THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Effect of firing cycle and aging on long-term chemical degradation of monolithic CAD-CAM ceramics

Murat Sert, DDS, PhD,[a] Meryem Gülce Subaşı, DDS, PhD,[b] Mustafa Borga Donmez, DDS, PhD,[c]
Gülce Çakmak, DDS, PhD,[d] and Burak Yilmaz, DDS, PhD[e]

ABSTRACT

Statement of problem. Previous studies have shown the susceptibility of dental ceramics to degradation when subjected to certain media. However, knowledge on the effect of repeated firings and thermocycling on the ion elution of computer-aided design and computer-aided manufacturing (CAD-CAM) ceramics is lacking.

Purpose. The purpose of this in vitro study was to compare the effect of repeated firings on the ion elution of CAD-CAM materials before and after thermocycling.

Material and methods. Bar-shaped specimens were prepared from 4 different CAD-CAM materials (monolithic zirconia [Z], zirconia-reinforced lithium silicate glass-ceramic [S], lithium disilicate glass-ceramic [EX], and leucite-reinforced glass-ceramic [E]) and divided into 3 groups according to the number of repeated glaze firings (1 firing [1F], 2 firings [2F], and 4 firings [4F]). Specimens were placed into deionized water (pH 7.4) and stored at 37 °C for 168 hours. Inductively coupled plasma-optic emission spectrophotometry (ICP-OES) was used to measure the baseline values of the eluted ions in immersion. The specimens were then subjected to thermocycling. Then, surface roughness (R_a) and ion elution values were measured. The Kruskal-Wallis and Mann-Whitney U tests were used to analyze the ion elution data before and after thermocycling, and the effect of thermocycling on ion elution was assessed by the Wilcoxon signed rank test. R_a data were analyzed with 2-way analysis of variance (ANOVA) and the Tukey honestly significant difference tests (α=.05).

Results. Elution of some ions varied depending on the material-firing pair before (Al, As, B, Ba, Cr, Cu, Li, Mg, Na, P, and Zn) and after (Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, K, Li, Mg, Na, P, Y, and Zn) thermocycling. Before thermocycling, all firing groups within each material showed a similar number of significantly higher eluted ions. After thermocycling, the number of significantly higher eluted ions decreased in all materials, except for EX. The effect of thermocycling on the ion elution of the 1F group of Z (Al, Be, Ca, Cd, Co, Cr, Cu, K, Li, P, Y, and Zn), S (As, Be, Cd, Co, Cr, K, P, and Y), EX (B, Cu, and P), and E (B and Ba); 2F group of Z (Al, Be, Ca, Co, Cr, Cu, K, Li, P, and Y), S (Be, Cd, Co, K, Li, and Y), EX (P), and E (P); 4F group of Z (Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, K, Li, P, and Y), S (Al, Be, Cd, Co, Cr, Li, Mg, and Y), EX (Be, Ca, Cd, Co, K, Y, and Zn), and E (Ca and P) was nonsignificant ($P\geq.051$). The interaction between material and repeated firings ($P<.001$) had a significant effect on R_a. For 1F groups, E showed the highest R_a ($P\leq.003$), while Z had higher R_a than S (P=.009). For 2F groups, Z had higher R_a than S (P=.01). The differences among 4F groups were nonsignificant ($P\geq.677$). An increased number of repeated firings (2F and 4F) decreased the R_a of E ($P<.001$).

Conclusions. The effect of repeated firings and thermocycling on the chemical stability of the tested CAD-CAM materials varied. No clear trend was observed on the elution of different ions within material-firing pairs before thermocycling. However, thermocycling increased the number of significantly higher eluted ions for EX. The effect of thermocycling on the ion elution of materials varied depending on ions. Repeated firings decreased the surface roughness of E. (J Prosthet Dent 2022;■:■-■)

---

[a] Assistant Professor, Department of Medical Laboratory Techniques, Ankara Yildirim Beyazit University, Ankara, Turkey.

[b] Associate Professor, Department of Prosthodontics, Kütahya Health Sciences University, Faculty of Dentistry, Kütahya, Turkey.

[c] Assistant Professor, Department of Prosthodontics, Istinye University, Faculty of Dentistry, Istanbul, Turkey; and Visiting Researcher, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland.

[d] Senior Research Associate, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland.

[e] Associate Professor, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland; and Associate Professor, Department of Restorative, Preventive and Pediatric Dentistry, School of Dental Medicine, University of Bern, Bern, Switzerland; and Adjunct Professor, Division of Restorative and Prosthetic Dentistry, The Ohio State University, Columbus, Ohio.

Clinical Implications

Repeated glaze firings may impair the long-term clinical success of lithium disilicate glass-ceramics because of increased chemical degradation.

With improvements in computer-aided design and computer-aided manufacturing (CAD-CAM) technologies, various esthetic restorative materials have been introduced.[1,2] Parallel to these developments, monolithic CAD-CAM ceramics have facilitated the fabrication of restorations in a single visit, thereby increasing patient satisfaction.[3,4] However, as further esthetic or functional adjustments may be required after the fabrication process, a restoration may undergo repeated firings.[1,4-6]

Dental ceramics are mainly referred to as insoluble or minimally soluble.[7,8] However, previous studies have shown the solubility of dental ceramics at oral pH.[9-14] Considering that chemical degradation depends on chemical and mechanical environmental factors[11,13,15] and the chemical diversity among current dental ceramics, specifying that these materials are inert would be misleading.[16] Chemical degradation is associated with the elution of alkaline ions,[12,16,17] which are less stable when present in the glassy phase than in the crystalline phase.[9] Moreover, the chemical degradation of a ceramic surface increases roughness that results in plaque accumulation, antagonist wear, and poor esthetics.[12,14,17]

Previous studies on the chemical degradation of dental ceramics have focused on the effect of pH values[7,13,14,18,19] or immersion cycles.[20,21] Mechanical and optical properties of CAD-CAM ceramics after repeated firings have also been investigated.[1,4,5,22-27] However, the authors are unaware of a study investigating the effects of repeated firings on the chemical stability of CAD-CAM ceramics. Considering that some of the ions present in commonly used CAD-CAM ceramics are listed as toxic by the Agency for Toxic Substances and Disease Registry when certain thresholds are exceeded (Table 1),[28] studies on the inertness of CAD-CAM ceramics may inform clinicians significantly. Therefore, the purpose of the present study was to investigate the effect of repeated firings on the ion elution and surface roughness of 4 different CAD-CAM materials before and after thermocycling. The null hypotheses were that repeated firings would not affect the ion elution before or after thermocycling, that thermocycling would not affect the ion elution of the materials, and that material type and repeated firings would not affect the surface roughness.

Table 1. Agency for Toxic Substances and Disease Registry minimal risk levels (MRLs), March 2021

Element	Duration	Route	MRLs
Aluminum	Intermediate	Oral	1 mg/kg/d
	Chronic		
Arsenic	Acute	Oral	0.005 mg/kg/d
	Chronic		0.0003 mg/kg/d
Barium	Intermediate	Oral	0.2 mg/kg/d
Beryllium	Chronic	Oral	0.002 mg/kg/d
Boron	Acute	Oral	0.2 mg/kg/d
Cadmium	Intermediate	Oral	0.0005 mg/kg/d
	Chronic		0.0001 mg/kg/d
Chromium	Intermediate	Oral	0.005 mg/kg/d
	Chronic		0.0009 mg/kg/d
Cobalt	Intermediate	Oral	0.01 mg/kg/d
Copper	Acute	Oral	0.01 mg/kg/d
	Intermediate		
Zinc	Intermediate	Oral	0.3 mg/kg/d
	Chronic		

MATERIAL AND METHODS

An overview of the study is presented in Figure 1, and the monolithic CAD-CAM ceramics used in the present study are given in Table 2. One hundred and thirty-two bar-shaped specimens were wet-sectioned by using a low-speed sectioning machine (Secotom 10; Struers A/S) from 4 different CAD-CAM materials: monolithic zirconia (Z) (Lava All Zirconia; 3M ESPE); zirconia-reinforced lithium silicate glass-ceramic (S) (VITA SUPRINITY; VITA Zahnfabrik); lithium disilicate glass-ceramic (EX) (IPS e.max CAD; Ivoclar AG); and leucite-reinforced glass-ceramic (E) (IPS Empress CAD; Ivoclar AG) (n=33). Considering the 20% sintering shrinkage, Z specimens were prepared larger (22.5×5×1.5 mm) than the actual specimen size (18×4×1.2 mm). All sectioned specimens were cleaned in distilled water for 5 minutes in an ultrasonic bath (Eltrosonic Ultracleaner 07-08; Eltrosonic GmbH). Specimens were then divided into 3 groups according to the number of glaze firings (n=11) (Table 3); control (1F): Z-1F (sintering followed by glaze firing), S-1F (crystallization and glaze firing), EX-1F (crystallization and glaze firing), E-1F (glaze firing); 2F: Z-2F (sintering followed by 2 glaze firings), S-2F (crystallization and glaze firing followed by 1 glaze firing), EX-2F (crystallization and glaze firing followed by 1 glaze firing), E-2F (2 glaze firings); 4F: Z-4F (sintering followed by 4 glaze firings), S-4F (crystallization and glaze firing followed by 3 glaze firings), EX-4F (crystallization and glaze firing followed by 3 glaze firings), E-4F (4 glaze firings).

Before sintering, the Z specimens were stored in a plastic cup containing zirconia coloring liquid (A3, Lava Plus High Translucency Zirconia Dyeing Liquid; 3M ESPE) for 2 minutes. The specimens were removed from

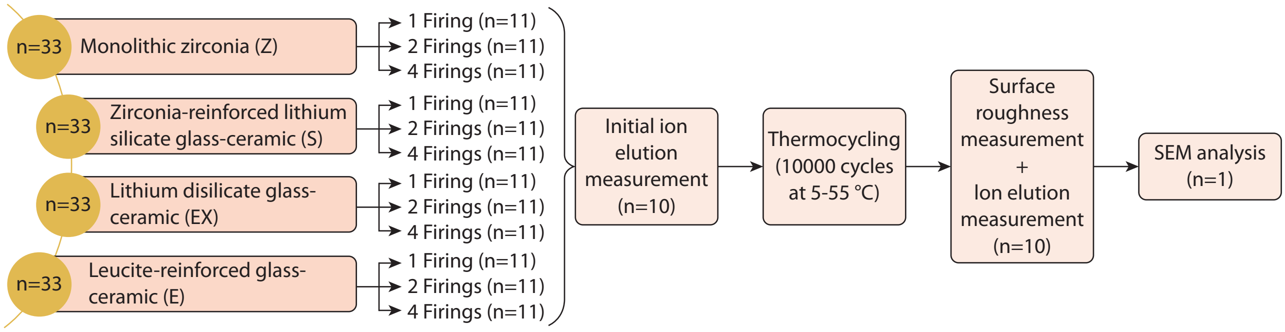

Figure 1. Overview of study. SEM, scanning electron microscope.

Table 2. Materials used

Material	Composition	Code	Manufacturer
Lava All Zirconia (zirconia)	ZrO_2	Z	3M ESPE
VITA SUPRINITY (zirconia-reinforced lithium silicate glass-ceramic)	ZrO_2, SiO_2, Li_2O, pigments	S	VITA Zahnfabrik
IPS e.max CAD (lithium disilicate glass-ceramic)	SiO_2, Li_2O, K_2O, MgO, Al_2O_3, P_2O_5, other oxides	EX	Ivoclar AG
IPS Empress CAD (leucite-reinforced glass-ceramic)	SiO_2, Al_2O_3, K_2O, Na_2O, CaO, other oxides, pigments	E	Ivoclar AG
VITA AKZENT Plus Glaze	Not provided	-	VITA Zahnfabrik
VITA AKZENT Plus Glaze LT Spray	Isobutane: 75%-<80% Ethanol, ethyl alcohol: 5-<10%	-	VITA Zahnfabrik
IPS e.max CAD Crystall/ Glaze Spray	Isobutane: 25%-50% Propan-2-ol: 10%-<25% Nonhazardous ingredients: to 100%	-	Ivoclar AG
IPS Empress Universal Glaze Spray	Isobutane: 50%-100% Propan-2-ol: 25%-50%	-	Ivoclar AG

Al_2O_3, aluminum oxide; CaO, calcium oxide; K_2O, potassium oxide; Li_2O, lithium oxide; MgO, magnesium oxide; Na_2O, sodium oxide; P_2O_5, phosphorus pentaoxide; SiO_2, silicon dioxide; ZrO_2, zirconium dioxide.

Table 3. Firing parameters of CAD-CAM materials used

Material	Crystallization and Glaze Firing	Glaze Firing
Z	Preheating: 20 °C/min to 800 °C; preheating: 10 °C/min to 1450 °C; holding time: 120 min at 1450 °C; cooling: 15 °C/min to 800 °C and 20 °C/min to 250 °C	Standby temperature: 500 °C; closing time: 4 min; heating rate: 80 °C/min; firing temperature: 900 °C; holding time: 1 min
S	Standby temperature: 400 °C; closing time: 4 min; heating rate: 55 °C/min; firing temperature: 840 °C; holding time: 8 min; V_1: 410 °C/V_2: 840 °C; long-term cooling: 680 °C	Standby temperature: 400 °C; closing time: 4 min; heating rate: 80 °C/min; firing temperature: 800 °C; holding time: 1 min
EX	Standby temperature: 403 °C; closing time: 6 min; heating rate, t_1: 90 °C/min/t_2: 30 °C/min; firing temperature, T_1: 820 °C/T_2: 840 °C; holding time, H_1: 10 min/H_2: 7 min; V_1: (1_1: 550 °C; 2_1: 820 °C)/V_2: (1_1: 820 °C; 2_1: 840 °C); long-term cooling: 700 °C	Standby temperature: 403 °C; closing time: 6 min; heating rate: 60 °C/min; firing temperature: 770 °C; holding time: 1-2 min; V_1: 450 °C/V_2: 769 °C
E	-	Standby temperature: 403 °C; closing time: 6 min; heating rate: 100 °C/min; firing temperature: 790 °C; holding time: 1-2 min

the liquid, left to dry for 2 hours, and sintered in a sintering oven (inFire HTC Speed; Dentsply Sirona) at 1450 °C for 120 minutes.

Recommended glaze materials (Z: VITA AKZENT Plus Glaze; VITA Zahnfabrik, S: VITA AKZENT Plus Glaze LT Spray; VITA Zahnfabrik, EX: IPS e.max CAD Crystall/Glaze Spray; Ivoclar AG, E: IPS Empress Universal Glaze Spray; Ivoclar AG) were applied on 1 surface of the specimens to provide a dry and uniform whitish glaze layer. Spray-formed glaze materials were applied from a distance of 10 cm. Then, crystallization and glazing were performed in 1 step for S and EX, while glazing was performed for Z and E in a ceramic oven (Programat P300; Ivoclar AG). Additional glazing cycles were performed for the 2F and 4F groups, without any adjustments between firings. All specimens were then ultrasonically cleaned for 15 minutes.

The specimens were sealed into polyethylene bottles containing 20 mL of deionized water (pH 7.4). Next, the bottles were placed in an incubator (Memmert model BE500; Memmert GmbH) for 168 hours for immersion (37 °C),[12] which has been shown to affect the clinical lifetime of a metal-ceramic restoration.[29,30] The concentration of the ions transferred (mg/kg) to the immersion solution was analyzed by using an inductively coupled plasma-optic emission spectrophotometer (ICP-OES) (SPECTRO GENESIS; SPECTRO Analytical Instruments GmbH) and static immersion test method.[31] The same operator (M.S.) repeated the measurements 3 times, and the mean values were recorded. The measured ions were aluminum (Al), arsenic (As), barium (Ba), beryllium (Be), boron (B), cadmium (Cd), calcium (Ca), chromium (Cr), cobalt (Co), copper (Cu), lithium (Li), magnesium (Mg), oxygen (O), phosphorus (P), potassium (K), silicon (Si), sodium (Na), titanium (Ti), yttrium (Y), zinc (Zn), and zirconium (Zr).

Specimens were then submitted to 10 000 cycles of thermocycling at 5 °C to 55 °C with a transfer time of 5 seconds and a duration time of 30 seconds (MTE-101; MOD Dental), which approximately simulated 1 year of

Table 4. Mean ±standard deviation values (mg/kg) of ions before thermocycling

Material	Firing Cycles	Ions																	
		Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	K	Li	Mg	Na	P	Y	Zn	
Z	1F	0.042 ±0.001 a	0.047 ±0.001 b	0.053 ±0.001 b	0.067 ±0.001 b	0.065 ±0.000 a	1.090 ±0.335 a	0.001 ±0.000 a	0.062 ±0.001 a	0.077 ±0.001 a	0.006 ±0.000 ab	0.198 ±0.030 a	0.371 ±0.091 a	0.204 ±0.005 a	0.737 ±0.028 a	0.067 ±0.01 a	0.064 ±0.000 a	0.036 ±0.002 a	—
	2F	0.044 ±0.005 a	0.046 ±0.001 b	0.052 ±0.003 b	0.067 ±0.000 b	0.065 ±0.000 a	0.889 ±0.150 a	0.001 ±0.000 a	0.062 ±0.001 a	0.076 ±0.001 a	0.006 ±0.000 a	0.183 ±0.044 a	0.312 ±0.042 a	0.207 ±0.01 a	0.751 ±0.053 a	0.067 ±0.01 a	0.064 ±0.000 a	0.036 ±0.002 a	—
	4F	0.042 ±0.001 a	0.045 ±0.001 a	0.047 ±0.001 a	0.065 ±0.001 a	0.065 ±0.000 a	1.080 ±0.427 a	0.001 ±0.000 a	0.062 ±0.001 a	0.075 ±0.002 a	0.006 ±0.000 b	0.196 ±0.031 a	0.310 ±0.101 a	0.215 ±0.003 b	0.804 ±0.028 b	0.059 ±0.006 a	0.064 ±0.000 a	0.038 ±0.005 a	—
S	1F	0.044 ±0.002 a	0.045 ±0.001 a	0.049 ±0.002 a	0.067 ±0.001 a	0.065 ±0.000 a	1.298 ±0.345 a	0.001 ±0.000 a	0.062 ±0.000 a	0.074 ±0.003 a	0.006 ±0.001 a	0.175 ±0.047 a	1.037 ±0.269 b	0.275 ±0.014 b	1.048 ±0.109 a	0.055 ±0.009 a	0.064 ±0.000 a	0.054 ±0.016 a	—
	2F	0.043 ±0.002 a	0.046 ±0.000 b	0.048 ±0.003 a	0.067 ±0.001 a	0.065 ±0.000 a	1.345 ±0.422 a	0.001 ±0.000 a	0.062 ±0.001 a	0.076 ±0.000 ab	0.008 ±0.005 b	0.213 ±0.036 a	0.896 ±0.469 ab	0.274 ±0.011 b	1.024 ±0.081 a	0.045 ±0.018 a	0.064 ±0.000 a	0.033 ±0.011 a	—
	4F	0.044 ±0.002 a	0.046 ±0.001 b	0.047 ±0.003 a	0.067 ±0.001 a	0.065 ±0.000 a	1.493 ±0.397 a	0.001 ±0.000 a	0.062 ±0.000 a	0.080 ±0.007 b	0.006 ±0.001 ab	0.222 ±0.052 a	0.574 ±0.313 a	0.062 ±0.005 a	1.087 ±0.137 a	0.049 ±0.018 a	0.064 ±0.000 a	0.060 ±0.062 a	—
EX	1F	0.040 ±0.001 a	0.046 ±0.001 a	0.054 ±0.002 b	0.067 ±0.000 a	0.065 ±0.000 a	1.489 ±0.948 a	0.001 ±0.000 a	0.062 ±0.001 a	0.076 ±0.001 b	0.006 ±0.001 a	0.189 ±0.033 a	0.430 ±0.081 a	0.213 ±0.015 a	0.783 ±0.076 a	0.069 ±0.01 a	0.064 ±0.000 a	0.036 ±0.003 a	—
	2F	0.040 ±0.001 a	0.046 ±0.001 a	0.049 ±0.001 a	0.068 ±0.001 a	0.065 ±0.000 a	1.540 ±1.046 a	0.001 ±0.001 a	0.062 ±0.001 a	0.071 ±0.003 a	0.006 ±0.000 a	0.197 ±0.050 a	0.392 ±0.101 a	0.210 ±0.009 a	0.789 ±0.04 ab	0.044 ±0.015 b	0.064 ±0.000 a	0.039 ±0.004 b	—
	4F	0.041 ±0.001 a	0.046 ±0.000 a	0.049 ±0.003 a	0.067 ±0.000 a	0.065 ±0.000 a	1.292 ±0.497 a	0.001 ±0.001 a	0.062 ±0.001 a	0.076 ±0.001 b	0.006 ±0.001 a	0.200 ±0.062 a	0.567 ±0.081 b	0.218 ±0.013 a	0.856 ±0.074 b	0.058 ±0.015 ab	0.064 ±0.000 a	0.037 ±0.003 ab	—
E	1F	0.043 ±0.003 b	0.045 ±0.000 a	0.002 ±0.001 a	0.054 ±0.001 a	0.065 ±0.000 a	1.030 ±0.143 a	0.001 ±0.000 a	0.062 ±0.001 a	0.077 ±0.001 a	0.006 ±0.001 a	0.188 ±0.043 a	0.350 ±0.079 a	0.237 ±0.034 a	0.873 ±0.072 a	0.059 ±0.012 a	0.064 ±0.001 a	0.034 ±0.002 ab	—
	2F	0.040 ±0.001 a	0.046 ±0.000 b	0.054 ±0.003 b	0.067 ±0.001 b	0.065 ±0.000 a	1.018 ±0.139 a	0.001 ±0.001 a	0.062 ±0.000 a	0.076 ±0.001 a	0.006 ±0.000 a	0.187 ±0.025 a	0.362 ±0.08 a	0.241 ±0.032 a	0.855 ±0.094 a	0.059 ±0.013 a	0.064 ±0.000 a	0.030 ±0.004 a	—
	4F	0.041 ±0.001 ab	0.045 ±0.001 ab	0.051 ±0.001 b	0.067 ±0.000 b	0.065 ±0.000 a	0.943 ±0.322 a	0.001 ±0.001 a	0.062 ±0.001 a	0.076 ±0.001 a	0.006 ±0.001 a	0.186 ±0.045 a	0.339 ±0.067 a	0.210 ±0.008 a	0.800 ±0.04 a	0.068 ±0.012 a	0.064 ±0.000 a	0.035 ±0.001 b	—

Different lowercase letters indicate significant differences in columns within each material (*P*<.05).

intraoral use.[31] The surface roughness (R_a) of all specimens was measured with a profilometer (Mitutoyo Surftest SV-2100; Mitutoyo Corp) (5.5 mm transverse length, 1 mm/s stylus speed, and 0.8 mm cutoff value) after thermocycling. Three measurements were obtained from the center of each specimen at least 0.5 mm away from each other to calculate the average R_a value. Thereafter, ion elution measurements were repeated.

To examine the effect of multiple firings on surface topography, 1 specimen from each group was evaluated with scanning electron microscopy (SEM) (LEO 440; Zeiss) at ×1000 magnification. Specimens used in this analysis were not used in R_a and ion elution analysis.

The statistical analysis was performed by using a software program (IBM SPSS Statistics, v25.0; IBM Corp). The normality of the data was assessed by using the Kolmogorov-Smirnov test. For each material, ion elution values (mg/kg) were analyzed with the Kruskal-Wallis and Mann-Whitney U tests before and after thermocycling. For each material-firing pair, ion elution values (mg/kg) at the baseline and after thermocycling were compared with the Wilcoxon signed rank test. R_a values were analyzed by 2-way analysis of variance (ANOVA) and Tukey HSD tests (α=.05).

RESULTS

Mean values and standard deviations of ions in each material-firing group before and after thermocycling are presented in Tables 4 and 5. The number of repeated firings affected the elution of some ions before (Al, As, B, Ba, Cr, Cu, Li, Mg, Na, P, and Zn) ($P\leq.045$) and after (Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, K, Li, Mg, Na, P, Y, and Zn) thermocycling ($P\leq.041$).

For the effect of number of repeated firings on ion elution before thermocycling, Z-1F showed higher As, B, and Ba elution; Z-2F showed higher As, B, Ba, and Cu elution; and Z-4F showed higher Mg and Na elution ($P\leq.04$). S-1F showed higher Li and Mg elution; S-2F showed higher As, Cu, and Mg elution; and S-4F showed higher As and Cr elution ($P\leq.024$). EX-1F showed higher B, Cr, Li, and P elution; EX-2F showed higher Li and Zn elution; and EX-4F showed higher Cr and Na elution ($P\leq.04$). E-1F showed higher Al elution; E-2F showed

Table 5. Mean ±standard deviation values (mg/kg) of ions after thermocycling

Material	Firing Cycles	Ions																
		Al	**As**	**B**	**Ba**	**Be**	**Ca**	**Cd**	**Co**	**Cr**	**Cu**	**K**	**Li**	**Mg**	**Na**	**P**	**Y**	**Zn**
Z	1F	0.042 ±0.001 a	0.045 ±0.001 a	0.088 ±0.001 a	0.064 ±0.001 a	0.065 ±0.000 a	1.036 ±0.123 a	0.001 ±0.001 a	0.062 ±0.001 a	0.074 ±0.003 a	0.006 ±0.001 a	0.194 ±0.038 a	0.372 ±0.090 a	0.057 ±0.002 a	0.680 ±0.013 a	0.067 ±0.010 a	0.064 ±0.000 a	0.038 ±0.010 a
	2F	0.042 ±0.001 a	0.045 ±0.001 a	0.088 ±0.001 a	0.065 ±0.001 a	0.065 ±0.000 a	0.955 ±0.063 a	0.001 ±0.001 a	0.062 ±0.001 a	0.075 ±0.003 a	0.006 ±0.000 a	0.171 ±0.045 a	0.279 ±0.138 a	0.058 ±0.001 a	0.691 ±0.020 a	0.065 ±0.013 a	0.064 ±0.000 a	0.050 ±0.006 b
	4F	0.041 ±0.001 a	0.045 ±0.001 a	0.088 ±0.001 a	0.065 ±0.001 a	0.065 ±0.000 a	0.986 ±0.088 a	0.001 ±0.000 a	0.062 ±0.001 a	0.075 ±0.002 a	0.006 ±0.001 a	0.209 ±0.027 a	0.287 ±0.131 a	0.057 ±0.002 a	0.699 ±0.051 a	0.073 ±0.020 a	0.064 ±0.000 a	0.045 ±0.009 ab
S	1F	0.046 ±0.001 a	0.045 ±0.001 a	0.085 ±0.003 a	0.065 ±0.001 a	0.065 ±0.000 a	1.070 ±0.236 a	0.001 ±0.000 a	0.062 ±0.001 a	0.073 ±0.003 a	0.006 ±0.001 a	0.186 ±0.046 a	0.696 ±0.130 a	0.059 ±0.003 a	0.789 ±0.053 a	0.062 ±0.014 a	0.064 ±0.000 a	0.045 ±0.011 a
	2F	0.046 ±0.004 ab	0.045 ±0.001 a	0.083 ±0.003 a	0.065 ±0.001 a	0.065 ±0.000 a	1.046 ±0.119 a	0.001 ±0.001 a	0.061 ±0.001 a	0.074 ±0.002 a	0.006 ±0.000 a	0.235 ±0.045 a	0.838 ±0.322 a	0.061 ±0.003 a	0.826 ±0.081 a	0.065 ±0.008 a	0.064 ±0.000 a	0.083 ±0.092 a
	4F	0.044 ±0.003 b	0.045 ±0.001 a	0.085 ±0.002 a	0.064 ±0.001 a	0.065 ±0.000 a	1.081 ±0.105 a	0.001 ±0.001 a	0.062 ±0.001 a	0.077 ±0.007 a	0.006 ±0.001 a	0.239 ±0.047 a	0.574 ±0.313 a	0.062 ±0.005 a	0.828 ±0.118 a	0.057 ±0.016 a	0.064 ±0.000 a	0.125 ±0.169 a
EX	1F	0.044 ±0.002 a	0.038 ±0.006 ab	0.042 ±0.041 a	0.058 ±0.006 a	0.063 ±0.002 a	0.887 ±0.230 ab	0.005 ±0.000 a	0.056 ±0.001 ab	0.067 ±0.006 ab	0.014 ±0.007 ab	0.142 ±0.048 a	0.043 ±0.012 a	0.063 ±0.006 ab	0.697 ±0.026 ab	0.045 ±0.029 ab	0.095 ±0.027 a	0.073 ±0.027 ab
	2F	0.044 ±0.001 a	0.033 ±0.001 a	0.006 ±0.001 b	0.053 ±0.001 b	0.062 ±0.000 a	0.804 ±0.080 b	0.005 ±0.000 a	0.056 ±0.001 b	0.063 ±0.001 b	0.019 ±0.001 a	0.363 ±0.134 b	0.034 ±0.017 a	0.064 ±0.004 b	0.739 ±0.042 a	0.035 ±0.016 a	0.116 ±0.000 a	0.095 ±0.006 a
	4F	0.042 ±0.001 a	0.045 ±0.001 b	0.089 ±0.001 a	0.064 ±0.001 a	0.065 ±0.000 b	1.050 ±0.284 a	0.005 ±0.000 b	0.056 ±0.001 a	0.071 ±0.003 a	0.005 ±0.001 b	0.200 ±0.033 ab	0.236 ±0.176 b	0.057 ±0.002 a	0.688 ±0.027 b	0.068 ±0.011 b	0.064 ±0.000 b	0.038 ±0.011 b
E	1F	0.046 ±0.002 a	0.034 ±0.001 a	0.003 ±0.004 a	0.054 ±0.001 ab	0.062 ±0.000 a	0.815 ±0.061 a	0.005 ±0.000 a	0.056 ±0.001 a	0.063 ±0.001 a	0.019 ±0.000 a	0.442 ±0.122 a	0.062 ±0.045 a	0.064 ±0.001 a	0.742 ±0.026 a	0.048 ±0.020 a	0.116 ±0.000 a	0.103 ±0.007 a
	2F	0.045 ±0.002 a	0.034 ±0.001 a	0.001 ±0.001 a	0.054 ±0.000 b	0.062 ±0.000 a	0.840 ±0.129 a	0.005 ±0.000 a	0.056 ±0.001 a	0.064 ±0.001 a	0.018 ±0.001 a	0.426 ±0.042 a	0.040 ±0.035 a	0.065 ±0.002 a	0.755 ±0.023 a	0.167 ±0.311 a	0.116 ±0.000 a	0.090 ±0.013 b
	4F	0.046 ±0.002 a	0.034 ±0.000 a	0.001 ±0.001 a	0.053 ±0.001 a	0.062 ±0.000 a	0.877 ±0.209 a	0.005 ±0.000 a	0.056 ±0.001 a	0.063 ±0.001 a	0.018 ±0.001 a	0.447 ±0.090 a	0.067 ±0.065 a	0.076 ±0.034 a	0.749 ±0.022 a	0.050 ±0.021 a	0.116 ±0.000 a	0.091 ±0.014 ab

Different lowercase letters indicate significant differences between different repeated firings in columns within each material-ion pair ($P<.05$).

higher As, B, and Ba elution; and E-4F showed higher B, Ba, and Zn elution ($P\leq.018$) (Table 4). For the effect of number of repeated firings on ion elution after thermocycling, Z-2F showed higher Zn elution ($P=.024$). S-1F showed higher Al elution ($P=.046$). EX-1F showed higher B, Ba, Cd, and Y elution; S-2F showed higher Cd, Cu, K, Mg, Na, Y, and Zn elution; and S-4F showed higher As, B, Ba, Be, Ca, Co, Cr, Li, and P elution ($P\leq.046$). E-1F showed higher Zn and E-2F showed higher Ba elution ($P\leq.036$) (Table 5).

Significant differences were observed in the ion elution of some material-firing pairs before and after thermocycling (Fig. 2). For Al, EX, E, S-1F, and S-2F showed a significant increase ($P\leq.046$). For As, all material-firing pairs other than S-1F and Z-4F showed a significant decrease ($P\leq.041$). For B, Z, S-2F, S-4F, and EX-4F showed a significant increase ($P=.005$). However, EX-2F, E-2F, and E-4F showed a significant decrease ($P=.005$). For Ba, all material-firing cycle pairs other than E-1F and Z-4F showed a significant decrease ($P\leq.006$). For Be, E, EX-1F, and EX-2F showed a significant decrease ($P\leq.014$). For Ca, all material-firing cycle pairs other than 1F-Z, 2F-Z, 4F-Z, 4F-EX, and 4F-E showed a significant decrease ($P\leq.013$). For Cd, E, EX-1F, and EX-2F showed a significant increase ($P\leq.018$). For Co, E, EX-1F, and EX-2F showed a significant decrease ($P\leq.008$). For Cr, EX, E, and S-2F showed a significant decrease ($P\leq.026$). For Cu, E and EX-2F showed a significant increase ($P\leq.005$), whereas S-2F showed a significant decrease ($P=.024$). For K, E, EX-2F, and S-4F showed a significant increase ($P\leq.022$), whereas EX-1F showed a significant decrease ($P=.013$). For Li, EX, E, and S-1F showed a significant decrease ($P\leq.007$). For Mg, all material-firing pairs other than S-4F showed a significant decrease ($P=.005$). For Na, every material-firing pair showed a significant decrease ($P\leq.022$). For P, S-2F, S-4F, and EX-4F showed a significant increase ($P\leq.046$). For Y, E, EX-1F, and EX-2F showed a significant increase ($P\leq.014$). For Zn, S-1F showed a significant decrease ($P=.007$), while every other material-firing pair showed a significant increase ($P\leq.028$), except for Z-1F and EX-4F ($P\geq.262$).

The SEM images revealed that small lines on the surface of Z-1F were replaced by small pores as the number of firings increased (Fig. 3). No visible differences were detected among the surfaces of S after a different

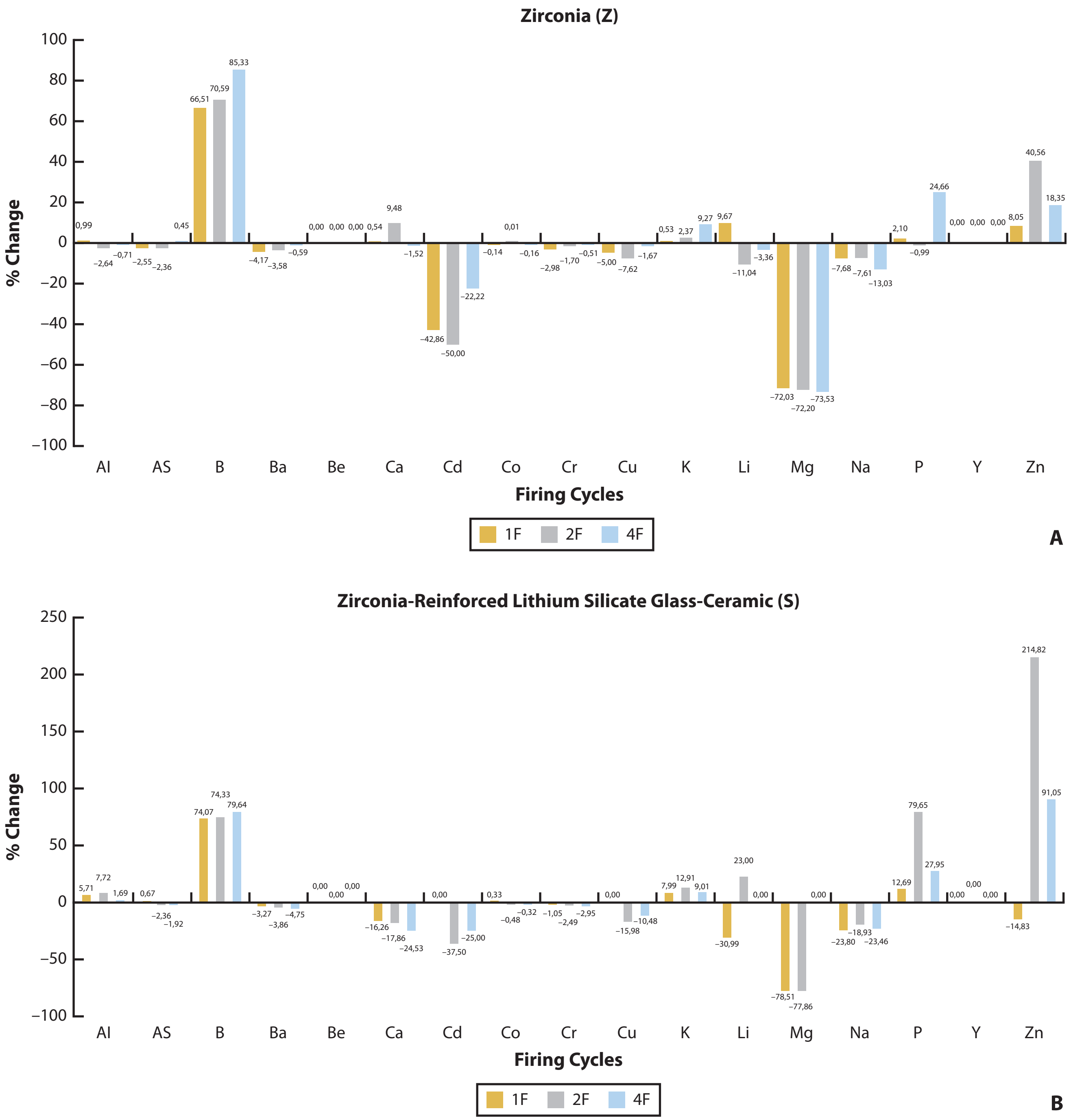

Figure 2. Percent change of ions after thermocycling within each firing stage. Negative value in y-axis indicates percent decrease. A, Zirconia. B, Zirconia-reinforced lithium silicate glass-ceramic.

number of repeated firings. EX-2F had multiple complex lines, which were not present in EX-1F and EX-4F. Small pores and lines were apparent on E-4F, whereas a similar topography was observed in E-1F and E-2F.

The 2-way ANOVA revealed that the type of material, number of firings, and their interaction affected the R_a ($P<.001$). When clinically relevant material-firing pairs were compared, only the R_a values of E changed significantly according to repeated firing, as E-1F presented higher values than E-2F and E-4F ($P<.001$). When 1F groups of the materials were compared, E showed the highest R_a among the materials ($P\leq.003$). In addition, Z had higher R_a than S ($P=.009$), while EX showed similar values to Z ($P=.945$) and S ($P=.413$). When 2F groups were compared, only the difference between Z and S was significant ($P=.01$) as Z showed higher R_a. No significant

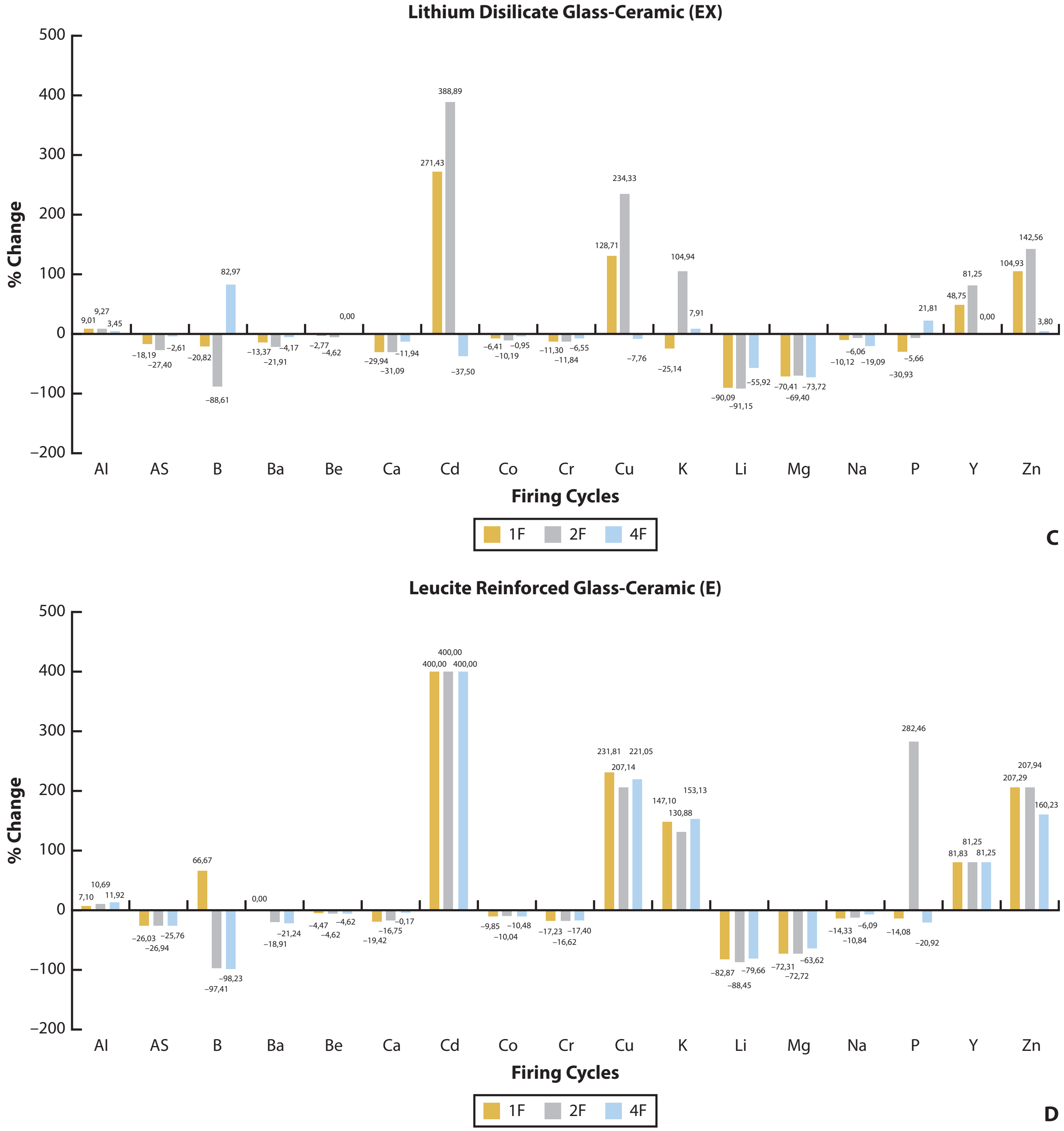

Figure 2. *(Continued).* C, Lithium disilicate glass-ceramic. D, Leucite-reinforced glass-ceramic.

differences were observed among the 4F groups ($P \geq .677$) (Table 6).

DISCUSSION

Elution of most of the ions investigated in the present study showed significant differences within each CAD-CAM material depending on repeated firings both before and after thermocycling, and significant differences were observed between the eluted values of each ion before and after thermocycling. In addition, the R_a of specimens was affected by both material type and repeated firing. Therefore, the null hypotheses were rejected.

Even though most CAD-CAM ceramic manufacturers recommend 1 extrinsic firing before cementation, occlusal, interproximal, or esthetic adjustments may

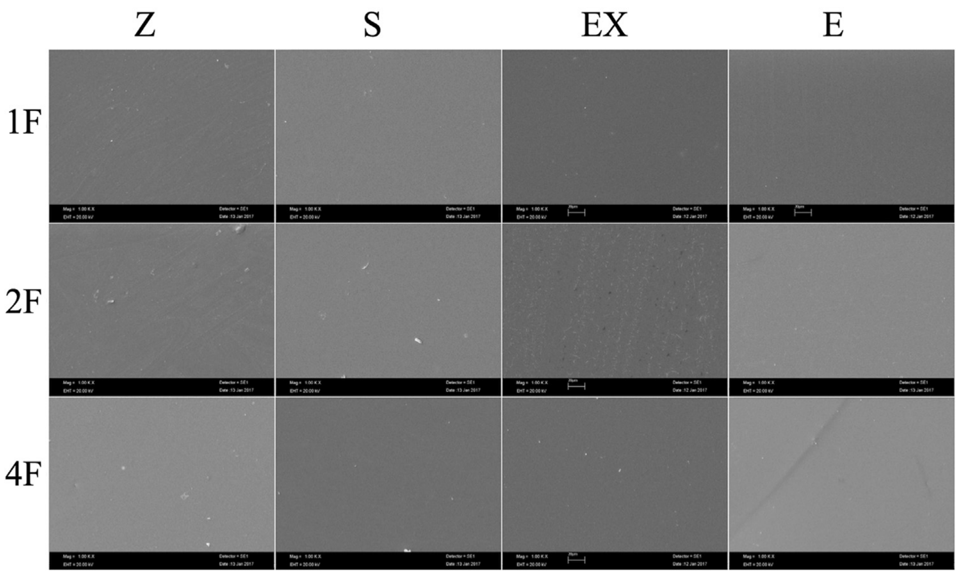

Figure 3. Representative SEM images of CAD-CAM material surfaces after different number of repeated firings (original magnification ×1000). CAD-CAM, computer-aided design and computer-aided manufacturing; SEM, scanning electron microscope.

require additional firings.[5] To the authors' knowledge, the present study was the first on the combined effect of repeated firings and thermocycling on ion elution of CAD-CAM ceramics. Before thermocycling, the number of ions released was significantly higher from each firing group within a material and was similar, ranging from 1 (E-1F) to 4 (Z-2F and EX-1F). However, after thermocycling, only the significantly higher number of ions released from EX-2F (Cd, Cu, K, Mg, Na, Y, and Zn) and EX-4F (As, B, Ba, Be, Ca, Co, Cr, Li, and P) increased.

The chemical degradation of dental ceramics in acidic media has been previously investigated.[7,8,11-14,19] Milleding et al[12] reported that immersion in 4% acetic acid solution at 80 °C for 18 hours increased the surface roughness of leucite ceramic, a finding that was corroborated by another study, in which organic acids were reported to negatively affect lithium disilicate and zirconia-reinforced lithium silicate ceramics.[8] In another study on the chemical degradation of dental ceramics, including a leucite glass-ceramic and an yttria-stabilized zirconia, oxide ceramics eluted significantly fewer ions than glass-ceramics, which was observed on a larger scale in the acidic medium.[11] However, other studies suggested that increasing the frequency of pH changes increased the corrosion of glass ceramics and Si ion elution compared with immersion in a constant pH environment.[20,21] Considering that Si, O, Ti, and Zr are the dominant elements in materials tested in the present study (Table 1), a higher amount of elution of these ions was expected. However, these elements were not detected in ICP-EOS analyses, regardless of thermocycling, possibly because these elements are present as chemical compounds formed with each other, and ion elution might not depend on the abundance of elements.[15] In addition, thermocycling was performed by using neutral-pH distilled water. However, these ions might be resistant to elution in neutral-pH liquids.

Table 6. Descriptive statistics of surface roughness (µm) values of different CAD-CAM ceramics and firing groups

Material	Number of Firings	Mean ±Standard Deviation
Z	1F	1.39 ±0.29^{aB}
	2F	1.21 ±0.37^{aB}
	4F	1.0 ±0.44^{aA}
S	1F	0.60 ±0.36^{aA}
	2F	0.42 ±0.33^{aA}
	4F	0.58 ±0.46^{aA}
EX	1F	1.09 ±0.52^{aAB}
	2F	0.73 ±0.39^{aAB}
	4F	0.69 ±0.29^{aA}
E	1F	2.26 ±1.0^{bC}
	2F	0.53 ±0.28^{aAB}
	4F	0.70 ±0.32^{aA}

Different superscript lowercase letters indicate significant differences among the firings within material, while different superscript uppercase letters indicate significant differences among materials within firings (*P*<.05).

Tai et al[32] reported a significant effect of simulated occlusal wear by using different antagonists on the leaching of Ni and Be ions from dental alloys. In an in vivo study, Elshahawy et al[15] concluded that Zn elution from Type IV gold crowns and Si elution from E crowns significantly increased after 3 months of clinical service. In the present study, ion elution of Zn from E significantly increased after thermocycling regardless of the number of repeated firings, whereas Si was not present in the analyses. However, a direct relation between the present study and that of Elshahawy et al[15] might be misleading considering the absence of mechanical aging in the present study. Future studies investigating the combined effect of thermomechanical aging and different repeated firings on chemical degradation of CAD-CAM ceramics are needed to increase knowledge on the clinical behavior of these materials.

Among the ions investigated in the present study, some (Al, As, B, Ba, Be, Cd, Cr, Co, Cu, and Zn) might have acute or chronic toxic effects if daily intake exceeds the thresholds stated by the Agency for Toxic Substances and Disease Registry (Table 1). The minimal risk levels of these toxic ions have been specified in a previous study on the ion elution of different esthetic materials when subjected to a home bleaching agent.[7] Lower elution values for Al, Ca, K, Li, Na, P, and Zn ions than the minimal risk levels were reported, whereas Cu levels were above the threshold for certain materials, including zirconia.[7] In the present study, As, B, Be, Cd, Cr, Co, and Zn levels exceeded the stated thresholds for each material-firing pair, regardless of aging. In addition, Cu levels were higher than the stated thresholds in EX-1F, EX-2F, and E after thermocycling. However, these results should be interpreted carefully, as the present study did not evaluate the daily release of each ion but focused on long-term ion release. Thus, future studies should focus on the daily release of ions from the tested materials to elaborate the knowledge on their toxicity after repeated firings and aging.

Even though repeated firings reduced the R_a of materials tested in the present study, only E showed a significantly lower R_a after repeated firings. This difference between E and the other materials tested may be attributed to the difference in the composition of restorative and glaze materials. Nevertheless, this result was consistent with a previous study, which reported that increased number of firings reduced the R_a of leucite-reinforced glass-ceramics.[25] Oğuz et al[27] evaluated the R_a of zirconia after repeated firings and reported similar results to those in the present study. To the authors' knowledge, no study has investigated the effect of repeated firings on the R_a of S. Therefore, the results on the R_a of S could not be compared. Meng et al[1] showed that repeated firing of lithium disilicate did not change the R_a, which was consistent with the results of the present study. Contrarily, in another study, repeated firings were shown to affect the R_a of lithium disilicate.[6] However, a staining liquid was also used in that study, which may have caused this difference. In addition, only R_a values were analyzed.

SEM images showed that the EX-4F did not display the complex multiple lines present in EX-2F, consistent with a previous study,[5] which showed that lithium disilicate displayed a complex mesh structure after the first and second firings. However, Meng et al[1] reported that polished lithium disilicate did not show any topographical difference after a different number of repeated firings. This difference may be related to the fact that the specimens were not polished but glazed in the present study. For Z, increased number of firings resulted in a smoother surface, which substantiates the R_a findings. No significant differences were observed among the different firing groups of S and E. Considering these results, it can be speculated that the effect of multiple firings on R_a is material-dependent.

Limitations of the present study included the absence of a priori power analysis. However, significant differences were observed. The materials tested in the present study are commonly used; however, alternatives with different chemical compositions are available, and only 1 type of each material type was tested. Another limitation was that thermocycling does not completely replicate intraoral conditions as both sides of the specimens were aged and distilled water was used. In addition, other parameters that can be measured with a profilometer, such as the average value of the absolute heights of the 5 highest peaks and deepest valleys (R_z) or root mean square value of the surface departures (R_q), might elaborate the understanding of the effect of the tested parameters on surface roughness. Previous studies on chemical degradation have used 4% acetic acid;[7,11-14,16,17,19] thus, future studies should investigate the ion elution from different CAD-CAM materials after multiple firings by using 4% acetic acid. Finally, the genotoxic effects of Ni-Cr-based alloys have been reported,[33] and this may be implemented in future in vivo studies investigating the effect of the ions eluted from the CAD-CAM materials tested in the present study after repeated firings on neighboring tissues.

CONCLUSIONS

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

1. No clear trend was found on the effect of repeated firings on the ion elution of materials before thermocycling.
2. After thermocycling, ion elution increased only from EX (2F and 4F groups); therefore, EX may be more susceptible to thermocycling after repeated firings.
3. No clear trend was found on the effect of thermocycling on the ion elution across materials.
4. The SEM images supported the measured surface roughness values, which revealed varied effects of number of firings on material surfaces at different stages. Only the surface roughness of E changed depending on the number of firings and the roughness decreased.

5. Surface roughness of materials was similar when compared with each other after 4 times of firing.

REFERENCES

1. Meng H, Xie H, Yang L, Chen B, Chen Y, Zhang H, et al. Effects of multiple firings on mechanical properties and resin bonding of lithium disilicate glass-ceramic. J Mech Behav Biomed Mater 2018;88:362-9.
2. Çakmak G, Subaşı MG, Yilmaz B. Effect of thermocycling on the surface properties of resin-matrix CAD-CAM ceramics after different surface treatments. J Mech Behav Biomed Mater 2021;117:104401.
3. Gunal B, Ulusoy MM. Optical properties of contemporary monolithic CAD-CAM restorative materials at different thicknesses. J Esthet Restor Dent 2018;30:434-41.
4. Nejatidanesh F, Azadbakht K, Savabi O, Sharifi M, Shirani M. Effect of repeated firing on the translucency of CAD-CAM monolithic glass-ceramics. J Prosthet Dent 2020;123:530.e1-6.
5. Ozdogan A, Ozdemir H. Effects of multiple firing processes on the mechanical properties of lithium disilicate glass-ceramics produced by two different production techniques. J Prosthet Dent 2021;125:527.e1-7.
6. Miranda JS, Barcellos ASP, MartinelliLobo CM, Caneppele TMF, Amaral M, Kimpara ET. Effect of staining and repeated firing on the surface and optical properties of lithium disilicate. J Esthet Restor Dent 2020;32:113-8.
7. Karaokutan I, Aykent F. Effect of a home bleaching agent on the ion elution of different esthetic materials. J Prosthodont 2020;29:805-13.
8. Sagsoz O, Polat Sagsoz N. Chemical degradation of dental CAD/CAM materials. Biomed Mater Eng 2019;30:419-26.
9. Anusavice KJ. Degradability of dental ceramics. Adv Dent Res 1992;6:82-9.
10. Junpoom P, Kukiattrakoon B, Hengtrakool C. Surface characteristic changes of dental ceramics after cyclic immersion in acidic agents and titratable acidity. Eur J Prosthodont Restor Dent 2010;18:177-84.
11. Milleding P, Haraldsson C, Karlsson S. Ion leaching from dental ceramics during static in vitro corrosion testing. J Biomed Mater Res 2002;61:541-50.
12. Milleding P, Wennerberg A, Alaeddin S, Karlsson S, Simon E. Surface corrosion of dental ceramics in vitro. Biomaterials 1999;20:733-46.
13. Kukiattrakoon B, Hengtrakool C, Kedjarune-Leggat U. The effect of acidic agents on surface ion leaching and surface characteristics of dental porcelains. J Prosthet Dent 2010;103:148-62.
14. Kukiattrakoon B, Hengtrakool C, Kedjarune-Leggat U. Degradability of fluorapatite-leucite ceramics in naturally acidic agents. Dent Mater J 2010;29:502-11.
15. Elshahawy W, Ajlouni R, James W, Abdellatif H, Watanabe I. Elemental ion release from fixed restorative materials into patient saliva. J Oral Rehabil 2013;40:381-8.
16. Jakovac M, Živko-Babić J, Ćurković L, Aurer A. Measurement of ion elution from dental ceramics. J Eur Ceram Soc 2006;26:1695-700.
17. Jakovac M, Živko-Babić J, Ćurković L, Carek A. Chemical durability of dental ceramic material in acid medium. Acta Stomatol Croat 2006;40:65-71.
18. Esquivel-Upshaw JF, Dieng FY, Clark AE, Neal D, Anusavice KJ. Surface degradation of dental ceramics as a function of environmental pH. J Dent Res 2013;92:467-71.
19. Kukiattrakoon B, Hengtrakool C, Kedjarune-Leggat U. Chemical durability and microhardness of dental ceramics immersed in acidic agents. Acta Odontol Scand 2010;68:1-10.
20. Esquivel-Upshaw JF, Ren F, Hsu SM, Dieng FY, Neal D, Clark AE. Novel testing for corrosion of glass-ceramics for dental applications. J Dent Res 2018;97:296-302.
21. Hsu SM, Ren F, Batich CD, Clark AE, Neal D, Esquivel-Upshaw JF. Effect of pH cycling frequency on glass-ceramic corrosion. Materials (Basel) 2020;13:3655.
22. Campanelli de Morais D, de Oliveira Abu-Izze F, Rivoli Rossi N, Gallo Oliani M, de Assunção ESRO, de Siqueira Anzolini Saavedra G, et al. Effect of consecutive firings on the optical and mechanical properties of silicate and lithium disilicate based glass-ceramics. J Prosthodont 2021;30:776-82.
23. Miranda JS, Barcellos ASP, Campos TMB, Cesar PF, Amaral M, Kimpara ET. Effect of repeated firings and staining on the mechanical behavior and composition of lithium disilicate. Dent Mater 2020;36:e149-57.
24. Fathi A, Farzin M, Giti R, Kalantari MH. Effects of number of firings and veneer thickness on the color and translucency of 2 different zirconia-based ceramic systems. J Prosthet Dent 2019;122:565.e1-7.
25. Yilmaz K, Ozkan P. Profilometer evaluation of the effect of various polishing methods on the surface roughness in dental ceramics of different structures subjected to repeated firings. Quintessence Int 2010;41:e125-31.
26. Gonuldas F, Yılmaz K, Ozturk C. The effect of repeated firings on the color change and surface roughness of dental ceramics. J Adv Prosthodont 2014;6:309-16.
27. Oğuz E, Özgür ME, Sungur S, Üçtaşlı S. Impact of multiple firings and resin cement type on shear bond strength between zirconia and resin cements. J Adv Prosthodont 2020;12:197-203.
28. The Agency for Toxic Substances and Disease Registry (ATSDR) web site. Available at: https://www.atsdr.cdc.gov/mrls/pdfs/ATSDR%20MRLs%20-%20March%202021%20-%20H.pdf. Accessed June 29, 2021.
29. De Backer H, Van Maele G, De Moor N, Van den Berghe L, De Boever J. A 20-year retrospective survival study of fixed partial dentures. Int J Prosthodont 2006;19:143-53.
30. Näpänkangas R, Raustia A. Twenty-year follow-up of metal-ceramic single crowns: a retrospective study. Int J Prosthodont 2008;21:307-11.
31. Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. J Dent 1999;27:89-99.
32. Tai Y, De Long R, Goodkind RJ, Douglas WH. Leaching of nickel, chromium, and beryllium ions from base metal alloy in an artificial oral environment. J Prosthet Dent 1992;68:692-7.
33. Alp G, Çakmak G, Sert M, Burgaz Y. Corrosion potential in artificial saliva and possible genotoxic and cytotoxic damage in buccal epithelial cells of patients who underwent Ni-Cr based porcelain-fused-to-metal fixed dental prostheses. Mutat Res Genet Toxicol Environ Mutagen 2018;827:19-26.

Corresponding author:
Dr Gülce Çakmak
Department of Reconstructive Dentistry and Gerodontology
University of Bern
Freiburgstrasse 7, Bern 3007
SWITZERLAND
Email: guelce.cakmak@zmk.unibe.ch

CRediT authorship contribution statement
Murat Sert: Methodology, Data curation, Data interpretation, Formal analysis. Gülce Çakmak: Methodology, Investigation, Project administration, Conceptualization. Meryem Gülce Subaşı: Methodology, Investigation, Project administration, Writing - original draft. Mustafa Borga Donmez: Writing - original draft, Critical revision of article. Burak Yilmaz: Supervision, Writing - review and editing, critical revision of article.

https://doi.org/10.1016/j.prosdent.2022.04.028