JPD THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Quantitative analysis of the color in six CAD-CAM dental materials of varied thickness and surface roughness: An in vitro study

Zhengda Wu, DDS,[a] Donghao Wei, DDS,[a] Jiehua Tian, DDS,[a] Yifan Zhang, DDS,[a] Ye Lin, DDS,[b] Ping Di, DDS[b]

ABSTRACT

Statement of problem. Computer-aided design and computer-aided manufacturing (CAD-CAM) monochromatic restorative materials are gaining popularity because of their convenience and efficiency. However, studies that quantitatively analyzed color change associated with thickness and surface roughness are sparse.

Purpose. The purpose of this in vitro study was to quantitatively evaluate the color of 6 CAD-CAM monochromatic materials of different thickness and surface roughness using the CIELab color system.

Material and methods. A total of 150 12×12-mm square specimens of 6 different CAD-CAM monochromatic materials (VITA Enamic HT [VE], IPS e.max CAD HT [LS], LAVA Ultimate HT [LU], Telio CAD HT [TE], VITA Suprinity HT [VS], and Celtra Duo HT [CD]) in shade A2 and 5 different thicknesses (from 0.5 mm to 2.5 mm, with 0.5-mm increments) were fabricated (n=5). After 3 different surface treatments (polished, roughened by SiC P800-grit, and P300-grit), CIELab color parameters (L*, a* and b*) were measured using a spectrophotometer (VITA Easyshade V), and surface roughness was measured with a profilometer (VK-X200). Color variation was quantified by ΔE_{00} and 50:50% acceptability and perceptibly thresholds. Data analyses were performed using MANOVA, 2-way ANOVA, post hoc Tukey-Kramer test, and the 1-sample *t* test (α=.05).

Results. The L*, a*, and b* of the monochromatic specimens were significantly influenced by material type, thickness, and surface roughness (*P*<.001). An overall increase in the L* (from 61.90 to 82.2), a* (from −4.22 to 1.16), and b* (from 5.48 to 43.22) of the specimens was observed with increased thickness. The roughened specimens exhibited lower L* and higher a* and b* than the polished ones (*P*<.001). The use of P300-grit for roughening resulted in greater ΔE_{00} compared with P800-grit (*P*<.001). As thickness decreased or surface roughness increased, the ΔE_{00} increased and exceeded the acceptability and perceptibly thresholds for color difference.

Conclusions. Material type, thickness, and surface roughness were major factors affecting the color of CAD-CAM monochromatic materials. Variations in thickness of 0.5 mm or more, as well as roughening treatments, may lead to clinically unacceptable color changes. (J Prosthet Dent xxxx;xxx:xxx-xxx)

The recent adoption of computer-aided design-computer-aided manufacture (CAD-CAM) technology in dentistry has empowered dentists to work independently of dental laboratory technicians.[1,2] The increasing demand for optimal esthetics has resulted in the growing popularity of CAD-CAM materials with excellent optical properties.[3,4] However, dentists should understand the optical properties of CAD-CAM materials to achieve the required esthetic outcomes.[1,5]

Color plays a pivotal role in creating natural-looking restorations, with color prediction being a key focus in dental research.[6–9] However, because of the characteristics of monochromatic blocks, the color of CAD-CAM restorations is susceptible to material type, thickness, and surface parameters,[5,10–14] and dentists should have an accurate understanding of color and its clinical influencing factors.[12,15,16] To quantitatively evaluate color, the Commission Internationale de l'Eclairage (CIE) Lab color space (CIELab) and spectrophotometers have been commonly used to quantitatively evaluate color in a feasible, straightforward, and valid manner.[17]

Supported in part by the National Central Healthcare Research Project [grant 2022ZD18].

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

[a] Lecturer, Department of Oral Implantology, Peking University School and Hospital of Stomatology, Beijing, PR China.

[b] Professor, Department of Oral Implantology, Peking University School and Hospital of Stomatology, Beijing, PR China.

Clinical Implications

The color of dental CAD-CAM monochromatic materials is influenced by material type, thickness, and surface roughness. Considering these factors is essential when striving for an esthetic dental restoration that accurately mimics the intricate color of a natural tooth.

Additionally, visual thresholds such as the acceptability threshold (AT) and the perceptibility threshold (PT) have been used as quality control tools to correlate numerical data with clinical observations and perceptions, and analyze dental research findings.[18–22]

Obtaining color information in different thicknesses is the first step in achieving predictable and highly esthetic monochromatic CAD-CAM restorations,[23,24] although, because of the characteristics of natural teeth, their natural appearance cannot be mimicked with a single shade. Previous studies have reported that the value, hue, and chroma of CAD-CAM material changed with increasing thickness,[24,25] resulting in the restoration color being unpredictable and inconsistent with the selected shade.[3,7,9–11,26,27]

The restoration color may change after repair or after adjustments like grinding or polishing,[16,28–30] and wear, aging, and acid etching will occur in daily use.[10,31] These factors could alter the topography and roughness of CAD-CAM materials, thereby affecting light transmittance and colorimetric characteristics.[31–36] Previous studies have primarily focused on color between different surface treatments such as glazing or aging.[29,31–35] However, studies that quantitatively evaluated the degree of color change after roughening treatments to simulate the wear of CAD-CAM restorations are lacking.

Various materials are available for CAD-CAM monochromatic restorations, including glass-ceramics, zirconia, polymethyl methacrylate, and composite resins.[37] Although companies manufacturing CAD-CAM materials claim color fidelity to natural teeth, the color of different materials with the same shade may vary depending on the product type and brand.[9,12] Differences in light transmission characteristics associated with color difference among materials have been attributed to the type and content of monomer and filler, size of the fillers, polymerization, distribution of defects, and porosity.[1,38,39] However, minimal independent quantitative data are available comparing commercially available materials.

Thus, the quantitative relationship of the color, material type, thickness, and surface roughness of different CAD-CAM monochromatic materials remains unclear, posing challenges in material selection and replicating tooth color. The present study aimed to quantitatively evaluate and compare the color of 6 contemporary CAD-CAM monochromatic materials with different thicknesses and surface roughness. The null hypothesis was that material type, thickness, and surface roughness would not affect color.

MATERIAL AND METHODS

The details of the 6 CAD-CAM monochromatic materials are listed in Table 1. The sample size was based on previous studies[1,26] using a power analysis software program (PASS 2021; NCSS, LLC), and a minimum of 4.8 specimens for each group was calculated to achieve 80% power, a 2-sided statistical significance level of 5%, and a detectable difference of 0.1. Square-shaped (12×12-mm) specimens in shade A2 and thicknesses from 0.5 mm to 2.5 mm with 0.5-mm increments (n=5) were prepared for the 6 materials.[5] The monochromatic blocks were sliced by using a constant water cooling precision wire cutting machine (STX-2–2A; Shenyang Kejing Automation Equipment Co Ltd) at a constant speed of 0.2 mm/minute.[26] For IPS e.max CAD HT blocks (Ivoclar AG) and VITA Suprinity HT blocks (VITA Zahnfabrik), the specimens were subsequently sintered in a ceramic furnace (Programat EP 5000; Ivoclar AG) as per the manufacturer's specifications.[34]

All specimens were polished sequentially on both sides using a series of wet silicon carbide papers (Suisun Co Ltd) up to SiC P2000 on a grinding machine

Table 1. Details and codes of tested materials

Material	Brand	Code	Main Components*	Manufacturer
Lithium-disilicate ceramic	IPS e.max CAD HT	LS	8–80% SiO_2, 11–19% Li_2O, 0–13% K_2O, 0–8% ZrO_2, 0–5% Al_2O_3	Ivoclar AG
Polymer-infiltrated ceramic	Vita Enamic HT	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 HT	LU	80% ceramic (69% SiO_2, 31% ZrO_2) 20% polymer (UDMA)	3 M ESPE
Polymethyl methacrylate (PMMA)	Telio CAD HT	TE	99.5% PMMA polymer	Ivoclar AG
Zirconia-reinforced lithium silicate ceramic	VITA Suprinity HT	VS	56–64% SiO_2, 1–4% Al_2O_3, 15–21% Li_2O, 8–12% ZrO_2, 1–4% K_2O	VITA Zahnfabrik
Zirconia-reinforced lithium silicate ceramic	Celtra Duo HT	CD	58% SiO_2, 18.5% Li_2O, 5% P_2O_5, 10.1% ZrO_2, 1.9% Al_2O_3, 2% CeO_2, 1% Tb_4O_7	Dentsply Sirona

TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

*As reported by manufacturers.

(M-Prep; Allied High Tech Products Inc).[1] Subsequently, all specimens were roughened on 1 side by using wet silicon carbide paper (Suisun Co Ltd) at SiC P300 and SiC P800 (M-Prep; Allied High Tech Products Inc) by the same operator (W.Z.).[1] The thickness of each specimen was determined using a digital micrometer with an accuracy of 0.02 mm (Mitutoyo IP65; Mitutoyo Corp).[1,26] Only specimens exhibiting a thickness variance of less than 0.02 mm were retained. Before color measurements, the specimens were ultrasonically cleaned in distilled water for 10 minutes, cleaned with isopropanol to remove grease residue, and dried with compressed air.[1,26]

The CIELab coordinates (L*, a*, b*, C* and H*, which represent lightness, the red-green axis, the yellow-blue axis, chroma, and hue, respectively) were obtained using a contact dental spectrophotometer (VITA Easyshade V; VITA Zahnfabrik) in "tooth single" mode under D65 illumination (De Luxe; PHILIPS Corp).[19] The spectrophotometer was set at an integrated illumination with a built-in white LED light source (D65) with 2-degree standard observer and (45:0) optical geometry.[18,39] The spectrophotometer demonstrated a repeatability of less than 0.1 units and a high level of inter- and intra-device reliability.[18,39] Before measurement, the spectrophotometer had been calibrated according to the manufacturer's guidelines. To eliminate the influence of background color, specimens were measured against a backdrop of air on a custom scaffold designed to hold the specimens (Fig. 1). The Ø5-mm probe was placed in the center of the specimen surface. Three sets of measurements were made by the same operator (W.Z.), with the order of measurement for each group randomized using the random number table method. The mean values of the 3 measurements were calculated for each specimen.[34]

The color change (ΔE_{00}) resulting from various surface roughening treatments was calculated by determining the difference in color coordinates between the specimens. ΔE_{00} was calculated using the CIEDE2000 color difference formula[19]:

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

where ΔL^*, ΔC^*, and ΔH^* refer to the difference in the lightness, chrome, and hue values. The parametric factors K_L, K_C, and K_H were set to 1.[19] The CIEDE2000 50:50% perceptibility threshold of 0.8 units and acceptability threshold of 1.8 units for ΔE_{00} by Paravina et al,[21] as well as the perceptibility thresholds of 1.1 units for ΔL^*, 3.2 units for Δa^*, and 1.1 units for Δb^* by Westland et al[22] were adopted.

The specimens were analyzed with a shape measurement laser microscope (VK-X200; Keyence). The probe of the laser microscope was positioned at the center of the specimen surface, and 3 sets of measurements were made for each group using the random number table method to obtain an average roughness profile.

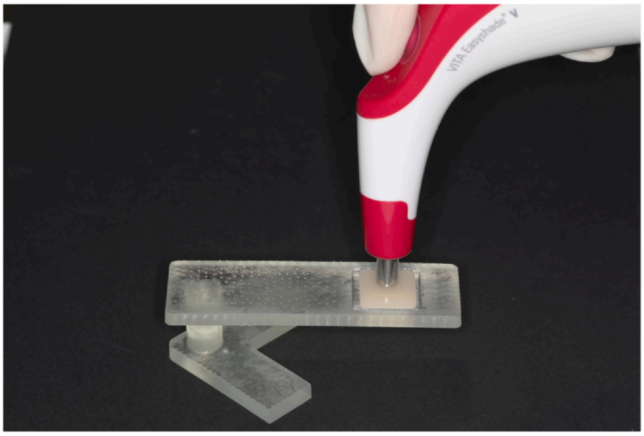

Figure 1. Color of specimens measured against backdrop of air on custom scaffold using VITA Easyshade V.

Statistical analyses were conducted by a statistician (W.D.) blinded to specimen preparation and measurements using a software program (IBM SPSS Statistics, v25.0; IBM Corp) (α=.05). Normality and homogeneity of the data were confirmed through the Shapiro-Wilk and Levene tests ($P>.05$). The effects of material type, thickness, surface roughness, and their interaction on color (L*, a*, and b*) were analyzed by using MANOVA (α=.05). The effects of material type, thickness, and their interaction on color change (ΔE_{00}) caused by surface roughness were analyzed using 2-way ANOVA (α=.05). Pairwise comparisons of color and ΔE_{00} were performed using the post hoc Tukey-Kramer test (α=.05). The ΔL^*, Δa^*, Δb^*, and ΔE_{00} were compared with the perceptibility and acceptability threshold using the 1-sample *t* test.

RESULTS

The MANOVA results showed a significant influence of material type, thickness, surface roughness, and their interaction on the L*, a*, and b* of the specimens ($P<.001$) (Table 2). Thickness exhibited the most substantial influence on L*, followed by material type and surface roughness. Material type had a greater impact on a* and b* than thickness and surface roughness.

The mean and standard deviation values of L*, a*, and b* for all specimens are presented in Tables 3 to 5. Pairwise comparisons of the simple main effects of the material type, thickness, and surface roughness on the L*, a*, and b* revealed noteworthy differences among the subgroups ($P<.001$). Furthermore, the disparities in the L*, a*, and b* values between different materials with the same thickness and surface treatment are

Table 2. Summary of MANOVA results of L*, a*, and b*

Value	Effect	Type III Sum of squares	Df	Mean Square	F	*P*	η_P^2
L*	Type	644.205	5	128.841	822.331	< .001	.919
	Thickness	6966.224	4	1741.556	11 115.526	< .001	.992
	Roughness	167.161	2	83.580	533.454	< .001	.748
	Type × Thickness	1201.774	20	60.089	383.518	< .001	.955
	Type × Roughness	58.807	10	5.881	37.534	< .001	.510
	Thickness × Roughness	30.272	8	3.784	24.152	< .001	.349
	Type × Thickness × Roughness	36.849	40	.921	5.880	< .001	.395
a*	Type	838.455	5	167.691	12 171.115	< .001	.994
	Thickness	219.644	4	54.911	3985.477	< .001	.978
	Roughness	13.795	2	6.898	500.634	< .001	.736
	Type × Thickness	37.656	20	1.883	136.654	< .001	.884
	Type × Roughness	2.487	10	.249	18.050	< .001	.334
	Thickness × Roughness	3.576	8	.447	32.446	< .001	.419
	Type × Thickness × Roughness	4.386	40	.110	7.958	< .001	.469
b*	Type	45 552.791	5	9110.558	42 471.264	< .001	.998
	Thickness	5850.013	4	1462.503	6817.843	< .001	.987
	Roughness	61.240	2	30.620	142.743	< .001	.442
	Type × Thickness	1388.768	20	69.438	323.705	< .001	.947
	Type × Roughness	28.440	10	2.844	13.258	< .001	.269
	Thickness × Roughness	5.401	8	.675	3.147	< .001	.165
	Type × Thickness × Roughness	64.364	40	1.609	7.501	< .001	.455

Table 3. Means and standard deviations of groups for L*, a*, and b* of polished specimens

Thickness	Material Type					
	VE	LS	LU	TE	SU	CD
L*						
0.5 mm	68.56 ±0.86^{d,A}	64.6 ±0.19^{a,A}	67.32 ±0.4^{c,A}	65.16 ±0.21^{a,A}	65.48 ±0.37^{ab,A}	71.66 ±0.15^{e,A}
1.0 mm	74.0 ±0.23^{ab,B}	74.64 ±0.15^{b,B}	73.76 ±0.52^{a,B}	76.56 ±0.17^{c,B}	74.2 ±0.5^{b,B}	73.12 ±0.15^{a,B}
1.5 mm	74.36 ±0.42^{a,C}	75.14 ±0.09^{ab,C}	75.58 ±0.13^{b,C}	78.8 ±0.14^{d,C}	76.52 ±0.16^{c,C}	73.96 ±0.51^{a,C}
2.0 mm	74.86 ±0.21^{ab,D}	75.68 ±0.08^{bc,D}	76.04 ±0.09^{c,D}	80.96 ±0.05^{e,D}	77.92 ±0.22^{d,D}	74.6 ±0.32^{a,D}
2.5 mm	75.26 ±0.39^{a,D}	75.64 ±0.11^{a,D}	76.7 ±0.1^{b,E}	82.2 ±0.28^{d,E}	78.06 ±0.17^{c,D}	75.04 ±0.31^{a,D}
a*						
0.5 mm	-1.96 ±0.05^{c,A}	-4.22 ±0.04^{a,A}	-4.16 ±0.05^{a,A}	-2.92 ±0.04^{b,A}	-1.48 ±0.13^{c,A}	-4.94 ±0.11^{a,A}
1.0 mm	-0.62 ±0.04^{b,B}	-3.54 ±0.11^{a,B}	-3.58 ±0.11^{a,B}	-0.78 ±0.08^{b,B}	-1.1 ±0.23^{b,AB}	-3.48 ±0.22^{a,B}
1.5 mm	0.24 ±0.05^{c,C}	-2.52 ±0.04^{b,C}	-3.58 ±0.16^{a,B}	-0.66 ±0.05^{c,B}	-0.48 ±0.04^{c,BC}	-2.62 ±0.13^{b,C}
2.0 mm	0.58 ±0.11^{c,C}	-2.32 ±0.04^{b,C}	-3.56 ±0.08^{a,B}	-0.38 ±0.04^{c,BC}	0.04 ±0.09^{c,C}	-2.16 ±0.09^{b,C}
2.5 mm	0.82 ±0.04^{c,D}	-2.2 ±0^{b,C}	-3.52 ±0.05^{a,B}	-0.08 ±0.08^{c,C}	0.16 ±0.05^{c,C}	-2 ±0^{b,C}
b*						
0.5 mm	5.74 ±0.09^{b,A}	1.18 ±0.13^{a,A}	1.06 ±0.15^{a,A}	11.56 ±0.18^{d,A}	22.98 ±0.15^{e,A}	8.68 ±0.57^{c,A}
1.0 mm	10.98 ±0.22^{b,B}	6.44 ±0.38^{a,B}	5.48 ±0.54^{a,B}	20.1 ±0.43^{c,B}	35.46 ±0.28^{d,B}	9.9 ±0.52^{b,B}
1.5 mm	13.82 ±0.2^{c,C}	9.72 ±0.08^{b,C}	7.5 ±0.1^{a,C}	22.5 ±0.4^{d,C}	38.66 ±0.93^{e,C}	10.38 ±0.18^{b,C}
2.0 mm	15.12 ±0.26^{c,D}	10.24 ±0.05^{b,D}	7.82 ±0.04^{a,D}	24 ±0.4^{d,D}	40.18 ±0.27^{e,D}	10.82 ±0.3^{b,D}
2.5 mm	15.42 ±0.13^{c,D}	10.48 ±0.04^{b,C}	8.4 ±0.24^{a,D}	24.4 ±0.07^{d,D}	41.42 ±0.9^{e,E}	11.52 ±0.18^{b,D}

Different superscript lowercase letters indicate significant difference among groups for each row. Different superscript uppercase letters indicate significant difference among groups for each column within each parameter (L*, a*, and b*) using the post hoc Tukey-Kramer test (α=.05).

shown in the pairwise comparison results outlined in Tables 3 to 5.

For the simple main effect of increasing thickness, a consistent rise in L*, a*, and b* was observed, ranging from 61.90 to 82.2 for L*, −4.22 to 1.16 for a*, and 5.48 to 43.22 for b*, respectively. In general, the disparities in L*, a*, and b* between adjacent thicknesses decreased as thickness increased ($P<.001$). The 1-sample *t* test results revealed that ΔL* and Δb* between 0.5 mm and 1.0 mm for all materials exceeded the PT for ΔL* and Δb* ($P<.001$), while Δa* between adjacent thicknesses for all materials was below PT for Δa* ($P<.001$).

Considering the simple main effects of surface roughness, rougher specimens exhibited decreased L*, along with elevated a* and b*. The corresponding surface roughness values are presented in Figure 2. The mean and standard deviation of ΔE_{00} between the polished specimens and those roughened with P800-grit and P300-grit are presented in Figure 3 and Figure 4, respectively. Results from the 2-way ANOVA analysis demonstrated that surface roughness was significantly influenced by both the roughness treatment (F=824.152, partial eta squared η_P^2=.949, $P<.001$) and the material (F=75.712, partial eta squared η_P^2=.810, $P<.001$).

The ΔE_{00} between the polished specimens and those roughened with either P800-grit or P300-grit for the same materials decreased with increasing thickness. The correlation between ΔE_{00} and surface roughness exhibited considerable variability across different materials. The 2-way ANOVA results regarding the influence of material type, thickness, and their interaction on ΔE_{00} are presented in Table 6. Post hoc pairwise comparisons after the 2-way ANOVA revealed that the use of P300-grit resulted in significantly larger ΔE_{00} as compared

Table 4. Means and standard deviations of groups for L*, a*, and b* of specimens roughened with P800-grit

Thickness	Material Type					
	VE	**LS**	**LU**	**TE**	**SU**	**CD**
L*						
0.5 mm	66.7 ±0.7^{d,A}	64.48 ±0.04^{ab,A}	66.02 ±0.44^{cd,A}	63.96 ±0.21^{a,A}	65.36 ±0.3^{bc,A}	71.06 ±0.23^{e,A}
1.0 mm	72.58 ±0.49^{a,B}	74.5 ±0.19^{c,B}	72.76 ±0.52^{a,B}	75.74 ±0.22^{d,B}	74.28 ±0.41^{bc,B}	73.2 ±0.26^{ab,B}
1.5 mm	73.4 ±0.29^{a,C}	75.04 ±0.15^{c,C}	74.9 ±0.31^{bc,C}	78.06 ±0.13^{e,C}	76.76 ±0.05^{d,C}	73.9 ±0.32^{ab,C}
2.0 mm	74.18 ±0.31^{a,D}	75.34 ±0.05^{bc,C}	75.76 ±0.72^{c,D}	80.24 ±0.31^{e,D}	78 ±0.12^{d,D}	74.66 ±1.37^{ab,D}
2.5 mm	74.4 ±0.1^{a,D}	75.56 ±0.13^{b,C}	75.82 ±0.23^{b,D}	81.74 ±0.31^{d,E}	78.84 ±0.29^{c,E}	75.14 ±0.31^{ab,D}
a*						
0.5 mm	-1.72 ±0.08^{bc,A}	-4.02 ±0.04^{a,A}	-3.86 ±0.05^{a,A}	-2.52 ±0.04^{b,A}	-0.96 ±0.15^{c,A}	-4.68 ±0.08^{a,A}
1.0 mm	-0.46 ±0.09^{c,B}	-3.46 ±0.13^{a,A}	-3.48 ±0.08^{a,AB}	-1.46 ±0.05^{bc,B}	-0.66 ±0.11^{c,A}	-3.5 ±0.23^{a,B}
1.5 mm	0.44 ±0.05^{c,C}	-2.5 ±0^{b,B}	-3.28 ±0.11^{a,AB}	-0.4 ±0.12^{c,C}	-0.36 ±0.09^{c,A}	-2.62 ±0.13^{ab,C}
2.0 mm	0.9 ±0.12^{d,C}	-2.12 ±0.04^{b,B}	-3.06 ±0.05^{a,B}	-0.26 ±0.05^{c,C}	0.1 ±0.07^{cd,B}	-1.9 ±0.07^{b,C}
2.5 mm	1.02 ±0.04^{d,C}	-2.08 ±0.04^{ab,B}	-3.06 ±0.05^{a,B}	-0.18 ±0.04^{c,C}	0.26 ±0.05^{cd,B}	-1.86 ±0.05^{b,C}
b*						
0.5 mm	6.66 ±0.09^{b,A}	2.02 ±0.16^{a,A}	3.06 ±0.15^{a,A}	12.1 ±0.21^{d,A}	23.26 ±0.15^{e,A}	8.7 ±0.49^{c,A}
1.0 mm	11.64 ±0.21^{c,B}	6.86 ±0.43^{a,B}	7.34 ±0.44^{a,B}	20.44 ±0.38^{d,B}	33 ±1.73^{e,B}	10.12 ±0.22^{b,B}
1.5 mm	14.68 ±0.16^{c,C}	9.74 ±0.11^{b,C}	7.84 ±0.13^{a,BC}	22.88 ±0.13^{d,C}	38.76 ±0.71^{e,C}	10.64 ±0.33^{b,B}
2.0 mm	15.6 ±0.19^{d,CD}	10.38 ±0.04^{b,D}	8.84 ±0.19^{a,CD}	24.34 ±0.18^{e,D}	40.74 ±2.22^{f,D}	11.82 ±0.16^{c,C}
2.5 mm	15.98 ±0.22^{c,D}	10.74 ±0.09^{b,D}	9.16 ±0.11^{a,D}	24.78 ±0.08^{d,D}	42.58 ±0.39^{e,E}	11.85 ±0.38^{b,C}

Different superscript lowercase letters indicate significant difference among groups for each row. Different superscript uppercase letters indicate significant difference among groups for each column within each parameter (L*, a*, and b*) using post hoc Tukey-Kramer test (α=.05).

Table 5. Means and standard deviations of groups for L*, a* and b* of specimens roughened with P300-grit

Thickness	Material Type					
	VE	**LS**	**LU**	**TE**	**SU**	**CD**
L*						
0.5 mm	63.62 ±0.18^{b,A}	64.2 ±0.5^{b,A}	63.46 ±0.1^{b,A}	61.9 ±0.27^{a,A}	64.56 ±0.3^{b,A}	70.06 ±0.29^{c,A}
1.0 mm	69.82 ±0.3^{a,B}	74.18 ±0.27^{c,B}	71.46 ±0.18^{b,B}	74.3 ±0.26^{c,B}	73.88 ±0.25^{c,B}	72.02 ±0.36^{b,B}
1.5 mm	72.98 ±0.15^{a,C}	75.06 ±0.23^{c,C}	73.98 ±0.12^{b,C}	76.98 ±0.21^{d,C}	76.14 ±0.21^{d,C}	72.72 ±0.36^{a,C}
2.0 mm	73.58 ±0.15^{a,CD}	75.34 ±0.21^{b,C}	74.96 ±0.12^{b,D}	79.64 ±0.21^{d,D}	77.34 ±0.27^{c,D}	73.14 ±0.21^{a,C}
2.5 mm	74.02 ±0.23^{a,D}	75.44 ±0.15^{b,C}	75.22 ±0.13^{b,D}	81.04 ±0.21^{d,E}	78.66 ±0.22^{c,E}	73.44 ±0.25^{a,C}
a*						
0.5 mm	-1.26 ±0.11^{bc,A}	-3.74 ±0.11^{a,A}	-3.62 ±0.08^{a,A}	-1.92 ±0.04^{b,A}	-0.72 ±0.19^{c,A}	-3.66 ±0.27^{a,A}
1.0 mm	-0.22 ±0.04^{b,B}	-3.06 ±0.13^{a,AB}	-3.48 ±0.19^{a,AB}	-0.86 ±0.11^{b,B}	-0.22 ±0.18^{b,A}	-2.66 ±0.18^{a,B}
1.5 mm	0.76 ±0.09^{d,C}	-2.16 ±0.05^{b,BC}	-3.34 ±0.11^{a,AB}	-0.5 ±0.07^{c,B}	0.02 ±0.25^{cd,AB}	-2.06 ±0.11^{b,B}
2.0 mm	1.06 ±0.18^{e,D}	-1.92 ±0.08^{b,B}	-3.16 ±0.11^{a,A}	-0.38 ±0.18^{cd,C}	0.36 ±0.25^{de,CD}	-2 ±0.07^{b,B}
2.5 mm	1.16 ±0.11^{e,C}	-1.92 ±0.04^{b,C}	-2.98 ±0.11^{a,AB}	-0.18 ±0.14^{cd,B}	0.58 ±0.33^{de,B}	-1.88 ±0.08^{bc,B}
b*						
0.5 mm	8.58 ±0.23^{c,A}	2.82 ±0.28^{a,A}	3.86 ±0.13^{a,A}	12.9 ±0.13^{d,A}	24.14 ±0.25^{e,A}	6.22 ±0.34^{b,A}
1.0 mm	12.4 ±0.21^{c,B}	7.56 ±0.26^{a,B}	8.06 ±0.19^{a,B}	20.84 ±0.27^{d,B}	34.38 ±0.16^{e,B}	10.36 ±0.38^{b,B}
1.5 mm	14.88 ±0.15^{c,C}	10.12 ±0.16^{b,C}	8.2 ±0.14^{a,B}	23.46 ±0.27^{d,C}	39.2 ±0.22^{e,C}	11 ±0.26^{b,BC}
2.0 mm	15.98 ±0.23^{c,D}	10.72 ±0.16^{b,C}	9 ±0.07^{a,BC}	25.02 ±0.11^{d,D}	40.62 ±0.3^{e,D}	11.74 ±0.34^{b,C}
2.5 mm	16.24 ±0.23^{d,D}	10.94 ±0.09^{b,C}	9.28 ±0.14^{a,C}	25.24 ±0.11^{e,D}	43.32 ±0.24^{f,E}	12.36 ±0.34^{c,C}

Different superscript lowercase letters indicate significant difference among groups for each row. Different superscript uppercase letters indicate significant difference among groups for each column within each parameter (L*, a*, and b*) using the post hoc Tukey-Kramer test (α=.05).

with P800-grit ($P<.001$). The 1-sample *t* test results revealed that decreasing thickness or increasing surface roughness led to a rise in ΔE_{00}, surpassing both the PT and AT for color difference ($P<.05$).

DISCUSSION

The null hypothesis that material type, thickness, and surface roughness would not affect color was rejected, as the results demonstrated the color of the 6 materials was significantly influenced by material type, thickness, and surface roughness. The color of CAD-CAM monochromatic materials was analyzed across a thickness range from 0.5 mm to 2.5 mm, aiming to simulate the thicknesses for most restorations, including veneers, complete crowns, inlays, and onlays.[1,15,23] The results showed that L*, a*, and b* were positively correlated with material thickness, with a curvilinear relationship. Thicker specimens were lighter, redder, and yellower than thinner specimens, consistent with other studies.[24,25] However, directional changes in color might diverge if tested against different backgrounds, where the a* and b* of CAD-CAM ceramics displayed a diminishing trend with increasing thickness against a white background.[14]

As the thickness increased, the ascending trend of L*, a*, and b* plateaued, indicating a diminishing difference between adjacent thicknesses in thicker specimens. Previous studies have suggested using second-degree polynomial regression as a predictive method for CIELab color coordinates in monolithic composite resins.[23] However, because of the limited range of thicknesses in the present study, the specific function type remained indistinct. The results showed that the variations in L*

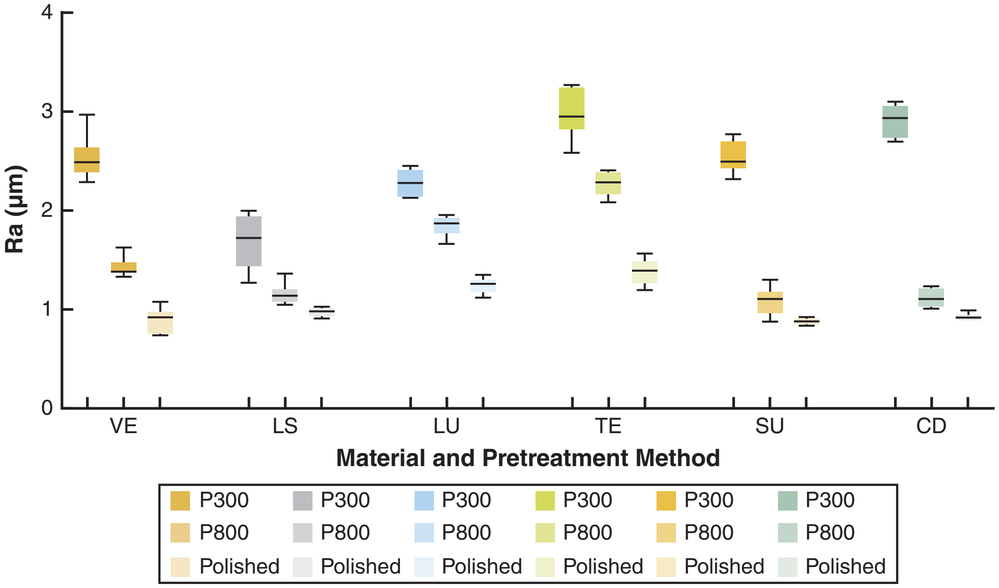

Figure 2. Mean and standard deviation of surface roughness after different pretreatment methods. CD, Celtra Duo; LS, IPS e.max; LU, LAVA Ultimate; TE, Telio CAD; VE, VITA Enamic; VS, VITA Suprinity.

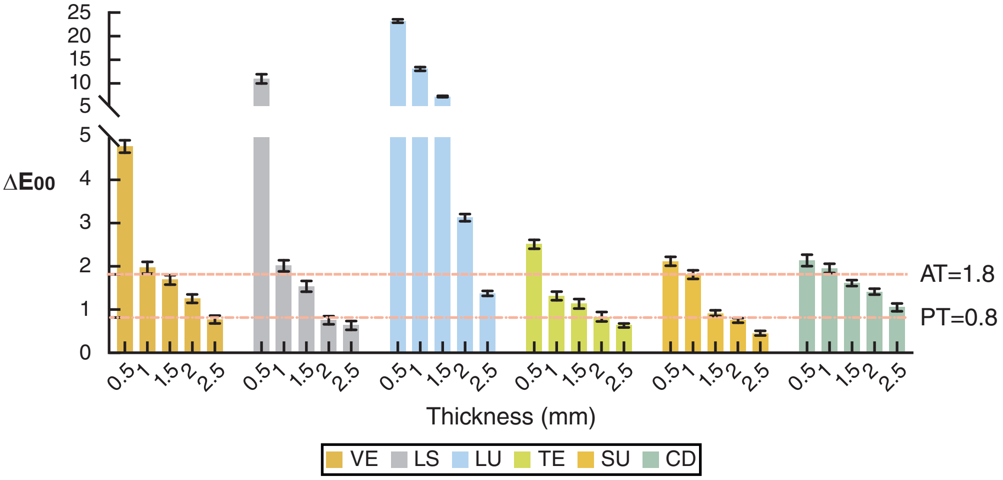

Figure 3. Mean and standard deviation of ΔE_{00} between polished specimens and those roughened with P800-grit. CD, Celtra Duo; LS, IPS e.max; LU, LAVA Ultimate; TE, Telio CAD; VE, VITA Enamic; VS, VITA Suprinity.

and b* for all materials between 0.5 mm and 1.0 mm surpassed the PT of L* and b*. However, the variations in a* between all adjacent thicknesses were below the PT of a*.[22] This difference implied that varying the thickness of CAD-CAM materials in lower thicknesses would result in perceptible alterations in lightness and yellowness. As the thickness surpassed 2.0 mm, the alterations in L*, a*, and b* for most materials ceased to exhibit statistical significance, indicating that color changes became insignificant beyond a certain thickness. Hence, attention is warranted when adjusting the thickness of restorations, as even small variations may lead to perceptible differences in color, especially in regions with minimal thickness. The relationship between material thickness and color is not linear, and improper thickness adjustment may induce unpredictable and unacceptable color shifts. Considerations pertaining to material type, shade selection, and thickness are essential to an esthetically pleasing restoration that authentically replicates the intricate color of a natural tooth.[25]

In this study, the 6 CAD-CAM monochromatic materials were evaluated based on their typical material types and common use in dentistry. Significant differences in L*, a*, and b* among these materials were found, consistent with previous studies.[15,24,25] The color of different materials was mainly reflected in L* and b*. Specifically, TE presented significantly higher L* than the other materials, while SU presented notably higher

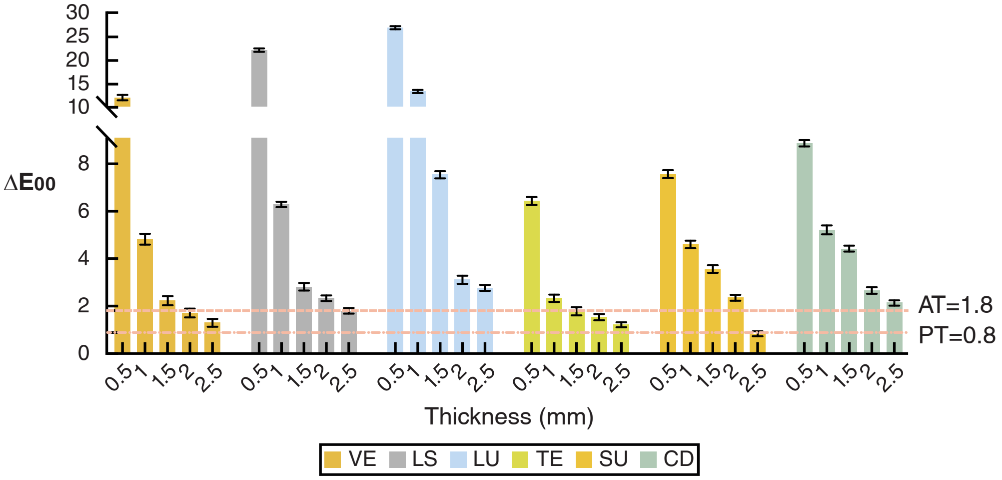

Figure 4. Mean and standard deviation of ΔE_{00} between polished specimens and those roughened with P300-grit. CD, Celtra Duo; LS, IPS e.max; LU, LAVA Ultimate; TE, Telio CAD; VE, VITA Enamic; VS, VITA Suprinity.

Table 6. Summary of 2-way ANOVA results of ΔE_{00}

Value	Effect	Type III Sum of Squares	Df	Mean Square	F	*P*	η_P^2
ΔE_{00}	Type	2267.662	5	453.457	152.915	< .001	.739
	Thickness	2285.862	4	866.916	292.341	< .001	.812
	Type × Thickness	800.664	20	114.293	38.542	< .001	.741

b* than the others. These disparities underscore the need for careful clinical material selection, especially in the esthetic zone, where color variations can be crucial. The internal structure and composition of materials such as the type of monomers and fillers, filler content, quantity and size, monomer polymerization degree, defect distribution, and porosity affected the optical properties, including color and translucency.[1,38,39] The color and translucency of the material are closely related. High translucency may allow more light to penetrate the material, resulting in reduced brightness.[30,39,40] The manufacturers of LS reported that the numbers of large and small lithium metasilicate crystals in the precrystallized state affect the translucency and color of the material.[41] However, more studies on the quantitative relationship between the color and translucency of CAD-CAM materials are needed.

Roughened surfaces alter the direction and incidence of light transmission, which can affect the color. In the present study, only 1 side of the specimens was roughened to simulate clinical or daily practice, such as grinding or mastication, which is consistent with previous studies.[1,36] The results indicated that increased surface roughness led to decreased lightness but increased a* and b*. As surface roughness increased, the color disparity between polished and roughened specimens increased. The results revealed that ΔE_{00} decreased with increasing thickness, a trend consistent with a previous study.[27] For specimens roughened by SiC P800-grit, the ΔE_{00} of all 0.5-mm specimens exceeded the AT. However, with increasing thickness, the ΔE_{00} could be below the AT and PT, indicating color alterations became acceptable and nearly imperceptible. In the case of specimens roughened by SiC P300-grit, only the ΔE_{00} of VE of 2.0-mm and 2.5-mm specimens, TE in 1.5 to 2.5 mm, and SU in 2.5 mm were acceptable but perceptible. The color change of all the other specimens was clinically unacceptable. Thinner restorations, such as veneers, were especially vulnerable to noticeable and clinically unacceptable color changes from variations in surface roughness.

Material-specific differences were observed in surface roughness and color variation after identical roughening treatments. Specifically, lithium disilicate ceramic (LS) displayed minimal variations in roughness and color, while resin-based materials (LU) exhibited greater variations in both parameters. This suggests interim restorations made from LU might be more susceptible to color alterations. Complete polishing after clinical modifications is essential to restore optimal surface and optical properties.[29]

Limitations of the present study included that underlying structures such as abutments and luting agents were not included; as a result the findings might not directly translate to the clinical situation. Secondly, the specimens were polished using the same wet silicon carbide paper rather than following the manufacturer's recommendations, potentially impacting subsequent surface roughness values. Thirdly, clinical spectrophotometers like Vita Easyshade V, while used in this study, may not offer the same accuracy as laboratory instruments, necessitating cautious interpretation of the results.[42] Future studies should encompass diverse material types, shades, and optical properties, including translucency, alongside clinical assessments to enhance the applicability of the findings in clinical dental practice.

CONCLUSIONS

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

1. The color of the 6 CAD-CAM monochromatic materials was significantly influenced by material type, thickness, and surface roughness.
2. CAD-CAM materials exhibited notable disparities in color characteristics, emphasizing the importance of meticulous selection in clinical practice. Variances in thickness of 0.5 mm or more could result in unacceptable color discrepancies among the materials.
3. Roughening treatments resulted in noticeable color changes, potentially reaching clinically unacceptable levels. Comprehensive polishing and subsequent adjustments are imperative to restore the color of CAD-CAM restorations.

REFERENCES

1. Awad D, Stawarczyk B, Liebermann A, Ilie N. Translucency of esthetic dental restorative CAD/CAM materials and composite resins with respect to thickness and surface roughness. *J Prosthet Dent*. 2015;113:534–540.
2. Joda T, Ferrari M, Gallucci GO, Wittneben JG, Bragger U. Digital technology in fixed implant prosthodontics. *Periodontol 2000*. 2017;73:178–192.
3. Shahmiri R, Standard OC, Hart JN, Sorrell CC. Optical properties of zirconia ceramics for esthetic dental restorations: A systematic review. *J Prosthet Dent*. 2018;119:36–46.
4. Zarone F, Di Mauro MI, Ausiello P, Ruggiero G, Sorrentino R. Current status on lithium disilicate and zirconia: A narrative review. *BMC Oral Health*. 2019;19:134.
5. Sen N, Us YO. Mechanical and optical properties of monolithic CAD-CAM restorative materials. *J Prosthet Dent*. 2018;119:593–599.
6. Pollini A, Morton D, Arunyanak SP, Harris BT, Lin WS. Evaluation of esthetic parameters related to a single implant restoration by laypeople and dentists. *J Prosthet Dent*. 2020;124:94–99.
7. Della Bona A, Pecho OE, Ghinea R, Cardona JC, Perez MM. Colour parameters and shade correspondence of CAD-CAM ceramic systems. *J Dent*. 2015;43:726–734.
8. Yilmaz B, Irmak O, Yaman BC. Outcomes of visual tooth shade selection performed by operators with different experience. *J Esthet Restor Dent*. 2019;31:500–507.
9. Carrillo-Perez F, Pecho OE, Morales JC, et al. Applications of artificial intelligence in dentistry: A comprehensive review. *J Esthet Restor Dent*. 2022;34:259–280.
10. Seyidaliyeva A, Rues S, Evagorou Z, Hassel AJ, Rammelsberg P, Zenthofer A. Color stability of polymer-infiltrated-ceramics compared with lithium disilicate ceramics and composite. *J Esthet Restor Dent*. 2020;32:43–50.
11. Egilmez F, Ergun G, Cekic-Nagas I, Vallittu PK, Lassila LVJ. Comparative color and surface parameters of current esthetic restorative CAD/CAM materials. *J Adv Prosthodont*. 2018;10:32–42.
12. Tabatabaian F, Karimi M, Namdari M. Color match of high translucency monolithic zirconia restorations with different thicknesses and backgrounds. *J Esthet Restor Dent*. 2020;32:615–621.
13. Gunal B, Ulusoy MM. Optical properties of contemporary monolithic CAD-CAM restorative materials at different thicknesses. *J Esthet Restor Dent*. 2018;30:434–441.
14. Tamam E, Gungor MB, Nemli SK. How are the color parameters of a CAD/CAM feldspathic ceramic of the material affected by its thickness, shade, and color of the substructure? *Niger J Clin Pract*. 2020;23:523–533.
15. Jirajariyavej B, Wanapirom P, Anunmana C. Influence of implant abutment material and ceramic thickness on optical properties. *J Prosthet Dent*. 2018;119:819–825.
16. Kanat-Erturk B. Color stability of CAD/CAM ceramics prepared with different surface finishing procedures. *J Prosthodont*. 2020;29:166–172.
17. Tabatabaian F, Beyabanaki E, Alirezaei P, Epakchi S. Visual and digital tooth shade selection methods, related effective factors and conditions, and their accuracy and precision: A literature review. *J Esthet Restor Dent*. 2021;33:1084–1104.
18. Igiel C, Lehmann KM, Ghinea R, et al. Reliability of visual and instrumental color matching. *J Esthet Restor Dent*. 2017;29:303–308.
19. Melgosa M, Ruiz-Lopez J, Li C, Garcia PA, Della Bona A, Perez MM. Color inconstancy of natural teeth measured under white light-emitting diode illuminants. *Dent Mater*. 2020;36:1680–1690.
20. Paravina RD, Perez 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.
21. Paravina RD, Ghinea R, Herrera LJ, et al. Color difference thresholds in dentistry. *J Esthet Restor Dent.*. 2015;27(Suppl 1):S1–9.
22. Westland S, Luo W, Li Y, Pan Q, Joiner A. Investigation of the perceptual thresholds of tooth whiteness. *J Dent*. 2017;67S:S11–S14.
23. Tejada-Casado M, Ghinea R, Perez MM, Ruiz-Lopez J, Lubbe H, Herrera LJ. Development of thickness-dependent predictive methods for the estimation of the CIEL*a*b* color coordinates of monolithic and layered dental resin composites. *Materials (Basel)*. 2023;16:761.
24. Ha R, Tsuchida Y, Shiozawa M, Takahashi H. Effect of thickness on color appearance of multilayer CAD/CAM composite resin blocks. *Odontology.*. 2022;110:664–672.
25. Ruiz-Lopez J, Espinar C, Lucena C, de la Cruz Cardona J, Pulgar R, Perez MM. Effect of thickness on color and translucency of a multi-color polymer-infiltrated ceramic-network material. *J Esthet Restor Dent*. 2023;35:381–389.
26. Wu Z, Tian J, Wei D, Di P, Lin Y. Quantitative analysis of color accuracy and bias in 4 dental CAD-CAM monolithic restorative materials with different thicknesses: An in vitro study. *J Prosthet Dent*. 2022;128. 92 e1- e7.
27. Kang CM, Peng TY, Shimoe S. Color accuracy of different types of monolithic multilayer precolored zirconia ceramics. *J Prosthet Dent*. 2020;124. 789 e1- e7.
28. Pordeus Batista LA, Vieira-Junior WF, Pacheco RR, Mori AA, Sundfeld D, Pini NIP. Color alteration with ceramic veneers according to the tooth type and preparation step: A clinical analysis. *J Prosthet Dent*. 2022;22:00362–00366.
29. Brescansin FN, Prochnow C, Guilardi LF, et al. Effect of different surface treatments on optical, colorimetric, and surface characteristics of a lithium disilicate glass-ceramic. *J Esthet Restor Dent*. 2021;33:1017–1028.
30. Li S, Zhang X, Xia W, Liu Y. Effects of surface treatment and shade on the color, translucency, and surface roughness of high-translucency self-glazed zirconia materials. *J Prosthet Dent*. 2022;128. 217 e1- e9.
31. Alp G, Subasi MG, Johnston WM, Yilmaz B. Effect of surface treatments and coffee thermocycling on the color and translucency of CAD-CAM monolithic glass-ceramic. *J Prosthet Dent*. 2018;120:263–268.
32. Maciel LC, Silva CFB, de Jesus RH, Concilio L, Kano SC, Xible AA. Influence of polishing systems on roughness and color change of two dental ceramics. *J Adv Prosthodont*. 2019;11:215–222.
33. Ural Ç, Duran İ, Evmek B, Kavut İ, Cengiz S, Yuzbasioglu E. Light transmittance and surface roughness of a feldspathic ceramic CAD-CAM material as a function of different surface treatments. *BMC Oral Health*. 2016;17:16.
34. Pereira GKR, Fraga S, Montagner AF, Soares FZM, Kleverlaan CJ, Valandro LF. The effect of grinding on the mechanical behavior of Y-TZP ceramics: A systematic review and meta-analyses. *J Mech Behav Biomed Mater*. 2016;63:417–442.
35. Kosmac T, Oblak C, Jevnikar P, Funduk N, Marion L. The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic. *Dent Mater*. 1999;15:426–433.

36. Wu Z, Tian J, Wei D, Zhang Y, Lin Y, Di P. Effects of thickness and polishing treatment on the translucency and opalescence of six dental CAD-CAM monolithic restorative materials: An in vitro study. *BMC Oral Health.* 2023;23:579.
37. Sulaiman TA. Materials in digital dentistry-A review. *J Esthet Restor Dent.* 2020;32:171–181.
38. Nakajima M, Arimoto A, Prasansuttiporn T, Thanatvarakorn O, Foxton RM, Tagami J. Light transmission characteristics of dentine and resin composites with different thickness. *J Dent.* 2012;40(Suppl 2):e77–e82.
39. Yilmaz Savas T, Akin C. Effects of sintering protocol and dipping time on the optical properties of monolithic zirconia. *J Prosthet Dent.* 2022;127. 801 e1- e8.
40. Ingram NT, Sampath AP, Fain GL. Why are rods more sensitive than cones? *J Physiol.* 2016;594:5415–5426.
41. Azzopardi N, Moharamzadeh K, Wood DJ, Martin N, van Noort R. Effect of resin matrix composition on the translucency of experimental dental composite resins. *Dent Mater.* 2009;25:1564–1568.
42. Akl MA, Sim CPC, Nunn ME, Zeng LL, Hamza TA, Wee AG. Validation of two clinical color measuring instruments for use in dental research. *J Dent.* 2022;125:104223.

Corresponding author:
Dr Ping Di
Department of Implantology
Peking University School and Hospital of Stomatology
22 South Zhongguancun Avenue
Haidian District, Beijing, 100081
PR CHINA.
Email: pkuss_diping@163.com

Copyright © 2023 by the Editorial Council of *The Journal of Prosthetic Dentistry*.
All rights reserved.
https://doi.org/10.1016/j.prosdent.2023.10.030