

Optical properties of advanced lithium disilicate

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Conflict of interest

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Abstract

Background. A variety of firing protocols are available for the IPS e.max lithium disilicate (LD) and can be used for new, 'advanced' LD (ALD). However, the impact of firing protocols on the optical properties of ALD is still unknown.

Objectives. The aim of the present study was to evaluate the color difference (ΔE_{00}), the translucency parameter (TP_{00}) and the whiteness index for dentistry (WID) for both LD glass ceramics after the processes of firing/glazing.

Material and methods. Fifty disk-shaped specimens, with a diameter of 10 mm and a thickness of 1.2 mm, were fabricated from IPS e.max CAD (LD; Ivoclar) and another 50 from CEREC Tessera™ (ALD; Dentsply Sirona). The specimens from each group were further divided into 5 subgroups ($n = 10$) according to the firing/glazing protocol applied: crystallization (c); one-step crystallization and glazing (cg); crystallization and refiring (c-r); two-step crystallization and glazing (c-g); or long-firing crystallization (lfc). The ΔE_{00} , TP_{00} and WID were assessed. The statistical analysis of ΔE_{00} was performed using the one-way analysis of variance (ANOVA) and Tukey's post hoc test, while TP_{00} and WID were analyzed with the two-way ANOVA and Tukey's post hoc test at a statistical significance level of 0.05. The cg groups were designated as the reference.

Results. The ANOVA showed that the firing procedures had no effect on ΔE_{00} , TP_{00} and WID in the case of LD. In addition, LD exhibited greater translucency and brightness as compared to ALD. For ALD, all color changes observed in relation to the reference firing protocol were clinically unacceptable. The ALD specimens which underwent 1 standard firing cycle showed higher TP_{00} and WID values than other ALD groups.

Conclusions. The choice of the firing protocol has no impact on the color, TP_{00} or WID of LD. Additionally, LD presents higher WID values than ALD, irrespective of the firing protocol used. Alternative firing protocols result in clinically unacceptable color variations when compared to the manufacturer-recommended protocol for ALD. Advanced LD is more sensitive to different firing protocols with regard to its optical properties, which makes the workflow less predictable in comparison with LD.

Keywords: CAD/CAM, optical properties, dental materials, glass ceramics

Introduction

In recent years, glass ceramics have become widely used due to their adequate bond strength, mechanical behavior and excellent optical properties.^{1,2} For instance, the translucency of lithium disilicate (LD) is higher as compared to the majority of zirconia ceramics.¹ Therefore, LD is one of the most commonly used ceramics for anterior veneers, posterior inlays, onlays and overlays, crowns, and bridges.³

When considering the specific needs of each clinical case, the satisfaction of the patient depends on providing a functional restoration whilst mimicking natural tooth appearance. Translucency, along with color, texture, size, and shape, determine the appearance and optical properties of restorations.^{4–6} These esthetic parameters are affected by various factors, including the thickness of the restoration, surface treatment, the firing temperature, the number of firing cycles, the type of substructure, and differences in the manufacturing process.⁵ Despite the favorable characteristics of the well-known LD, its esthetic properties can be altered, depending on the firing/glazing protocols applied,^{5,7–9} which reduces the predictability of the treatment outcome.

Consequently, alternative materials have been developed to address the limitations of LD.¹⁰ The manufacturer of CEREC Tessera™ (Dentsply Sirona, Charlotte, USA) refers to this new material as 'advanced' LD (ALD), and claims ALD has increased its mechanical strength as compared to conventional LD while maintaining high esthetic parameters. Advanced LD consists of a zirconia-enriched glass matrix and lithium aluminum silicate (LAS) crystals called virgilitite.¹¹ The material is indicated for single-unit crowns, inlays, onlays, and veneers. Despite sharing several indications with LD, the firing protocol differs. According to the manufacturer, the use of a glaze layer as a finishing protocol is a mandatory step to achieve the desired mechanical properties. Yet, the effects of using or not using this protocol on the esthetic parameters of color, translucency and whiteness remain unknown.

The color evaluation of a natural-looking tooth is not easy, since the internal build-up is layered and complex. In addition, visual color assessment can be subjective due to both psychological and physiological aspects.¹² Therefore, instruments such as colorimeters and spectrophotometers are commonly used to evaluate color changes in dental materials.¹³ To calculate the color difference (ΔE_{00}), the International Commission on Illumination (Commission internationale de l'éclairage – CIE) recommends the use of the CIEDE2000 color difference formula, which is currently the standard and most commonly used equation in the dental field to quantify color.¹² To define translucency, specimens should be evaluated over a black-and-white background. The difference between the reflected colors (the translucency parameter – TP_{00}) provides a value corresponding to the human visual perception of translucency.¹⁴ Another parameter determined

to assess the esthetic performance of a dental material is the whiteness index for dentistry (WID), which is crucial in terms of the patient's demands.¹⁵ Since ALD requires the application of a glaze layer, dentists and dental technicians need to know if and how this layer can affect the optical properties of the material in comparison with LD. Additionally, it is important to investigate the impact of different firing protocols and processing methods on the esthetic outcome.¹⁶

Therefore, the present study investigated the impact of different firing/glazing protocols on the optical properties of LD and ALD. The null hypotheses were as follows: different firing protocols would not affect the (1) color, (2) translucency and (3) WID of both LD and ALD, and (4) no difference would be observed between the tested materials.

Material and methods

In the present study, 2 different reinforced glass-ceramic systems were tested. Their brand names, composition and manufacturer information are summarized in Table 1.

Fifty disk-shaped (10 mm in diameter and 1.2 mm in thickness) LD and ALD specimens were fabricated from each ceramic in the A2 shade in accordance with the VITA® classical shade guide (VITA Zahnfabrik, Bad Säckingen, Germany). Then, the ceramic disks from each group were further divided into 5 subgroups ($n = 10$) according to the evaluated firing/glazing protocols: crystallization (c); one-step crystallization and glazing (cg); crystallization and refiring (c-r); two-step crystallization and glazing (c-g); or long-firing crystallization (lfc) (Fig. 1, Table 2). As indicated by the ALD manufacturer, the recommended firing protocol is crystallization with glazing in one step. This firing protocol was also adopted for LD as the reference.

The sample size was calculated using statistical software (OpenEpi, v. 3.01; https://www.openepi.com/Menu/OE_Menu.htm) to achieve 80% statistical power performed with a 95% confidence interval (CI). The mean (M) and standard deviation (SD) values from a previous report that evaluated the relative translucency of LD and ALD¹⁷ were employed.

Table 1. Characteristics of the ceramic dental materials evaluated in the study

Material	Brand name	Chemical composition	Manufacturer
LD	IPS e.max CAD	SiO ₂ : 57–80% Li ₂ O: 11–19% K ₂ O: 0–13% P ₂ O ₅ : 0–11% ZrO: 0–8% ZnO ₂ : 0–8% coloring oxides: 0–8%	Ivoclar, Schaan, Liechtenstein
ALD	CEREC Tessera	Li ₂ Si ₂ O ₅ : 90% Li ₃ PO ₄ : 5% Li _{0.5} Al _{0.5} Si _{1.5} O ₆ (virgilitite): 5%	Dentsply Sirona, Charlotte, USA

LD – lithium disilicate; ALD – advanced lithium disilicate.

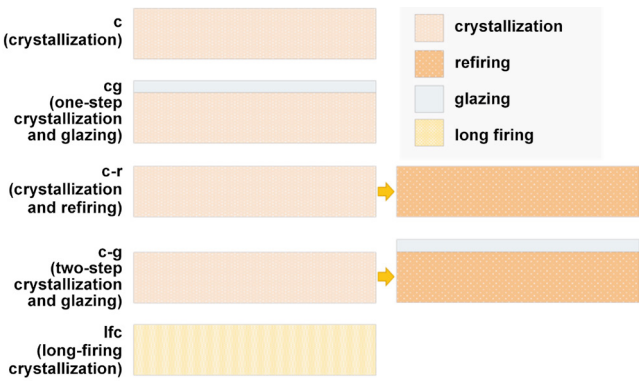


Fig. 1. Schematic illustration of the evaluated firing protocols, applied to both lithium disilicate (LD) and advanced lithium disilicate (ALD) specimens

Ceramic blocks of both materials were shaped into cylinders with a diamond drill of an internal diameter of 10 mm (Diamant Boart, Brussels, Belgium), connected to a bench drill (SBE 1010 Plus; Metabo, Nürtingen, Germany) under constant water cooling. All specimens were cut and polished with #800, #1,000 and #1,200 grit sandpaper (CarbiMet® SiC abrasive paper; Buehler, Lake Bluff, USA) in a polishing machine (EcoMet® 30; Buehler) until the final thickness of 1.20 ± 0.09 mm was achieved. The disks were divided into 5 subgroups ($n = 10$) according to the firing protocol. The IPS e.max CAD Crystall Glaze Spray (Ivoclar) was used for LD, and the Universal Spray Glaze (Dentsply Sirona) was used for ALD. All firing cycles for the 5 subgroups were pre-programmed in a ceramic oven (Programat® P300; Ivoclar) according to the manufacturers' instructions.

Table 2. Distribution of the study groups according to the ceramic material and the firing protocol (as per the manufacturers' instructions)

Glass ceramic	Subgroup	Step 1	Step 2
IPS e.max CAD (LD)	LDc		–
	LDcg	LD firing crystallization:	–
	LDc-r	– closing time: 6 min – stand-by temperature: 403°C – heating rate: 60°C/min – firing temperature: 770°C – holding time: 10 s – heating rate: 30°C/min – firing temperature: 850°C – holding time: 10 min – vacuum 1: 550–770°C – vacuum 2: 770–850°C – long-term cooling: 700°C/min	another LD firing crystallization
	LDc-g		IPS e.max CAD Crystall Glaze Spray firing: – closing time: 6 min – pre-heating temperature: 403°C – heating rate: 90°C/min – firing temperature: 820°C – holding time: 10 s – heating rate: 30°C/min – firing temperature: 840°C – holding time: 3 min – vacuum 1: 550–820°C
	LDlfc	LD long-firing crystallization: – closing time: 6 min – stand-by temperature: 403°C – heating rate: 60°C/min – firing temperature: 770°C – holding time: 10 s – heating rate: 30°C/min – firing temperature: 850°C – holding time: 13 min – vacuum 1: 550–770°C – vacuum 2: 770–850°C – long-term cooling: 700°C/min	–
CEREC Tessera (ALD)	ALDc	ALD firing crystallization:	–
	ALDcg	– closing time: 2 min – pre-heating temperature: 400°C – heating rate: 55°C/min – firing temperature: 760°C – holding time: 2 min – vacuum 1 and vacuum 2: off – long-term cooling: 0°C/min	–
	ALDc-r		another ALD firing crystallization
	ALDc-g		Universal Spray Glaze firing
	ALDlfc	ALD long-firing crystallization: – closing time: 2 min – pre-heating temperature: 400°C – heating rate: 55°C/min – firing temperature: 760°C – holding time: 4 min – vacuum 1 and vacuum 2: off – long-term cooling: 0°C/min	–

Firing protocols: c – crystallization; cg – one-step crystallization and glazing; c-r – crystallization and refining; c-g – two-step crystallization and glazing; lfc – long-firing crystallization.

The color was measured with a spectrophotometer (VITA Easyshade®; VITA Zahnfabrik), which provided the lightness (L^*), red–green axis (a^*) and yellow–blue axis (b^*) values from the CIELab color space for the specimens against white, black and grey backgrounds, using box-blocking harsh lighting (Table 3). Before each measurement session, the spectrophotometer was calibrated according to the manufacturer's instructions. Each specimen was measured 3 times consecutively on each background, and the average was calculated to give the final value. The values obtained against the grey background were used to calculate the difference in color perception (ΔE_{00}), using the CIEDE2000 formula (Equation 1)¹²:

$$\Delta E_{00} = \left[\left(\frac{DL}{k_L \cdot S_L} \right)^2 + \left(\frac{DC}{k_C \cdot S_C} \right)^2 + \left(\frac{DH}{k_H \cdot S_H} \right)^2 + R_T \left(\frac{DC}{k_C \cdot S_C} \right) \cdot \left(\frac{DH}{k_H \cdot S_H} \right) \right]^{0.5} \quad (1),$$

where DL, DC and DH refer to the differences in lightness (L'), chroma (C') and hue (H') among the specimens. The weighting functions S_L , S_C , and S_H adjust the overall color difference to account for variations in the position of the color difference in the $L^*a^*b^*$ coordinates. Meanwhile, the parametric factors k_L , k_C and k_H serve as correction terms for the experimental conditions. R_T is the rotation function that compensates for the interaction between the chroma and hue differences, specifically in the blue region.¹³ For ΔE_{00} , the acceptability threshold (AT) is 1.77, while the perceptibility threshold (PT) is 0.81.¹² Thus, values under 0.81 can be considered irrelevant and negligible. Values between 0.81 and 1.77 are visible to the untrained eye, yet clinically acceptable, whereas values above 1.77 are clinically unacceptable.

Additionally, TP_{00} was calculated using the $L^*a^*b^*$ values from the white and black backgrounds (Equation 2):

$$TP_{00} = \left[\left(\frac{L'_B - L'_W}{k_L \cdot S_L} \right)^2 + \left(\frac{C'_B - C'_W}{k_C \cdot S_C} \right)^2 + \left(\frac{H'_B - H'_W}{k_H \cdot S_H} \right)^2 + R_T \left(\frac{C'_B - C'_W}{k_C \cdot S_C} \right) \cdot \left(\frac{H'_B - H'_W}{k_H \cdot S_H} \right) \right]^{0.5} \quad (2)$$

where:

TP_{00} – transparency parameter;

other parameters – as defined above;

W refers to the white background, and

B refers to the black background.

Table 3. $L^*a^*b^*$ parameters for the backgrounds used

Background	L^* value	a^* value	b^* value
White	16.90 ± 0.62	0.40 ± 0.00	4.87 ± 0.21
Black	1.23 ± 0.19	24.60 ± 0.94	45.63 ± 6.30
Grey	13.00 ± 1.72	0.50 ± 0.08	3.97 ± 0.49

Data presented as mean ± standard deviation ($M \pm SD$).

L^* – lightness; a^* – value on the red–green axis; b^* – value on the yellow–blue axis.

The TP_{00} values closer to 100 indicate more transparent specimens, and the TP_{00} values closer to 0 indicate more opaque specimens.¹⁸

The $L^*a^*b^*$ coordinates were obtained over the black background and WID was calculated according to the following equation (Equation 3)¹⁵:

$$WID = 0.511L^* - 2.324a^* - 1.100b^* \quad (3)$$

where:

WID – whiteness index for dentistry;

L^* – lightness;

a^* – value on the red–green axis; and

b^* – value on the yellow–blue axis.

Higher WID values indicate whiter specimens, while lower WID values indicate less white specimens.

Statistical analysis

To evaluate the color differences for the ceramic groups, the visible and clinical acceptability thresholds were determined, and no further statistical analysis was performed. The cg groups were used as a point of reference in comparison to other methods, in accordance with the indication set forth by the ALD manufacturer. The ΔE_{00} was analyzed using the one-way analysis of variance (ANOVA) with $\alpha = 0.05$ and Tukey's post hoc test within each ceramic. The TP_{00} and WID were evaluated using the two-way ANOVA ($\alpha = 0.05$) and Tukey's post hoc test, based on the firing protocol and the ceramic used.

Results

Table 4 presents the mean L^* , a^* and b^* values against the white, black and grey backgrounds. The mean values of L^* , a^* and b^* on the grey background were used to calculate ΔE_{00} for different protocols within the same material group (Table 5). For LD, when considering LDcg as the reference for the firing protocol, there were no discernible color differences as compared to other protocols ($\Delta E_{00} < 0.81$; $p > 0.05$). However, when comparing the firing protocols with each other, there were perceptible and acceptable color differences between LDc-r and LDc-g, between LDc-g and LDc, and between LDc-g and LDlfc ($0.81 < \Delta E_{00} < 1.77$). For ALD, unacceptable color variations were encountered in all comparisons to ALDcg (the recommended crystallization protocol), with $\Delta E_{00} > 1.77$. Additionally, ALDc and ALDc-r were significantly different from each other ($p = 0.041$).

For TP_{00} , the two-way ANOVA showed significant differences with regard to the type of ceramic ($p < 0.001$), the firing protocol ($p < 0.001$), and their interaction ($p < 0.001$). Lithium disilicate was more translucent

Table 4. L*a*b* parameters for the backgrounds used according to the study groups

Background	Group	L* value	a* value	b* value
White	LDc	93.08 ±0.32	−0.83 ±0.07	14.20 ±0.35
	LDcg	92.91 ±0.42	−0.83 ±0.10	13.82 ±0.48
	LDc-r	92.99 ±0.20	−0.74 ±0.13	14.30 ±0.63
	LDc-g	92.80 ±0.33	−0.89 ±0.10	13.05 ±0.48
	LDlfc	93.06 ±0.43	−0.79 ±0.07	14.28 ±0.30
	ALDc	84.65 ±1.52	−0.67 ±1.45	37.85 ±5.43
	ALDcg	85.64 ±1.72	−0.88 ±1.87	37.30 ±7.09
	ALDc-r	85.91 ±1.20	4.93 ±1.90	52.63 ±4.82
	ALDc-g	87.10 ±0.55	4.09 ±2.19	50.14 ±5.73
	ALDlfc	85.63 ±0.56	2.76 ±2.12	48.54 ±5.95
Black	LDc	75.56 ±0.24	−1.67 ±0.05	8.50 ±0.23
	LDcg	75.24 ±0.38	−1.66 ±0.07	8.21 ±0.40
	LDc-r	75.24 ±0.46	−1.56 ±0.10	8.63 ±0.39
	LDc-g	74.99 ±0.52	−1.68 ±0.07	7.67 ±0.35
	LDlfc	75.36 ±0.26	−1.62 ±0.06	8.52 ±0.26
	ALDc	70.72 ±2.14	−4.72 ±1.23	24.13 ±5.67
	ALDcg	71.35 ±2.81	−4.81 ±1.47	23.54 ±6.88
	ALDc-r	74.61 ±0.85	0.16 ±1.78	40.16 ±5.16
	ALDc-g	75.32 ±1.09	−0.64 ±2.07	37.25 ±6.67
	ALDlfc	73.52 ±1.03	−1.80 ±1.72	34.93 ±5.88
Grey	LDc	86.31 ±0.29	−1.19 ±0.05	12.07 ±0.32
	LDcg	86.07 ±0.21	−1.18 ±0.09	11.69 ±0.53
	LDc-r	85.99 ±0.28	−1.15 ±0.10	12.10 ±0.48
	LDc-g	85.89 ±0.34	−1.25 ±0.09	10.97 ±0.46
	LDlfc	86.26 ±0.38	−1.16 ±0.07	12.15 ±0.24
	ALDc	79.04 ±1.67	−2.13 ±1.33	32.57 ±5.40
	ALDcg	79.97 ±1.95	−2.27 ±1.66	32.14 ±6.75
	ALDc-r	80.99 ±1.16	2.93 ±1.85	46.85 ±5.43
	ALDc-g	82.25 ±0.60	2.20 ±2.06	44.35 ±5.86
	ALDlfc	80.49 ±0.44	1.09 ±1.94	43.27 ±5.71

Data presented as $M \pm SD$.

(12.40 ±0.07) than ALD (10.76 ±1.41). Regarding the firing protocol, the highest mean TP₀₀ values were found in the cg (12.38 ±0.03) and c (12.23 ±0.08) groups, followed by the lfc (11.32 ±1.55), c-g (11.11 ±1.94) and c-r (10.88 ±2.20) groups. Considering the interaction of factors, no statistical differences in translucency were observed between the LD firing protocols. In the case of ALD, the cg and c groups showed the highest translucency, showing similar values. Protocols lfc, c-g and c-r showed the lowest values, with no significant differences between them. The statistical outcomes are summarized in Table 6 and graphically depicted in Fig. 2.

The two-way ANOVA revealed differences in terms of WID, based on the type of ceramic, the firing protocol, and the interaction of factors ($p < 0.001$ in all cases). The LD specimens exhibited greater whiteness

Table 5. Color difference from shade A2 according to the CIE Lab color space (ΔE) and CIEDE2000 (ΔE_{00}) with regard to the ceramic material and the firing protocol

Group	ΔE				ΔE ₀₀				Group	ΔE				ΔE ₀₀							
	LDcg	LDc	LDc-r	LDc-g	LDlfc	LDcg	LDc	LDc-r		LDc-g	LDlfc	ALDcg	ALDc	ALDc-r	ALDc-g	ALDlfc	ALDc-g	ALDc-r	ALDc	ALDcg	ALDlfc
LDcg	–	0.67 ±0.53 ^A	0.73 ±0.38 ^A	–	0.71 ±0.50 ^A	–	0.47 ±0.34 ^A	0.49 ±0.27 ^A	0.73 ±0.34 ^A	0.48 ±0.33 ^A	ALDcg	–	5.46 ±5.33 ^A	15.85 ±7.78 ^B	13.40 ±8.95 ^{AB}	13.06 ±7.86 ^{AB}	–	2.74 ±2.47 ^A	6.90 ±3.37 ^B	6.02 ±3.92 ^{AB}	5.68 ±3.47 ^{AB}
LDc	0.67 ±0.53 ^A	–	0.56 ±0.33	0.47 ±0.34 ^A	0.48 ±0.28	0.47 ±0.34 ^A	–	0.39 ±0.21	0.84 ±0.32	0.34 ±0.17	ALDc	5.46 ±5.33 ^A	–	15.51 ±7.60	14.59 ±7.10	11.36 ±6.50	2.74 ±2.47 ^A	–	6.69 ±3.03	6.51 ±3.12	4.90 ±2.72
LDc-r	0.73 ±0.38 ^A	0.56 ±0.33	–	0.49 ±0.27 ^A	0.62 ±0.29	0.49 ±0.27 ^A	0.39 ±0.21	–	0.82 ±0.36	0.43 ±0.19	ALDc-r	15.85 ±7.78 ^B	15.51 ±7.60	–	6.48 ±3.89	6.37 ±4.44	6.90 ±3.37 ^B	6.69 ±3.03	–	2.70 ±1.49	2.70 ±1.54
LDc-g	1.06 ±0.49 ^A	1.24 ±0.45	1.20 ±0.53	–	1.29 ±0.52	0.73 ±0.34 ^A	0.84 ±0.32	0.82 ±0.36	–	0.88 ±0.37	ALDc-g	13.40 ±8.95 ^{AB}	14.59 ±7.10	6.48 ±3.89	–	8.87 ±5.10	6.02 ±3.92 ^{AB}	6.51 ±3.12	2.70 ±1.49	–	3.81 ±1.80
LDlfc	0.71 ±0.50 ^A	0.48 ±0.28	0.62 ±0.29	–	–	0.48 ±0.33 ^A	0.34 ±0.17	0.43 ±0.19	0.88 ±0.37	–	ALDlfc	13.06 ±7.86 ^{AB}	11.36 ±6.50	6.37 ±4.44	8.87 ±5.10	–	5.68 ±3.47 ^{AB}	4.90 ±2.72	2.70 ±1.54	3.81 ±1.80	–

Data presented as $M \pm SD$. Different capital letters show statistically significant differences between the groups (ANOVA, Tukey's post hoc test; $p < 0.05$). Considered thresholds: 50:50% perceptibility threshold (PT) – $\Delta E = 1.22$, $\Delta E_{00} = 0.81$; 50:50% acceptability threshold (AT) – $\Delta E = 2.66$, $\Delta E_{00} = 1.77$.

Table 6. Translucency parameter according to the CIELab color space (TP) and CIEDE2000 (TP_{00}), and the whiteness index for dentistry (WID) with regard to the ceramic material and the firing protocol

Group	TP	TP_{00}	WID
LDcg	18.56 ± 0.57^{BC}	12.40 ± 0.39^A	34.21 ± 0.86^A
LDc	18.44 ± 0.39^{BC}	12.29 ± 0.26^A	33.87 ± 0.57^A
LDc-r	18.65 ± 0.43^{BC}	12.44 ± 0.31^A	33.50 ± 0.96^A
LDc-g	18.62 ± 0.34^{BC}	12.48 ± 0.26^A	35.13 ± 0.75^A
LDlfc	18.63 ± 0.35^{BC}	12.42 ± 0.22^A	33.69 ± 0.64^A
ALDcg	20.25 ± 1.01^A	12.36 ± 1.54^A	4.78 ± 11.31^B
ALDc	19.98 ± 0.83^A	12.17 ± 1.18^A	3.18 ± 8.69^B
ALDc-r	17.56 ± 1.12^C	9.33 ± 0.68^B	-25.45 ± 9.97^C
ALDc-g	18.10 ± 1.42^{BC}	9.74 ± 1.13^B	-20.15 ± 11.41^C
ALDlfc	18.81 ± 0.75^B	10.23 ± 1.03^B	-16.05 ± 11.63^C

Data presented as $M \pm SD$. Different capital letters show statistically significant differences between the groups (ANOVA, Tukey's post hoc test; $p < 0.05$).

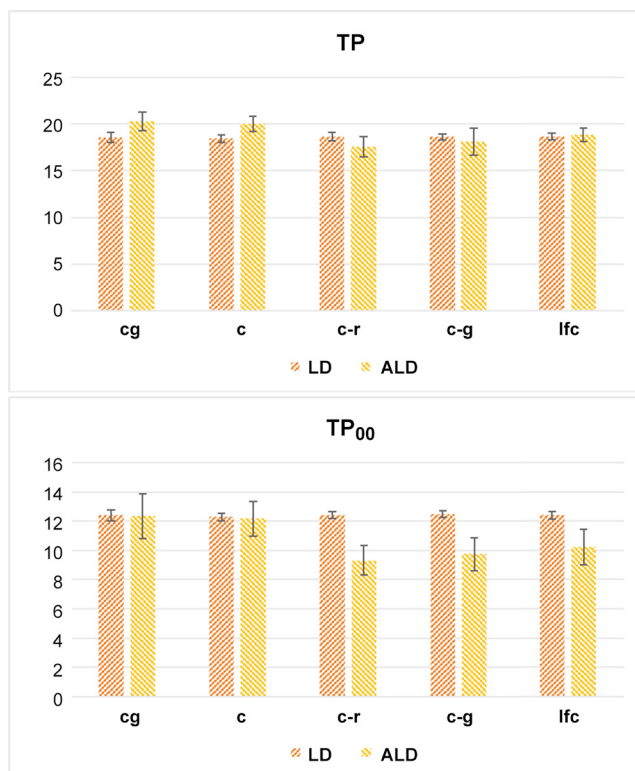


Fig. 2. Column charts of the translucency parameter according to the CIELab color space (TP) and CIEDE2000 (TP_{00}) with regard to the ceramic material and the firing protocol

(34.08 ± 0.64) than the ALD specimens (-10.74 ± 13.85). The highest WID values could be noticed in groups cg (19.49 ± 20.81) and c (18.52 ± 21.70), while the lowest values were encountered in the lfc (8.82 ± 35.16), c-g (7.49 ± 39.09) and c-r (4.02 ± 41.69) groups. Different protocols did not significantly affect the WID of LD. However, for ALD, the lfc, c-g and c-r exhibited darker values. The statistical analysis of the WID values is summarized in Table 6 and graphically depicted in Fig. 3.

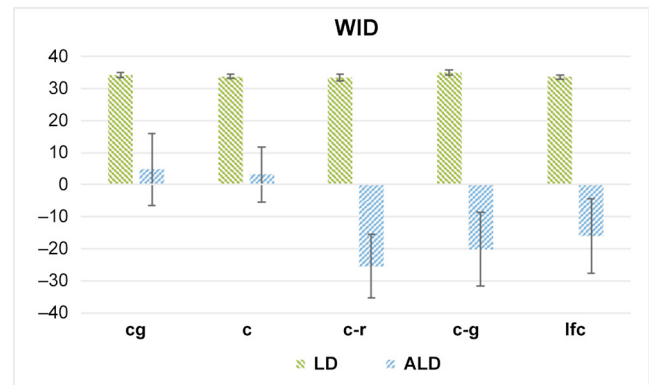


Fig. 3. Column chart of the whiteness index for dentistry (WID) with regard to the ceramic material and the firing protocol

Discussion

The present study investigated ΔE_{00} , TP_{00} and WID for 2 types of LD after subjecting the materials to different firing/glazing protocols. For LD, all color differences were either not visible or negligible and acceptable. All ALD groups presented visible and clinically unacceptable color differences in relation to the reference firing protocol (cg), which leads to the partial acceptance of the 1st hypothesis. It is well established that the color remains stable under different conditions for conventional LD.^{17,19–21} In general, the mean ΔE_{00} values were below the perceivable threshold, indicating that the firing times and temperatures, combined or not with glazing, do not affect the color of LD.¹ For ALD, all ΔE_{00} values were clinically unacceptable when compared to the reference group, indicating that ALD is highly susceptible to the evaluated firing protocols. When observing the alternative firing protocols, the highest ΔE_{00} values relative to the reference protocol were observed for the c-r group, which underwent 2 standard firing cycles without glazing.

Considering translucency, LD exhibited comparable behavior across different firing protocols, indicating that the processing protocol also does not affect translucency, which disagrees with previous literature.¹⁹ Conversely, the translucency of the ALD samples was affected, which partially supports the 2nd hypothesis. In a study by Miranda et al., translucency changes occurred in most LD groups after more than 2 firing sessions,²⁰ which exceeds the number of sessions conducted in the present study. On the contrary, ALD has only recently become available, and variations among different firing protocols are still being verified.²² Lithium disilicate showed higher TP_{00} values as compared to ALD, which differs from a previous study that reported similar and higher relative TP_{00} for LD and ALD.¹⁷ The authors used similar specimen dimensions to those utilized in the present study; however, the measurement was performed using a different device. The authors claimed that different chemical composition and crystalline structures had a greater influence on translucency.¹⁷

The present results corroborate the existing literature, indicating that the grain size also has a considerable effect on translucency²³; LD with larger crystals than ALD,^{24,25} exhibits greater translucency.²³

Similar WID values were found for the LD groups, while the ALD groups presented differences among the firing protocols, which leads to the partial acceptance of the 3rd hypothesis.

When comparing both materials, variations in translucency and WID were noted, rejecting the 4th hypothesis. The WID for ALD presented statistically significant differences as compared to LD, regardless of the firing protocol.

A similar effect in terms of color changes can be observed for TP₀₀ and WID, wherein the ALDc-r group exhibited lower mean values as compared to the ALDcg group. It was previously reported that the crystallization temperature can alter the optical properties of the material⁸ and ALD appeared to be more susceptible to the firing protocols than LD. There is a wider variety of firing protocols for LD offered by the manufacturer: 1 firing cycle without glazing (c); 1 firing cycle with glazing (cg); and 1 crystallization cycle followed by another firing cycle with glazing (c-g). It seems that this variety of firing protocols cannot be implemented in ALD if its optical properties are taken into consideration. When compared to the protocol indicated by the manufacturer (cg), the color difference of the c-g specimens was greater. However, no statistical difference was observed in comparison with the c-r protocol. This suggests that the glaze serves as a protection layer against optical degradation in case of firing cycles longer than the one indicated by the manufacturer of ALD. Similar behavior could be noticed regarding the translucency and WID parameters. The refiring of ceramics can result in alterations to their mechanical and optical properties.^{22,26} Moreover, esthetic degradation is notable relative to groups with a single standard firing protocol for the ALD samples.

Nevertheless, for the ALD samples, crystallization alone (c) promoted the lowest ΔE_{00} , and did not result in significant differences in TP₀₀ and WID when compared to the cg protocol. One similarity between these groups is that they underwent just one firing cycle at the same parameters, which seems to have had a less harmful effect on the esthetic outcome. It appears that ALD behaves better with a single firing cycle applied in accordance with the parameters set forth by the manufacturer, differing from those for the lfc group. The lfc protocol was used to observe whether the effects found for groups c-g and c-r would be withdrawn due to the elimination of the temperature drop between the firing cycles. This would eliminate material cooling, which is a relevant factor influencing the optical properties of the material.²⁶ Unacceptable color changes, and differences in the TP₀₀ and WID values were observed upon comparison with the reference protocol, indicating that longer firing cycles than the one indicated

by the manufacturer impair the optical properties of ALD, reinforcing the idea that ALD is highly susceptible to firing protocols. The WID is an important parameter, especially when considering restorations in esthetic areas and the necessity for matching the bleached teeth.¹⁵ Translucency represents the degree of light transmittance through an object and is determined by its characteristics, such as the reflection and/or scattering of light and the absorption of radiation. Interestingly, a recent study has demonstrated a significant increase in roughness for LD and ALD when applying a glaze layer, which would be expected to affect the esthetic parameters.²² In the present study, however, the glaze did not seem to be a determinant of color changes and translucency, contrary to the one-step glaze application protocol (cg), since another firing decreased translucency and WID.

When working in collaboration with a dental laboratory, it is common for the clinician to receive the final restoration without being aware of the firing protocol that has been employed. Moreover, the advent of new restorative materials has brought processing variations. For instance, some studies have advised additional firing for ALD to increase its strength and decrease or eliminate micro-fissures.^{22,24} Ultimately, clinical decisions should be made based on the best scientific evidence available, the clinician's expertise and the patient's perceptions. Notably, the colorimeter device used to assess the color in the present study has an average accuracy of $\Delta E < 0.5$, and performs equally well in laboratory and clinical settings, making it suitable for clinically relevant interpretation.²⁷ The human eye starts to detect color differences at different values.¹² The perceptibility and acceptability thresholds for color differences are, therefore, a point of discussion in the literature. The conclusions derived from these values are subjective, given that color perception can be influenced by external stimuli, or even memory.¹⁵ Furthermore, it is important to ensure that the documentation is well conducted, and that the patient's needs and expectations are taken into account.

One of the main physical aspects that influence the optical properties of the material is its surface roughness.²⁸ As reported by Lu et al., the surface roughness of LD and ALD was not affected by an additional firing cycle, but by glazing.²² Although the 2nd firing cycle with glaze application impaired the fracture resistance of LD, the same strategy improved the mechanical behavior of ALD. In addition, scanning electron microscopy (SEM) indicated that refiring could not alter the surface morphology of the material, while glaze application led to smoother surfaces. Thus, it was suggested that the glassy phase on the ceramic could be partially molten during the 2nd firing, leading to better mechanical behavior, which implies the formation of different internal and superficial structures.²² Nonetheless, what is beneficial for ALD in terms of its mechanical properties has proven to be a critical problem when optical properties are considered.

When examining its mechanical behavior, ALD benefited from the 2nd firing cycle with glaze application (the c-g protocol), whereas the manufacturer's protocol (cg – 1 firing cycle with glaze application) resulted in lower flexural strength, which was still superior to that obtained with a single firing cycle without glazing (c).^{22,26} This study revealed that only the c protocol promoted similar translucency and whiteness, although this was accompanied by an unacceptable color change. Therefore, to maintain the optical properties of ALD indicated by the manufacturer, the cg protocol is advocated. Dental restorations require a balance between mechanical and optical properties. Thus, if a modification to the ALD firing protocol were to be implemented with the objective of improving mechanical properties, this would result in alterations to the optical properties of the restoration.

Limitations

Although the study provides valuable insights into the optical properties of ALD under various firing protocols, several limitations should be acknowledged. Firstly, the study did not investigate the potential influence of different kinds of surface treatment on the optical outcomes, which could have impacted the results.^{29,30} Additionally, variations in the restoration thickness and design were not accounted for, which could have affected light transmission and color perception.³¹ Moreover, the absence of fatigue testing limits the understanding of the long-term performance and durability of the materials under different firing conditions.³² Furthermore, the study did not explore the effects of bonding to different substrates, which could have influenced the overall optical behavior of the restorations.³³ Addressing these limitations in future research would provide a more comprehensive understanding of the optical behavior of LD and ALD restorations. The use of only one measuring device (VITA Easyshade) and only one specimen thickness can also be considered as the limitations of this study. To imitate clinical use, varying disk thicknesses should be investigated. Future research should employ different measuring devices, and consider the use of esthetic characterization and pigment solutions.³⁴ Additionally, there are dipping glazes which can influence the studied outcomes, and researchers are encouraged to explore them in future studies.

Conclusions

Advanced LD is highly susceptible to changes in color, translucency and WID, whereas LD demonstrates stability in the evaluated optical properties. All alternative firing protocols for ALD result in clinically unacceptable color variations when compared to the manufacturer-recommended protocol (cg).

Ethics approval and consent to participate

Not applicable.

Data availability

The datasets supporting the findings of the current study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable.

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