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RESEARCH AND EDUCATION

Illuminant metamerism between natural teeth and zirconia restorations evaluated with a chromatic adaptation transform

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Shade matching in dentistry presents a formidable challenge for the restorative team,[1] and esthetic complications stemming from color mismatches are both common[2] and costly.[3] The challenges are manifold and have been described in the dental literature at great length.[4] Tooth color comprises different factors, including the influence of the light source, the reflectance and transmittance of the tooth, and the human visual system.[5] The human eye responds to a given stimulus not exactly based on wavelength integration across the visible spectrum but on the integrated stimulation of 3 types of receptors referred to as the L, M, and S cones.[6] If 2 separate stimuli cause the same L, M, and S cone responses, then, when viewed under the same illuminant, they will look the same, regardless of their spectral composition. To form a pair with a visually appreciable degree of metamerism, when the illuminant is changed, the spectral composition of the 2 stimuli must intersect at 3 or more wavelengths located within the L, M, and S cone sensitivity spectrum and with reasonable convergence among them.[7] Illuminant metamerism thus refers to the phenomenon in which 2 objects with different spectral reflectance properties can appear to have the same color under one illumination but not under another.[8]

ABSTRACT

Statement of problem. Little is known about the effect of illuminant metamerism between natural teeth and zirconia restorations, despite their increasing clinical popularity.

Purpose. The purpose of this in vitro study was to compare illuminant metamerism between pairs of natural teeth and layered zirconia restorations and pairs of natural teeth and monolithic zirconia restorations under 10 different illuminants and analyze their metameric potential.

Material and methods. Spectral reflectance factors were obtained from 10 pairs of extracted natural teeth and layered zirconia restorations and 28 pairs of extracted natural teeth and monolithic multilayer zirconia restorations. Each pair showed a color match that was within the visual threshold for clinical acceptability (CIEDE2000≤1.8). A special index of metamerism for the change of illuminant (M_{ilm}) was calculated from the CIEDE2000 color difference equation. Descriptive statistics and the one-sample *t* test were used to analyze the results for the M_{ilm} and for both groups of layered and monolithic zirconia restorations (α=.05).

Results. Layered zirconia restorations reached a mean ±standard deviation value for M_{ilm}=0.3 ±0.2 and M_{ilm}=0.5 ±0.4 for monolithic zirconia restorations (P<.01).

Conclusions. The effect of illuminant metamerism between natural teeth and zirconia crowns was weak and generally within the clinical acceptability limit. (J Prosthet Dent xxxx;xxx:xxx-xxx)

The field of dentistry has generally accepted the view that illuminant metamerism can contribute negatively to the quality of a perceived color match when viewed by the patient under changing light conditions.[9–14] The effect of illuminant metamerism has also been taught in predoctoral and graduate programs.[15]

The complexity of color appearance under different lighting conditions is demonstrated in Figure 1. The intraoral situation depicted on the left shows the visual appearance under a light source representing average daylight with a correlated color temperature (CCT) of approximately 6500 K. Shown in the middle is a simulation of the corresponding color under a fluorescent type of illumination with a CCT of approximately 4200 K. Despite the strong color

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Clinical Implications

Illuminant metamerism between natural teeth and closely matching zirconia restorations should not be a major concern for esthetically challenging restorations.

cast, a reasonable representation of a normal tooth color is still preserved because of the visual mechanisms of simultaneous color contrast and chromatic adaptation. Finally, the image on the right reveals the effect of color inconstancy, which is simply the difference in visual appearance between the conditions in the top and middle rows.

The Commission Internationale de L'Eclairage (CIE) recommends a chromatic adaptation transform (CAT) to predict the corresponding colors, for instance, of teeth under an illuminant that is different from the reference illuminant (D65). A comprehensive description of this type of advanced colorimetry and its potential applications in dentistry was provided by Fairchild.[16] The current CIE recommendation for this operation is CIECAM02, but a more recent version known as CAT16 is set to replace it because of its better performance as demonstrated in psychophysical experiments.[17,18] Typical test illuminants currently recommended by the CIE are standard illuminant A and 1 of the FL-type illuminants representing fluorescent lamps, usually FL2, FL7, or FL11.[19] By convention, these are simply referred to as F2, F7, and F11 in the scientific literature and are hereafter referred to accordingly.

The European Union Commission has recently published a new Restriction of Hazardous Substances Directive, which effectively bans the sale of any light sources containing mercury by August 2023.[20] The recent Tracking Report on Lighting published by the International Energy Agency indicates that these sources are set to be superseded by more modern light-emitting diode (LED) lamps. It estimates that currently more than half of the world's lighting markets already use LED technology, with increasing adoption.[21] To account for this shifting trend, the CIE has recently introduced a range of LED illuminants. These include LED-B1 to LED-B5 to represent the phosphor-converted blue LEDs which are currently predominantly used, and LED-BH1 to represent blue hybrid LEDs.[19]

A special index of metamerism (M_{ilm}) has been recommended by the CIE to provide an appropriate metric for the evaluation of metamerism, which is simply the color difference between the measured CIELab values of 2 objects under the reference and test illuminant evaluated with a suitable color difference equation such as CIEDE2000 (ΔE_{00}).[19] In the case of Figure 1, this would be the color difference between both maxillary central incisors shown on the left and in the middel. The image on the right depicts the effect of color inconstancy, and 2 teeth are said to be metameric if they possess different color inconstancies.[8] A ranking scale for visual thresholds in clinical dentistry was provided by Paravina et al,[22] suggesting that a color difference of less than 1.8 ΔE_{00} units is clinically acceptable.

Because of its clinical and laboratory advantages, the use of zirconia restorations has experienced impressive growth over the last 10 years. A recent report estimates that the market for zirconia restorations is set to grow from $292.7 million in 2023 to $510 million by 2030.[23] From a laboratory perspective, such restorations are seen as more cost effective to produce than glass-ceramic restorations, and clinicians appreciate the better mechanical strength of zirconia. A recent survey conducted by the American Dental Association showed that 45% of participants used monolithic zirconia restorations and that, in the anterior region, layered zirconia was used in 42% of all crowns. Interestingly, the same survey also listed shade matching among the top 2 cited disadvantages of zirconia restorations.[24]

Previous work has investigated similar aspects in relation to other materials that are commonly used in restorative dentistry, but with more basic colorimetric methods. One early study[25] investigated the effects of metamerism on pairs of dental materials and bovine teeth with a similar color under 2 illuminants. The spectral reflectance factors obtained were simply converted to CIELab values for the reference and test illuminants, and the color differences were

Figure 1. Sequence of intraoral images to demonstrate chromatic adaptation. A, Appearance of natural smile under light source representing average daylight with CCT of approximately 6500 K. B, Same situation with corresponding color simulated under fluorescent type of illumination with CCT of about 4200 K. Appearance of normal tooth color preserved despite strong color cast. C, Noticeable difference between both conditions known as color inconstancy (illustration adapted from Fairchild[16]). CCT, correlated color temperature; K, Kelvin.

then evaluated using the shortest Euclidian distance (ΔE^*_{ab}). This approach subsequently became the standard in dental research. The results showed an average color difference of 1 ΔE^*_{ab} from the change of illuminant, which is barely visible. Others[26] have proposed a modified metamerism index by calculating the ratio of color differences between parameric pairs of specimens measured under the reference and test conditions. When they compared 10 human dentin specimens with dental materials, they concluded that no evidence of a metameric effect could be found. The modified metamerism index was applied in several studies thereafter,[27–29] including a study[30] that investigated the metameric effect between natural teeth measured in vivo and 2 shade guide brands. Much like in previous studies, only a very moderate metameric effect, which was well below the threshold for clinical acceptability, could be found.

The aim of this study was to quantify illuminant metamerism between pairs of natural teeth and closely matching zirconia restorations milled from multilayer monolithic zirconia materials and manually veneered zirconia restorations using the CAT16 chromatic adaptation transform. The null hypothesis was that a change in illuminant would not result in color changes exceeding the threshold for clinical acceptability of $\Delta E_{00} \leq 1.8$.

MATERIAL AND METHODS

The specimens in this study were divided into 3 initial groups. The first consisted of 114 human maxillary central teeth (ethical committee approval number: LTDESN-164), which were extracted for periodontal reasons and contained no fillings or caries and showed no signs of damage. The teeth were cleaned, polished with pumice, and stored in a 1% thymol solution to prevent dehydration and preserve their color. The second group consisted of 31 hand-layered zirconia restorations of various, unspecified custom shades. The third group consisted of 75 monolithic zirconia restorations, which were milled from multilayered blanks (Table 1). The shade selection for the monolithic zirconia restorations was based on a statistical evaluation of the shade preferences of 230 dental practitioners for a total of 9630 patients. These data were provided by a digital dental laboratory (biodentis GmbH) and showed that the A-shades from the Vita Classical shade guide were the most popular choices (Fig. 2). Shades from A1 to

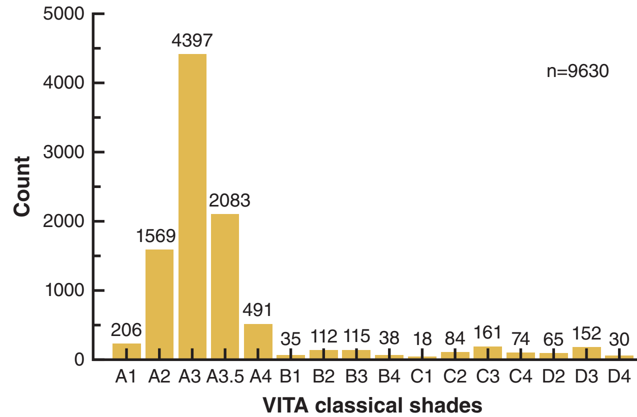

Figure 2. Statistical evaluation showing shade preference of 230 dental practitioners (courtesy of biodentis GmbH).

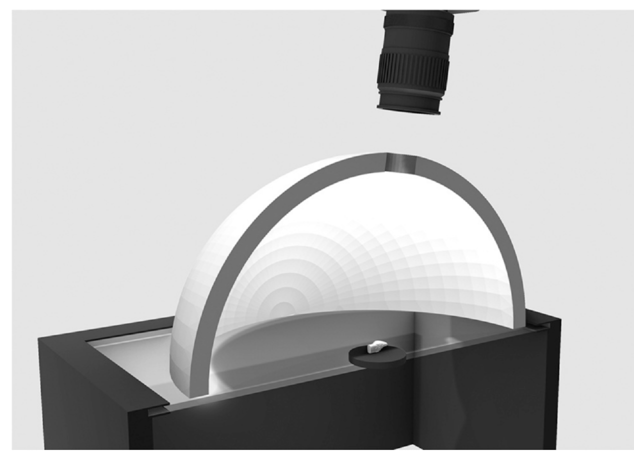

Figure 3. Schematic illustration showing cross-section of illumination geometry used for study.

A3.5, and 1 bleach shade were included to take account of the increased preference for brighter tooth shades by the public, a trend that may not be fully represented in previous data.[31] Both groups of zirconia restorations had a labial thickness of between 1.2 and 1.7 mm and were seated over shade ND4 tooth-colored dies (Natural Die Material; Ivoclar AG).

A calibrated telespectroradiometer (SperctraScan PR-670; Photo Research Inc) was used. The advantages of a telespectroradiometer when measuring natural teeth have included the prevention of edge loss[32] and having a visual geometry that correlates well with human perception (Fig. 3).[33] The telespectroradiometer was used

Table 1. List of multilayer zirconia blanks and shades included in study

Manufacturer	Source	Shades
IPS e.max ZirCAD prime	Ivoclar AG	BL-4, A1 to A3.5
Cercon xt ML	Dentsply Sirona Deutschland GmbH	BL, A1 to A3.5
Amann Girrbach Zolid FX	Amann Girrbach AG	A0, A1 to A3.5
Katana STML	Kuraray Europe GmbH	NW, A1 to A3.5
ZirkonZahn Pretau 2 Dispersive	Zirkonzahn GmbH	Bleach 1, A1 to A3.5

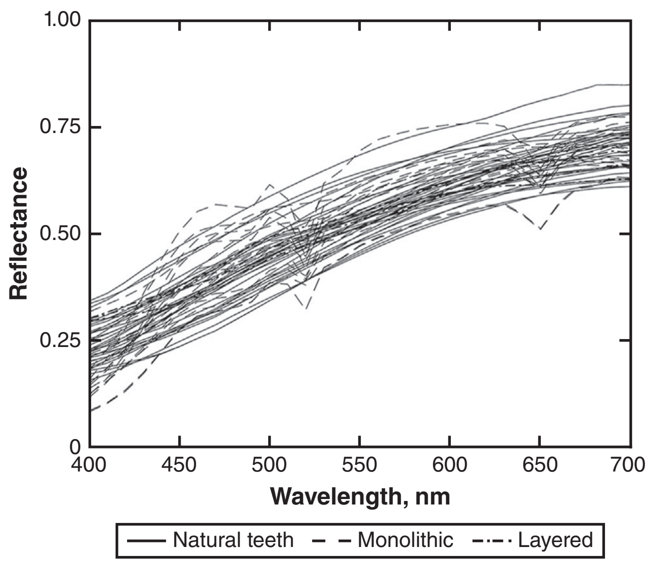

Figure 4. Spectral reflectance factors of parameric pairs consisting of natural teeth and layered zirconia restorations and natural teeth and monolithic zirconia restorations included in study. Each pair showed color difference within threshold for clinical acceptability. Layered, layered zirconia restorations; Monolithic, monolithic zirconia restorations.

together with an integrating hemisphere to provide 8-degree diffuse reflectance, as described by Molenaar et al.[34] The distance between the target tooth and the telespectroradiometer was approximately 40 cm, and the measurement aperture was set to 1 degree, which represented a measurement spot of approximately 20 mm^2. This arrangement was chosen because it provided illumination from all spatial directions and hence ideal conditions for the collection of spectral reflectance factors from diffusely scattering media like human teeth or dental materials, which do not have a flat surface. The original design was adapted by replacing the halogen rods with a xenon light source (XBO 75W/2; Zeiss).

When 2 objects present with a close visual match under 1 set of viewing conditions but without sharing actual colorimetric equality ($\Delta E_{00}\neq0$), they are referred to as a parameric pair.[8] For the final test groups to be evaluated, a computer routine (MATLAB R2022a; MathWorks) identified parameric pairs consisting of either a natural tooth and a monolithic zirconia crown (28 pairs) or of a natural tooth and a layered zirconia crown (10 pairs) with a color difference that was coincidentally within the visual threshold for clinical acceptability of $\Delta E_{00}\leq1.8$ when calculated under CIE standard illuminant D65 for the CIE 1931 standard colorimetric observer (Fig. 4).

The M_{ilm} recommended by the CIE requires that 2 samples differ spectrally but possess colorimetric equality ($\Delta E_{00}=0$) under a reference illuminant, usually CIE standard illuminant D65 for the CIE 1931 standard colorimetric observer, to form a metameric pair. However, 1 study analyzed the frequency of metamerism in natural scenes and concluded that the probability of finding such a metameric pair was "vanishingly small."[35] It is much more common for 2 samples to appear to be a metameric match without possessing actual colorimetric equality under the reference illuminant, in which case they form a parameric pair.[36] To abolish the residual color difference, the CIE recommends a multiplicative correction for the calculation of a M_{ilm} for parameric pairs,[19] and this was followed accordingly.

Despite the new legislation that will lead to the eventual discontinuation of all FL-illuminants, it was decided to follow the CIE guidelines and include illuminants F2, F7, and F11, as well as CIE standard illuminant A, in the investigation since these are still widely used around the world. To focus on the more modern LED illuminants that are set to replace them, CIE illuminants LED B1 to B5 and LED BH1 were also included (Table 2). Older types such as LED-V1, V2, and LED-RGB which mix red, green, and blue to create white light, have already been superseded and were therefore not included in this study.[37]

The spectral reflectance factors of all specimens were first transformed to trichromatic XYZ values for each of the 10 test illuminants and for the CIE 1931 standard colorimetric observer to serve as the test condition. To predict the corresponding colors under the reference illuminant D65 for the same observer condition, CAT16 was used with an adaptation luminance LA=64 cd/m^2, which equals a photopic illuminance of 1000 lx, a degree of adaptation D=1, and an average surround F=1.[38] The resulting trichromatic XYZ values were then converted to the CIELab color space under the same reference condition. The M_{ilm} was then calculated using the ΔE_{00} color difference equation with weighting functions S_L, S_C, and S_H set to 2:1:1 in accordance with Pecheo et al,[39] who showed that these parameters provided a good representation of the visual perception when the Vita classical shades were used. A schematic flow chart of the computation is shown in Figure 5.

Descriptive statistics and the 1-sample t test were used to analyze the results for the M_{ilm} and for both groups of layered and monolithic zirconia restorations, with a test value of 1.8 representing the threshold for clinical acceptability. A statistical software program (IBM SPSS Statistics, v26.0; IBM Corp) was used for the analysis (α=.05).

Table 2. List of all included test illuminants with corresponding correlated color temperatures (CCT)

Test Illuminant	A	LED-B1	LED-B2	LED-B3	LED-B4	LED-B5	LED-BH1	F2	F7	F11
CCT	2856 K	2733 K	2998 K	4103 K	5109 K	6598 K	2851 K	4230 K	6500 K	4000 K

K, Kelvin.

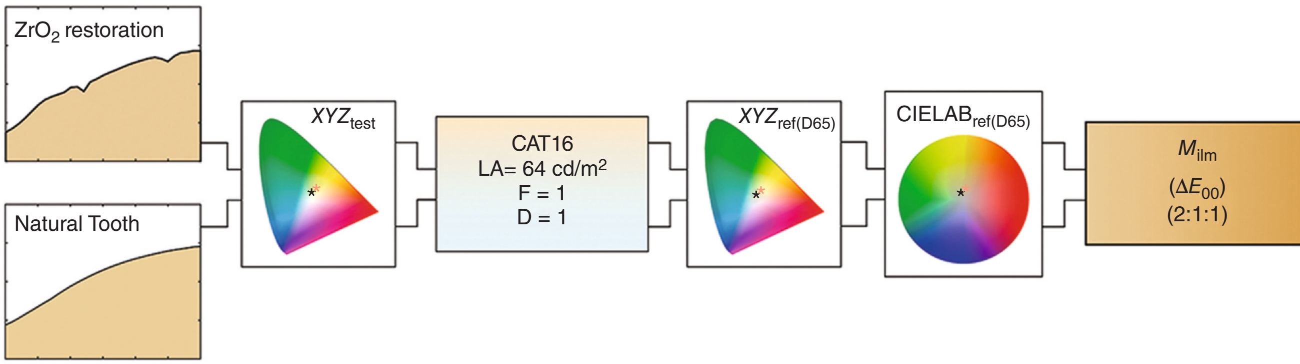

Figure 5. Flow chart showing computation of M_{ilm} using CIE 1931 standard colorimetric observer. CAT16, chromatic adaptation transform; D, degree of adaptation; ΔE_{00}, CIEDE2000 color difference equation; F, average surround; LA, luminance adaptation; M_{ilm}, special index of metamerism; *XYZ*, CIE trichromatic color space.

RESULTS

The mean ±standard deviation color differences for the layered and monolithic groups were 0.3 ±0.2 ΔE_{00} units (min=0.1, max=1.1) and 0.5 ±0.4 ΔE_{00} units (min=0.3, max=1.9), respectively. The 1-sample *t* test revealed that the mean of the measured values for the M_{ilm} was significantly (P<.01) below the test value of 1.8 shown in Table 3. The M_{ilm} by the type of CIE illuminant for the group of layered and monolithic zirconia restorations is shown in Figure 6, and the 3 components of their average color differences are shown in Figure 7. Figure 8 shows the frequency of M_{ilm} by the type of zirconia restoration.

DISCUSSION

The null hypothesis was accepted for both groups (layered and monolithic zirconia restorations), since M_{ilm} was significantly lower than the test value for the visual threshold of clinical acceptability. This suggests that illuminant metamerism between natural teeth and

Table 3. One Sample *t* test for M_{ilm} between both groups and natural teeth (test value=1.8, α=.05)

M_{ilm}	t	df	P	Mean Difference
Layered zirconia restorations	64.5	99	<.001	-1.50
Natural teeth	80			
Monolithic zirconia restorations	58.4	279	<.001	-1.27
Natural teeth	77			

df, degrees of freedom; M_{ilm}, special index of metamerism.

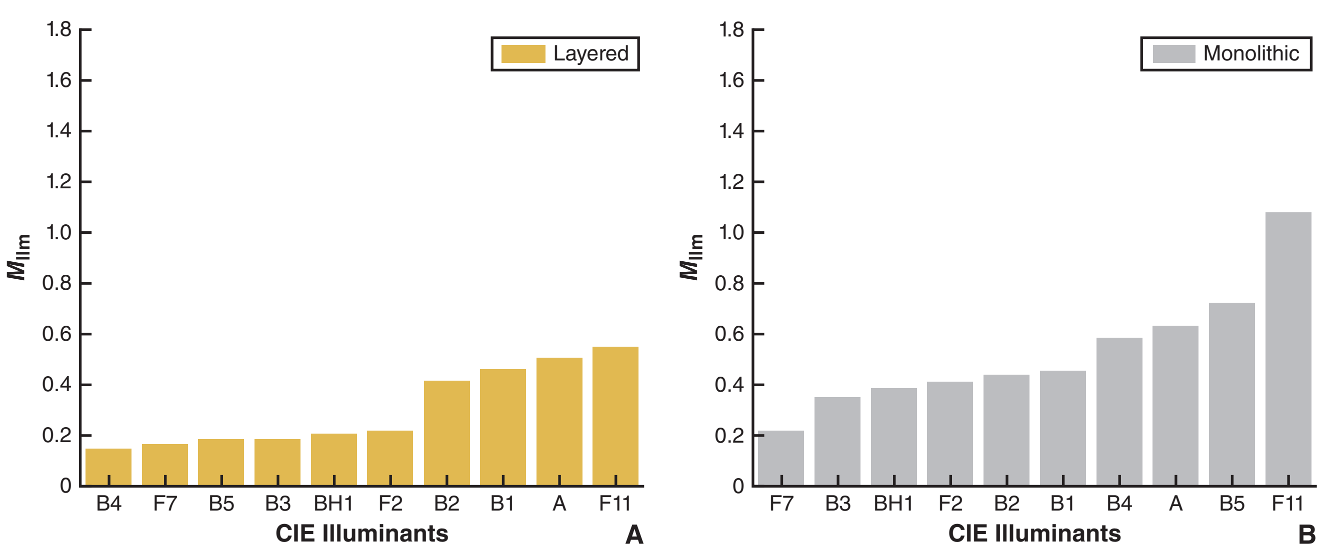

Figure 6. Mean results of M_{ilm} ranked by type of CIE illuminant and for groups of (A) layered zirconia restorations and (B) monolithic zirconia restorations. Layered, layered zirconia restorations; M_{ilm}, special index of metamerism; Monolithic, monolithic zirconia restorations.

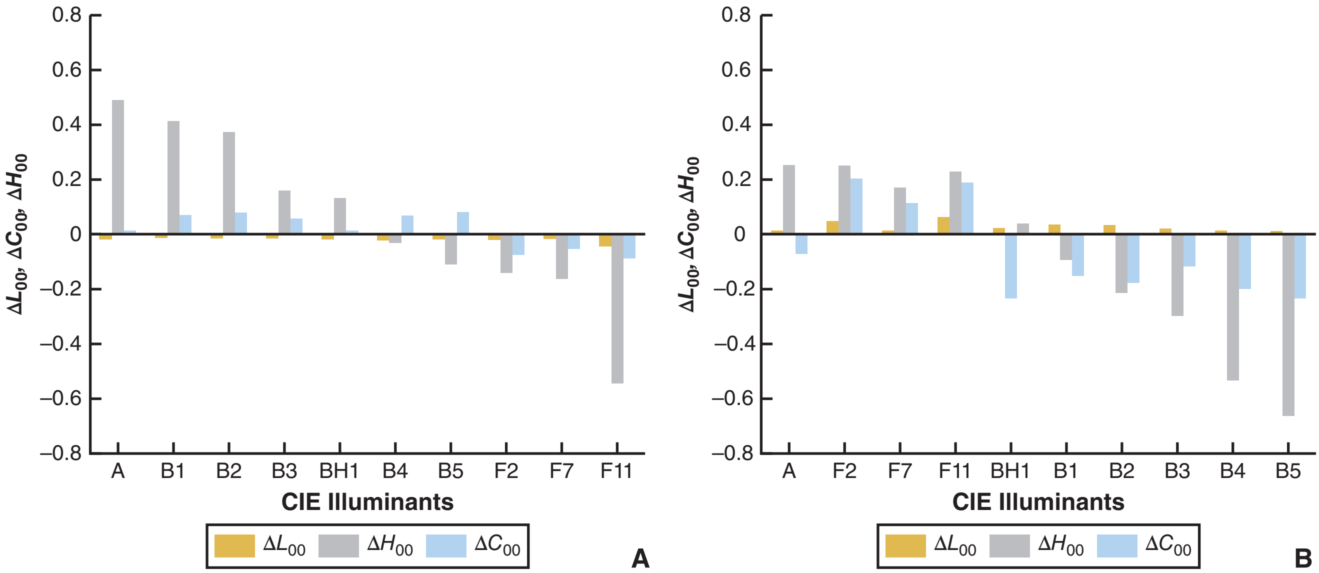

Figure 7. Three components of average color differences for groups of (A) layered zirconia restorations and (B) monolithic zirconia restorations by CIE test illuminants. ΔC_{00} chroma difference; ΔH_{00}, hue difference; ΔL_{00}, lightness difference.

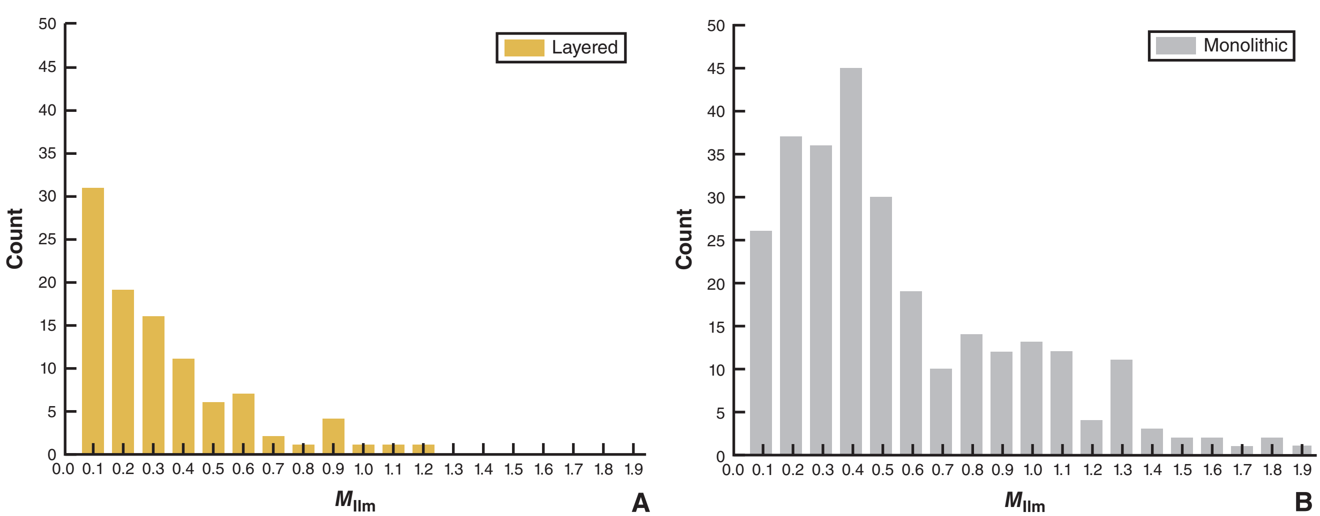

Figure 8. Frequency of M_{ilm} by groups of (A) layered crowns and (B) monolithic crowns. On average, layered crowns reached smaller values than monolithic crowns under all test illuminants. Layered, layered zirconia restorations; M_{ilm}, special index of metamerism; Monolithic, monolithic zirconia restorations.

closely matching zirconia restorations should not be a major concern for the clinician when considering such restorations. Although the overall metameric effect was generally very small, it was slightly smaller for layered zirconia restorations than for monolithic restorations. The result of the present study challenges the currently established paradigm regarding the role of illuminant metamerism in dentistry.[10,11,40] The results can be explained by the fact that the zirconia restorations generally exhibited smooth spectral reflectance curves that matched those of their natural tooth partners reasonably well (Fig. 4). Natural teeth, layered zirconia restorations, and Katana STML all exhibited smooth reflectances, whereas all other monolithic groups showed distinct dips at 520 nm and 650 nm (Fig. 4). These dips are indicative of the presence of erbium ions (Er^{3+}), which are often used as a red or pink coloring component and exhibit narrow absorption bands at these specific wavelengths in the visible spectrum.[41] Katana STML, however, does not incorporate Er^{3+} as a color component.[42] When present, these dips caused multiple crossover points with the spectra of their parameric partner, but in most cases, they were too small to cause any significant color differences. This finding suggests that when a natural tooth and a zirconia restoration match to a clinically acceptable degree, they do so precisely because of their spectral similarities. Therefore, the assumption that the difference in chemical composition between dental materials and natural teeth must lead to inherently different spectral characteristics[13] may be incorrect.

The color difference of 1 monolithic crown (Amann Girrbach Zolid A3) exceeded the value for clinical acceptability by 0.08 ΔE_{00} units under illuminant F11. However, the current range of fluorescent types of lamps, including F11, is set to be discontinued and replaced by LED lamps toward the end of 2023.[20] The LED illuminants tested in this study were unproblematic, suggesting their introduction might reduce any metamerism between natural teeth and closely matching zirconia restorations in general.

Limitations of the present study included the fact that only A-shades were tested since research funding did not permit testing the complete range of multilayer zirconia blanks from all manufacturers to cover the entire range of the Vita Classical shades.

Future research might evaluate tooth color by replacing the CIELab system with a more modern color appearance model such as CIECAM16 in combination with a color difference equation such as CAT16-UCS.[18] This approach would require new thresholds for clinical acceptability since the current ones are based on the use of the ΔE^*_{ab} and ΔE_{00} color difference equations. The ΔE_{00} color difference is still recommended by the CIE for small color differences (ΔE^*_{ab}<5), although there is abundant evidence to challenge this recommendation.[18] Therefore, the application of CAT16-UCS in dental-related color research may provide a new avenue for scientific inquiry.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Illuminant metamerism between natural teeth and both layered and monolithic zirconia restorations was small and well within the limits of clinical acceptability, except for 1 case where this threshold was exceeded by 0.08 CIE units (and which was not statistically significant).
2. Although the metameric effects were small overall, layered zirconia restorations were, on average, slightly less metameric than their monolithic counterparts.

APPENDIX A. SUPPLEMENTAL MATERIAL

Supplemental data associated with this article can be found in the online version at doi:10.1016/j.prosdent.2023.07.035.

REFERENCES

1. Joiner A, Luo W. Tooth colour and whiteness: A review. *J Dent*. 2017;67:3–10.
2. Douglas RD, Steinhauer TJ, Wee AG. Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch. *J Prosthet Dent*. 2007;97:200–208.
3. Corcodel N, Zenthofer AJ, Setz AJ, Rammelsberg P, Hassel AJ. Estimating costs for shade matching and shade corrections of fixed partial dentures for dental technicians in Germany: A pilot investigation. *Acta Odontol Scand*. 2011;69:319–320.
4. Vichi A, Louca C, Corciolani G, Ferrari M. Color related to ceramic and zirconia restorations: A review. *Dent Mater*. 2011;27:97–108.
5. Burkinshaw SM. Colour in relation to dentistry. *Br Dent J*. 2004;10:33–41.
6. Merbs SL, Nathans J. Absorption spectra of human cone pigments. *Nature*. 1992;356:433–435.
7. Hunt RWG, Pointer MR. Measuring colour. Willey; 2011:117–142.
8. Berns R. Billmeyer and Saltzman's principles of color technology. Willey; 2019:157–168.
9. Fondriest J. Shade matching in restorative dentistry: the science and strategies. *Int J Periodontics Restorative Dent*. 2003;23:467–479.
10. Sakaguchi RL, Ferracane J, Powers JM. Craig's restorative dental materials. Elsevier: Mosby; 2019:52.
11. Chu S, Paravina RD, Sailer I, Mieleszko AJ. Color in dentistry: A clinical guide to predictable esthetics. Berlin: Quintessence Publishing; 2017:68–112.
12. Sproull RC. Color matching in dentistry. Part III. Color control. *J Prosthet Dent*. 1974;31:146–154.
13. Yamamoto M. Metal-ceramics. Chicago: Quintessence Publishing; 1985:233–235.
14. McLean JW. The science and art of dental ceramics. Chicago: Quintessence Publishing; 1979:137.
15. Paravina RD, O'Neill PN, Swift Jr EJ, Nathanson D, Goodacre CJ. Teaching of color in predoctoral and postdoctoral dental education in 2009. *J Dent*. 2010;38:34–40.
16. Fairchild MD. Color appearance models and complex visual stimuli. *J Dent*. 2010;38:25–33.
17. Li C, Li Z, Wang Z, et al. Comprehensive color solutions: CAM16, CAT16, and CAM16–UCS. *Col Res Appl*. 2017;42:703–718.
18. Luo MR, Xu Q, Pointer M, et al. A comprehensive test of colour-difference formulae and uniform colour spaces using available visual datasets. *Col Res Appl*. 2023;48:267–282.
19. CIE 015. Colorimetry. Technical report. CIE Central Bureau; 2018.
20. European Union Commission Delegated Directive. Official Journal of the European Union. 2023;66. Available at: ⟨http://data.europa.eu/eli/dir_del/2022/284/oj⟩.
21. International Energy Agency. Lighting Tracking Report 2022. Available at: ⟨https://www.iea.org/reports/lighting⟩.
22. Paravina RD, Pérez MM, Ghinea R. Acceptability and perceptibility thresholds in dentistry: A comprehensive review of clinical and research applications. *J Esthet Restor Dent*. 2019;31:103–112.
23. Coherent Market Insights. Zirconia Based Dental Materials Market to Surpass US$ 510.5 Million by 2030. 2022. Available at: ⟨https://www.prnewswire.com/news-releases/zirconia-based-dental-materials-market-to-surpass-us-510–5-million-by-2030–coherent-market-insights-301612420.html⟩.
24. Lawson NC, Frazier K, Bedran-Russo AK, Khajotia S, Park J, Urquhart O. Zirconia restorations: An American Dental Association Clinical Evaluators Panel survey. *J Am Dent Assoc*. 2021;152:80–81.
25. Hang G, Jun-wu X, Sheng-qian A, Huizhou X. Influence of two light sources on the color of various kinds of ceramic materials. *West China J Stomatol*. 1993;11:192–194.
26. Lee Y, Powers J. Metameric effect between resin composite and dentin. *Dent Mater*. 2005;21:971–976.
27. Kim S, Lee Y, Lim B, Rhee S, Yang H. Metameric effect between dental porcelain and porcelain repairing resin composite. *Dent Mater*. 2007;23:374–379.
28. Lee Y, Lim B, Kim C, Powers J. Color characteristics of low-chroma and high-translucence dental resin composites by different measuring modes. *J Biomed Mater Res*. 2001;58:613–621.
29. Kim B, Yu B, Lee Y. Shade distribution of indirect resin composites compared with a shade guide. *J Dent*. 2008;36:1054–1060.
30. Corcodel N, Helling S, Rammelsberg P, Hassel A. Metameric effect between natural teeth and the shade tabs of a shade guide. *Eur J Oral Sci*. 2010;118:311–316.
31. Carey C. Tooth whitening: what we now know. *J Evid Based Dent Pract*. 2014;14:70–76.
32. Van der Burgt TP, ten Bosch JJ, Borsboom PCF, Kortsmit WJPM. A comparison of new and conventional methods for quantification of tooth color. *J Prosthet Dent*. 1990;63:155–162.

33. Pop-Ciutrila I, Ghinea R, Gomez M, Colosi H, Dudea D, Badea M. Dentine scattering, absorption, transmittance and light reflectivity in human incisors, canines and molars. *J Dent*. 2015;43:1116–1124.
34. Molenaar R, ten Bosch JJ, Zijp JR. Determination of Kubelka–Munk scattering and absorption coefficients by diffuse illumination. *Appl Opt*. 1999;38:2068–2077.
35. Foster DH, Amano K, Nascimento SMC, Foster MJ. Frequency of metamerism in natural scenes. *J Opt Soc Am*. 2006;23:2359–2372.
36. Berns R. Metamerism and color inconstancy. Billmeyer and Saltzman's Principles of Color Technology. Willey; 2019:157–168.
37. Jost S., Ngo M., Ferrero A., et al. Determination of illuminants representing typical white light emitting diodes sources. CIE Midterm Meeting.
38. Melgosa M, Ruiz-López J, Li C, García P, Della Bona A, Pérez M. Color inconstancy of natural teeth measured under white light-emitting diode illuminants. *Dent Mater*. 2020;36:1680–1690.
39. Pecho OE, Ghinea R, Alessandretti R, Pérez MM, Della Bona A. Visual and instrumental shade matching using CIELAB and CIEDE2000 color difference formulas. *Dent Mater*. 2016;32:82–92.
40. Oliveira D. Color science and shade selection in operative dentistry. Springer; 2022:7–8.
41. Abdlaty R, Fang Q. A novel dual-path high-throughput acoustooptic tunable filter imaging spectropolarimeter. *J Spectr Imaging*. 2020;9:1–11.
42. Fujisaki H., Kawamura K. "ZpexSmile" with enhanced color grading and transclucency of dental zirconia "Zpex" [In Japanese]. 2014.

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