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RESEARCH AND EDUCATION

Quantitative analysis of color accuracy and bias in 4 dental CAD-CAM monolithic restorative materials with different thicknesses: An in vitro study

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ABSTRACT

Statement of problem. Computer-aided design and computer-aided manufacturing (CAD-CAM) monolithic restorative materials have become a popular option because of advantages such as convenience and efficiency. However, studies that quantitatively analyzed their color accuracy and bias are lacking.

Purpose. The purpose of this in vitro study was to evaluate the color accuracy and bias of 4 CAD-CAM monolithic restorative materials with different thicknesses by using the CIELab color space.

Material and methods. Four types of dental CAD-CAM monolithic restorative materials in shade A2, lithium disilicate glass-ceramic (IPS e.max CAD), infiltrated ceramic (VITA Enamic), resin-nano ceramic (LAVA Ultimate), and polymethyl methacrylate (Telio CAD), were prepared as 12×12-mm specimens of 10 different thicknesses (from 0.5 to 5.0 mm) (N=200, n=5). After polishing with SiC P1500-grit, CIELab color coordinate parameters of the specimens were measured with a spectrophotometer (VITA Easyshade V). The color accuracy and bias were described by ΔE_{00}, ΔL^*, Δa^*, and Δb^* in the CIELab color space, and the data were analyzed by using a 2-way ANOVA, post hoc Tukey-Kramer test, and the *t* test (α=.05).

Results. The ΔE_{00}, ΔL^*, Δa^*, and Δb^* were significantly influenced by material type and thickness ($P<.001$). Specimens at a thickness of 0.5 mm represented the maximum ΔE_{00}. The minimum ΔE_{00} was observed at a thickness of 2.0 mm for LAVA Ultimate, 1.5 mm for VITA Enamic and Telio CAD, and 4.0 mm for IPS e.max CAD. The ΔE_{00} of all specimens significantly exceeded the 50:50% acceptability threshold (1.8 unit) ($P<.001$). LU exhibited higher ΔE_{00}, Δa^*, and Δb^* than the other 3 materials in all thickness expect for 0.5 mm. For color bias, the ΔE_{00} was more influenced by Δb^* and ΔL^* than Δa^*.

Conclusions. The color accuracy and bias were significantly affected by material type and thickness. The color inaccuracy of the tested materials was statistically significant and clinically perceptible. Improved clinical outcomes may be expected from the 1.5-mm- to 2.0-mm-thick restorations. (J Prosthet Dent 2022;128:92.e1-e7)

Dental monolithic restorative materials with good mechanical properties, biocompatibility, and esthetics are gaining popularity.[1,2] Indirect restorations made with monolithic materials by computer-aided design and computer-aided manufacturing (CAD-CAM) are cost-effective and time-saving, with the restoration being provided in a single visit.[3,4]

The optical properties of CAD-CAM monolithic restorative materials play an important role in their success.[5,6] Color accuracy, a primary property contributing to the esthetic outcomes, is 1 of the main factors making the restorations appear natural and similar to the adjacent teeth.[5,7,8] However, replicating tooth color is difficult and still presents a challenge.[9] The color and shade inconsistency of CAD-CAM monolithic materials has been reported,[3,8,10-12] and the color of different materials with the same specified shade may vary by different product type and brand.[10,13] This color

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Clinical Implications

Type and thickness affected the color accuracy of dental CAD-CAM monolithic restorative materials. These factors should be considered to achieve optimal esthetics.

or shade inconsistency and variations among the materials could lead to inaccurate restoration color.[8,10-13] The Commission Internationale de l'Eclairage (CIE) CIELab color space and spectrophotometers have been commonly used to evaluate color differences in a straightforward, feasible, and valid manner.[14-16] Visual thresholds have been widely used as quality control tools and guides for color difference in the evaluation and selection of dental materials and the analysis of clinical and in vitro research findings.[17] The final color of restorations fabricated from some CAD-CAM monolithic materials could be significantly different from the designated shade tabs, a difference which may exceed the color perceptibility threshold and lead to a poor esthetic outcome.[8,10,18] This color inaccuracy limits the use of CAD-CAM monolithic materials, especially in the esthetic zone.

Although the key factors that influence the color of different dental CAD-CAM monolithic materials have been investigated,[6,11,18-23] only a few studies have provided data for material selection and clinical application.[11,20,24,25] However, quantitative studies on the color inaccuracy or bias of CAD-CAM monolithic materials, as well as related factors, are lacking. The purpose of this study was to quantitatively evaluate the color inaccuracy and bias of 4 commonly used dental CAD-CAM monolithic restorative materials in the CIELab color space with a spectrophotometer. The null hypothesis was that no significant color inaccuracy would be apparent for the tested materials.

MATERIAL AND METHODS

The 4 types of dental CAD-CAM monolithic restorative materials tested in this study are shown in Table 1. A total of 200 square (12×12 mm) specimens in shade A2 were fabricated. For each material and thickness (0.5 to 5.0 mm, with a 0.5-mm increment), 5 specimens were prepared.[6] The CAD-CAM blocks were sliced by using a precision wire cutting machine (STX-2-2A; Shenyang Kejing Automation Equipment Co Ltd) operating at a low speed (0.2 mm/min) under constant water cooling. Specimens obtained from IPS e.max CAD blocks were sintered in a ceramic furnace (Programat EP 5000; Ivoclar AG) in accordance with the manufacturer's recommendations.[26]

Table 1. Details and codes of tested materials

Material	Brand	Code	Main Components*	Manufacturer
Lithium-disilicate ceramic	IPS e.max CAD	LS	8%-80% SiO_2, 11%-19% Li_2O, 0-13% K_2O, 0-8% ZrO_2, 0-5% Al_2O_3	Ivoclar AG
Dual-network ceramic	VITA Enamic	VE	86% ceramic (58%-63% SiO_2, 20%-23% Al_2O_3, 9%-11% Na_2O, 4%-6% K_2O, 0-1% ZrO_2), 14% polymer (UDMA, TEGDMA)	VITA Zahnfabrik
Resin nanoceramic	Lava Ultimate	LU	80% ceramic (69% SiO_2, 31% ZrO_2), 20% polymer (UDMA)	3M ESPE
Polymethyl methacrylate (PMMA)	Telio CAD	TE	99.5% PMMA polymer	Ivoclar AG

TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate. *As reported by manufacturers.

The specimens were surface ground and polished (M-Prep; Allied High Tech Products Inc). The same operator (W.Z.) polished all specimens on both sides with wet P1500-grit silicon carbide paper (Suisun Co Ltd). Specimen thicknesses were determined by using a digital micrometer with an accuracy of 0.02 mm (Mitutoyo IP65; Mitutoyo Corp).[6,24]

Before color measurements, all specimens were ultrasonically cleaned in distilled water for 10 minutes, cleaned with isopropanol to remove grease residue, and dried with compressed air.[19]

The CIELab coordinates (L*, a*, and b*, which represent lightness, the red-green axis, and the yellow-blue axis, respectively) of each specimen were obtained by using a dental spectrophotometer (VITA Easyshade V; VITA Zahnfabrik) in "tooth single" mode under D65 illumination. The spectrophotometer had integrated illumination with a built-in white LED light source (D65) with 2-degree standard observer and (45:0) optical geometry,[27] which could obtain CIE L*a*b* parameters in repeatability less than 0.1 units and represented a high level of interdevice and intradevice reliability.[28,29] Before each measurement, the spectrophotometer was calibrated according to the manufacturer's guidelines. The Ø5-mm probe was placed in the center of the specimen surface, and 3 measurements were made by the same operator (W.Z.). The mean values of the 3 measurements were calculated for each specimen.

To control factors that may affect the accuracy of dental shade guide tabs, the CIELab color coordinates of A2 in the VITA Classical shade system (L*=77.7, a*=–0.3, b*=17.5, C=17.5, and H=91.0) calibrated by VITA Easyshade V were used as the standard color reference in the present study.[10,30,31] The color difference (ΔE_{00}, ΔL^*, Δa^*, and Δb^*) was calculated as the difference between the color coordinates of the specimens and standard

Table 2. Summary of 2-way ANOVA results of ΔE_{00}, ΔL^*, Δa^*, and Δb^*

Measure	Source of Variation	Type III Sum of Squares	Df	Mean Square	F	*P*	Partial Eta Squared h_P^2
ΔE_{00}	Thickness	7008.88	9	778.764	667.278	<.001	.974
	Type	4839.75	3	1613.251	1382.30	<.001	.963
	Thickness×type	3989.99	27	147.777	126.62	<.001	.955
	Error	186.732	160	1.167	-	-	-
ΔL^*	Thickness	1916.32	9	212.924	889.11	<.001	.981
	Type	10.81	3	3.603	15.04	<.001	.227
	Thickness×type	219.07	27	8.114	33.88	<.001	.856
	Error	36.88	160	.239	-	-	-
Δa^*	Thickness	10.87	9	1.207	167.81	<.001	.907
	Type	160.65	3	53.549	7442.67	<.001	.993
	Thickness×type	35.50	27	1.315	182.74	<.001	.970
	Error	1.11	160	.007	-	-	-
Δb^*	Thickness	320.00	9	35.555	587.98	<.001	.972
	Type	1254.96	3	418.321	6917.74	<.001	.993
	Thickness×type	593.71	27	21.989	363.64	<.001	.985
	Error	9.31	160	.060	-	-	-

shade A2. ΔE_{00} was calculated from the CIEDE2000 color difference formula[32]:

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

where ΔL^*, ΔC^*, and ΔH^* refer to the difference in the lightness, chroma, and hue values. The parametric factors K_L, K_C, and K_H were set to 1, as previously described.[33] A CIEDE2000 50:50% perceptibility threshold of 0.8 units and acceptability threshold of 1.8 units provided by Paravina et al[34] were used.

Statistical analyses were performed with a software program (IBM SPSS Statistics, v25.0; IBM Corp) (α=.05). Results of the Shapiro-Wilk test and Levene test determined that the data were normally distributed and homogeneous (*P*>.05). The effects of material type, thickness, and their interaction on color accuracy (ΔE_{00}) and color bias (ΔL^*, Δa^*, and Δb^*) were analyzed by using a 2-way ANOVA (α=.05). Pairwise comparisons were performed by using the post hoc Tukey-Kramer test (α=.05). The color difference compared with the perceptibility and acceptability threshold was analyzed by using the *t* test.

RESULTS

Table 2 summarizes the 2-way ANOVA results on the effects of material type and thickness on ΔE_{00}, ΔL^*, Δa^*, and Δb^*. Figure 1 presents the mean and standard deviation of the tested parameters, as well as the pairwise comparisons results.

The results of 2-way ANOVA indicated that ΔE_{00}, ΔL^*, Δa^*, and Δb^* of the specimens were significantly influenced by material type, thickness, and their interaction (*P*<.001) (Table 2). The ΔE_{00} was more influenced by Δb^* (F=363.629; partial eta squared h_P^2=0.997; *P*<.001) and ΔL^* (F=321.447; partial eta squared h_P^2=0.980; *P*<.001) than by Δa^* (F=61.078; partial eta squared h_P^2=0.408; *P*<.001).

The maximum ΔE_{00}, ΔL^*, Δa^*, and Δb^* were found in the 0.5-mm specimens of all groups expect for $\Delta a^*$of VE and Δb^* of TE, which were found in the 5.0-mm specimens. The minimum ΔE_{00} was observed in the 2.0-mm specimens of LU (17.0), the 1.5-mm specimens of VE (5.5) and TE (5.0), and the 4.0-mm specimens of LS (7.0). The *t* test results revealed that the minimum ΔE_{00} of all groups was significantly higher than the color difference acceptability threshold of 1.8 unit (*P*<.001).

For the simple main effects of material type on ΔE_{00}, ΔL^*, Δa^*, and Δb^*, significant differences were found among the groups (*P*<.001). The pairwise comparisons among the groups in different thicknesses are shown in Figure 1. LU exhibited higher ΔE_{00}, Δa^*, and Δb^* than the other 3 materials in all thicknesses expect for 0.5 mm. For TE and VE, the ΔE_{00} decreased sharply from 0.5 mm to 1.0 mm but then had a steady increase from 1.0 mm to 5.0 mm. For LS and LU, the ΔE_{00} declined sharply from 0.5 mm to 1.5 mm, with a smaller decline from 1.5 mm to 5.0 mm. The ΔL^* (Fig. 1B) in different thicknesses showed a similar trend among the tested materials and followed that of ΔE_{00} (Fig. 1A), while the trends of Δa^* (Fig. 1C) and Δb^* (Fig. 1D) in different thicknesses were significantly different among the tested materials (*P*<.05).

DISCUSSION

Based on the results, the null hypothesis was rejected, as significant color inaccuracy was found in the tested materials. Unacceptable color inaccuracy in comparison with the designated shades for CAD-CAM monolithic restorative materials has been reported in previous

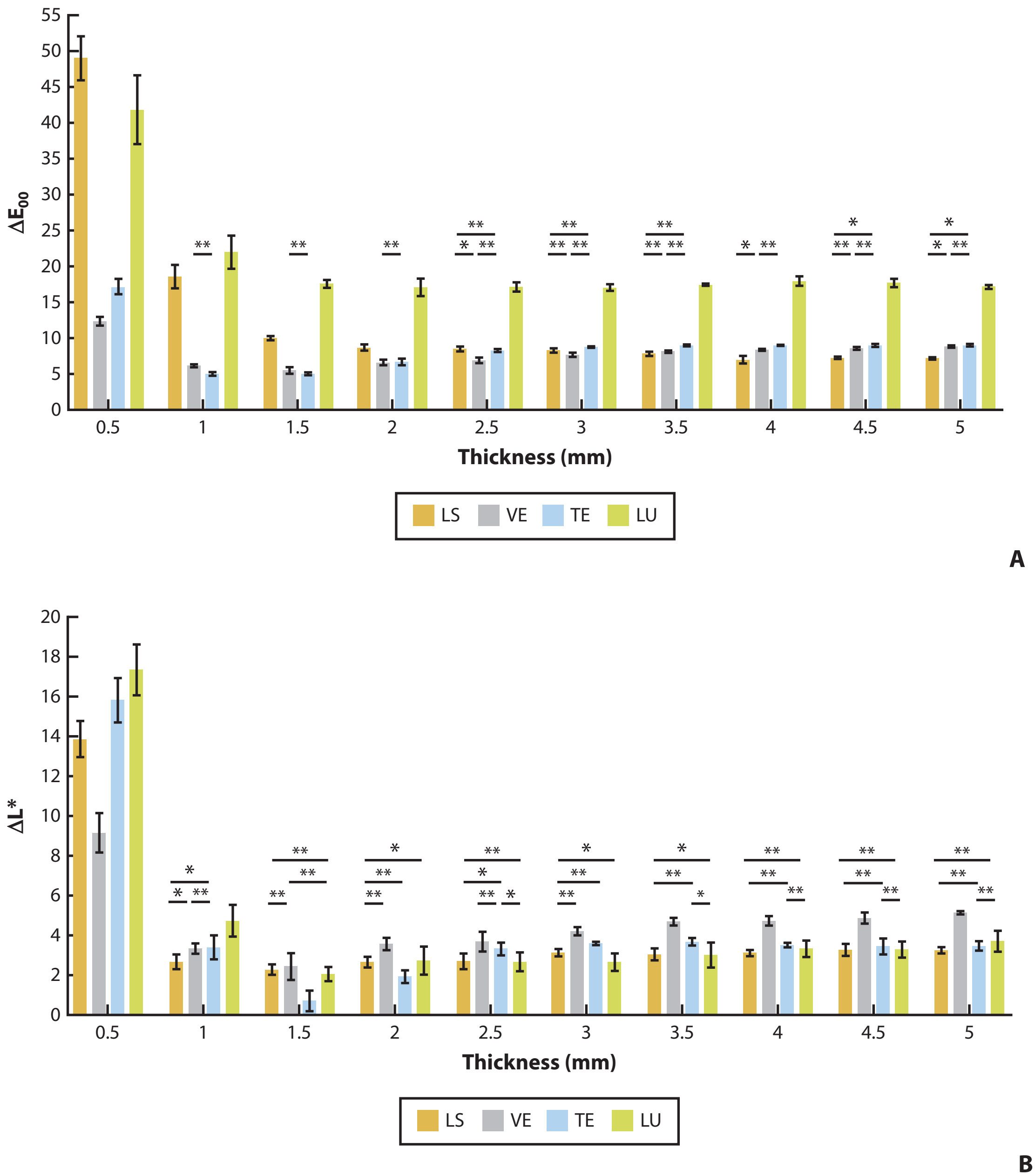

Figure 1. Mean and standard deviation and pairwise comparison result among materials in different thicknesses. A, ΔE_{00}. B, ΔL^*.

studies.[8,10,18] Visual color difference thresholds, as a quality control tool, have been widely used to guide the selection of esthetic dental materials, evaluate clinical performance, promote subsequent standardization, and interpret visual and instrumental findings in clinical dentistry and dental research.[17]

The CIEDE2000 50:50% perceptibility threshold of 0.8 units and acceptability threshold of 1.8 units provided by Paravina et al[34] have been recently used in dental research and were also used in the present study. Although dental materials are matched to different shade guide systems, dental shade guides may not be ideal for color matching. The colors in dental shade guides have been reported to differ by brand, production time, disinfection techniques, and preservation conditions, which may cause color variation and affect the accuracy of shade matching.[10,30] In order to control factors that may affect the accuracy of dental shade guides, the color coordinates of A2 in the VITA Classical shade system, calibrated by VITA Easyshade V (L^*=77.7, a^*=–0.3, b^*=17.5, C=17.5, and H=91.0), were used as standardized color coordinates in the present study.[31] By

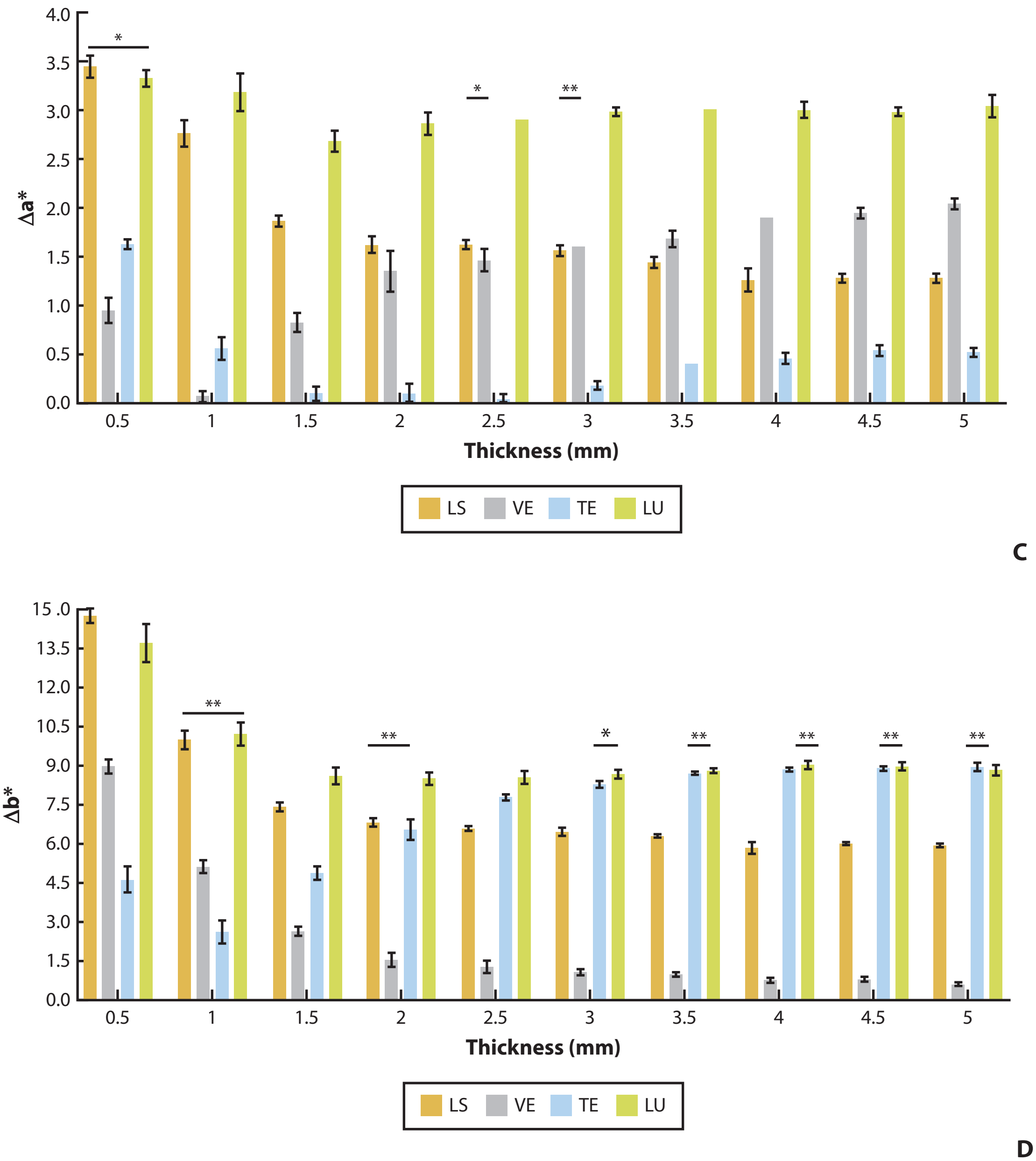

Figure 1. (*Continued*). C, Δa*. D, Δb*. *.05>*P*>.001, ***P*≥.05. LS, IPS e.max; LU, LAVA Ultimate; TE, Telio CAD; VE, VITA Enamic.

comparing with standardized color coordinates, the present results revealed that the color difference between the specimens and standard shade A2 of all tested materials significantly exceeded the acceptability threshold. This finding indicated that when the 4 materials tested in the present study were processed and polished without any other surface treatments, the color difference between all groups and the designated shade was perceptible and clinically unacceptable.

The present results revealed that the ΔE_{00} was significantly affected by material type, thickness, and their interaction, consistent with the findings of Kang et al.[12] However, in contrast to the study of Kang et al, the present study found that thickness had a greater influence on the accuracy of final color than material type. An influence of thickness on color matching has also been reported previously for a limited thickness range of 0.5 to 2.5 mm, selected to simulate the thickness of veneers and complete crowns.[11,20,24,25] CAD-CAM monolithic materials are increasingly being used for implant-supported restorations, where the maximum thickness exceeds 2.5 mm. However, studies that reported the color accuracy of CAD-CAM monolithic materials with thicknesses greater than 2.5 mm are lacking. Therefore, the thickness range in the present study extended to 5.0 mm. In the present study, thicknesses greater than 2.5 mm had a significant effect on ΔE_{00} and the CIELab color coordinates, which could affect the color accuracy and represented different effects among the material groups. A thickness variation will lead to altered translucency of materials, which could lead to color inaccuracy. A strong correlation between translucency and L* value was reported by Lee,[22] possibly because increasing thickness reduced translucency and, subsequently, changed brightness.

The variation of ΔE_{00} and thickness among different materials had similarities. The maximum ΔE_{00} of the tested materials was observed at a thickness of 0.5 mm, which ranged from 12.3 to 49.0, and was significantly higher than the acceptability threshold ($P<.001$). These results suggest that caution should be exercised when selecting shades for veneers, especially ultrathin veneers, because of the significant difference between the true color and the labeled shade in these prostheses. The ΔE_{00} decreased with increasing thicknesses until the minimum thickness was reached, consistent with Bayindir and Koseoglu[35] and Chongkavinit and Anunmana.[26] The minimum ΔE_{00} of materials was observed at different thicknesses: 2.0 mm for LU, 1.5 mm for VE and TE, and 4.0 mm for LS. From the clinical point of view, the tested materials could more closely match the designated color in the thicknesses of complete monolithic crowns.

The ΔE_{00} declined sharply from 0.5 mm to 1.0 mm or 1.5 mm of the tested materials, with more significant variations in the lower thicknesses. Therefore, care should be taken when adjusting the thickness of restorations because a small variation in thickness may result in a perceptible color difference, especially in thin regions. The ΔE_{00} did not significantly change after the thickness increased past a certain point. This may be because, when the thickness was increased, translucency decreased, and more light was reflected and refracted inside the materials, as detected by the spectrophotometer.[8,20] At a certain thickness, most light refraction and reflection occurred in the shallow parts of the materials; the deeper part had less influence on the color changes of the materials.[21]

In contrast to previous studies which only listed the CIELab color coordinates, the effects of color bias on ΔE_{00} were analyzed. Comparison of the L*, a*, and b* of the specimens with the standardized color coordinates was performed to quantify the color bias in terms of the lightness (L*), red-green axis (a*), and yellow-blue axis (b*) (Fig. 1B-D). The results revealed that ΔL^* and Δb^* had a greater impact on the ΔE_{00} than Δa^* and that the variations in ΔL^* and Δb^* in different thicknesses were similar to those of ΔE_{00}. The results indicated that, with increasing thickness, mismatched ΔL^* and Δb^* may be the main factors causing color differences. Regarding the color distribution of the tested materials, yellow, after excluding red, had the greatest impact on color inaccuracy.

The significant differences of ΔE_{00}, ΔL^*, Δa^*, and Δb^* among the tested materials are shown in Figure 1B-D. Different CAD-CAM monolithic materials with the same designated shade varied in terms of the final color, consistent with previous studies.[13,24] Differences in the inner structures and compositions of the tested materials have been reported to influence the color.[6,21-23] Differences in light transmission characteristics among CAD-CAM monolithic materials may be attributed to the monomer and filler type, content, amount, and size of the fillers, polymerization, distribution of defects, and porosity.[6,23] Furthermore, the light transmission characteristics of esthetic CAD-CAM monolithic materials may be related to the inorganic content of the materials.[36] The manufacturers of LS reported that the number of large and small lithium meta-silicate crystals in the precrystallized state affect the color difference of lithium disilicate glass-ceramic material.[21] LU is a resin-nanoceramic material having a resin matrix structure with fillers, whereas VE is a polymer-infiltrated glass-ceramic material. Koizumi et al[36] reported that the inorganic filler content of VE was significantly higher than that of LU. Awad et al[6] reported that some fillers act as radio-opacifiers, where high levels of such particles affect the color and translucency of the material; this may explain the differences in color between nanoceramic resin and polymer-infiltrated-feldspathic ceramic network materials.

Specific shade guide reference systems for different materials are needed in addition to universal shade guide systems such as the VITA classical shade system. The range of ΔE_{00} and degree of color inaccuracy of the 4 tested materials differed by thickness. Selecting materials based on the labeled shade on the products may lead to significant inaccuracy and color mismatch of the prosthesis. The degrees of inaccuracy and color mismatch vary by thickness when the same material is selected for different clinical situations.

Limitations of this study included that the results may not directly translate to clinical situations because the effects of underlying structures such as abutment material and luting agent, as well as the dry condition, were not taken into consideration. In addition, some materials used in this study can be glazed, which can affect the color of the material. Different materials, shades, and optical properties like translucency should be included in future studies. Clinical assessments should be included to evaluate color accuracy more precisely.

CONCLUSIONS

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

1. The color accuracy and bias were significantly affected by material type and thickness. L* and b* had a greater impact on color accuracy and bias than a*.
2. The color inaccuracy of the tested materials was statistically significant and clinically perceptible. Materials at a thickness of 0.5 mm represented the greatest color inaccuracy. Improved clinical outcomes may be expected from the 1.5-mm- to 2.0-mm-thick restorations.

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