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Effect of Glazing Protocol on the Surface Roughness and Optical Properties of Lithia-Based Glass-Ceramics

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Abstract: Background: New lithia-based glass–ceramics, including Advanced Lithium Disilicate (ALD), have become popular in dentistry. However, it is unclear if glazing protocols for ALD might compromise its surface or optical properties. Thus, evaluating color and translucency changes in ALD and traditional lithium disilicate (LD) is crucial. Methods: This study aimed to assess how different firing protocols affect the surface and optical properties of LD and ALD. Sixty disc-shaped specimens were prepared, divided into three subgroups based on firing protocols, and subjected to surface roughness analysis. Specimens were immersed in coffee, wine, and water for 7 days, and then brushed. Color and translucency were measured. Results: Firing protocols significantly influenced surface roughness in LD (0.09–1.39 µm) and ALD (0.05–0.88 µm). Color differences were observed in both LD and ALD after 7 days, with visible changes within clinically acceptable thresholds. Translucency remained stable across firing protocols and staining liquids. Conclusions: Varying firing protocols impact surface roughness and color stability in LD and ALD. Despite differences, color and translucency changes remained within acceptable clinical thresholds, suggesting both materials are suitable for dental applications. Therefore, this study reinforces the reliability and versatility of these materials in restorative dentistry.

Keywords: dental materials; dental ceramics; lithia disilicate; optical phenomena; roughness

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1. Introduction

In recent decades, Lithia-Based Glass–Ceramics have gained significant popularity as a dental restorative material due to their exceptional combination of aesthetics and mechanical properties [1]. Their composition, which includes lithium disilicate crystals within a glass matrix, contributes to the translucency of this material, enabling it to closely replicate the optical characteristics found in natural teeth. This inherent aesthetic attribute, in conjunction with their notable resistance to flexural stress and fractures, establishes IPS e.max as a reliable lithium disilicate (LD) and versatile option for various clinical indications, spanning from anterior to posterior dental restorations [2].

LD ceramic restorations can be produced by two different methods. The first conventional method is the heat-pressing method. The second approach, which is a more controlled process, can be achieved by using Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technology [2]. The utilization of CAD/CAM milling enhances the manufacturing of indirect restorations, reducing inherent defects and consequently enhancing their mechanical properties [3]. Within the CAD/CAM method, there are two ways to process LD restorations: hard and soft machining. Hard machining involves the milling of

restorations from ceramic blocks that are fully crystallized. This process is time-intensive because of the hardness of the material and the wear it causes on the milling bur. Soft machining causes less wear on the milling bur because the ceramic blocks are partially crystallized. However, this procedure is also time-consuming, because to achieve full crystallization of the ceramic, thermal processing is needed [4].

A novel lithia-based glass–ceramic, named Advanced Lithium Disilicate (ALD) (CEREC Tessera, Dentsply Sirona, York, PA, USA), has recently been introduced to the market [1] and can be employed for various clinical indications, including crowns, onlays/inlays, and veneers [5]. ALD involves hard machining and is followed by a fast firing cycle with glaze (4 min and 30 s). The material contains lithium aluminum silicate crystals, called virgilite. The virgilite crystals are activated by the firing process and new virgilite crystals are formed, measuring in the nanometer range. This provides additional strength to the material [5]. Additionally, the crystals contribute to excellent aesthetics, which provides a convincing resemblance to natural teeth [4]. However, there is a lack of previous literature concerning the optical properties and how this important aesthetic feature can be affected by different firing protocols.

For dental restorations, achieving a smooth surface is a desirable objective for various reasons. Research has shown that higher surface roughness is associated with reduced flexural strength [6]. The surface roughness of hard dental materials is also of great importance when taking bacterial retention and biofilm formation into consideration, as bacteria in the oral cavity easily adhere to ceramic restorations within the oral cavity when polishing or glazing are inadequate [7,8]. Thereby, polishing and glazing procedures are recommended to enhance the emergence profile and occlusal relations of restorations [3]. According to the manufacturers of ALD, a glaze layer must be applied for the ceramic to achieve its final strength [9].

Different firing protocols can be applied to LD and ALD after milling the ceramic blocks to their desired shape. The firing protocol that has been recommended by the manufacturers is one-step firing in combination with glaze. The second firing protocol is a two-step firing in which the ceramic is crystallized during the first firing and will be refired with a glaze layer during the second firing. According to research, ALD showed higher strength with two-step firing, while LD showed higher strength with one-step firing. With both materials, the surface roughness will increase when a glaze layer is applied, regardless of which firing protocol is used [4]. Because different firing protocols change the surface properties of different lithium disilicates, it is questionable whether the optical properties of the materials will be affected. For ALD, little is known in the literature regarding optical properties.

Ceramic blocks of LD and ALD are produced in a variety of different shades and degrees of translucency to match the clinical situation. A restoration must not only match the initial shade but also sustain its aesthetic appeal for several years. Noticeable changes in color and translucency of the material could potentially affect the acceptability of the restoration. Discoloration may result in a variety of problems, such as the dissatisfaction of patients, expenses for replacement, and additional unnecessary working hours for the dentist [10]. Discoloration of teeth and restorative materials can be associated with pigmented beverages such as coffee and red wine. These beverages contain natural pigments and are considered risk factors for tooth discoloration. According to research, red wine was observed to result in more severe tooth staining when compared to coffee [11]. Because of its high esthetic results and easy fabrication process by CAD/CAM systems, lithium disilicate has lately been the most frequently applied choice for indirect restorations [12]. Therefore, it is of great importance to evaluate the influence of different staining liquids on the color and translucency change in both lithia-based glass–ceramics.

Thus, the objective of this study was to evaluate the effect of different firing protocols on the surface roughness and optical properties of two lithium disilicates. The null hypotheses state that different firing protocols would promote [1] different surface roughness values from the manufacturer's recommendation and would negatively affect [2] color stability and [3] translucency parameters when submitted to different pigment solutions.

2. Materials and Methods

2.1. Specimens Preparation

Six (6) blocks of CAD/CAM lithium disilicates (IPS e.max CAD–LD and Cerec Tessera blocks–ALD) were shaped into cylinders (Ø = 10 mm) using a diamond drill (Metabo SBE 1010 Plus). The cylinders were sliced into sixty (60) discs with a thickness of approximately 1.2 mm, using a precision sawing machine (Isomet 100, Buehler, IL, USA) under constant water irrigation. Afterward, both sides of the discs were polished using an orbital polishing machine (Ecomet polisher, Buehler LTD) using #1200 grit silicon carbide papers (Microcut, silicon carbide, Buehler) until the final thickness of 1.2 mm.

The specimens of each ceramic were randomly divided into three subgroups (n = 10) according to the firing and glazing protocols: crystallized (*c*), crystallized with glaze in one step (*cg*), and crystallized followed by a glaze firing in two steps (*c-g*). The firing and glaze protocols used in the study are presented in Table 1, and this information was extracted from previous research [4]. The glaze materials were applied following the manufacturers' guidelines. The glaze indicated by each manufacturer was used for the firing protocol groups *cg* and *c-g*. All the firing procedures were processed in the same furnace (Programat P100; Ivoclar Vivadent, Schaan, Liechtenstein). The information on the used materials is summarized in Table 2.

Table 1. Firing and glaze protocols were used in the study.

Group	Ceramic	Firing Protocol	Firing 1	Firing 2
LD*c*	Lithium disilicate—LD IPS e.max CAD, Ivoclar	*c*: Crystallization	LD crystallization firing: * 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 until 770 °C. Vacuum 2: 770 until 850 °C. Long-term cooling: 700 °C/min.	-
LD*cg*		*cg*: One-step crystallization and glaze firing		-
LD*c-g*		*c-g*: Two-step crystallization and glaze firing		Universal Spray Glaze firing
ALD*c*	Advanced Lithium Disilicate—ALD Tessera Blocks, Sirona	*c:* Crystallization	ALD crystallization firing: ** 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 2: off. Long-term cooling: 0 °C/min.	-
ALD*cg*		*cg*: One-step crystallization and glaze firing		-
ALD*c-g*		*c-g*: Two-step crystallization and glaze firing		Universal Spray Glaze firing

* LD crystallization firing is the same protocol indicated for the firing of IPS e.max CAD with the application of IPS e.max Crystall Glaze Spray in one step; ** ALD crystallization firing is the same protocol indicated for matrix firing, one-step crystallization/glazing firing, and Universal Spray Glaze firing.

Table 2. Materials used in the study.

Material	Commercial Name	Manufacturer	Composition (wt%)
Pre-crystallized lithium disilicate glass-ceramic (LD)	IPS e.max CAD	Ivoclar, Schaan, Liechtenstein	SiO_2, 57.0–80.0%; Li_2O, 11.0–19.0%; K_2O, 0.0–13.0%; P_2O_5, 0.0–11.0%; other oxides
Spray glaze	IPS e.max CAD Crystall glaze spray	Ivoclar, Schaan, Liechtenstein	Glazing powder, propellant, isobutane
Advanced lithium disilicate (ALD)	CEREC Tessera	Dentsply Sirona, Hanau-Wolfgang, Germany	Glass zirconia matrix, lithium disilicate, virglite ($LiAlSiO_6$)
Spray glaze	Universal Spray Glaze	Dentsply Sirona, Hanau-Wolfgang, Germany	Silicate glass, isopropyl alcohol, isobutane, propellant

2.2. Surface Roughness Analysis

To evaluate the effect of firing protocols on the ceramics' surface roughness, all discs were submitted to surface roughness analysis, considering the arithmetic average roughness (Ra in µm). Each surface was measured three times in 3 random different areas with a read length of 5 mm and a speed of 0.2 mm/s using a profilometer (Mitutoyo SJ-400, Tokyo, Japan). The analysis was performed following ISO 4287–1997 standards [13], with a Gaussian Filter and cut-off wavelength value of 0.8 mm [14]. The mean surface roughness (Ra) of each specimen was calculated.

2.3. Staining Procedures

After the roughness measurements and the baseline color and translucency measurements had been performed, transparent tape was applied to the intaglio surface of the specimens to prevent the discs from discoloring on both sides [15]. The specimens, each divided into their subgroup [n = 4 (coffee/wine) n = 2 (water) N = 10], were immersed in closed containers. Each container contains 40 mL of the staining liquid [16]. All containers were stored in an incubator at 37 °C. At the end of each immersion period, before color and translucency measurements, the discs were rinsed with distilled water and wiped with a dry paper towel [17]. Staining liquids were changed after every measurement.

The staining liquids were coffee, red wine, and distilled water. The coffee solution was made according to the manufacturer's instructions, in which 10 g of coffee (Nescafé® Classic, Nestle Japan, Kobe, Japan) was added to 500 mL of distilled boiled water [17]. After cooling down to room temperature, the coffee solution was filtered through a paper filter. The red wine (Domaine Marquis de Belloc, Merlot, 2009 at room temperature) was filtered through a paper filter.

2.4. Color and Translucency Measurements

The color and translucency measurements were carried out using a digital spectrophotometer (VITA Easyshade Advance® V, VITA Zahnfabrik, Bad Säckingen, Germany). The spectrophotometer was calibrated with the white reference provided in the same device before measuring each group. All measurements were recorded as CIE L*a*b* values. Specimens were measured against a gray, black, and white background, using a box to protect against harsh lighting. Each specimen was measured three times against each background. The average per specimen for each background was calculated [3,18]. Measurements were performed at baseline and after 24 h, 3 days, and 7 days.

2.5. Brushing

After the completion of the staining period, all specimens were rinsed with distilled water and wiped with a dry paper towel. After rinsing and drying, all specimens were brushed with an oscillating-rotating electrical toothbrush with a round brush head (Oral-B iOTM, Series 7, Procter & Gamble) and a solution made with 125 g of toothpaste (Colgate Sensitive, Colgate-Palmolive Indústria e Comércio, São Paulo, Brazil) suspended in 500 mL of distilled water [19]. The specimens were placed in a special device with the exact measurements of the discs to restrict the brushing area. The electrical toothbrush contains a smart pressure sensor that provides positive feedback by providing a green light when optimal pressure (0.8–2.5 N) is used [20]. All discs were brushed for 3 s, corresponding to 1 day of brushing (84 sites, 240 s of brushing per day, 240/84 = 2.9 s per site per day). After brushing, the discs were rinsed with water and wiped with a dry paper towel. All discs were measured again using the same measuring method as described above.

2.6. Color Change (ΔE_{00})

Color change measurements were carried out against a gray background [n = 4 (coffee/wine) n = 2 (water) N = 10]. To calculate the difference in color perception, the ΔE_{00} for CIEDE2000 equations was used [21]:

$$DE_{00} = \left[\left(\frac{DL}{K_L * S_L} \right)^2 + \left(\frac{DC}{K_C * S_C} \right)^2 + \left(\frac{DH}{K_H * S_H} \right)^2 + R_T \left(\frac{DC}{K_C * S_C} \right) * \left(\frac{DH}{K_H * S_H} \right) \right]^{0.5}$$

The L* value corresponds to the level of lightness (L* = 0 corresponds to black, L* = 1 corresponds to white), while the * value signifies the presence of the red-green color component (−a* = green; +a* = red). The yellow and blue color components are represented along the b* axis (−b* = blue; +b* = yellow) (21). The acceptability threshold (AT) for color change (ΔE_{00}) is 1.77. The perceptibility threshold (PT) is 0.81. This indicates that

values under 0.81 are not clinically visible and, thus irrelevant. Values between 0.81 and 1.77 are clinically visible and acceptable. Values above 1.77 are clinically unacceptable [21].

2.7. Translucency Parameter (TP)

The translucency parameter (TP) was evaluated according to the color difference between the black and white background measurement [n = 4 (coffee/wine) n = 2 (water) N = 10]. This difference was calculated using CIEDE2000 (TP_{00}) (22).

$$TP_{00} = \left[\left(\frac{L\prime_B - L\prime_W}{K_L * S_L} \right)^2 + \left(\frac{C\prime_B - C\prime_W}{K_C * S_C} \right)^2 + \left(\frac{H\prime_B - H\prime_W}{K_H * S_H} \right)^2 + R_T \left(\frac{C\prime_B - C\prime_W}{K_C * S_C} \right) * \left(\frac{H\prime_B - H\prime_W}{K_H * S_H} \right) \right]^{0.5}$$

To obtain the value of change in translucency (ΔTP_{00}), the baseline TP value must be subtracted from the TP value from the measuring moments of 24 h, 3 days, or 7 days. The acceptability threshold (AT) for translucency change (ΔTP_{00}) is 2.62. The perceptibility threshold (PT) is 0.62. Therefore, values under 0.62 are not clinically visible, and irrelevant. Values between 0.62 and 2.62 are clinically visible but acceptable. Values above 2.62 are clinically visible and unacceptable.

2.8. Statistical Analysis

Surface roughness, color change, and translucency parameter measurements were evaluated using an analysis of variance (ANOVA). One-way ANOVA and the Tukey post hoc test ($\alpha = 0.05$) were used to evaluate surface roughness, considering the firing protocols for each ceramic. For color and translucency changes, a two-way ANOVA and the Tukey post hoc test ($\alpha = 0.05$) were used considering firing protocols and staining liquids. The color and translucency difference considering the evaluation period was evaluated using repeated measures of the one-way ANOVA and the Bonferroni post hoc test ($\alpha = 0.05$).

3. Results

The mean and standard deviation of the surface roughness (Ra) are presented in Table 3. For LD and ALD, one-way ANOVA showed that the firing protocol affected Ra ($p < 0.001$; F = 173.149; $p < 0.001$; F = 51.826, respectively). Applying glaze spray for both one-step (*cg*) and two-step (*c-g*) firing protocols increased the Ra in both LD and ALD. The two-step firing (*c-g*) showed higher Ra than the one-step firing (*cg*).

Table 3. Mean surface roughness (Ra) in μm and standard deviation (sd).

Group	Ra (Mean ± sd)
LD *	
c	0.09 ± 0.01 ^{C}
cg	0.78 ± 0.16 ^{B}
c-g	1.39 ± 0.22 ^{A}
ALD *	
c	0.05 ± 0.01 ^{C}
cg	0.52 ± 0.16 ^{B}
c-g	0.88 ± 0.27 ^{A}

One-way ANOVA and Tukey post hoc test ($\alpha = 0.05$). Letters in each row represent statistical significances for Ra between firing techniques (*c*, *cg*, and *c-g*). * LD and ALD are not compared to each other in this table.

The ΔE_{00} mean and standard deviation values for LD and ALD are presented in Table 4. Figure 1 depicts line charts illustrating the color change per staining liquid for LD and ALD, considering firing protocols and periods of evaluation.

For LD, a color difference was only observed between crystallized specimens (*c*) immersed in coffee (C) for 24 h and 3 days in comparison to the color change after brushing. Considering the groups for each period of evaluation, *c*C showed lower values than *c-g*Wi

for both 24 h and 7 days. Considering the firing protocols for color change after 7 days, statistical differences in ΔE_{00} were not found (*c*: 0.46 ± 0.31 ^{A}; *cg*: 0.69 ± 0.29 ^{A}; and *c-g*: 0.71 ± 0.36 ^{A}). When considering staining solutions, significant color changes were found after 7 days with wine immersion being different from water, while coffee was similar to both (Wa: 0.39 ± 0.16 ^{B}; C: 0.57 ± 0.32 ^{AB}; and Wi: 0.78 ± 0.34 ^{A}). Between all observed values, three conditions were considered clinically visible and acceptable according to the acceptability threshold: *cg*C after 7 days and brushing and *c-g*Wi after 7 days.

Table 4. Color change (ΔE_{00}) values and standard deviation (sd) for LD and ALD according to different firing protocols, staining liquids, and periods of evaluation.

Group	Period *			
	24 h	**3 Days**	**7 Days**	**Brushing**
		LD **		
cWa	0.27 (0.03) ^{ABa}	0.27 (0.15) ^{Aa}	0.32 (0.14) ^{ABa}	0.50 (0.34) ^{Aa}
cgWa	0.40 (0.16) ^{ABa}	0.49 (0.26) ^{Aa}	0.52 (0.21) ^{ABa}	0.64 (0.22) ^{Aa}
c-gWa	0.23 (0.01) ^{ABa}	0.52 (0.23) ^{Aa}	0.35 (0.08) ^{ABa}	0.52 (0.07) ^{Aa}
cC	0.15 (0.06) ^{Bb}	0.21 (0.08) ^{Ab}	0.33 (0.15) ^{Bab}	0.55 (0.12) ^{Aa}
cgC	0.64 (0.40) ^{ABa}	0.67 (0.38) ^{Aa}	0.83 (0.42) ^{ABa}	0.81 (0.31) ^{Aa}
c-gC	0.49 (0.08) ^{ABa}	0.46 (0.12) ^{Aa}	0.58 (0.07) ^{ABa}	0.59 (0.26) ^{Aa}
cWi	0.67 (0.32) ^{ABa}	0.57 (0.19) ^{Aa}	0.68 (0.40) ^{ABa}	0.77 (0.30) ^{Aa}
cgWi	0.35 (0.16) ^{ABa}	0.49 (0.06) ^{Aa}	0.63 (0.09) ^{ABa}	0.64 (0.10) ^{Aa}
c-gWi	0.77 (0.22) ^{Aa}	0.43 (0.10) ^{Aa}	1.04 (0.37) ^{Aa}	0.78 (0.20) ^{Aa}
		ALD **		
cWa	0.36 (0.06) ^{Aa}	0.45 (0.19) ^{Aa}	0.67 (0.16) ^{ABCa}	0.46 (0.05) ^{Aa}
cgWa	0.26 (0.03) ^{Aa}	0.71 (0.47) ^{Aa}	0.77 (0.16) ^{ABa}	0.49 (0.26) ^{Aa}
c-gWa	0.20 (0.14) ^{Aa}	0.20 (0.01) ^{Aa}	0.29 (0.03) ^{BCa}	0.34 (0.07) ^{Aa}
cC	0.59 (0.26) ^{Aab}	0.49 (0.33) ^{Ab}	0.81 (0.25) ^{Aa}	0.82 (0.33) ^{Aab}
cgC	0.41 (0.22) ^{Aa}	0.39 (0.34) ^{Aa}	0.29 (0.19) ^{BCa}	0.37 (0.13) ^{Aa}
c-gC	0.24 (0.17) ^{Aa}	0.30 (0.11) ^{Aa}	0.43 (0.21) ^{ABCa}	0.48 (0.27) ^{Aa}
cWi	0.21 (0.11) ^{Aa}	0.24 (0.10) ^{Aa}	0.47 (0.11) ^{ABCa}	1.12 (0.82) ^{Aa}
cgWi	0.34 (0.26) ^{Aa}	0.21 (0.10) ^{Aa}	0.32 (0.09) ^{BCa}	0.40 (0.07) ^{Aa}
c-gWi	0.40 (0.25) ^{Aa}	0.34 (0.31) ^{Aa}	0.27 (0.14) ^{Ca}	0.39 (0.11) ^{Aa}

* Periods compared to baseline condition. ** LD and ALD are not compared to each other in this table. Uppercase letters in each column represent statistical significances for color difference (ΔE_{00}) between firing techniques (*c*, *cg*, and *c-g*) and staining solutions (water, coffee, and wine), depicted by two-way ANOVA and Tukey post hoc tests ($\alpha = 0.05$). Lowercase letters in each row represent statistical differences for color difference (ΔE_{00}) for each color measurement period, depicted by repeated measures one-way ANOVA and Bonferroni post hoc tests ($\alpha = 0.05$). The acceptability threshold (AT) for color variation (ΔE_{00}) is 1.77. The perceptibility threshold (PT) is 0.81. Values between 0.81 and 1.77 are clinically visible but acceptable and presented in bold.

For ALD, a significant color change was observed for *c*C between 3 days and 7 days. Furthermore, between different groups at 7 days, significant color changes were observed between firing protocols and staining solutions. Considering the firing protocols for color change after 7 days, statistical differences were found in ΔE_{00} (*c*: 0.65 ± 0.2 ^{A}; *cg*: 0.39 ± 0.24 ^{B} and *c-g*: 0.34 ± 0.17 ^{B}). The highest color change was found in c, which is significantly higher than *cg* and *c-g*. Firing protocols *cg* and *c-g* showed similar changes compared to each other. Between different staining solutions, variations in color change were also found after 7 days (Wa: 0.57 ± 0.25 ^{A}; C: 0.51 ± 0.31 ^{AB}; and Wi: 0.35 ± 0.14 ^{B}). A significant difference was found between water and wine, with the highest color change in water. Water and wine were both similar to coffee. For ALD, three conditions were considered clinically visible and acceptable according to the ranges of the threshold: *c*C after 7 days and brushing and *c*Wi after brushing.

The translucency parameter (TP) mean and standard deviation values for LD and ALD are presented in Table 5. Figure 2 presents line charts illustrating absolute translucency parameter values for each staining liquid for LD and ALD, considering firing protocols and periods of evaluation.

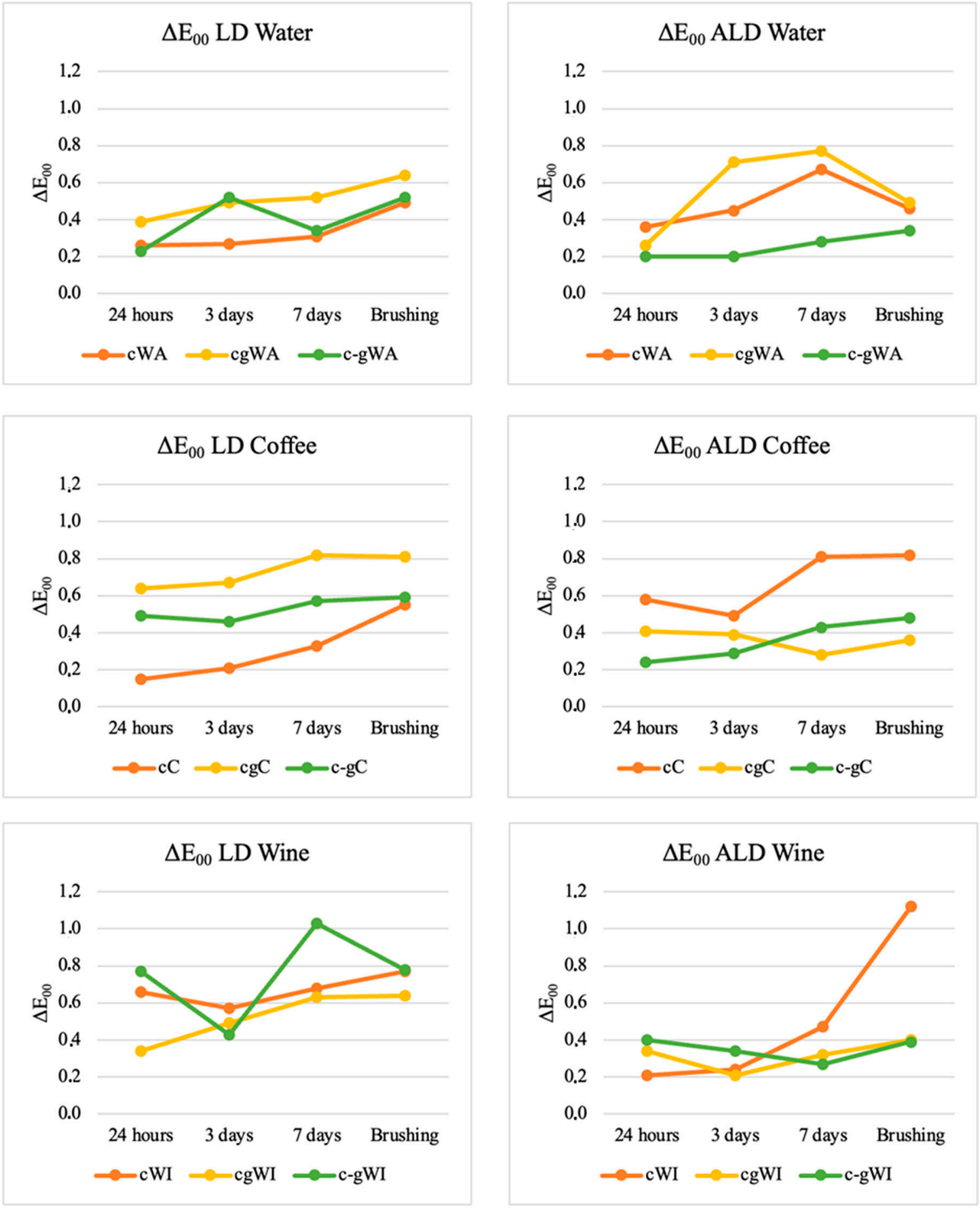


Figure 1. Line charts for LD and ALD, with ΔE values (y-axis) for each staining liquid (water, coffee, and wine), considering periods of evaluation (x-axis) and firing protocols (*c*, *cg*, and *c-g*).

For LD, differences were observed in the crystallized specimens (c) immersed in coffee (C) between the baseline measurement and measurements after 24 h and 3 days. Also, differences were observed between baseline and 24 h in one-step-glazed specimens (*cg*) that were immersed in coffee (C). In two-step-glazed specimens (*c-g*) that were immersed in water (Wa), a difference was found between 24 h and 3 days. The Tukey test did not show any statistical differences in the translucency parameter values considering firing protocols after 7 days (*c*: 12.70 ± 0.24^{A}; *cg*: 13.02 ± 0.36^{A} and *c-g*: 12.96 ± 0.41^{A}). Considering the staining liquids for changes in TP after 7 days, no significances were found (Wa: 12.86 ± 0.21^{A}; C: 12.95 ± 0.47^{A} and Wi: 12.86 ± 0.30^{A}).

Table 5. Mean translucency parameter (TP) and standard deviation (sd) for LD and ALD according to different firing protocols, staining liquids, and periods of evaluation.

Group	Baseline	24 h	3 Days	7 Days	Brushing
			LD *		
cWa	12.65 (0.55) ^{Aa}	13.17 (0.44) ^{Aa}	13.35 (0.86) ^{Aa}	12.86 (0.44) ^{Aa}	12.98 (0.39) ^{Aa}
cgWa	12.51 (0.03) ^{Aa}	12.88 (0.12) ^{Aa}	12.76 (0.03) ^{Aa}	12.81 (0.06) ^{Aa}	12.72 (0.05) ^{Aa}
c-gWa	12.65 (0.07) ^{Aab}	13.12 (0.11) ^{Aa}	12.98 (0.11) ^{Ab}	12.90 (0.16) ^{Aab}	12.85 (0.15) ^{Aab}
cC	12.45 (0.12) ^{Ab}	12.89 (0.17) ^{Aa}	12.73 (0.16) ^{Aa}	12.61 (0.24) ^{Aab}	12.84 (0.33) ^{Aab}
cgC	12.74 (0.51) ^{Ab}	12.92 (0.45) ^{Aa}	13.04 (0.32) ^{Aab}	13.12 (0.53) ^{Aab}	13.00 (0.46) ^{Aab}
c-gC	12.91 (0.43) ^{Aa}	13.27 (0.49) ^{Aa}	13.20 (0.46) ^{Aa}	13.11 (0.52) ^{Aa}	13.16 (0.57) ^{Aa}
cWi	12.59 (0.13) ^{Aa}	12.92 (0.45) ^{Aa}	12.77 (0.10) ^{Aa}	12.70 (0.14) ^{Aa}	12.74 (0.19) ^{Aa}
cgWi	12.69 (0.34) ^{Aa}	12.87 (0.27) ^{Aa}	12.89 (0.37) ^{Aa}	13.02 (0.26) ^{Aa}	12.82 (0.38) ^{Aa}
c-gWi	12.69 (0.25) ^{Aa}	12.88 (0.28) ^{Aa}	13.07 (0.24) ^{Aa}	12.85 (0.43) ^{Aa}	12.88 (0.33) ^{Aa}
			ALD *		
cWa	12.58 (1.00) ^{Aa}	13.21 (1.44) ^{Aa}	12.76 (0.57) ^{Aa}	12.63 (1.10) ^{Aa}	12.42 (0.77) ^{Aa}
cgWa	13.66 (1.94) ^{Aa}	13.79 (1.71) ^{Aa}	13.76 (1.91) ^{Aa}	13.41 (1.61) ^{Aa}	13.50 (1.86) ^{Aa}
c-gWa	14.41 (0.50) ^{Aa}	14.38 (0.65) ^{Aa}	14.29 (1.19) ^{Aa}	14.30 (0.86) ^{Aa}	14.20 (0.87) ^{Aa}
cC	12.54 (1.20) ^{Aa}	12.72 (0.93) ^{Aa}	12.69 (1.00) ^{Aa}	12.71 (0.99) ^{Aa}	12.45 (1.12) ^{Aa}
cgC	11.85 (0.34) ^{Ab}	12.18 (0.40) ^{Aa}	12.03 (0.53) ^{Aab}	11.87 (0.50) ^{Aab}	11.86 (0.46) ^{Ab}
c-gC	12.41 (0.35) ^{Aa}	12.78 (0.60) ^{Aa}	12.52 (0.33) ^{Aa}	12.49 (0.37) ^{Aa}	12.22 (0.28) ^{Aa}
cWi	13.97 (1.43) ^{Aa}	13.91 (1.49) ^{Aa}	13.84 (1.57) ^{Aa}	13.78 (1.27) ^{Aa}	13.70 (1.47) ^{Aa}
cgWi	13.73 (1.35) ^{Aa}	13.74 (1.35) ^{Aa}	13.68 (1.39) ^{Aa}	13.63 (1.32) ^{Aa}	13.61 (1.56) ^{Aa}
c-gWi	12.09 (0.62) ^{Aa}	12.40 (0.46) ^{Aa}	12.24 (0.46) ^{Aa}	12.06 (0.37) ^{Aa}	12.07 (0.40) ^{Aa}

* LD and ALD are not compared to each other in this table. Uppercase letters in each column represent statistical significances for the translucency parameter (TP) between firing techniques (*c*, *cg*, and *c-g*) and staining solutions (water, coffee, and wine), depicted by two-way ANOVA and Tukey post hoc tests ($\alpha = 0.05$). Lowercase letters in each row represent statistical differences for the translucency parameter (TP) for each color measurement period, depicted by repeated-measures one-way ANOVA and Bonferroni post hoc tests ($\alpha = 0.05$).

For ALD, the only difference that was observed was in the one-step-glazed specimens (*cg*) that were immersed in coffee (C). Specimens at the 24 h measurement showed a statistically higher TP value than at baseline and after brushing. Considering the firing protocols for the translucency parameter after 7 days, no statistical differences were observed (*c*: 13.12 ± 1.15 ^{A}; *cg*: 12.88 ± 0.31 ^{A}; *c-g*: 12.68 ± 0.97 ^{A}). Also, no significances in TP were found between different staining liquids after 7 days (Wa: 13.45 ± 1.21 ^{A}; C: 12.36 ± 0.71 ^{A} and Wi: 13.16 ± 1.27 ^{A}).

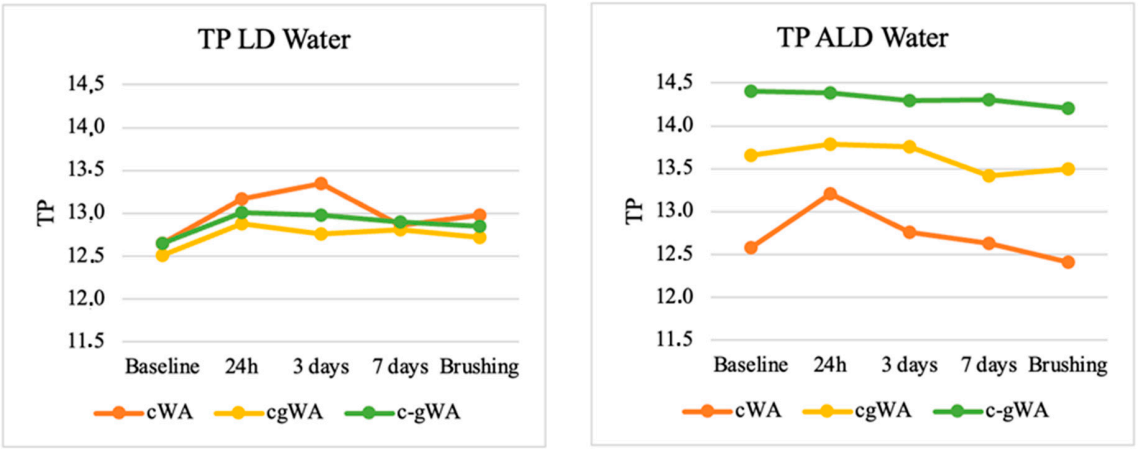


Figure 2. *Cont.*

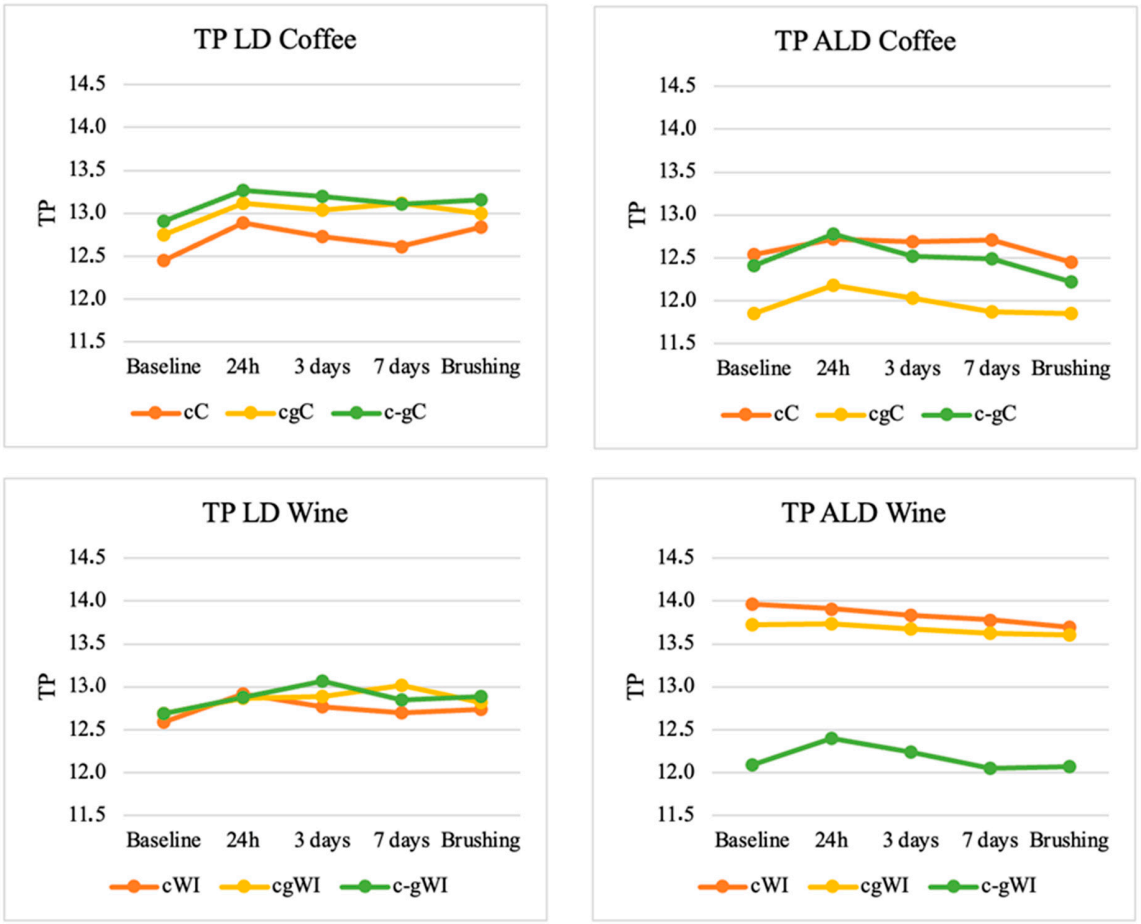


Figure 2. Line charts for LD and ALD, with TP values (y-axis) for each staining liquid, considering periods of evaluation (x-axis) and firing protocols (c, *cg*, and *c-g*).

The ΔTP_{00} mean and standard deviation values for LD and ALD are presented in Table 6. Figure 3 shows line charts illustrating the ΔTP_{00} per staining liquid for LD and ALD, considering firing protocols and periods of evaluation.

Table 6. Translucency parameter change (ΔTP_{00}) values and standard deviation (sd) for LD and ALD according to different firing protocols, staining liquids, and periods of evaluation.

Group	Period *			
	24 h	3 Days	7 Days	Brushing
	LD **			
cWa	0.53 (0.11) ^{Aa}	0.71 (0.30) ^{Ba}	0.21 (0.11) ^{Aa}	0.33 (0.17) ^{Aa}
cgWa	0.37 (0.16) ^{Aa}	0.26 (0.06) ^{ABa}	0.30 (0.10) ^{Aa}	0.21 (0.09) ^{Aa}
c-gWa	0.37 (0.04) ^{Aa}	0.34 (0.04) ^{ABa}	0.25 (0.08) ^{Aa}	0.20 (0.08) ^{Aa}
cC	0.44 (0.06) ^{Aa}	0.28 (0.05) ^{Aa}	0.17 (0.13) ^{Aa}	0.40 (0.38) ^{Aa}
cgC	0.38 (0.07) ^{Aa}	0.30 (0.23) ^{Aa}	0.37 (0.13) ^{Aa}	0.25 (0.11) ^{Aa}
c-gC	0.37 (0.20) ^{Aa}	0.30 (0.08) ^{Aa}	0.20 (0.09) ^{Aa}	0.25 (0.15) ^{Aa}
cWi	0.33 (0.32) ^{Aa}	0.18 (0.06) ^{Aa}	0.14 (0.15) ^{Aa}	0.14 (0.11) ^{Aa}
cgWi	0.18 (0.14) ^{Aa}	0.20 (0.10) ^{Aa}	0.54 (0.25) ^{Aa}	0.13 (0.07) ^{Aa}
c-gWi	0.19 (0.11) ^{Aa}	0.37 (0.11) ^{ABa}	0.41 (0.50) ^{Aa}	0.36 (0.36) ^{Aa}

Table 6. *Cont.*

Group	Period *			
	24 h	3 Days	7 Days	Brushing
	ALD **			
cWa	0.63 (0.44) ^{Aa}	0.31 (0.25) ^{Aa}	0.07 (0.07) ^{Aa}	0.16 (0.23) ^{Aa}
cgWa	0.16 (0.18) ^{Aa}	0.10 (0.03) ^{Aa}	0.24 (0.33) ^{Aa}	0.16 (0.08) ^{Aa}
c-gWa	0.11 (0.04) ^{Aa}	0.49 (0.18) ^{Aa}	0.26 (0.16) ^{Aa}	0.27 (0.29) ^{Aa}
cC	0.29 (0.12) ^{Aa}	0.21 (0.19) ^{Aa}	0.26 (0.29) ^{Aa}	0.07 (0.14) ^{Aa}
cgC	0.33 (0.07) ^{Aa}	0.23 (0.13) ^{Aa}	0.14 (0.09) ^{Aa}	0.10 (0.08) ^{Aa}
c-gC	0.37 (0.36) ^{Aa}	0.18 (0.14) ^{Aa}	0.08 (0.05) ^{Aa}	0.19 (0.11) ^{Aa}
cWi	0.21 (0.12) ^{Aa}	0.28 (0.32) ^{Aa}	0.27 (0.17) ^{Aa}	0.27 (0.33) ^{Aa}
cgWi	0.13 (0.08) ^{Aa}	0.17 (0.08) ^{Aa}	0.16 (0.12) ^{Aa}	0.35 (0.25) ^{Aa}
c-gWi	0.30 (0.16) ^{Aa}	0.24 (0.08) ^{Aa}	0.20 (0.19) ^{Aa}	0.19 (0.16) ^{Aa}

* Periods compared to baseline condition. ** LD and ALD are not compared to each other in this table. Uppercase letters in each column represent statistical significances for translucency differences (ΔTP_{00}) between firing techniques (*c*, *cg*, and *c-g*) and staining solutions (water, coffee, and wine), depicted by two-way ANOVA and Tukey post hoc tests ($\alpha = 0.05$). Lowercase letters in each row represent statistical differences for translucency differences (ΔTP_{00}) for each color measurement period, depicted by repeated measures one-way ANOVA and Bonferroni post hoc tests ($\alpha = 0.05$). The acceptability threshold (AT) for translucency change (ΔTP_{00}) is 2.62. The perceptibility threshold (PT) is 0.62. Values between 0.62 and 2.62 are clinically visible but acceptable and presented in bold.

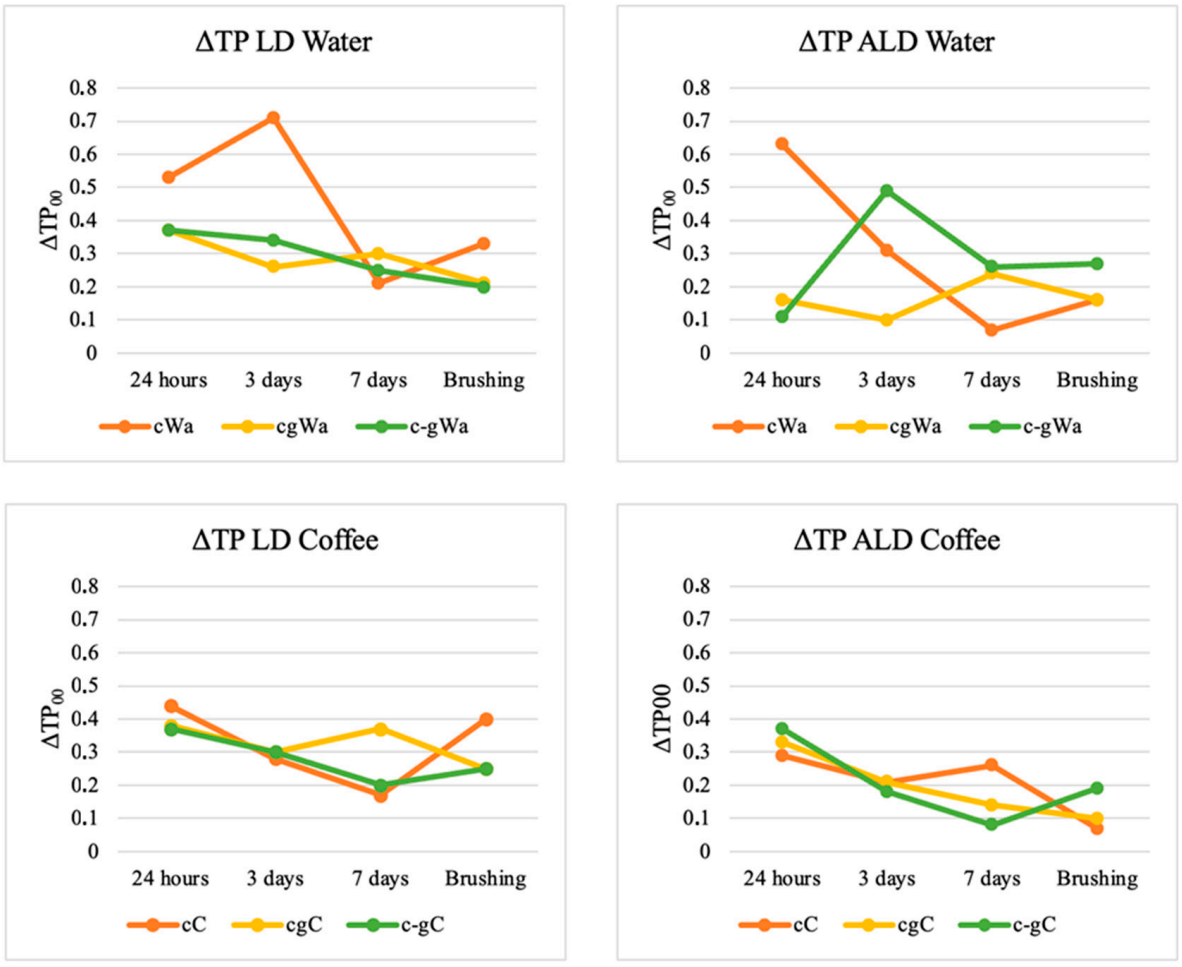


Figure 3. *Cont.*

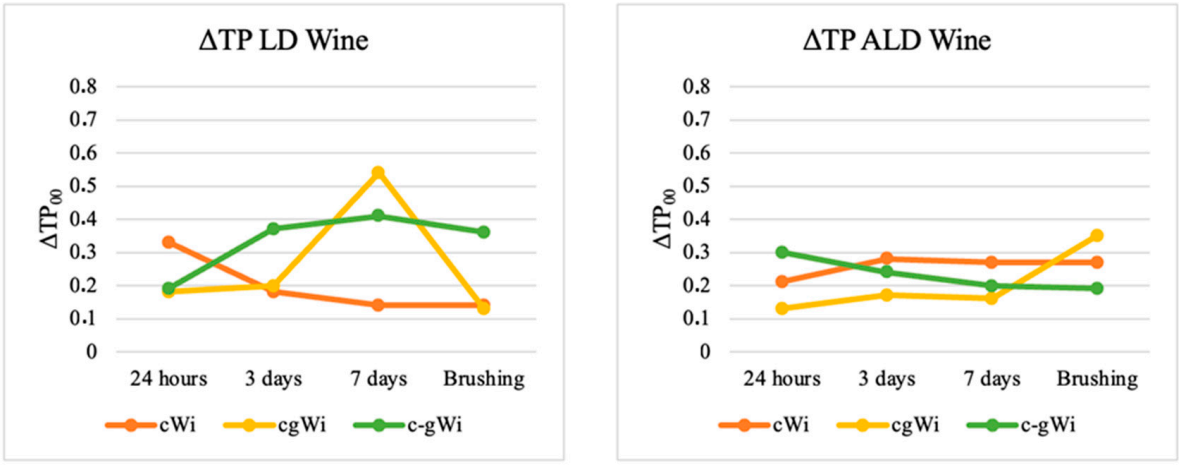


Figure 3. Line charts for LD and ALD, with ΔTP_{00} values (y-axis) for each staining liquid, considering periods of evaluation (x-axis) and firing protocols (*c*, *cg*, and *c-g*).

For LD, a difference was observed between groups after 3 days, and cWa showed a significantly higher value compared to other groups. Considering different firing protocols for changes in translucency, no statistical changes were found after 7 days (*c*: 0.16 ± 0.12 ^{A}; *cg*: 0.43 ± 0.20 ^{A}; and *c-g*: 0.30 ± 0.31 ^{A}). For a change in translucency considering the staining liquids, no significances were observed (Wa: 0.25 ± 0.09 ^{A}; C: 0.25 ± 0.14 ^{A}; and Wi: 0.36 ± 0.35 ^{A}). A clinically visible and acceptable change in translucency, according to the acceptability threshold, was seen with cWa after 3 days.

Considering different firing protocols for ALD, no significant changes in TP00 after 7 days were found (*c*: 0.22 ± 0.21 ^{A}; *cg*: 0.17 ± 0.14 ^{A}; and *c-g*: 0.17 ± 0.15 ^{A}). Significant differences in TP_{00} were not found between different staining solutions after 7 days (Wa: 0.19 ± 0.19 ^{A}; C: 0.16 ± 0.17 ^{A}; and Wi: 0.21 ± 0.15 ^{A}). According to the acceptability threshold, a clinically visible and acceptable translucency change with water was seen after 24 h.

4. Discussion

This study aimed to evaluate the effect of different firing protocols on the surface roughness and optical properties of two lithium disilicates. Because of their popularity, predicting the aesthetic lifespan of different lithium disilicate materials is crucial; due to their exceptional combination of aesthetics and mechanical properties, they are commonly used as dental restorative materials. In addition, the consumption of various staining foods and beverages daily, potentially affects their appeal over time [17]. Currently, little is known about the optical properties of the recently released 'advanced' lithium disilicate (ALD) that could be affected by different firing protocols or exposure to different pigment liquids.

According to the results, the first hypothesis that different firing protocols would promote different surface roughness values was accepted. For both ceramics, the mean surface roughness was higher for the *cg* and *c-g* groups when compared to the c groups, with the highest average Ra found in the *c-g* groups in both LD and ALD. The *c-g* group experienced an additional firing cycle compared to both the c and *cg* groups.

In the present study, the surface roughness values of LD and ALD are not directly compared to each other. However, a previous study stated that LD groups (c, *cg*, and *c-g*) showed a significantly higher mean Ra than the ALD groups (c, *cg*, and *c-g*) (4). In principle, LD has a higher average Ra value than ALD. A factor that may play a role in the surface roughness is the composition of the materials itself: Lithium disilicate primarily consists of needle-shaped lithium disilicate crystals (1.0 µm) embedded within a glossy matrix [5]. Using the CAD/CAM technique, partially crystallized LD blocks are used. The size of the crystals is determined during the final crystallization process [22]. Different from LD, ALD not only contains lithium disilicate crystals but also virgilite crystals (0.5 µm), in a

glassy matrix with zirconia [5]. According to the manufacturer, during the firing process of ALD, new virgilite crystals are formed, measuring in the nanometer range [5,23]. In a prior study, the impact of surface characteristics following multiple firings of LD without the use of glaze was examined. These findings are consistent with previous research indicating that additional firing cycles increase surface roughness [24]. Other research investigated the effect of glazing techniques and firing protocols on the surface roughness of ALD [4]. The research findings indicated that ALDc exhibited a statistically lower Ra compared to ALD*cg* and ALD*c-g*. Also, no statistically significant difference in Ra between one- and two-step-glazed ALD was found. SEM pictures in this study confirmed this finding as ALD*cg* and ALD*c-g* showed similarities in the surface morphology. It should be noted, however, that the study included only two specimens per group, in contrast to ten specimens per group in the present study. The existing literature provides limited insights into the surface properties of ALD following multiple firings. Further research is needed to determine if the phenomenon observed in LD also applies to ALD. Should this be the case, the quantity of firings should be considered, as achieving a smooth surface for indirect restorations is a desirable objective for various reasons.

The threshold for the Ra of hard dental materials where no impact on bacterial adhesion and retention could be observed is 0.2 µm [7]. In this study, both protocols involving glaze application, regardless of the firing protocol, were measured higher than this Ra threshold. In addition to the inherent material properties, the method of applying the glaze layer is another factor that could contribute to an increase in surface roughness. Glaze can be applied by using a powder-in-liquid/pasta technique or a spray technique. According to previous research, using the spray technique, a thinner layer of glaze can be applied than by using other techniques. The same research stated that a rougher surface was promoted by the spray technique than by applying the glaze by brush [25].

The second hypothesis was that different firing protocols would negatively affect the color stability of LD and ALD when submitted to different pigment solutions. This hypothesis was rejected. After 7 days and examining various firing protocols, a significant color change was only observed in ALDc. In the context of different staining liquids, the most significant color change after 7 days was observed in LD with wine, while ALD exhibited the most substantial color change with water. When taking the acceptability threshold (AT) for color variation (ΔE_{00}) [21] into consideration, for both LD and ALD, three conditions per group were clinically visible and acceptable. It must be noted that visible color changes in ALD were only visible in the crystallized (c) group, which is not the recommended firing protocol by the manufacturer. Other mean ΔE_{00} values were below the clinically perceptible threshold, which means that the color changes were not visible and, thus, irrelevant.

In general, wine contains various compounds, including phenolic compounds like tannins, anthocyanins (responsible for the red color), and other organic molecules. These compounds can interact with the surface of inorganic materials such as glass–ceramic, leading to color changes over time [26,27]. The acidity of wine, along with its alcohol content, can also play a role in these interactions. Acids can react with certain pigments, altering their chemical structure and causing color shifts. Additionally, the alcohol in wine can act as a solvent, potentially dissolving or dispersing the pigments in the materials, further affecting their color stability. Obviously, this effect is more predominant for porous materials such as composites, but some effects can also be observed in silica-based structures such as the evaluated ceramic materials [26,27].

According to a recent study [18], it was concluded that there was no perceptible color change in LD and ALD after coffee thermocycling. The firing protocol that was applied for LD was two-step glaze firing and the firing protocol for ALD was one-step glaze firing. These findings contrast with previous studies, which found no perceptible color change in LD and ALD after coffee thermocycling [18,28–30]. Other previous studies have also shown that LD is resistant to visible color changes, which does not corroborate with the results in the present study [28–30]. In the previously cited studies, staining was induced through

a method involving 5000 rounds of coffee thermocycling with temperatures fluctuating between 55° and 5 °C, corresponding to 6 months of clinical staining [31].

Both LD and ALD can be used for minimally invasive preparations. The manufacturer guidelines for both materials advise different recommendations for the minimum thickness of veneers and crowns. For LD a minimal thickness of 1.0 mm is advised [32]. ALD has a recommended minimum labial thickness of 0.6 mm for veneers and a 1.0 mm thickness for anterior crowns [33]. In the present study, all specimens were sliced into discs with a thickness of approximately 1.2 mm. According to previous research, the thickness of LD ceramic affected the color stainability significantly. A lower color change was measured in specimens with a 2.0 mm thickness than specimens with a 1.5 mm thickness. It is stated that ceramics with a 2 mm thickness are effective in masking the underlying color of, for example, dentin or metal [34]. Other research investigated the color stability of LD specimens at four different thicknesses, and all specimens were sliced at 1.2 mm or thinner. No perceptible color change was measured after coffee thermocycling, but different firing protocols have not been taken into account [29]. Additional research is required to assess the impact of various staining solutions on ALD with varying thicknesses. This material is promoted by the manufacturer for its exceptional aesthetic qualities [35], yet there is a dearth of knowledge on this topic within the current literature.

Based on the results of the current study, it could be stated that brushing in the short term does not affect the visible color change in LD and ALD. According to the acceptability threshold, LD-*cg*C and ALD-cC both showed visible color changes after 7 days and after brushing. Previous in vitro research investigated the influence of toothbrushing on extrinsically stained lithium disilicate [36]. A statistically significant color change was only found after 288 h of brushing, which is equivalent to 12 years of clinical toothbrushing. However, a significant change was not visible according to the perceptibility and acceptability threshold, so the outcome was not considered clinically significant. Currently, there are no published studies that evaluate the effect of toothbrushing on the optical properties of ALD.

Finally, the third hypothesis is that different firing protocols would negatively affect the translucency parameter (TP) when submitted to different pigment solutions. This hypothesis could be rejected. Between different firing protocols after 7 days, no significant changes were found in TP and TP_{00}. Also, no changes were found between different staining liquids after 7 days. According to the acceptability threshold, clinically visible and acceptable changes were observed in TP_{00} [37,38]. In LD, changes were found after 3 days, and in ALD, they were found after 24 h. The ΔTP_{00} values were close to the perceptibility threshold of 0.62, so visible changes were minimal. Also, it must be noted that those visible changes were found in the control groups with distilled water. In previous research, specimens were stored in distilled water at 37 degrees Celsius for 24 h to rehydrate the ceramics before baseline color and translucency measurements [28]. In this research, coinciding with the results from the present study, no clinical effect on TP was seen after 5000 cycles of coffee thermocycling in LD.

In the current study, two staining liquids were evaluated: coffee and wine. An immersion period of 7 days was chosen, which corresponds to 7 months of staining in vivo [39]. In previous research, LD specimens were stained with a variety of staining liquids with different acidities for 4 weeks, which corresponds to 2.5 years of clinical staining [17]. No significant changes in ΔTP_{00} were found between different staining solutions. No studies within the current literature have examined the translucency change in ALD with wine, so no comparisons could be made with results from this research.

The optical characteristics are important, but we should also consider the mechanical properties of various lithia-based glass-ceramics, such as hardness, fracture toughness, and Young's modulus. These properties are crucial for determining the material's suitability for different dental applications. According to a few data from the literature, some aspects can be summarized below to compose the final idea that materials that share a clinical indication can behave very differently (Table 7) in the same condition [40–43].

Table 7. Mechanical Properties of Both Evaluated Materials Available in the Literature.

Ceramic	Fatigue Parameter (*n*)	Flexural Strength—One-Step Firing (MPa)	Fracture Load of Crowns (N)	Fatigue Parameter (*n*)	Hardness (GPa)	Elastic Modulus (GPa)
Lithium disilicate - LD PS e.max CAD, Ivoclar	14.1 [41]	402.9 ± 78.4 [4]	434.96 ± 88.01 [40]	14.1 [41]	6.63 ± 0.21 [42]	103 [43]
Advanced Lithium Disilicate - ALD Tessera Blocks, Sirona	21.4 [41]	282.1 ± 64.4 [4]	437.46 ± 69.17 [40]	21.4 [41]	7.37 ± 0.19 [42]	103 [43]

As previously mentioned, color and translucency measurements in this study were evaluated using a digital spectrophotometer. Although an attempt has been made to keep external factors such as ambient light and the location of the measurement box as stable as possible, it is challenging to ensure their perpetually identical conditions. The notable significant differences in the control group may be attributed to the use of this particular spectrophotometer. Therefore, the spectrophotometer used in this study should be evaluated in terms of repeatability and validity in future in vivo studies.

The primary limitation of this in vitro study is the inability to fully replicate the complex oral environment. To gain a more comprehensive understanding of the optical properties of LD and ALD under various firing protocols, future in vitro studies should consider extended durations and a broader range of staining solutions to better simulate clinical conditions. Long-term clinical research is also necessary to investigate the optical properties of LD and ALD in the intraoral environment under different firing protocols as well as in different designs and masses such as crowns or endocrowns [44] to fully replicate a bonded lithia-based glass-ceramic restoration.

5. Conclusions

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

1. Different firing protocols promote different surface roughness values in LD and ALD.
2. Different firing protocols affect the color stability of LD and ALD when exposed to different staining solutions. However, all visible changes were clinically acceptable.
3. Brushing in the short term has no clinically visible effect on color change after staining in LD and ALD.
4. Visible changes in translucency were not observed in LD and ALD specimens with one- and two-step crystallization with glaze firing according to the threshold for translucency change.

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