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Effects of dentin and enamel porcelain layer thickness on the color of various ceramic restorations

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Abstract

Objective: To investigate the effects of dentin and enamel porcelain layer thickness on the color of various ceramic restorations.

Materials and methods: Eighty specimens (shade A2 and A3, n = 10) (20 mm in length, 4 mm in width, 1.5 mm in thickness respectively) of casting ceramic (EM); alumina ceramic (AL); zirconia ceramic (ZR); and porcelain-fused-metal (PFM) were prepared. The color distributions of each specimen were measured at 4 places using a spectroradiometer. The dentin/enamel porcelain (D/E) layer thicknesses of the 4 places were 0.8/0.2 mm, 0.6/0.4 mm, 0.4/0.6 mm, and 0.2/0.8 mm. The color differences (ΔE_{00}) between the specimens and the corresponding color shade tabs were calculated. Data were analyzed using three-way repeated-measures ANOVA and Holm–Sidak pairwise comparisons (a = 0.05). The acceptability threshold (AT) was used to analyze the results.

Results: The minimum ΔE_{00} values were 1.31 (0.6/0.4 mm for EM), 1.41 (0.8/0.2 mm for AL), and 1.92 (0.2/0.8 mm for ZR) for shade A2, and 0.93 (0.6/0.4 mm for EM), 0.89 (0.8/0.2 mm for AL), and 1.34 (0.8/0.2 mm for ZR) for shade A3. Most of them were below AT value (1.8). For AL and ZR (shade A2) and ZR (shade A3), the D/E layer thicknesses of 0.8/0.2 mm and 0.6/0.4 mm had lower ΔE_{00} values than 0.4/0.6 mm and 0.2/0.8 mm ($p \leq 0.001$).

Conclusions: The dentin/enamel porcelain layer thickness that was most color-matched to the shade tab was different for various ceramic restorations. The color of shade A2 AL and ZR and shade A3 ZR was closer to the shade tab when dentin porcelain was thicker than enamel porcelain.

Clinical significance: Matching the shade of ceramic restoration to the shade tab color is a great challenge in esthetic dentistry. The dentin/enamel porcelain layer thickness is an important factor to influence the improved color matching.

KEYWORDS
ceramic restoration, CIEDE2000, color differences, layered porcelain thickness, spectroradiometer

1 | INTRODUCTION

Dental porcelain, which has high wear resistance, high strength, high toughness, and excellent esthetic, is the most suitable material for replacing natural tooth tissues.1–3 However, the reproduction of selected shades with dental porcelain is not an easy task because many factors may affect the results. Several studies have shown that the thickness of the porcelain layer is a key factor in color matching, and the individual thickness of each layer and the ratio between the layers are important factors in achieving the best color match for the traditional porcelain-fused-to-metal restorations.[1,4,5] With the popularity of ceramic materials, all-ceramic restorations have been increasingly applied in clinical dentistry. All-ceramics, with their excellent biocompatibility, margin fitness, esthetics and translucency, and so forth, could lead to future esthetic dentistry.[6–8] To meet the demand for esthetic restorations, the use of all-ceramic crowns requires high-quality shades and optical properties because these crowns do not require the use of an opaque porcelain covered metal layer.[9,10] Therefore, the thickness of the dentin porcelain layer and enamel porcelain layer is important for color match, with the disappearance of the opaque porcelain layer for all-ceramic restorations. However, all ceramic systems have different compositions, organizations, contents, and crystal phases, which may affect the optical properties of these systems.[11,12] Regarding different all-ceramic systems, there is very limited scientific literature available regarding the effects of the individual thickness of each porcelain layer upon the resultant color, and no quantitative analysis has been conducted to investigate the best color-matched layer thickness between the dentin/enamel porcelain layers for the various ceramic systems.

To obtain the color closest to the natural tooth in restorations, it is necessary to perform two different steps: (i) the use of the shade guide to select the best possible shade (ii) to use the appropriate dental material to reproduce this shade in accordance with the selected shade guide.[13] Therefore, the accuracy of the reproduction of the natural tooth color is determined by the color difference between the restoration's color and the corresponding shade tab's color. In other words, the most color-matched restoration should be the restoration with the minimum color difference.

The most space (∼1 mm) was occupied by enamel porcelain and dentin porcelain for metal-ceramic or all-ceramic restorations, which could mimic the complex anatomy and optical appearance of the enamel and dentin of the natural tooth.[14] The apparent color of the natural tooth is the result of light absorption, scattering, and reflectance from the enamel and dentin.[15] As a general rule, the dentin porcelain influences on chroma and hue, and the enamel porcelain influences on lightness and translucency. Different synthetic color effects should be produced when various thicknesses of dentin porcelain and enamel porcelain are placed together, which determines the resultant color of different ceramic systems.[16]

Perceptibility threshold and acceptability threshold are the two major thresholds for assessing color differences.[17,18] Just perceived color difference is the smallest color difference perceived by a human observer. The color difference that 50% of observers can notice corresponds to 50:50% perceptibility threshold. Analogously, the color difference that is acceptable for 50% of observers corresponds to 50:50% acceptability threshold.[18,19] A color difference (using the color-difference formula CIEDE2000) more than 1.8 was considered as a clinically unacceptable color difference,[18] a standard which has been frequently used in previous studies.[20,21]

This study compared the color differences between four ceramic systems, which have been most commonly used in current clinical dentistry, with various dentin and enamel porcelain layer thicknesses and corresponding shade tabs.[22] The purpose of this study was to evaluate the influence of different dentin and enamel porcelain layer thicknesses on the resultant colors of various ceramic systems and to investigate the most color-matched D/E layer thicknesses to the corresponding shade tabs. The hypothesis of this study is that there is influence on the color difference between the ceramic materials and the corresponding shade tabs using different ceramic systems and different D/E layer thicknesses.

2 | MATERIALS AND METHODS

A porcelain-fused-metal system (PFM) and three all-ceramic systems, including one hot pressure casting ceramic (EM), one glass-infiltrated alumina ceramic (AL), and one CAD-CAM zirconia ceramic (ZR), were included in the study to represent metal-ceramic or all-ceramic restorations with various dentin and enamel porcelain thicknesses and colors. The information about these systems is listed in Table 1.

Composite specimens (Brilliant new line, Colte'ne/Whaledent AG, Altstätten, Switzerland) with Dentin A2/B2 shade and Dentin A3/D3 shade were fabricated to represent backgrounds with various colors.

An adhesive system (RelyX™ Unicem&U100, 3 M ESPE, St. Paul, Minnesota) with translucent shade was included in the study.

2.1 | Preparation of specimens—PFM and all-ceramic specimens

A total of 80 cuboid specimens (40 shade A2 and 40 shade A3) (20 mm in length, 4 mm in width, 1.5 mm in thickness respectively) were fabricated ($n = 10$).[23] The specimens were fabricated according to routine laboratory procedures: two firings of opaque layer, one firing of dentine layer and enamel layer, and finally, self-glazing. The thickness of each layer was adjusted using wet silicon carbide paper (320-, 600-, 800-, 1000-, and 1200-grit) and controlled using a digital micrometer (Mitutoyo Manufacturing Company, Ltd., Kawasaki, Japan), conforming to routine clinical criteria: the Co—Cr metal (Kulzer, Aite Functional Alloy Material Development Co., Zhengzhou, China) basic layer was 0.3 ± 0.01 mm and the opaque layer was 0.2 ± 0.01 mm for PFM specimens, and the ceramic basic layer with various systems was 0.5 ± 0.01 mm for all-ceramic specimens. The material of the basic layer of various all-ceramic systems was casting ceramic (IPS e.max, Ivoclar, Schaan, Liechtenstein) for EM, alumina

TABLE 1 Information of layer materials from the experimental groups used in the present study

Code	Layer	Material	Composition	Shade	Manufacturer
PFM	MetalInfrastructure	ET	Co-Cr metal		Aite, Zhengzhou, China
	DentinEnamel	Vintage Halo	Porcelain-fused-metal	A2A3	Shofu, Tokyo, Japan
EM	CeramicInfrastructure	IPS e.max	Casting ceramic	A2A3	Ivoclar, Schaan, Liechtenstein
	DentinEnamel	IPS e.max	Hot pressure casting ceramic	A2A3	Ivoclar, Schaan, Liechtenstein
AL	CeramicInfrastructure	VITA In-Ceram	Alumina ceramic	A2A3	Vita, Bad Sackingen, Germany
	DentinEnamel	VITA VM7	Glass-infiltrated alumina ceramic	A2A3	Vita, Bad Sackingen, Germany
ZR	CeramicInfrastructure	Procera	Zirconia ceramic	A2A3	Nobel Biocare, Coteborg, Sweden
	DentinEnamel	Nobel Rondo	CAD-CAM zirconia ceramic	A2A3	Nobel Biocare, Coteborg, Sweden

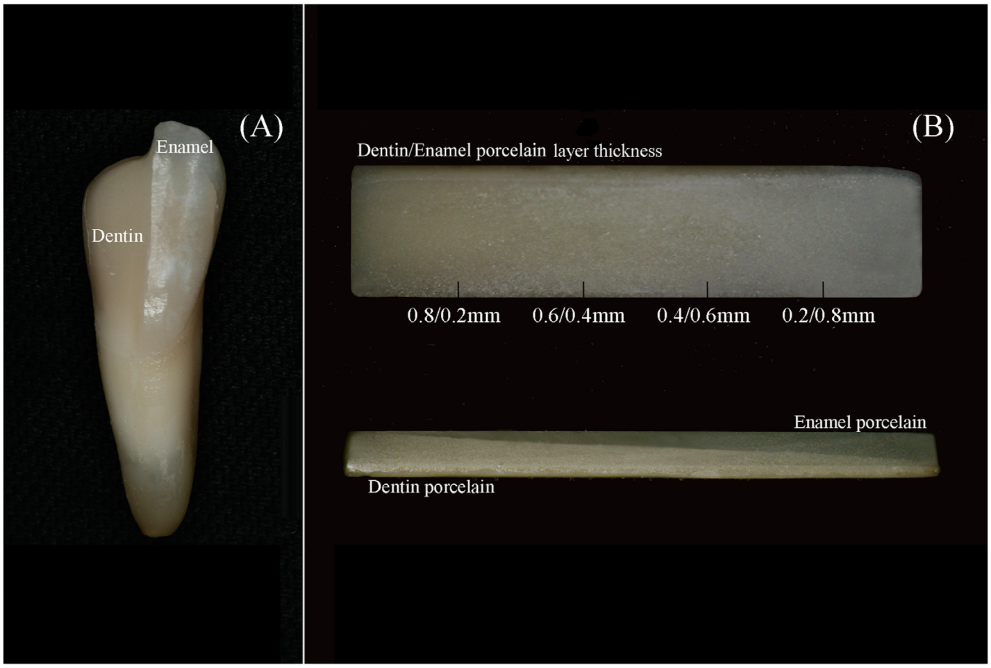

FIGURE 1 (A) Enamel and dentin of natural tooth; (B) Specimens with various dentin/enamel porcelain layer thicknesses

ceramic (VITA In-Ceram, Vita, Bad Sackingen, Germany) for AL, and zirconia ceramic (Procera, Nobel Biocare, Gothenburg, Sweden) for ZR, and the shades were low transparency shades A2 and A3. The thickness of all specimens' basic layers was 0.5 ± 0.01 mm after glazing.

The 1.0 ± 0.01 mm dentine layer was placed and fired on the basic layer. Dentine layers of wedge-like dimensions were adjusted and polished using wet silicon carbide paper in the following dimensions: height increasing from 0 to 1.0 mm, a width of 4.0 mm, and a length of 20 mm. The gradient of wedge-like specimens was controlled by 0.2, according to the measure of the thickness of the specimens after polishing using the digital micrometer, in the following thicknesses: 1.5 mm in the thickest point, 0.5 mm in the thinnest point, and 1.0 mm in the middle point.

The enamel layer was placed and fired on the wedge-like dentine layer in accordance with the manufacturer's instructions. Wet silicone carbide paper was used to polish the surface of the enamel layer to achieve cuboid specimens 20 mm in length, 4 mm in width, and 1.5 mm in thickness. Finally, a self-glazed process was performed at the manufacturer's recommended temperature. No internal or external staining was used in the fabrication procedure. To avoid color measurement errors caused by mismatched positions, 4 marker lines were inscribed in the long edge of each one-fifth of the specimens. The D/E layer thicknesses of the 4 marker lines were 0.8/0.2, 0.6/0.4, 0.4/0.6, and 0.2/0.8 mm, respectively. (Figure 1(B)).

2.2 | Preparation of specimens—Composite background specimens

Cuboid composite specimens (20 mm in length, 4 mm in width, 4 mm in thickness) were fabricated and served as the background colors to mimic the prepared tooth substrate. To standardize the shapes and thicknesses of the composites, a special mold using silicone impression material was designed. Composite resins were packed into the silicon molds, with a cover glass pressing on the top, and the resins were light cured on both surfaces for 40 s using a light-polymerizing unit (Spectrum, Dentsply Inc., Pennsylvania, York). Then, 80 cube-shaped composite specimens were fabricated (40 Dentin A2/B2 shade and 40 Dentin A3/D3 shade) and stored in distilled water for 24 h at 37°C to ensure complete polymerization. An adhesive system (RelyX™ Unicem&U100, 3 M ESPE, St. Paul, Minnesota) with translucent shade was applied between the PFM or all-ceramic specimens and composite background specimens to mimic the bonding between restoration and prepared tooth substrate. Dentin A2/B2 shade composite specimens were bonded and under the A2 shade metal or all ceramic specimens, and Dentin A3/D3 shade composite specimens were bonded and under the A3 shade metal or all ceramic specimens. Then, 200 g of pressure was applied on the top surfaces of the ceramic for 10 s. Then, 40 s of light curing was performed for all specimens. Each specimen was kept in a dark and humidity where no damage could occur.

2.3 | Color measurements

A spectroradiometer (PR-650 Spectra Scan, Photo Research Inc., Chatsworth, California) with a Macro-Spectra MS-75 and SL-0.5X lens and two fiber-optic light cables consisted the color measurement apparatus. The fiber light cables were connected to two tungsten-halogen lamps (Osram GmbH, München, Germany) to provide illumination source. The spectroradiometer and the fiber optic light cables, positioned at a 45° right and left to the vertical plane, provided an optical configuration of 0° observation and 45° illumination to the object, which was recommended for measuring the color of translucent materials.[24] The spectroradiometer was standardized to 91.4 mm from the measured object with a measurement aperture size 1.5 mm in diameter. The light source was OL 2150 (Optronic Laboratories Inc., Orlando, Florida). For all color measurements, spectral reflectance of each specimen was obtained from 380 to 780 nm, with 2 nm intervals. The relative spectral radiance measured for all specimens at each wavelength was converted into spectral reflectance factors (R) based on measurements of a white reflectance standard [$L^* = 99.98$, $a^* = 0.16$, and $b^* = 0.03$]. CIE (Commission International de l'Echairage) L*, a*, and b* values were calculated according to the CIE 1931 2 degrees Colorimetric Standard Observer and the CIE D65 standard illuminant for each specimen.[25,26] All color data were expressed in terms of the three coordinate values (L*, a*, and b*), which were established by CIE. Before measurement, the spectroradiometer was calibrated with a white reflectance standard tile [$L^* = 99.98$, $a^* = 0.16$, and $b^* = 0.03$] supplied by the manufacturer. A customized jig with a pointer was used to hold the specimens and confirm the position of the mark lines in the specimens (Figure 2(A)). Color errors as determined by repeated measurements after 1 week using this instrumental measuring system were less than 0.027 per △E unit.[27]

A gingival shade guide (Shofu Inc., Kyoto, Japan) was used as the specimen holder for fixing the Vitapan classical shade tabs (shades A2 and A3, VITA Zahnfabrik, Bad Sackingen, Germany) and ensuring that the surface being measured was perpendicular to the measurement axis of the spectroradiometer. The operator could observe the shade tab through the viewing eyepiece of the spectroradiometer and could unambiguously adjust the measuring aperture of 1.5 mm diameter black spot to the target site of the middle third region by regulating the modified equipment. After adjusting the equipment in four directions of up/down/left/right for approximately 0.5 mm, five measurements for each shade tab were taken (Figure 2(C)).

2.4 | Calculating the color differences

The color differences ($\triangle E_{00}$) between the specimens and corresponding color shade tabs were calculated using the color-difference formula CIEDE2000.

CIEDE2000 color differences ($\triangle E_{00}$) were calculated as: $\triangle E_{00} = [(\triangle L'/K_L S_L)^2 + (\triangle C'/K_C S_C)^2 + (\triangle H'/ K_H S_H)^2 + R_T(\triangle C'/K_C S_C)(\triangle H'/K_H S_H)]^{1/2}$.[24] $\triangle C'$and $\triangle H'$ were the differences in chroma and hue for a pair of samples.[28] S_L, S_C, and S_H were the weighing functions for the lightness, chroma, and hue components, respectively. RT (the so-called rotation term) referred to a function of the interaction between chroma and hue differences in the blue region.[29] K_L, K_C, and K_H were the parametric factors used to affect the illuminating and viewing conditions in color difference evaluation. CIE indicated that the values of K_L, K_C, and K_H were 1.0 under reference experimental conditions representative of industrial practice.[26] The CIEDE2000 equation (with parametric values of 1) was used

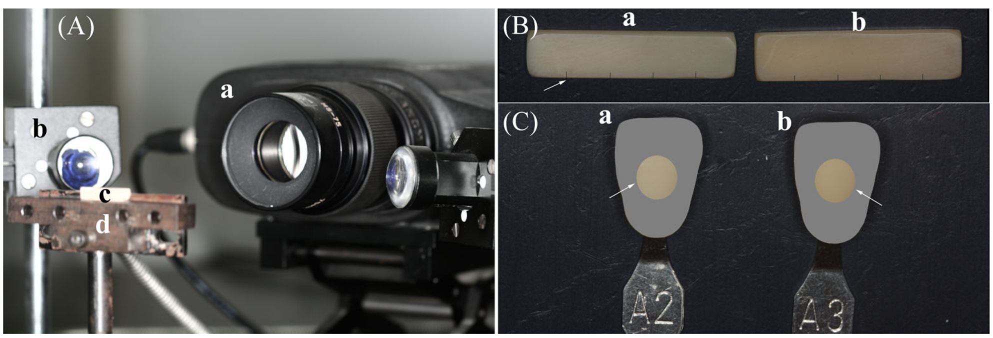

FIGURE 2 (A) Color measuring system:(A-a) PR650 spectroradiometer; (A-b) D65 light source; (A-c) specimen on the jig; (A-d) holder for specimens. (B) Specimens: (B-a) Specimen on shade A2；(B-b) Specimen on shade A3. (C) Vitapan classical shade tabs: (C-a) Shade A2; (C-b) Shade A3. The arrow indicates the position marker lines and color measuring regions

TABLE 2 Means of color difference (ΔE_{00}) and results of pairwise comparisons

		D/E layer thickness			
Shade	Ceramic system	0.8/0.2 mm	0.6/0.4 mm	0.4/0.6 mm	0.2/0.8 mm
A2	PFM	2.67 ± 0.32^{aA}	2.56 ± 0.73^{aA}	2.53 ± 0.63^{aA}	3.21 ± 0.57^{aA}
	EM	2.17 ± 0.72^{aA}	1.31 ± 0.27^{bB}	2.19 ± 0.34^{aA}	3.38 ± 0.54^{cA}
	AL	1.41 ± 0.46^{aB}	2.49 ± 0.37^{bA}	4.29 ± 1.07^{cB}	5.42 ± 1.05^{dB}
	ZR	1.92 ± 0.53^{aB}	2.40 ± 0.49^{aA}	4.33 ± 0.89^{bB}	4.84 ± 1.34^{bB}
A3	PFM	4.11 ± 0.83^{aA}	2.96 ± 0.57^{bA}	2.60 ± 0.66^{bA}	2.51 ± 0.64^{bA}
	EM	2.38 ± 0.37^{aB}	0.93 ± 0.46^{bB}	$1.96 \pm 0.54^{aA,B}$	3.69 ± 0.34^{cB}
	AL	0.89 ± 0.27^{aC}	$0.93 \pm 0.28^{a,bB}$	1.63 ± 0.39^{bB}	2.96 ± 0.65^{cA}
	ZR	1.34 ± 0.42^{aC}	2.50 ± 0.11^{bA}	4.48 ± 0.31^{cC}	6.30 ± 0.37^{dC}

Note: [a,b,c,d]Different lowercase letters represent statistically significant differences among the different D/E layer thicknesses (rows) within the same shade and ceramic system (pairwise comparisons using Holm-Sidak corrected Student's *t*-tests; $p \leq 0.05$). [A,B,C]Different capital letters represent statistically significant differences among the different ceramic systems (columns) within the same shade and D/E layer thickness (pairwise comparisons using Holm-Sidak corrected Student's *t*-tests; $p \leq 0.05$).

TABLE 3 The effect of shade, ceramic system and dentin/enamel porcelain (D/E) layer thickness on color differences (ΔE_{00})

Source	SS	df	MS	*F*-value	*p*-value
D/E layer thickness	213.997	3	71.332	180.500	<0.001
Shade	7.663	1	7.663	26.442	<0.001
Ceramic system	72.411	3	24.137	83.284	<0.001
D/E layer thickness*shade	6.543	3	2.181	5.519	=0.001
D/E layer thickness*ceramic system	157.060	9	17.451	44.159	<0.001
Shade*ceramic system	60.642	3	20.214	69.748	<0.001
D/E layer thickness*shade*ceramic system	32.179	9	3.575	9.048	<0.001

throughout and that all color difference values refer to this. After color differences, visual thresholds (50:50% acceptability threshold value and 95% confidence interval) would be used to analyze the results.

2.5 | Statistical analysis

The three-way repeated-measures ANOVA was used to observe the effect of shade, ceramic system, and dentin/enamel porcelain (D/E) layer thickness on color differences (ΔE_{00}). In the model, the shade and ceramic system were considered as between- subjects factors whereas dentin/enamel porcelain (D/E) layer thickness (0.8/0.2, 0.6/0.4, 0.4/0.6, and 0.2/0.8 mm) as within-subjects factor. All pairwise comparisons were performed using the Holm-Sidak corrected Student's *t*-tests. Statistical significance was set a = 0.05. The statistical analyses were accomplished using SPSS Package (version 11.0 for Windows, SPSS Inc., Chicago, Illinois).

3 | RESULTS

Table 2 shows the CIEDE2000 color difference values between the different D/E layer thicknesses of the specimens from the different ceramic system groups and the corresponding shade tab from VITA Classical shade guide. Considering the shade A2, the lowest and the greatest ΔE_{00} values were 2.53 (0.4/0.6 mm) and 3.21 (0.2/0.8 mm) for PFM ($p \leq 0.05$), 1.31 (0.6/0.4 mm) and 3.38 (0.2/0.8 mm) for EM ($p \leq 0.05$), 1.41 (0.8/0.2 mm) and 5.42 (0.2/0.8 mm) for AL ($p \leq 0.05$), and 1.92 (0.2/0.8 mm) and 4.84 (0.8/0.2 mm) for ZR ($p \leq 0.05$). For shade A3, the lowest and the greatest ΔE_{00} values were 2.51 (0.2/0.8 mm) and 4.11 (0.8/0.2 mm) for PFM ($p \leq 0.05$), 0.93 (0.6/0.4 mm) and 3.69 (0.2/0.8 mm) for EM ($p \leq 0.05$), 0.89 (0.8/0.2 mm) and 2.96 (0.2/0.8 mm) for AL ($p \leq 0.05$), and 1.34 (0.8/0.2 mm) and 6.30 (0.2/0.8 mm) for ZR ($p \leq 0.05$). The D/E layer thicknesses of 0.8/0.2 mm and (or) 0.6/0.4 mm had lower ΔE_{00} than 0.4/0.6 mm and (or) 0.2/0.8 mm on shade A2 AL and ZR ($p < 0.001$) and on shade A3 ZR ($p < 0.001$). It indicated that the ΔE_{00} values were decreased when dentin porcelain was thicker than enamel porcelain for shade A2 AL and ZR and shade A3 ZR.

The results of three-way repeated-measures ANOVA showed that the shade, the ceramic system, and the D/E layer thickness have significant influences on color differences (ΔE_{00}) between specimens and corresponding color shade tabs, and significant interactions between the three factors ($p < 0.001$) (Table 3).

The results of pairwise comparisons for the statistically significant differences among the different ceramic systems within the same shade and D/E layer thickness were shown in Table 2. On shade A2,

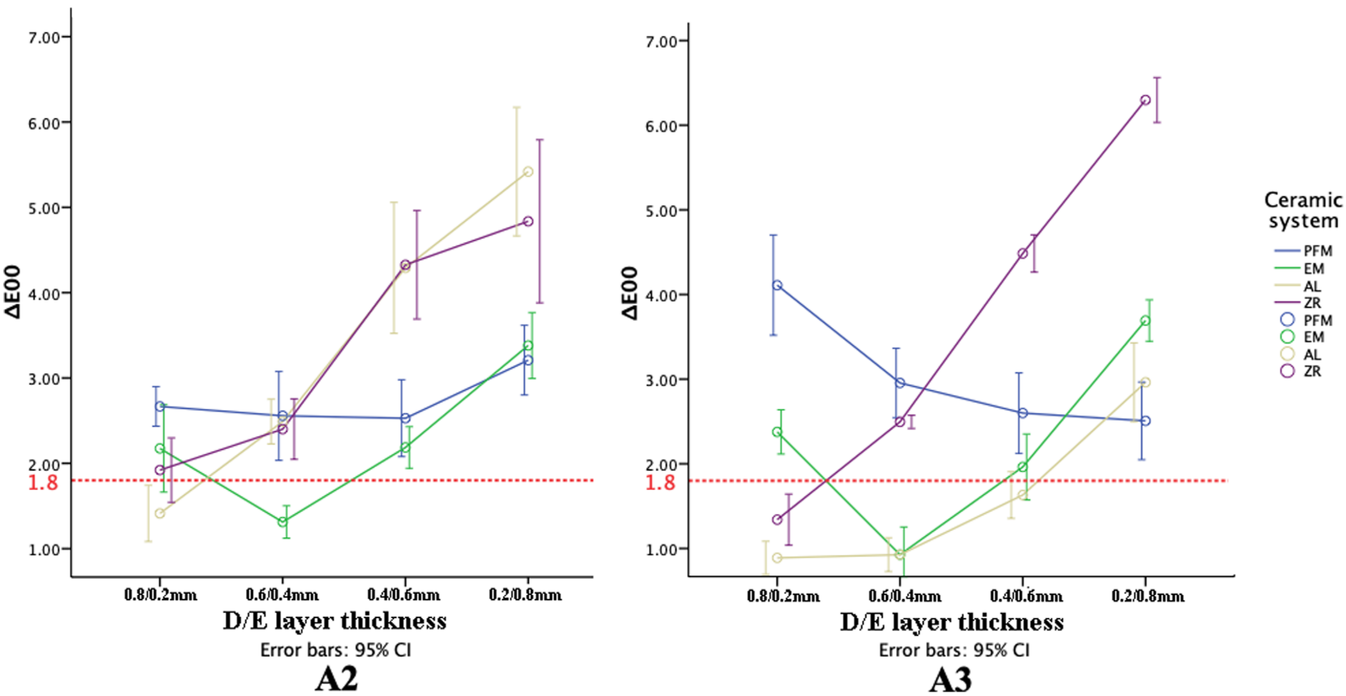

FIGURE 3 The line graphs of dentin/enamel porcelain (D/E) layer thickness on the color differences (ΔE_{00}) between various ceramic systems and corresponding color shade tabs. The color difference threshold of 1.8 was considered a clinically unacceptable color difference. The vertical bars at each data point represented the 95% confidence intervals

the EM had the minimum ΔE_{00} when the D/E layer thicknesses of 0.6/0.4 mm ($p < 0.05$), and the AL and ZR had higher ΔE_{00} than PFM and EM when the D/E layer thicknesses of 0.4/0.6 mm and 0.2/0.8 mm ($p < 0.001$). On shade A3, the maximum ΔE_{00} acquired was PFM when the D/E layer thicknesses of 0.8/0.2 mm ($p < 0.001$), and ZR when the D/E layer thicknesses of 0.4/0.6 mm and 0.2/0.8 mm ($p < 0.001$). It indicated that the ΔE_{00} values of shade A2 AL and ZR and shade A3 ZR more than corresponding shade PFM and EM when enamel porcelain was thicker than dentin porcelain.

Figure 3 shows the color differences (ΔE_{00}) values between the different D/E layer thickness from the ceramic systems and the corresponding color shade tabs. These values were analyzing using the acceptability threshold (1.8 ΔE_{00} units). The ceramic groups AL (0.8/0.2 mm for shade A2 and 0.8/0.2 mm, 0.6/0.4 mm, and 0.4/0.6 mm for shade A3), EM (0.6/0.4 mm for shades A2 and A3), and ZR (0.8/0.2 mm for shade A3) showed ΔE_{00} values below the acceptability threshold.

4 | DISCUSSION

The Commission International de l'E ´clairage (CIE) defined the color space (L*a*b*) and color-difference formula CIELAB in 1976 to describe and quantify color. [30] To improve the accuracy of visual color assessment in industrial applications, the CIE has recently proposed a CIELAB-based color difference formula (CIEDE2000).[31] The CIEDE2000 performs a specific correction on the nonuniformity of the CIELAB space (weighting functions S_L, S_C, and S_H), and considers the parameters of the effects of illumination and observation conditions in the color difference evaluation (parameter factors K_L, K_C, and K_H). The interactive term (R_T) between chroma and hue differences is introduced in the CIEDE2000 to improve the performance of the blue, as well as the scaling factor for the CIELAB a * scale used to improve the gray performance.[26] The formula is officially called the latest color difference equation, and based on small color differences, is considered more accurate in experimental data than the CIELAB formula.[31–33]

To measure the color of translucent samples, the spectroradiometer and the optical fiber optic cable were located at approximately 45° from the vertical plane to provide an optical arrangement of 0° observation and 45° illumination for the objects in this study.[24] In addition, the spectroradiometer provided a larger area of illumination and a relatively small viewing area to avoid "edge loss". Meanwhile, the custom jigs with a pointer were used to provide repeatable and suitable color measurements for samples.

The null hypothesis was accepted because the results of three-way repeated-measures ANOVA showed that the shade, the ceramic system and the D/E layer thickness have significant influences on color differences (ΔE_{00}), and significant interactions between the three factors ($p < 0.001$). For PFM, the D/E layer thickness of 0.8/0.2 mm had the maximum ΔE_{00} on shade A3 ($p < 0.001$, Table 3), and all ΔE_{00} values went beyond the threshold of 1.8 (clinically unacceptable color difference) (Figure 3).[18] This result indicates that the color matching of metal-ceramic restorations and the corresponding shade tabs is not satisfactory, and increasing enamel porcelain thickness can acquire more color-matched PFM on shade A3 for clinical application. This result agreed with a previous study, which found that changes in the enamel porcelain thickness of high chromatic shades had a greater impact than changes in the low chroma and three-dimensional color (brightness, hue, and chroma) with reduced enamel porcelain thickness.[34]

Ceramics with high crystalline content results in higher flexural strength, but also decreases translucency, which can directly influence the optical properties of ceramic material.[35,36] Hot pressure casting ceramic restorations, such as IPS e.max® is a lithium disilicate-based glass-ceramic ($Li_2Si_2O_5$) with a flexural strength of 262 ± 88 MPa.11 Glass-infiltrated alumina ceramic restorations, such as VITA VM7® is a two-phase glassy feldspathic ceramic(Si 19.6%; Al 4.9%; K 4.0%; Na 2.4%; Ca 0.7%; C 25.7%; and O 42.2%)with a flexural strength of 63.5 ± 9.9 MPa.[37,38] Nobel Rondo ® is a ceramic with Yttrium-stabilized tetragonal zirconia (Y-TZP) substructures with a flexural strength of 78 ± 12 MPa.39 The minimum ΔE_{00} values acquired were the D/E layer thicknesses of 0.6/0.4 mm for EM ($p < 0.05$), and 0.8/0.2 mm for shade A2 AL ($p < 0.05$) and shade A3 ZR ($p < 0.001$) (Table 3), and ΔE_{00} values fell into the range of clinically acceptable color difference (Figure 3). This result indicates that the most color-matched porcelain layer thicknesses are 0.6 mm dentin porcelain and 0.4 mm enamel porcelain for hot pressure casting ceramic restorations, and 0.8 mm dentin porcelain and 0.2 mm enamel porcelain for shade A2 glass-infiltrated alumina ceramic restorations and shade A3 CAD-CAM zirconia ceramic restorations.

For shade A2 AL and ZR and shade A3 ZR, the D/E layer thicknesses of 0.8/0.2 and (or) 0.6/0.4 mm had lower ΔE_{00} than 0.4/0.6 and (or) 0.2/0.8 mm ($P < 0.001$, Table 3). It indicated that the ΔE_{00} values were decreased when dentin porcelain was thicker than enamel porcelain for shade A2 AL and ZR and shade A3 ZR. ΔE_{00} values fell into the range of clinically acceptable color difference when the D/E layer thicknesses of 0.8/0.2 mm for AL and shade A3 ZR (Figure 3). It is noted that compared with the metal-ceramic system, increasing the dentin porcelain thickness can acquire a more color-matched effect to the corresponding shade tabs for glass-infiltrated alumina ceramic restorations and CAD-CAM zirconia ceramic restorations. The possible explanation is that the apparent color of natural teeth is the result of the reflectance from the dentin modified by the absorption, scattering, and thickness of the enamel.[15] The higher transparent and better optical quality of all-ceramic material could enhance the effect of the dentin layer on the sophisticated blending of final color. This result agreed with a previous study, which suggested increased porcelain thickness (particularly increased dentin layer) and increased porcelain opacity resulted in decreased ΔE and better masking ability of the dental backgrounds.40

In this study, flattened specimens were used as the models for color evaluation to accurately control the thickness of ceramic layers, which were different from the curving specimens such as veneers and crowns. The color of prosthetic material is mainly determined by its inherent optical properties, however, external factors such as surface curvature and texture may also influence the final color. The spectroradiometer could measure a circular area with 1.5 mm in diameter, which is small enough to avoid the color of natural teeth or restorative materials as determined by surface curvature or texture. The Vitapan Classical shade tabs were used to represent the color of natural teeth because they are the most popular and classical shade guide system in commercial dentistry.[13] The thickness of the middle third of these shade tabs was different from that of the ceramic samples bonded on the composite background samples used in this study. However, shade tabs were the most commonly used reference for shade matching in dental clinical practice. Moreover, the thickness of both had reached the requirements of infinite optical thickness.[41,42]

The limitations of this study included that only shade A2 and shade A3 specimens, which represented the normal color rather than discolored tooth substrate and restorations, were investigated in the study. The translucent shade adhesive agent was applied into the interspace between ceramic specimen and composite specimen to avoid the influence of adhesive agent color on the final color in this study. The application of different color luting composites seems to be a promising approach for adjusting the resultant color. Therefore, further investigation into the effect of various shades of ceramic systems and adhesive systems will be conducted in our next study, and it is hoped that the study will add to the overall clinical picture.

5 | CONCLUSIONS

Within the limitations of this study, the following conclusions can be drawn:

(1) The dentin/enamel porcelain layer thickness that was most color-matched to the shade tab was 0.6/0.4 mm for EM, and 0.8/0.2 mm for shade A2 AL and shade A3 ZR.

(2) When dentin porcelain was thicker than enamel porcelain，the color of shade A2 AL and ZR and shade A3 ZR was closer to the shade tab.

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DATA AVAILABILITY STATEMENT

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

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