also be considered as one of the limitations of this study because these teeth have optical, physical, and chemical properties that are different from those observed for human teeth.²²

Considering the limitations and findings of this study, the use of blue covarine containing toothpastes should not be prescribed as the primary whitening agent, or as a substitute to traditional dental bleaching techniques in challenging chromatic cases, such as aging, trauma, endodontic treatments, etc. In addition, we believe that additional studies should be conducted to investigate the utility of toothpastes containing blue covarine as maintenance agents after the completion of traditional dental bleaching procedures.

CONCLUSIONS

All staining solutions used promoted significant changes in the color of bovine specimens. These color alterations were more pronounced in the specimens subjected to staining with black tea (BT). The use of traditional (Ab) and blue covarine containing toothpastes (Op) for one (1D) or seven cumulative days (7D) progressively and significantly reduced the specimens' discoloration levels achieved by the in vitro staining solutions investigated. The tooth-whitening effects promoted with the toothpastes investigated were not statistically significant. Based on the results of the statistical analysis performed we accepted the null hypothesis proposed for this study.

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STATEMENT OF AUTHORS' RESPONSIBILITIES

Morgana Oliveira was responsible for the design of the experiment, preparation of specimens, discussion of results, and conclusion.

Eduardo Fernández was responsible for the introduction, experimental design, and discussion of results.

Janaína Bortolatto was responsible for statistical analysis and description of the results.

Osmir Oliveira Junior was responsible for statistical analysis and description of the results and conclusions.

Matheus Bandeca was responsible for the introduction, experimental design, and discussion of results.

Sharukh Khajotia was responsible for the analysis and discussion of results and translation.

Fernando Florez was responsible for the analysis and discussion of results and translation.

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OPTICAL DENTAL WHITENING EFFICACY Oliveira et al.

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