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Effects of simulated gastric acid on the optical properties of CAD/CAM glass-ceramics

Uticaj simulirane želudačne kiseline na optička svojstva CAD/CAM staklokeramike

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Abstract

Background/Aim. The influence of glazing and polishing procedures on surface changes in contemporary computer-aided design (CAD) and computer-aided manufacturing (CAM) – CAD/CAM glass-ceramics during exposure to simulated gastric acid remains unclear. The aim of this study was to investigate the effects of simulated gastric acid on the optical properties of glazed or polished glass-ceramic materials based on lithium disilicate, advanced lithium disilicate, and zirconia-reinforced lithium silicate. **Methods.** The specimens were divided into six experimental groups according to the ceramic material and surface-finishing procedure recommended by the manufacturers: CEREC Tessera™-glazed (CTG), CEREC Tessera™-polished (CTP), IPS e.max® CAD-glazed (IPSG), IPS e.max® CAD-polished (IPSP), VITA Suprinity®-glazed (VSG), and VITA Suprinity®-polished (VSP), with 10 specimens allocated to each group (n = 10). To simulate gastric conditions, the samples were immersed in hydrochloric acid (HCl, 0.06 M; pH 1.2) and incubated at 37 °C for 96 hrs. Before and after acid immersion, perceptual lightness (L*), red-green (a*), and yellow-blue (b*) coordinate values were recorded using a calibrated digital spectrophotometer. Color difference (ΔE_{00}) and translucency parameter (TP_{00}) were subsequently calculated using the CIEDE2000 formula. The data were analyzed using the Kruskal-Wallis and Wilcoxon signed-rank tests at a significance level of $p < 0.05$. **Results.** Acid immersion did not significantly affect the ΔE_{00} of the tested CAD/CAM glass-ceramics ($p > 0.05$). In contrast, TP_{00} was significantly influenced by both ceramic material and surface-finishing protocol. Significant reductions in TP_{00} values were observed in the CTG, CTP, and IPSG groups after acid immersion, whereas IPSP, VSG, and VSP showed no significant changes. Analysis of ΔTP_{00} revealed significant intergroup differences, with the highest median values observed in the IPSG, CTP, and VSP groups and the lowest in IPSP. **Conclusion.** Within the limitations of this *in vitro* study, no significant differences in ΔE_{00} were observed among the tested experimental groups following exposure to simulated gastric acid. However, TP_{00} appeared to be more sensitive to the acid challenge than color, and the changes varied according to the tested ceramic material and surface-finishing protocol.

Keywords:
ceramics; color; dental materials; fluorescence; gastric acid; materials testing.

Apstrakt

Uvod/Cilj. Uticaj postupaka glaziranja i poliranja na promene površinskih osobina savremenih staklokeramičkih materijala izrađenih primenom kompjuterski potpomognutog dizajniranja (*computer-aided design* – CAD) i kompjuterski potpomognute izrade (*computer-aided manufacturing* – CAM) – CAD/CAM tokom izlaganja simuliranoj želudačnoj kiselini još uvek nije dovoljno razjašnjen. Cilj rada bio je da se ispita uticaj simulirane želudačne kiseline na optička svojstva glaziranih ili poliranih staklokeramičkih materijala na bazi litijum-disilikata, naprednog litijum-disilikata i litijum-silikata ojačanog cirkonijom. **Metode.** Uzorci su podeljeni u šest eksperimentalnih grupa prema vrsti keramičkog materijala i postupku završne obrade površine koji preporučuju proizvođači: CEREC Tessera™-glazirana (CTG), CEREC Tessera™-polirana (CTP), IPS e.max® CAD-glazirana (IPSG), IPS e.max® CAD-polirana (IPSP), VITA Suprinity®-glazirana (VSG) i VITA Suprinity®-polirana (VSP), sa po 10 uzoraka u svakoj grupi (n = 10). Radi simulacije uslova u želucu, uzorci su potopljeni u hlorovodoničnu kiselinu (HCl, 0,06 M; pH 1,2) i inkubirani na temperaturi od 37 °C tokom 96 sati. Pre i nakon potapanja u kiselinu, početne vrednosti koordinata perceptivne svetline (L*), žutocrvene (a*) i žutoplave (b*) izmerene su pomoću kalibrisanog digitalnog spektrofotometra. Razlika u boji (ΔE_{00}) i vrednosti

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parametra translucencije (TP‰) naknadno su izračunate pomoću formule CIEDE2000. Podaci su analizirani primenom Kruskal-Wallis-ovog i Wilcoxon-ovog *signed-rank* testa, uz nivo značajnosti od $p < 0,05$. **Rezultati.** Potapanje u kiselinu nije značajno uticalo na ΔE‰ ispitivanih CAD/CAM staklokeramika ($p > 0,05$). Nasuprot tome, na TP‰ značajno su uticali i vrsta keramičkog materijala i postupak završne obrade površine. Značajno smanjenje vrednosti TP‰ uočeno je u grupama CTG, CTP i IPSG nakon potapanja u kiselinu, dok u grupama IPSP, VSG i VSP nisu utvrđene značajne promene. Analiza promene parametra ΔTP‰ pokazala je značajne razlike između grupa, pri čemu su najviše vrednosti medijane zabeležene u grupama IPSG, CTP i VSP, a najniže u grupi IPSP. **Zaključak.** Uz uvažavanje ograničenja ove *in vitro* studije, nisu utvrđene značajne razlike u vrednostima ΔE‰ između ispitivanih eksperimentalnih grupa nakon izlaganja simuliranoj želudačnoj kiselini. Međutim, TP‰ se pokazao osetljivijim na delovanje kiseline u poređenju sa bojom, a promene su varirale u zavisnosti od ispitanog keramičkog materijala i postupka završne obrade.

Ključne reči:
keramika; boja; stomatološki materijali; fluorescencija; želudačna kiselina; materijali, testiranje.

Introduction

Dental erosion is the chemical dissolution of tooth structure by acids without bacterial involvement [1]. An example of an external risk factor includes beverages like soft drinks, which increase dietary acidity, while gastric acid is an internal risk factor [2–5].

The etiology of acid in the intraoral region is multifactorial, including, but not limited to, gastroesophageal reflux disease (GERD), eating disorders such as bulimia nervosa, and nausea during pregnancy. GERD is a prevalent medical condition with a global prevalence ranging from 2.5% to 28.8% worldwide, with a higher prevalence observed in Europe and the United States [6, 7]. GERD can develop when the upper esophageal sphincter involuntarily relaxes, allowing acid from the stomach to pass into the mouth [8]. Bulimia nervosa is a clinical condition that includes eating disorders such as excessive concern about body weight and shape, self-induced purging, and preventing weight gain [9]. In addition to erosive tooth wear, high levels of intraoral acid can also affect the surface properties of restorative materials [10–12].

Advancements in ceramics, bonding protocols, and fabrication methods have facilitated the production of aesthetically pleasing, biocompatible, and durable fixed prosthetic restorations. Translucency parameter (TP‰) and optical properties that affect the aesthetic outcomes of ceramic restorations have been linked to patient satisfaction [13, 14]. Finishing and polishing enhance the restoration's surface quality, protect opposing teeth from abrasion, and prevent bacteria from adhering to the restoration surface. In the literature, there are studies reporting that polishing and finishing of the restoration improve color stability [15, 16].

IPS e.max® CAD (IPS) was introduced in 2006 as a lithium disilicate glass-ceramic material prepared for computer-aided design (CAD) and computer-aided manufacturing (CAM) – CAD/CAM systems. Its use has increased over time for chairside restorations, due to its aesthetic nature, impressive strength, durability, and ease of use. VITA Suprinity® (VS) is a zirconia-reinforced lithium silicate (ZLS) glass-ceramic containing 8–12% by weight (wt%) zirconium dioxide (ZrO_2) [17–19].

CEREC Tessera™ (CT) is an advanced lithium disilicate glass-ceramic introduced in 2021. It consists of lithium disilicate and lithium aluminum silicate (virgilite) crystals embedded in a zirconia-enriched glassy matrix [20]. To the best of our knowledge, no previous study has evaluated the effect of simulated gastric acid exposure on the optical properties of this recently introduced material. The manufacturer also offers a rapid glazing/crystallization protocol that shortens the overall fabrication time of CT restorations [20]. Contemporary CAD/CAM glass-ceramics differ considerably in crystalline composition, crystal morphology, crystal volume fraction, and glass matrix characteristics. These microstructural differences may influence their optical behavior, chemical durability, and resistance to acid-induced degradation [21, 22].

Restoration surfaces encountered clinically may be either factory-glazed or adjusted and subsequently polished [23]. Despite the widespread clinical use of glazing and mechanical polishing, their effects on the mechanical and optical properties of glass-ceramic materials remain incompletely understood, and no standardized protocol has yet been established for the final finishing of milled ceramic surfaces [13, 23, 24]. Previous investigations have demonstrated that surface-finishing procedures significantly influence the optical properties, surface integrity, and resistance of ceramic materials to environmental degradation [25, 26]. Therefore, evaluating three contemporary CAD/CAM glass-ceramic systems under identical simulated gastric acid conditions may improve understanding of how material composition and surface-finishing influence their optical performance.

The aim of this study was to examine the effects of simulated gastric acid on the optical properties of glazed and polished CAD/CAM glass-ceramics under standardized experimental conditions.

The first null hypothesis was that simulated gastric acid immersion would not cause significant differences in color change (ΔE‰) among the tested ceramic materials and surface-finishing procedures. The second null hypothesis was that no significant differences in TP‰ would be observed among the tested ceramic materials and surface-finishing procedures following simulated gastric acid immersion.

Methods

As this was an *in vitro* study performed exclusively on commercially available CAD/CAM ceramic materials, ethical approval was not required. An *a priori* sample size calculation was performed using G*Power software (version 3.1.9.7; Heinrich Heine University Düsseldorf, Düsseldorf, Germany). The calculation was based on a two-way fixed-effects analysis of variance – ANOVA for evaluating the material × surface-finishing interaction in a 3 × 2 factorial design. Assuming an effect size of $f = 0.60$, a significance level of $\alpha = 0.05$, and a statistical power of 80% ($1-\beta = 0.80$), the minimum required sample size was calculated to be 31 specimens. To provide equal allocation across the six experimental groups, at least 36 specimens were required (n = 6 *per* group). Considering previous *in vitro* research evaluating the color stability and TP‰ of CAD/CAM ceramics [26], the sample size was increased to 10 specimens *per* group, resulting in a total of 60 specimens. Under these assumptions, the final sample size provided approximately 98.7% statistical power for detecting the specified interaction effect.

Chemical compositions, crystal structures, and firing temperatures of the three different tested materials are presented in Table 1. A total of 60 ceramic specimens with dimensions of 10 × 10 mm and a thickness of 1.0 ± 0.05 mm were prepared from A2 HT color blocks using a precision cutting machine (Isomet 1000, Buehler, Lake Bluff, IL, USA) (n = 20 *per* material). The specimens' surfaces were then polished with 400, 600, 800, and 1200-grit silicon carbide papers [27, 28] (3M ESPE, St. Paul, MN, USA) under water cooling for 15 s prior to the application of the polishing or glazing procedures. The thickness of each specimen was subsequently measured with a digital micrometer (Minitech 233 Press, Grenoble, France) with an accuracy of 0.01 mm.

Subsequently, the specimens were divided into two subgroups according to the surface-finishing treatment to be applied (n = 10). To minimize inter-operator variability, all polishing, glazing, and color measurement procedures were performed by a single prosthodontist (D.D.E.). Before the study, the operator was calibrated according to the experimental protocol and standardized for all experimental procedures.

The specimens were allocated into six experimental groups (n = 10 *per* group) according to the ceramic material and surface-finishing protocol: CT-glazed (CTG), CT-polished (CTP), IPS-glazed (IPSG), IPS-polished (IPSP), VS-glazed (VSG), and VS-polished (VSP).

All specimens were fabricated under highly standardized laboratory conditions and possessed identical dimensions, thicknesses, shades, and surface preparation procedures. The glazing and polishing procedures were carried out using the manufacturer-recommended systems specific to each ceramic material to reflect routine clinical practice, in accordance with the methodology described by Demirel et al. [29]. To minimize operator-related variability, all glazing, polishing, and optical measurements were performed by a single operator under standardized laboratory conditions. All polishing procedures were performed using low-speed handpieces operated by the same operator at a standardized rotational speed to ensure procedural consistency.

The appropriate glaze material was applied to one surface of the specimens in the CTG, IPSG, and VSG groups and fired in a porcelain furnace (Programat P300, Ivoclar Vivadent). Likewise, one surface of the specimens in the CTP, IPSP, and VSP groups was polished using the manufacturer-recommended polishing system with rubber polishers mounted on a low-speed handpiece (NSK, Nakanishi Inc., Tochigi, Japan). The groups, materials, and surface-finishing protocols are summarized in Table 2.

Table 1

The chemical compositions, crystallization, and firing temperatures of the used materials

Material	CEREC Tessera™	IPS e-max® CAD	VITA Suprinity®
Manufacturer	Dentsply Sirona, York, PA, USA	Ivoclar Vivadent, Schaan, Liechtenstein	Vita Zahnfabrik, Bad Säckingen, Germany
Chemical composition, wt%	$Li_2Si_2O_5$: 90%, Li_3PO_4: 5%, $Li_{0.5}Al_{0.5}Si_2.5O_6$: 5%, (the lithium disilicate and virgilite crystals are embedded in a zirconia-enriched glassy matrix)	SiO_2: 57–80%, Li_2O: 11–19%, K_2O: 0–13%, other oxides: 0–8%	SiO_2: 56–64%, Li_2O: 15–21%, ZrO_2: 8–12%, P_2O_5: 3–8%, K_2O: 1–4%, Al_2O_3: 1–4%, CeO_2: 0–4%, pigments: 0–4%
Crystallization	supplied fully crystallized; final matrix firing (glaze firing) performed at 760 °C (≈ 2 min; approximately 4.5 min in CEREC SpeedFire), producing surface healing and final mechanical properties	standing-by: 403 °C, heating cycle: 90 °C/min, firing cycle: 650 °C, heating cycle 20 °C/min, firing cycle: 730 °C, holding cycle: 2 min	standby: 400 °C heating cycle: 55 °C /min firing cycle: 840 °C vacuum on/off: 410/840 °C cooling cycle: 680 °C

***Note*: CEREC Tessera™ composition is expressed as crystalline phases (wt%) as reported by the manufacturer [20], whereas IPS e.max® CAD and VITA Suprinity® are expressed as oxide content [27]. Data were compiled from the manufacturers' technical documentation [20] and previous studies [17–20, 27].**

Table 2

Materials and finishing protocols used in the groups

Groups	Materials used (manufacturer)	Glazing/polishing protocol
CEREC Tessera™		
CTG	Universal Spray Glaze (DeguDent GmbH, Hanau-Wolfgang, Germany)	starting application: 400 °C closing time: 1 min pre-heating: 1 min heating cycle: 55 °C/min final cycle: 760 °C waiting time: 2 min no vacuum
CTP	OptraGloss Ceramic Kit (Ivoclar Vivadent AG, Schaan, Liechtenstein)	pre-polishing with dark blue (Flame VP), high brightness polisher (Light Blue/Flame HP) high gloss polisher (Light Blue/Wheel HP)
IPS e.max CAD®		
IPSG	IPS e.max® Ceram Glaze Spray (Ivoclar Vivadent AG, Schaan, Liechtenstein)	standing-by application: 403 °C heating cycle: 60 °C/min firing cycle: 710 °C
IPSP	OptraGloss Ceramic Kit (Ivoclar Vivadent AG, Schaan, Liechtenstein)	pre-polishing with dark blue (Flame VP) high brightness polisher (Light Blue/Flame HP) high gloss polisher (Light Blue/Wheel HP)
VITA Suprinity®		
VSG	Vita Akzent Plus Glaze (VITA Zahnfabrik H. Rauter GmbH & Co. KG, Bad Säckingen, Germany)	standing-by application: 400 °C closing time: 4 min heating increase rate: 80 °C /min holding cycle: 800 °C holding cycle: 1 min
VSP	Vita Suprinity® Polishing Set (VITA Zahnfabrik H. Rauter GmbH & Co. KG, Bad Säckingen, Germany)	pre-polishing using pink diamond polishing using white diamond

CTG – CEREC Tessera™-glazed; CTP – CEREC Tessera™-polished; IPSG – IPS e.max® CAD-glazed; IPSP – IPS e.max® CAD-polished; VSG – VITA Suprinity®-glazed; VSP – VITA Suprinity®-polished.
***Note*: Data were compiled from the manufacturers' technical documentation [20] and previous studies [17–20, 27].**

Color measurements were performed before and after simulated gastric acid aging using a digital spectrophotometer (VITA EasyShade Advance 4.0, VITA Zahnfabrik GmbH, Bad Säckingen, Germany). The instrument was calibrated according to the manufacturer's instructions before each measurement session [30]. All measurements were conducted in the same laboratory under standardized ambient lighting conditions to ensure consistency throughout the study. Because the spectrophotometer incorporates a standardized internal light source, the influence of ambient lighting on color measurements was minimized.

Measurements were performed against standardized white, black, and neutral gray backgrounds. The neutral gray background was used exclusively for ΔE_{00} measurements obtained before and after simulated gastric acid immersion to ensure identical optical conditions for repeated color assessment, whereas the white and black backgrounds were used for TP_{00} calculations [31]. During each measurement, the spectrophotometer tip was positioned perpendicular to the specimen surface using a standardized measurement geometry in accordance with the manufacturer's operating instructions [30]. Three consecutive measurements were obtained for each specimen, and the mean L*, a*, and b* values were used to calculate the ΔE_{00} and TP_{00} values for statistical analysis. The L* coordinate represents perceptual lightness (0 = black, 100 = white), whereas the a* and b* coordinates represent the red-green and yellow-blue chromatic axes, respectively, with positive and negative values indicating the direction of color change.

ΔE_{00} were calculated using the CIEDE2000 formula [32, 33] from measurements obtained over the neutral gray background at baseline and after simulated gastric acid aging:

$$\Delta E_{00} = [(\Delta L'/(kLSL))^2 + (\Delta C'/(kCSC))^2 + (\Delta H'/(kHSH))^2 + RT(\Delta C'/(kCSC))(\Delta H'/(kHSH))]^{1/2}$$

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ represent the differences in lightness, chroma, and hue, respectively; SL, SC, and SH are the corresponding weighting functions; kL, kC, and kH are the parametric correction factors; and RT is the rotation term accounting for the interaction between chroma and hue differences, as described by Sharma et al. [32].

The TP_{00} was determined from the color coordinates measured over the white and black backgrounds using the CIEDE2000-based translucency approach. For all calculations, the parametric factors for lightness, chroma, and hue were set to 1 under reference conditions [33, 34]. Three consecutive measurements were performed for each specimen. The mean L*, a*, and b* values obtained from these measurements were calculated and subsequently used to determine the ΔE_{00} and TP_{00} values for statistical analysis. The greater the TP_{00} value, the higher the material's

translucency. A value of 0 reveals the presence of opacity, while high TP_{00} values indicate translucent materials:

$$TP_{00} = \{[(L'B - L'W)/SL]^2 + [(C'B - C'W)/SC]^2 + [(H'B - H'W)/SH]^2 + RT[(C'B - C'W)/SC][(H'B - H'W)/SH]\}^{1/2}$$

TP_{00} values were calculated according to Paravina et al. [33]. Subsequently, the absolute change in translucency parameter (ΔTP_{00}) was calculated as the absolute difference between the baseline and post-immersion TP_{00} values and used for statistical analysis. ΔTP_{00} was defined as the absolute difference between the TP_{00} values measured before and after simulated gastric acid immersion ($|TP_{00baseline} - TP_{00post}|$).

The specimens were immersed in hydrochloric acid (HCl) 0.06 M, pH 1.2 to simulate gastric acid exposure according to a previously published protocol [22, 34, 35]. The specimens were stored in the acid for 96 hrs at 37 °C in an incubator, and the pH was monitored every 24 hrs [22, 35]. After acid immersion, the specimens were rinsed with distilled water. Color measurements were then repeated, and the ΔE_{00} was calculated according to the CIEDE2000 formula [32]. Subsequently, TP_{00} values were recalculated [34].

Representative specimens from each group were examined before and after simulated gastric acid immersion using a field-emission scanning electron microscope (FESEM) (Gemini SEM 300, ZEISS, Oberkochen, Germany). Prior to analysis, all specimens were sputter-coated with a thin gold–palladium (Au–Pd) layer using a sputter coater to improve electrical conductivity and minimize charging artifacts. Surface morphology and microstructural alterations were then evaluated under standardized imaging conditions at ×10,000 magnification.

Statistical analysis

Descriptive statistics were presented as median and interquartile range for numerical variables. The normality of data distribution was assessed using the Shapiro-Wilk test. Intergroup comparisons were performed using the Kruskal-Wallis test, followed by the Dunn multiple comparison test with Bonferroni correction when significant differences were detected. Within-group comparisons between baseline and post-immersion measurements were performed using the Wilcoxon signed-rank test. Effect sizes were calculated and reported as η^2H for the Kruskal-Wallis test and r for the Wilcoxon signed-rank test, together with 95% confidence intervals where appropriate. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using the SPSS Statistics version 22.0 (IBM Corp., Armonk, NY, USA).

Results

The results of the statistical analyses evaluating the effect of simulated gastric acid immersion on the ΔE_{00} of the glass-ceramic materials are presented in Table 3. No significant differences in ΔE_{00} values were observed among the experimental groups ($p = 0.152$). The distribution of ΔE_{00} values among the study groups is illustrated in Figure 1.

The results of the statistical analyses of TP_{00} values are presented in Table 4, and Figure 2 illustrates the TP_{00} values of the experimental groups. Significant differences in TP_{00} values were observed among the groups both before and after simulated gastric acid immersion ($p < 0.001$). Before simulated gastric acid immersion, the VSG and VSP groups exhibited significantly higher TP_{00} values than the CTG group. After simulated gastric acid immersion, the CTG, CTP, and IPSG groups demonstrated significantly lower TP_{00} values than the IPSP, VSG, and VSP groups.

According to the Wilcoxon signed-rank test, simulated gastric acid immersion resulted in significant reductions in TP_{00} values in the CTG ($p = 0.005$), CTP ($p = 0.028$), and IPSG ($p = 0.005$) groups, whereas no significant changes were observed in the IPSP ($p = 0.169$), VSG ($p = 0.059$), or VSP ($p = 0.445$) groups (Table 4).

The absolute ΔTP_{00} after simulated gastric acid immersion differed significantly between the experimental groups ($p = 0.003$) (Table 5).

Field-emission scanning electron microscope results

Representative FESEM micrographs of the tested glass-ceramics before and after simulated gastric acid immersion were presented in Figure 3. The CTG before acid immersion exhibited a relatively smooth and homogeneous surface (Figure 3a). After acid immersion, the surface displayed

Table 3

Color difference (ΔE_{00}) of the groups

Groups	Median (Q1–Q3)	95% CI	*H*-test	*p*-value	η^2H
CTG	1.5 (1.22–1.74)	1.09–1.86	8.077	0.152	0.057
CTP	1.83 (1.65–1.95)	1.65–1.99			
IPSG	1.63 (1.6–1.71)	1.57–1.93			
IPSP	1.71 (1.25–2.00)	1.25–2.00			
VSG	1.5 (1.5–2.3)	1.50–2.30			
VSP	2.09 (2.04–2.09)	1.85–2.25			

Q1-Q3 – first quartile-third quartile; CI – confidence interval; CTG – CEREC Tessera™-glazed; CTP – CEREC Tessera™-polished; IPSG – IPS e.max® CAD-glazed; IPSP – IPS e.max® CAD-polished; VSG – VITA Suprinity®-glazed; VSP – VITA Suprinity®-polished.

***Note*: Descriptive and inferential statistics for ΔE_{00} values of the six experimental groups after simulated gastric acid immersion. Group comparisons were performed using the Kruskal-Wallis test**.

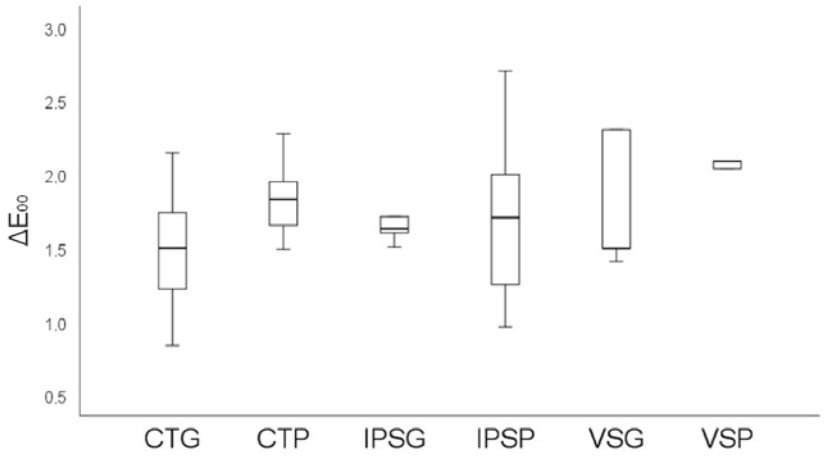

Fig. 1 – Box-and-whisker plots illustrating the distribution of color difference (ΔE_{00}) values for the six experimental groups following simulated gastric acid immersion. The boxes represent the interquartile range, the horizontal line within each box indicates the median, and the whiskers denote the minimum and maximum values. CTG – CEREC Tessera™-glazed; CTP – CEREC Tessera™-polished; IPSG – IPS e.max® CAD-glazed; IPSP –IPS e.max® CAD-polished; VSG – VITA Suprinity®-glazed; VSP – VITA Suprinity®-polished.

Table 4

Translucency parameter (TP_{00}) values before and after simulated gastric acid immersion for each experimental group

Groups	TP_{00} before		TP_{00} after		*Z*	*p*-value	*r*
	median (Q1–Q3)	95% CI	median (Q1–Q3)	95% CI			
CTG	11.68 (10.32–15.98)[a]	10.24–15.98	9.68 (8.29–10.16)[a]	7.13–10.42	-2.803	0.005*	0.886
CTP	14.17 (12.71–19.19)[ab]	12.56–19.19	10.53 (6.77–12.65)[a]	6.77–13.21	-2.191	0.028*	0.693
IPSG	17.09 (16.11–17.52)[ab]	15.90–17.59	10.84 (10.08–11.4)[a]	10.08–11.40	-2.803	0.005*	0.886
IPSP	18.07 (16.15–19.4)[b]	15.92–19.40	18.00 (16.3–18.43)[b]	13.79–18.43	-1.376	0.169	0.435
VSG	21.99 (21.41–22.24)[c]	21.41–22.24	18.21(18.21–23.14)[b]	18.21–23.14	-1.886	0.059	0.596
VSP	21.54 (17.09–24.45)[c]	17.09–24.88	20.48 (17.14–22.74)[b]	17.14–22.74	-0.764	0.445	0.242
H-test	42.035		27.778				
p-value	0.001**		0.001**				
η^2H	0.686		0.422				

Q1–Q3 – first quartile-third quartile; CI – confidence interval; CTG – CEREC Tessera™-glazed; CTP – CEREC Tessera™-polished; IPSG – IPS e.max® CAD-glazed; IPSP – IPS e.max® CAD-polished; VSG – VITA Suprinity®-glazed; VSP – VITA Suprinity®-polished.

***Note*: *$p < 0.05$; **$p < 0.001$. Different superscript lowercase letters within the same column indicate statistically significant differences between groups (Dunn *post hoc* test with Bonferroni correction, $p < 0.05$), whereas groups sharing at least one superscript letter do not differ significantly. *p*-values represent within-group comparisons between baseline and post-immersion measurements using the Wilcoxon signed-rank test. η^2H denotes the effect size for the Kruskal-Wallis test.**

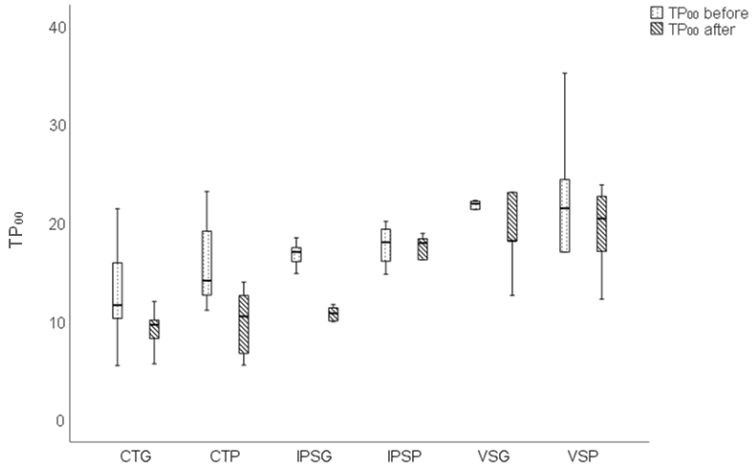

Fig. 2 – Translucency parameter (TP_{00}) values before and after simulated gastric acid immersion for the six experimental groups. The boxes represent the interquartile range, the horizontal line within each box indicates the median, and the whiskers denote the minimum and maximum values. CTG – CEREC Tessera™-glazed; CTP – CEREC Tessera™-polished; IPSG – IPS e.max® CAD-glazed; IPSP – IPS e.max® CAD-polished; VSG – VITA Suprinity®-glazed; VSP – VITA Suprinity®-polished.

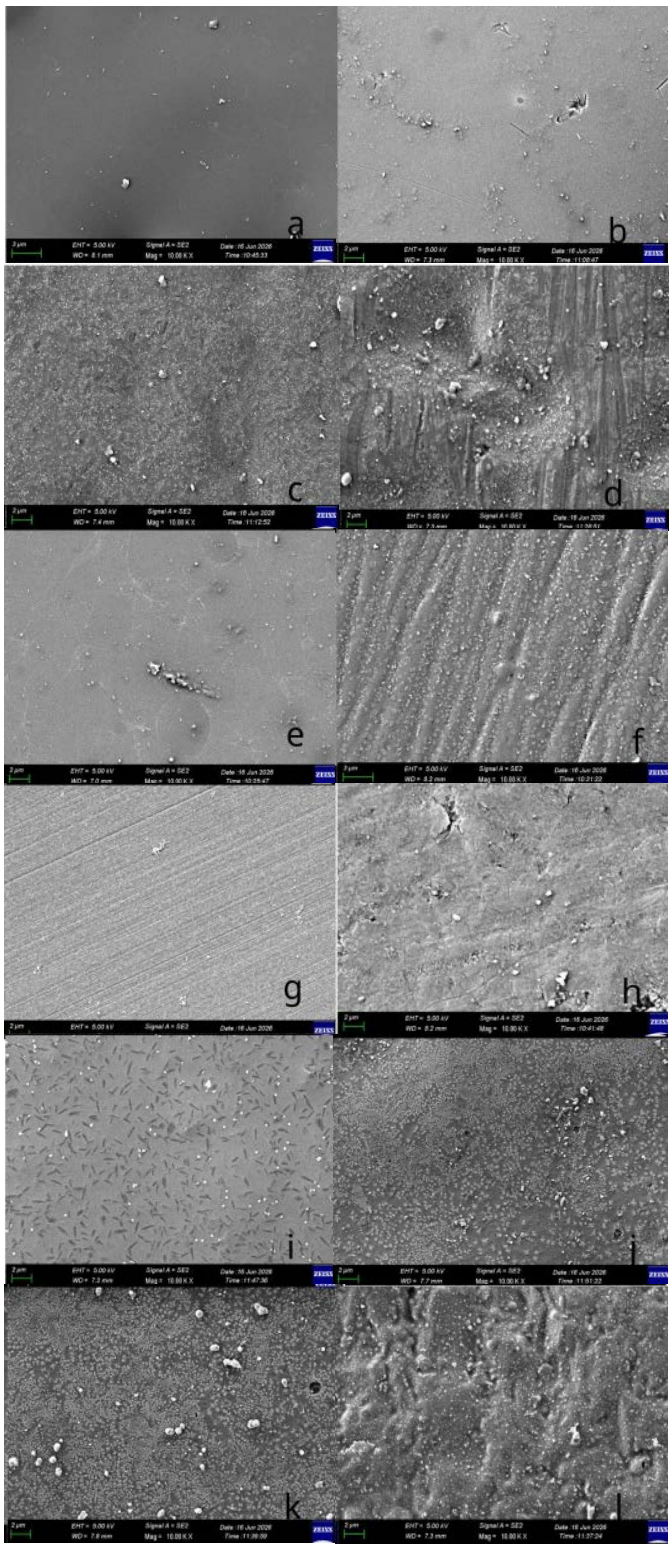

Fig. 3 – Representative FESEM micrographs of the tested glass-ceramics before and after simulated gastric acid immersion (magnification × 10,000): CTG before (a) and after acid immersion (b); CTP before (c) and after acid immersion (d); IPSG before (e) and after acid immersion (f); IPSP before (g) and after acid immersion (h); VSG before (i) and after acid immersion (j); VSP before (k) and after acid immersion (l). FESEM – field-emission scanning electron microscope; CTG – CEREC Tessera™-glazed; CTP – CEREC Tessera™-polished; IPSG – IPS e.max® CAD-glazed; IPSP – IPS e.max® CAD-polished; VSG – VITA Suprinity®-glazed; VSP – VITA Suprinity®-polished.

Table 5

Absolute change in translucency parameter (ΔTP_{00}) of the experimental groups after simulated gastric acid immersion

Groups	Median (Q1–Q3)	95% CI (median)	*H*-test	*p*-value	η^2H
CTG	2.23 (1.02–7.31)[ab]	0.87–7.31	17.604	0.003*	0.233
CTP	5.13 (1.31–11.89)[a]	1.31–11.89			
IPSG	6.02 (5.03–7.00)[a]	5.01–7.03			
IPSP	0.96 (0.35–1.54)[b]	0.35–3.14			
VSG	2.40 (0.90–3.78)[ab]	0.90– 3.78			
VSP	4.64 (3.75–6.83)[a]	2.91–6.84			

Q1-Q3 – first quartile-third quartile; CI – confidence interval; CTG – CEREC Tessera™-glazed; CTP – CEREC Tessera™-polished; IPSG – IPS e.max® CAD-glazed; IPSP – IPS e.max® CAD-polished; VSG – VITA Suprinity®-glazed; VSP – VITA Suprinity®-polished.
***Note*: *$p < 0.05$. Different superscript letters indicate statistically significant differences between groups. Kruskal-Wallis test was used for comparisons between groups.**

increased granular irregularities and scattered superficial deposits (Figure 3b). Before acid immersion, the polished CTP exhibited a relatively granular surface with distinct polishing grooves (Figure 3c). After simulated gastric acid immersion, these polishing grooves remained evident, and the surface morphology appeared largely preserved, although slight accentuation of the surface irregularities was observed (Figure 3d). IPSG presented a relatively smooth and homogeneous surface before acid immersion (Figure 3e), while after immersion, the overall surface morphology was largely preserved with the presence of superficial particles (Figure 3f). The IPSP exhibited characteristic polishing grooves before acid immersion (Figure 3g), whereas localized surface defects and increased surface irregularity were observed after immersion (Figure 3h). The VSG exhibited numerous uniformly distributed elongated crystalline structures before acid immersion (Figure 3i), and these crystalline features remained distinguishable after immersion with only minor superficial deposits (Figure 3j). Similarly, the VSP specimen displayed a fine granular surface before acid immersion (Figure 3k), while a slightly more irregular surface morphology with scattered deposits was observed after immersion (Figure 3l). Overall, FESEM examination demonstrated that the extent of surface morphological alterations following simulated gastric acid immersion differed among the tested glass-ceramic materials and according to the surface-finishing protocol.

Discussion

In the present study, the effects of simulated gastric acid immersion on the optical properties of glazed and polished CAD/CAM glass-ceramics were investigated. The first null hypothesis was accepted because no significant differences were observed in the ΔE_{00} values among the investigated groups. However, significant changes in TP_{00} values were observed in the CTG, CTP, and IPSG groups following simulated gastric acid immersion. Therefore, the second null hypothesis was rejected.

All specimens were standardized using sequential silicon carbide abrasive papers up to 1200-grit prior to the application of glazing or polishing procedures [27, 28]. Although the same surface preparation protocol was applied to all groups, differences in crystalline structure, crystal size, and glass matrix composition among the investigated ceramics may have resulted in material-specific surface characteristics following abrasion. Since the optical behavior of ceramic materials is influenced not only by their intrinsic microstructure but also by surface characteristics, the interaction between the ceramic substrate and the corresponding finishing protocol may have contributed to the observed outcomes. Therefore, the present findings should be interpreted within the context of the specific glazing and polishing systems used for each material, as these protocols represent the clinically intended finishing procedures for the investigated CAD/CAM ceramics. This methodological approach is consistent with that adopted by Demirel et al. [29], who evaluated each material using manufacturer-recommended finishing protocols to better reflect clinical practice. Consequently, the influence of microstructural differences and material-specific finishing procedures on the observed results cannot be completely excluded.

Studies evaluating the effects of simulated gastric acid on the optical properties of contemporary CAD/CAM glass-ceramics, particularly ZLS and advanced lithium disilicate materials, remain limited [36–38].

Previous studies have demonstrated that the corrosive effects of acidic media on dental ceramics depend on factors such as acid concentration, pH, temperature, and exposure duration [22, 25, 35–38]. Although ISO 6872 [39] recommends a solubility test using 4% acetic acid for 16 hrs at 80 °C, accelerated ageing protocols employing stronger acidic environments have been widely adopted to simulate long-term clinical exposure. In the present study, HCl (pH 1.2) was selected according to the method described by Hunt and McIntyre [40], and specimens were continuously immersed for 96 hrs at 37 °C. This protocol was chosen to facilitate comparison with previous studies under standardized laboratory conditions. Previous reports have suggested that such accelerated immersion protocols may correspond to more than 10 years of clinical exposure [41], although the original Hunt and McIntyre [40] protocol has been estimated to represent approximately 2–3 years of *in vivo* conditions.

While continuous immersion does not reproduce the protective effects of saliva or the intermittent nature of gastroesophageal reflux, no standardized *in vitro* gastric acid ageing protocol has yet been established [42]. Therefore, continuous immersion remains a valid and widely accepted approach for evaluating acid-induced changes in dental ceramics and facilitating comparisons among different materials.

Several studies have reported perceptibility and acceptability thresholds for ΔE_{00} in dentistry [33, 43]. Paravina et al. [33] proposed ΔE_{00} values of 0.8 and 1.8 as the perceptibility and acceptability thresholds for dentists. Ghinea et al. [43] further reported 50 : 50% perceptibility and acceptability thresholds of $\Delta E_{00} = 1.25$ and $\Delta E_{00} = 2.23$, respectively.

Consistent with these thresholds, Alhotan et al. [37] evaluated the color stability of pressable and machinable ZLS glass-ceramics following simulated gastric acid immersion. After 96 hrs, ΔE_{00} values remained below the perceptibility threshold, whereas after 192 hrs, all groups exceeded the perceptibility threshold but remained below the acceptability threshold. Likewise, Cruz et al. [36] reported no statistically significant differences in ΔE_{00} between crystallized IPS and VS after 96 hrs of simulated gastric acid immersion, and both materials exhibited clinically imperceptible color changes. Similarly, no statistically significant differences in ΔE_{00} values were observed among the investigated materials after 96 hrs of simulated gastric acid immersion in the present study. Although the median ΔE_{00} values of some groups approached or were above the thresholds proposed in previous studies, simulated gastric acid immersion did not produce statistically significant ΔE_{00} among the investigated materials.

The present findings are partially consistent with those of Kulkarni et al. [38], who investigated the influence of artificial gastric acid combined with toothbrush abrasion on feldspathic porcelain, lithium disilicate glass-ceramic, and monolithic zirconia. Significant alterations in surface roughness, color, and gloss were reported for feldspathic porcelain and lithium disilicate, whereas monolithic zirconia remained largely unaffected. Likewise, no statistically significant color changes were detected in the CAD/CAM glass-ceramics evaluated in the present study, indicating that simulated gastric acid exerted only a limited effect on color stability. Similarly, Alnasser et al. [44] reported no statistically significant changes in the surface roughness of lithium disilicate ceramics polished with silicon carbide papers after 45 and 91 hrs of exposure to simulated gastric acid (5% HCl), further supporting the limited influence of simulated gastric acid on the surface characteristics of lithium disilicate ceramics.

Several studies have investigated the TP_{00} of contemporary CAD/CAM glass-ceramics [38, 44–46]. Kulkarni et al. [38] evaluated the optical changes of lithium disilicate glass-ceramic following artificial gastric acid exposure combined with toothbrush abrasion. Although the IPS specimens exhibited significant changes in color, gloss, and surface roughness, TP_{00} did not change significantly in any of the tested materials. Freitas et al. [45] examined crystallized specimens and reported that CT exhibited TP_{00} comparable to IPS and higher than VS.

Dal Piva et al. [46] evaluated the optical properties of IPS and CT following different firing and glazing protocols. They reported that firing procedures did not significantly affect the ΔE_{00} or TP_{00} values of IPS, whereas CT exhibited clinically unacceptable ΔE_{00} compared with the manufacturer-recommended firing protocol. Furthermore, IPS exhibited greater TP_{00} and brightness than CT irrespective of the firing protocol, suggesting that CT is more sensitive to variations in thermal processing. In the present study, all firing and glazing procedures were performed according to the manufacturers' recommendations. The only exception was the CTP group, in which glazing and the associated firing cycle were intentionally omitted to represent the polished clinical condition. While these findings emphasize the influence of manufacturing and surface-finishing procedures on the initial optical properties of CAD/CAM ceramics, the long-term preservation of TP_{00} under adverse oral conditions is equally important for clinical performance. Accordingly, the present study evaluated the effect of simulated gastric acid exposure on the ΔTP_{00} of CAD/CAM glass-ceramics with different surface-finishing protocols. Although all tested materials exhibited some degree of TP_{00} alteration following acid immersion, the magnitude of the change varied according to the ceramic type. Similarly, Tango et al. [14] demonstrated that the retention of TP_{00} differed significantly among CAD/CAM restorative materials after exposure to staining solutions and artificial aging, indicating that the ability to preserve TP_{00} is material dependent. Consistent with this concept, the present study also demonstrated material-dependent differences in ΔTP_{00} following simulated gastric acid immersion.

Previous studies investigating virgilite-containing lithium disilicate ceramics have demonstrated that microstructural alterations can influence optical properties. Rizk et al. [47] reported that repeated firing cycles significantly reduced TP_{00} values while increasing ΔE_{00} values, indicating that changes within the crystalline and glass phases can modify light transmission and scattering behavior. Although the aging protocol differed from that used in the present study, these findings suggest that alterations in the crystal-glass matrix may affect the optical performance of advanced lithium disilicate ceramics. Similarly, the significant reduction in TP_{00} observed in the CT groups may be associated with acid-induced microstructural changes. However, unlike the findings of Rizk et al. [47], no significant differences in ΔE_{00} were detected among the investigated materials, suggesting that simulated gastric acid exposure had a greater influence on TP_{00} than on overall color stability under the present experimental conditions.

Elsaka and Elnaghy [21] demonstrated that VS possesses a homogeneous fine crystalline structure, whereas conventional lithium disilicate ceramics, such as IPS, are characterized by needle-shaped lithium disilicate crystals embedded within a glassy matrix. A finer and more homogeneous crystal distribution may promote more

uniform light transmission and enhance resistance to optical changes following acid exposure. Conversely, degradation of the crystal-glass matrix interface may increase optical heterogeneity and adversely affect TP‰. The previous study has also reported that acidic media can dissolve the glassy matrix and expose crystalline phases in both lithium disilicate and ZLS ceramics, thereby compromising their optical properties [21].

When interpreted in relation to the proposed TP‰ perceptibility (0.62) and acceptability (2.62) thresholds for ΔTP‰ [34], the median ΔTP‰ values of all groups were above the proposed perceptibility threshold. The median values of the IPSP, CTG, and VSG groups remained below the proposed acceptability threshold, whereas those of the CTP, IPSG, and VSP groups were above this reference value. These findings indicate that the magnitude of TP‰ change at the group level was above the proposed acceptability threshold in the latter groups. However, threshold comparisons based on group medians should not, by themselves, be interpreted as evidence of a statistically significant directional change or as indicating that every individual specimen underwent a clinically unacceptable change.

The observed differences in TP‰ and ΔTP‰ may be related to variations in material composition, crystalline structure, crystal size distribution, and the refractive index relationship between the crystalline and glassy phases. Based on previously reported microstructural characteristics, the consistently higher TP‰ values observed for VS may be partly associated with its relatively fine and homogeneous ZLS crystal structure and the proposed refractive-index relationship between its crystalline and glassy phases, which could potentially facilitate light transmission and reduce light scattering. However, these explanations remain hypothetical because crystal size distribution, refractive indices, and phase composition after acid exposure were not directly characterized in the present study. Although the VSP group exhibited a relatively high median absolute ΔTP‰, no significant within-group difference was detected by the Wilcoxon signed-rank test. This apparent discrepancy reflects the different statistical concepts represented by the two analyses. Whereas the Wilcoxon test evaluates paired changes while preserving the direction of change, ΔTP‰ represents only the absolute magnitude of the change irrespective of whether TP‰ increased or decreased. Consequently, opposite directions of change among individual specimens may result in a relatively high median ΔTP‰ despite the absence of a statistically significant directional change. Therefore, the VSP findings most likely reflect inter-specimen variability rather than a uniform material response to acid exposure, and their clinical significance should be interpreted with caution. Overall, these findings suggest that the optical response to simulated gastric acid may have been influenced by both the reported microstructural characteristics of the ceramic and the applied surface-finishing protocol.

The observed differences in TP‰ and ΔTP‰ among the tested materials may be attributed not only to their intrinsic microstructural characteristics but also to the surface-finishing protocol applied. In agreement with the findings of Al-Johani et al. [27], surface treatment has a significant influence on the optical and topographical properties of CAD/CAM lithium silicate-based glass-ceramics. The authors demonstrated that surface-finishing procedures modify surface morphology and roughness, thereby affecting light transmission and optical behavior. These observations suggest that the optical response of the tested ceramics may have been influenced by the combined effects of their reported microstructural characteristics and the applied surface-finishing protocols, rather than by material composition alone.

FESEM observations revealed more pronounced surface irregularities in CT, comparatively limited alterations in IPS, and largely preserved surface morphology in VS after acid exposure. These observations were generally consistent with the optical findings; however, they do not provide direct evidence regarding crystal size distribution, refractive indices, or phase composition.

Limitations of the study

Despite these findings, several limitations of the present study should be acknowledged. The limitation of this study is that the power analysis was based on a large effect size; therefore, smaller material × surface-finishing interaction effects may not have been detected.

Although the specimens were fabricated under standardized laboratory conditions with uniform dimensions, thicknesses, and shades, formal randomization was not performed during allocation to the surface-finishing groups. Therefore, the potential for allocation-related bias cannot be completely excluded and should be acknowledged as a methodological limitation of the present study. In addition, each ceramic material was finished using the glazing and polishing system recommended by its manufacturer. Although this approach reflects routine clinical practice, differences in the glazing materials and polishing systems may have influenced the optical outcomes. Furthermore, as with all *in vitro* studies, the experimental conditions could not fully reproduce the complexity of the oral environment, including saliva, temperature fluctuations, pH changes, and the intermittent nature of gastric reflux. Finally, surface characterization was limited to qualitative FESEM observations. Although FESEM supported the interpretation of the optical findings by demonstrating acid-induced surface alterations, additional quantitative analyses, including surface roughness, microhardness, and three-dimensional surface topography, would provide a more comprehensive understanding of the relationship between surface degradation and the optical behavior of CAD/CAM glass-ceramics. Furthermore, crystal size distribution, refractive indices, and phase composition after acid exposure were not directly characterized. Therefore, the proposed microstructural explanations for the observed optical differences should be regarded as hypotheses based on

previously published evidence. Moreover, only a single ceramic shade (A2 HT), specimen thickness (1 mm), and simulated gastric acid exposure protocol were evaluated. Therefore, the present findings should be interpreted with caution and cannot be generalized to all clinical situations. Further *in vitro* and clinical studies incorporating different material configurations, restoration thicknesses, shades, and more clinically relevant aging and exposure protocols are warranted.

Conclusion

Within the limitations of this *in vitro* study, simulated gastric acid exposure did not result in significant differences in color difference among the tested experimental groups. However, translucency appeared to be more sensitive to the acid challenge than color. The changes in translucency parameter and in the extent of change in the translucency parameter indicated that the susceptibility of translucency to acidic challenge varied among the tested ceramic materials and surface-finishing protocols. These findings are limited to the investigated ceramic materials, shade, specimen thickness, and simulated gastric acid exposure protocol and should not be directly generalized to other computer-aided design/computer-aided manufacturing ceramics or clinical reflux conditions.

Conflict of interest

The authors declare no conflict of interest.

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