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Original Article

Spectrophotometric evaluation of color errors generated in the visual color duplication procedure for current ceramic veneers

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Abstract *Background/purpose:* Color errors associated with the visual color duplication approach for ceramic laminate veneers are still challenging in esthetic dentistry. The aim of this study is to evaluate color errors generated during traditional visual shade matching approach.
Materials and methods: Eighteen stooth-shaped veneer discs (shade A2 and 0.7 mm in thickness) were fabricated using six veneer materials. The veneer specimens placed on five extracted teeth with nominal shade A2 formed veneer-tooth combinations. Color coordinates of the A2 shade tab, the extracted teeth, and the veneer-tooth combinations were measured using a spectrophotometer. Then, the veneers were reduced to 0.5 mm, and 0.3 mm in thickness consecutively. Color measurements were performed repeatedly. Color differences of the extracted teeth to veneer-tooth combinations (ΔEt-v), veneer-tooth combinations to shade tab (ΔEv-s), and translucency parameter (TP) values were calculated and analyzed using Two-way ANOVA.
Results: ΔEt-v ranged from 2.0937 to 5.0603 (mean of 3.1833±1.5485). Mean of ΔEv-s was 4.0103±1.8508. ΔEt-v and ΔEv-s values were significantly influenced by veneer material and thickness ($P<0.05$). TP values decreased gradually with the lessening of veneers thickness.
Conclusion: Acceptable color duplication of ceramic veneers cannot be achieved by routine visual shade replica protocols, when the thickness of veneers is less than 0.7 mm. Specified color matching standards for the ceramic veneers are needed.

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Introduction

The use of ceramic laminate veneers as an alternative to full-coverage crowns is clinically prevalent because of its minimal invasion and aesthetic superiority.[1] As a more conservative restoration modality, ceramic laminate veneer offers further advantages in terms of remarkable biocompatibility with surrounding tissues, natural light transmission, color stability and suitable thermal expansion coefficient.[1,2] For ceramic veneer restorations, durable bonding and ideal color matching are of crucial importance to achieve clinical success.[3,4] The concept of non-preparation or minimal-preparation of tooth tissue[5] using ceramic veneers with thicknesses around 0.3 mm—0.7 mm, followed the evolution of appropriate enamel bonding which has been verified as a reliable bonding.[6–8] A number of clinical studies have found that laminate veneers bonded upon enamel substrates delivered positive clinical outcomes over a period of 10 years or more.[9,10] The majority failure of ceramic veneer restorations was observed in the form of unsatisfied color matching.[11] To create a natural-looking, practically indistinguishable veneer, blending harmoniously with the surrounding tissues, has been probably the biggest stumbling block in the application of ceramic veneers.[12,13]

Routine color duplication contains two steps in sequence: shade selection using shade guides, then color reproduction using matched porcelain powder materials.[14] It is called visual color matching method and remains the dominating color replica approach in clinical practice. No upgraded color selection schemes, or color replica protocols have been established in dentistry for all-ceramic materials to date. More and more studies have proved that the visual color reproduction procedure is unreliable and unpredictable for usage of all ceramic materials.[15] Moreover, the color of underlying tooth tissue makes the color replica of ceramic laminate veneers even more complicated.[16] Color duplication has been considered as one of the weakest links in aesthetic dentistry.[17,18]

Manufacturers have been striving to improve the optical properties of all-ceramic materials for better aesthetic outcomes.[19] Several all-ceramic veneer products are still emerging recently.[19] The compositions of these products are of various crystalline contents, such as lithium disilicate, fluorapatite or leucite, and different sizes of the crystal particles.[20] It has been declared that various chemical components of these novel products could provide more choices for optical properties, such as opalescence and translucency.[21] However, few literatures have been available for investigating the clinical performance of these products. Moreover, previous studies usually used composite resins as the backgrounds. Color replica ability of these products has not been fully demonstrated in clinical situation. Furthermore, ultra-thin ceramic veneer has been highly favored as the mainstream of aesthetic restoration for anterior teeth, but related optical properties research is still insufficient.

The aim of this study was to evaluate the shade matching ability of these newly-developed ceramic veneer materials with various thicknesses using traditional visual shade matching approach. And extracted teeth were used as the abutment teeth to simulate the clinical color replica process more practically. The null hypotheses were as follows: (1) under the current color duplication protocols, all-ceramic veneers could achieve ideal color matching to the corresponding teeth, and (2) color errors would not be affected by the ceramic material and veneer thickness.

Materials and methods

The study protocol was reviewed and approved by the Ethics Committee of the School and Hospital of Stomatology, Wuhan University. Patients (ranging in age from 14 to 21 years), who donated their teeth for orthodontic reasons, were asked to read and sign a consent form prior to teeth extraction.

Visual color determination of the extracted teeth

Fifteen freshly extracted non-carious premolars, free from enamel defect, bleaching treatment, and restorative replacement, were collected for this study. All the teeth were scaled and polished with rubber cups, and stored in 0.01% sodium azide (Sigma, St. Louis, MO, USA) solution in a humid environment at 37 °C for less than 3 weeks. Three prosthodontists, with a negative history of visual color deficiency, performed the visual color assessment of the extracted teeth using Vita Lumin Vacuum shade guide (VITA Zahnfabrik, Bad Säckingen, Germany). The observers selected the best match shade tab to the middle third region of the extracted teeth, and recorded the results independently. Then the results were assessed, and five teeth, determined as A2 by all three of the prosthodontists, were involved in the study. The buccal enamel surface of the selected teeth was flattened using water-cooled silicon carbide paper and polished using 0.5 mm aluminum oxide slurry to obtain a standardized enamel surface (around 2.0 mm in diameter). The teeth were embedded into a 16 mm × 16 mm × 16 mm cube mold using epoxy resin (XIONGYING Testing Equipment Ningbo, Zhejiang, China). After the epoxy resin cubes completely cured, silicon carbide paper was used to grind off the residual epoxy resin and unveil the flatten surface (Fig. 1).

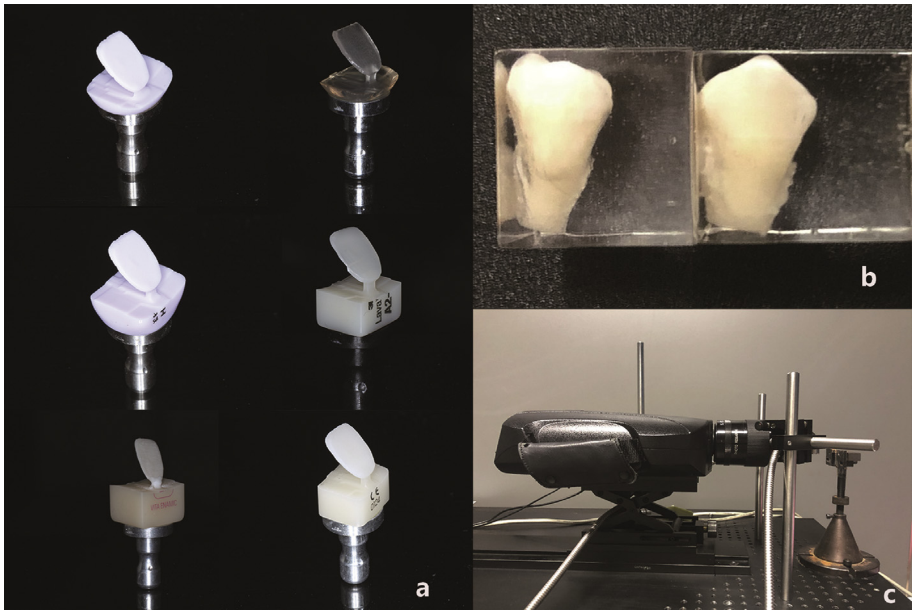

Figure 1 Veneer specimens, extracted teeth and PR655. (a) Veneer specimens; (b) extracted teeth; (c) PR-655 Spectra Scan.

Fabrication of ceramic veneer specimens

A CAD-CAM system (Roland DWX-50CAD/CAM, Tokyo, Japan) was employed to fabricate the veneers. A total of 18 ceramic veneers, with nominal shade A2, were fabricated using six commercial veneer materials (Vita Mark II; Vita Sprinity; Vita Enamic; 3M Ultimate; IPS e.max HT; IPS e.max LT) according to the recommended fabrication protocols (Table 1). For the uniformity and accuracy of fabrication procedures, the veneers were simplified as flat disks with tooth-shape, fabricated by a custom designed CAD program (Fig. 1) The thickness of each veneer was achieved by using silicon carbide paper and controlled with a digital micrometer (WDGAGE, Zhejiang, China) to 0.7 ± 0.05 mm. Finally, a self-glazing process was performed at the temperatures recommended by manufacturers. No internal or external staining was used in the fabrication procedure.

Spectrophotometric assessments of veneer specimens

The veneers were placed on the flat surface of the extracted teeth to form veneer—tooth combinations. For the convenience of separation, no luting agents were applied between the veneers and teeth, replaced by a refractive liquid ($n = 1.50$, Suzhou Chemical Inc., Suzhou, China) to fulfill an optical connection.[22]

A spectrophotometer (PR-655 Spectra Scan, equipped with MS-75 and SL-0.5X lens; Photo Research, Chatsworth, GA, USA) was used for the color measurements. Standardized illumination source D65, and two fiber optic cables (Model OL 53, Optronic Laboratories, Orlando, FL, USA) were used to provide an optical configuration of 0° observation and 45° illumination, recommended by Bolt et al.[23] for measuring the color of translucent materials (Fig. 1). The distance between the measured objects and the spectrophotometer was standardized to 91.4 mm, and the measurement aperture size was 1.5 mm in diameter. 2° observer angle configuration and 380—780 nm measurement wavelengths with a 2 nm interval were applied. The reflected spectrum statistics were converted and recorded in accordance with the CIE $L^*a^*b^*$ system established by the Commission Internationale de l'Eclairage (CIE).[24] Prior to each series of color measurements, an internal instrument calibration was performed with a standardized calibration tile ($L^* = 99.9300$, $a^* = -0.0100$, $b^* = 0.0500$).

The color coordinates of an A2 shade tab (mid 1/3 region), the involved teeth, and the veneer—tooth combinations were registered from 3 measurements. The means of color coordinates were recorded as $L_{s/t/v}^*$, $a_{s/t/v}^*$, and $b_{s/t/v}^*$, where the subscript letters "s", "t" and "v" refer to color coordinates of the A2 shade tab, the involved teeth, and the veneer—tooth combinations, respectively. Color difference (ΔE) was determined by the following formula: $\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$. $\Delta E_{t\text{-}v}$, $\Delta E_{t\text{-}s}$, and $\Delta E_{v\text{-}s}$ were registered as the color differences of the tooth to the veneer, the tooth to the shade tab, and the veneer to the shade tab. Furthermore, color parameters of each veneer based on a white (CIE $L^* = 99.99$, $a^* = 0.16$, and $b^* = -0.03$) and a black (CIE $L^* = 2.24$, $a^* = 0.47$, and $b^* = 0.53$) backing were measured and applied to determine the translucency parameter (TP). Correspondingly, the TP values of the veneers were defined as: $TP = [(L_B^* - L_W^*)^2 + (a_B^* - a_W^*)^2 + (b_B^* - b_W^*)^2]^{1/2}$,[24] where the subscript letters "B" and "W" refer to color coordinates recorded against the black and the white backing separately. After the first session of measurements, the ceramic veneers and the teeth were separated. The thickness of the veneers was reduced to 0.5 ± 0.05 mm, and then 0.3 ± 0.05 mm using silicon carbide paper. Subsequently, the above-mentioned measurements were performed repeatedly.

Table 1 The main components and sources of 6 kinds of veneer materials.

Code[a]	Material	Material type	Main components	Manufacturer
VM	Vita Mark II	Machinable feldspar-based ceramics	60%–64% SiO_2, 20%–23%, Na_2O; The average crystal particle size is 2–6 μm	VITA Zahnfabrik, Bad Sackingen, Germany
VS	Vita Suprinity	Zirconia-reinforced lithium silicate-based cutting ceramics	8%–12% ZrO_2, 55%–64% SiO_2; The average crystal particle size is 0.5 μm	VITA Zahnfabrik, Bad Sackingen, Germany
VE	Vita Enamic	Compound material	86% ceramic network structure (SiO_2, Na_2O, K_2O, etc.); polymer resin polymer network structure	VITA Zahnfabrik, Bad Sackingen, Germany
MU	3M Ultimate	Compound material	80% prepolymerized nano ceramic particles, prepolymerized silica (20 nm), ZrO_2 (4–11 nm); resin polymer matrix	3M ESPE, St. Paul, MN, USA
EMHT	IPS e.max HT	Lithium disilicate based cutting ceramics	60%–70% 0.2–2.0 μm (SiO_2、LiO_2)、K_2O	Ivoclar Vivadent, Schaan, Liechtenstein
EMLT	IPS e.max LT	Lithium disilicate based cutting ceramics	60%–70% 0.2–2.0 μm (SiO_2、LiO_2)、K_2O	Ivoclar Vivadent, Schaan, Liechtenstein

[a] VM: Vita Mark II; VS: Vita Sprinity; VE: Vita Enamic; MU: 3M Ultimate; EMHT: IPS e.max HT; EMLT: IPS e.max LT.

Analysis of the statistics

Two-way analysis of variance (ANOVA) was used to analyze the effects of the two main factors (ceramic material, veneer thickness) to the $\Delta E_{t\text{-}v}$ and TP values. Afterwards, Tukey multiple comparison tests were performed to evaluate the difference among ceramic materials. Linear regression analysis was applied to evaluate the possible relationships between $\Delta E_{t\text{-}s}$ and $\Delta E_{t\text{-}v}$ values. SPSS statistical software (SPSS 25.0 for Windows, SPSS, Chicago, IL, USA) was used for statistics analysis. The significance test level was preset as $\alpha = 0.05$.

Results

Color differences between extracted teeth and veneers ($\Delta E_{t\text{-}v}$)

Color differences of tooth to veneer ($\Delta E_{t\text{-}v}$) were displayed in Table 2. Half of the $\Delta E_{t\text{-}v}$ values (9/18) were less than 3.0 with the mean of 3.1833 ± 1.5485. The highest values were observed in group VE (0.7 mm: 3.8255; 0.5 mm: 3.6050; 0.3 mm: 5.0603) and the lowest values were found in group VS (0.7 mm: 2.6407; 0.5 mm: 2.0937; 0.3 mm: 2.1117).

Two-way ANOVA analysis demonstrated that $\Delta E_{t\text{-}v}$ values were significantly influenced by ceramic material and veneer thickness ($P < 0.05$, Table 3) and no interaction effect was identified from the combination ($P = 0.071$, Table 3). Tukey post hoc test revealed that there were no significant differences among six ceramic systems at the thickness of 0.7 mm. But at the thickness of 0.5 mm and 0.3 mm, differences were detected among ceramic materials. At the thickness of 0.3 mm, $\Delta E_{t\text{-}v}$ values of EMHT and VE reached 4.2798 and 5.0603, respectively, which were significantly higher than those in other groups ($P < 0.05$, Table 2).

Color differences between extracted teeth and A2 shade tab ($\Delta E_{t\text{-}s}$)

Color differences of the tooth to shade tab ($\Delta E_{t\text{-}s}$) were listed in Table 4. The mean of $\Delta E_{t\text{-}s}$ values was 5.0103 ± 1.3521 (ranged from 3.0130 to 7.1811). The results of linear regression analysis were exhibited in Fig. 2a–f. No significant association between $\Delta E_{t\text{-}s}$ and $\Delta E_{t\text{-}v}$ was found in all groups ($R^2 = 0.006$, 0.051, 0.242, 0.446, 0.367, and 0.063 for group EMLT, EMHT, VE, VM, MU, and VS, respectively.)

Color differences between veneers and A2 shade tab ($\Delta E_{v\text{-}s}$)

Color differences of veneer to shade tab were displayed in Fig. 3. All of the $\Delta E_{v\text{-}s}$ values were greater than 4.0 with the mean of 4.0103 ± 1.8508, except for that of group EMLT, at thickness of 0.7 mm ($\Delta E_{v\text{-}s} = 2.3658$). The highest value of $\Delta E_{v\text{-}s}$ was 5.7461 in group EMHT, at thickness of 0.5 mm.

Translucency parameter (TP)

Translucency parameter (TP) values of different ceramic veneer systems were illustrated in Fig. 4. The TP values decreased gradually with the lessening of thickness. The lowest TP values were presented in group VS at all of the three thicknesses. TP values of group EMHT and MU were relatively higher than that of other groups at three thicknesses.

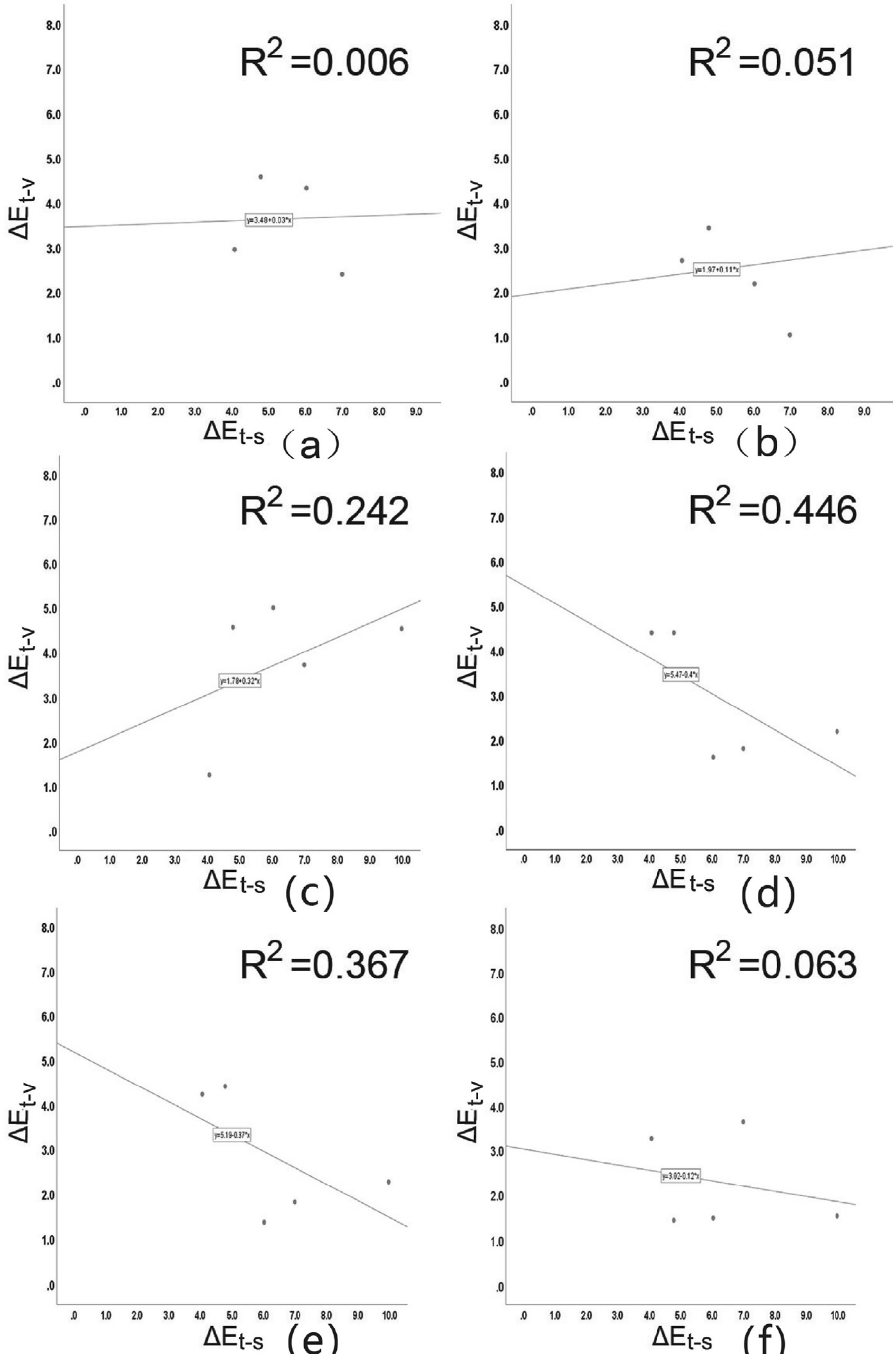

Figure 2 Linear regression analysis of relationship between values of $\Delta E_{t\text{-}s}$* and $\Delta E_{t\text{-}v}$*. $\Delta E_{t\text{-}s}$: color difference between the tooth and the shade tabs. $\Delta E_{t\text{-}v}$: color difference between the tooth and the veneers. (a),(b),(c),(d),(e),(f): Relationship between values of $\Delta E_{t\text{-}s}$ and $\Delta E_{t\text{-}v}$ for IPS e.max LT, IPS e.max HT, Vita Enamic, Vita Mark II, 3M Ultimate, and Vita Sprinity group, respectively.

Discussion

The esthetic and restorative dentistry has long been hampered by the shade matching problem of all ceramic materials.[11] Inadequate technologies to aid the dentist and technician in the appropriate color replica procedure has rendered this part of dentistry more art than science.[25]

The purpose of the present study was to evaluate the color errors generated in the routine color replica protocols using the newly-developed veneer products. Therefore, the traditional visual color replica procedures were still adopted.

To obtain a durable bonding strength for ceramic veneers, tooth reduction should remain within the enamel layer, which was described as 0.7—0.8 mm in thickness.[26] Therefore, the buccal region of the extracted teeth was prepared to get a flat surface around 2.0 mm in diameter, which could ensure the tooth

Table 2 $\Delta E_{t\text{-}v}$* value and the results of Tukey post hoc analysis.

Thickness (mm)	Code*	$\Delta E_{t\text{-}v}$*	Intervals of Tukey		
0.7	VS	2.6407 ± 1.0000	a		
	VE	3.8255 ± 1.4136	a		
	VM	2.8930 ± 1.3316	a		
	MU	2.8342 ± 1.3532	a		
	EMLT	3.3147 ± 0.9277	a		
	EMHT	2.6646 ± 1.0569	a		
0.5	VS	2.0937 ± 0.8380	a		
	VE	3.6050 ± 1.9481		b	
	VM	3.3296 ± 0.6888	a		
	MU	2.7996 ± 1.1764	a		
	EMLT	3.5241 ± 1.4410		b	
	EMHT	2.6955 ± 1.5455	a		
0.3	VS	2.1117 ± 1.1240	a		
	VE	5.0603 ± 1.4826			c
	VM	3.1970 ± 1.5716		b	
	MU	3.1450 ± 1.4937	a		
	EMLT	3.2853 ± 1.7953		b	
	EMHT	4.2798 ± 2.4143			c

*$\Delta E_{t\text{-}v}$: color differences between the tooth and the veneer.
VS: Vita Sprinity; VE: Vita Enamic; VM: Vita Mark II; MU: 3M Ultimate; EMHT: IPS e.max HT; EMLT: IPS e.max LT.

reduction less than 0.5 mm and increase the accuracy of the color measurements.

Human eye is very efficient in detecting even tiny differences in the color between two objects,[11,17,22] whereas, determining tooth color by visual is considered highly subjective. Despite considerable effort, the identification of a ΔE value for the "clinically acceptable differences" is a very difficult task and the establishment of a widely accepted limit remains controversial.[27] In the present study, the threshold of $\Delta E = 2.72$ has been considered as a clinically acceptable color difference.[28] And $\Delta E = 3.7$ has been regarded as a clinically unacceptable color difference.[21,29,30]

It was obvious that 3/18 $\Delta E_{t\text{-}v}$ values fell into the range of clinically unacceptable color difference ($\Delta E = 3.7$). Meanwhile, favorable color replica was still occasionally achieved, for 5/18 $\Delta E_{t\text{-}v}$ values were less than 2.72. Based on these criteria, the first null hypothesis that all ceramic veneers could achieve ideal color matching to the corresponding teeth was partially rejected.

According to the results of Two-way ANOVA analysis, $\Delta E_{t\text{-}v}$ values were significantly influenced by the ceramic material and veneer thickness. No interaction effects between two factors were found. At the thickness of 0.7 mm, no significant differences among six veneer systems were observed. But with the decreasing of veneer thickness, the influences of ceramic material to $\Delta E_{t\text{-}v}$ values were detected. Similar results were also noted in a previous study.[31] With respect to the effects of veneer thickness, Tukey post hoc analysis revealed that the $\Delta E_{t\text{-}v}$ values were higher in thickness of 0.3 mm, whereas, there were no obvious differences between thickness of 0.7 mm and 0.5 mm. All these conclusions rejected the second null hypothesis that color errors would not be affected by the ceramic material and veneer thickness.

The values of $\Delta E_{t\text{-}s}$ and $\Delta E_{v\text{-}s}$ were used to represent the errors generated in the step of color selection and specimen fabrication, respectively. The mean of $\Delta E_{t\text{-}s}$ values was 5.0103 ± 1.3521, which fell into unacceptable color difference range. It indicated that the visual color selection using shade guide was unreliable, which was consistent with several previous studies.[32,33] Most of the $\Delta E_{v\text{-}s}$ values

Table 3 Two-way ANOVA analysis of $\Delta E_{t\text{-}v}$[a].

Source	df	Sum of Squares	Mean Squares	F	*P*
Ceramic system (C)	5	84.544	16.909	8.349	0.000
Thickness (T)	2	14.712	7.356	3.632	0.028
C × T	10	35.340	3.534	1.745	0.071
Error	252	510.389	2.025		
Total	270	3381.009			

[a] $\Delta E_{t\text{-}v}$: color differences between the tooth and the veneer.

Table 4 Color coordinates of the selected teeth and color differences of tooth to shade tab ($\Delta E_{t\text{-}s}$*).

	Tooth			A2 Shade Tab			$\Delta E_{t\text{-}s}$*
Code	L*	a*	b*	L*	a*	b*	
1	70.6734	3.7371	16.1516	74.8736	4.5047	17.5685	4.4987
2	72.9190	2.6029	10.9254				7.1811
3	71.2422	3.0906	14.4812				4.9717
4	71.8220	2.7505	13.4904				5.3871
5	73.5807	3.9029	20.2226				3.0130

*$\Delta E_{t\text{-}s}$: color differences between the tooth and shade tab.

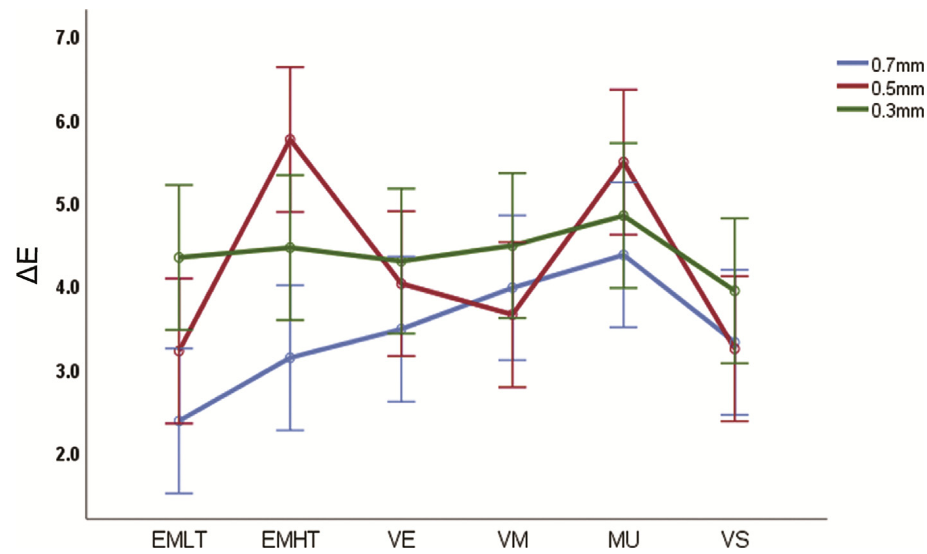

Figure 3 Color difference of veneer to shade tab ($\Delta E_{v\text{-}s}$*). EMHT: IPS e.max HT; EMLT: IPS e.max LT; VE: Vita Enamic; VM: Vita Mark II; MU: 3M Ultimate; VS: Vita Sprinity. $\Delta E/\Delta E_{v\text{-}s}$: Color difference between veneer and shade tab. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

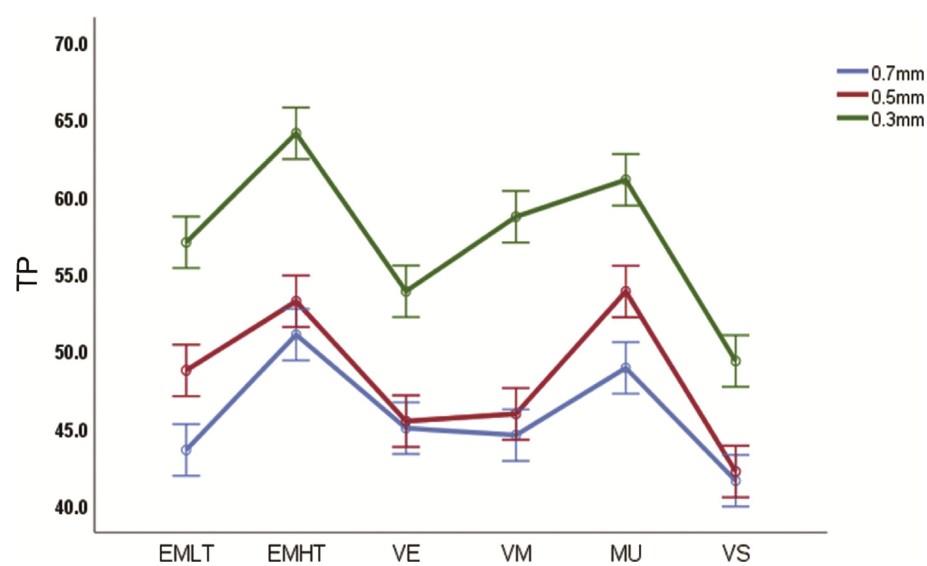

Figure 4 Translucency parameter (TP) of different ceramic materials and thicknesses. EMLT: IPS e.max LT; EMHT: IPS e.max HT; VE: Vita Enamic; VM: Vita Mark II; MU: 3M Ultimate; VS: Vita Sprinity. TP: Translucency parameter.

were higher than 3.7 with the mean of 4.0103. It suggested that the traditional color reproduction protocol was not suitable for all ceramic veneers which have been proven by several previous studies.[15,33,34] Although the same nominal A2 was selected, the color differences of A2 shade tab and A2 shade veneers, fabricated from A2 ingots, were higher than clinically acceptable color difference. Regression analysis was performed to assess the possible relationship between $\Delta E_{t\text{-}s}$ and $\Delta E_{t\text{-}v}$ values but weak to no correlations were found. It revealed that there was no remarkable relevance between color errors generated in two steps of color replica.

Translucency is identified as the most primary factor in controlling aesthetics and a critical consideration in the selection of materials for veneers.[24,35–37] In order to obtain a natural-looking esthetic restoration, the TP values of veneer materials should be close to that of natural enamel.[38] At the thickness of 0.7 mm, TP values of the veneer materials ranged from 41.6259 to 51.0927, with a mean of 45.8135 ± 3.4155, which was similar to the TP value of enamel in a prior study.[39] However, while the thickness of veneers decreased, TP values were significantly enhanced, which might remarkably affect the optical properties of esthetic restoration.

The limitations of this study included the fabrication of the flattened specimens rather than tooth-shaped veneers might decrease the relevance to the actual clinical situation. Additionally, only one dentin shade background was evaluated. Further study of discolored teeth substrate is necessary.

Within the limitations of this in-vitro study, the following conclusions can be drawn: a. Some of the veneer materials could achieve a clinical acceptable color matching with the thickness of 0.7 mm and 0.5 mm under current circumstances. And no significant difference was found among the six veneer products when the thickness was 0.7 mm. b. Routine visual shade replica protocol used presently is not suitable for ceramic veneer restorations. A specified color matching standard should be established for the ceramic laminate veneers.

Declaration of Competing Interest

The authors have no conflicts of interest relevant to this article.

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