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ORIGINAL ARTICLE

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Influence of polishing technique and coffee thermal cycling on the surface roughness and color stability of additively and subtractively manufactured resins used for definitive restorations

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Abstract

Purpose: To evaluate how different polishing techniques and coffee thermal cycling affect the surface roughness and stainability of additively and subtractively manufactured resins used for definitive prostheses.

Materials and Methods: Two additively manufactured composite resins (Crowntec, CT and VarseoSmile Crown Plus, VS) and a subtractively manufactured resin nanoceramic (Cerasmart, CS) were used to fabricate 90 rectangular-shaped specimens (14 × 12 × 1 mm) ($n = 30$). After baseline surface roughness (R_a) measurements, specimens were divided into three groups based on the polishing technique; conventional polishing with a 2-stage polishing kit (CP) and surface sealant application (Optiglaze, OG or Vita Akzent LC, VA) ($n = 10$). After polishing, specimens were subjected to 10,000 cycles of coffee thermal cycling. R_a and color coordinate measurements were performed after polishing and after coffee thermal cycling. Color difference (ΔE_{00}) was calculated. Scanning electron microscope images were taken at each time interval. Kruskal–Wallis or 1-way analysis of variance (ANOVA) were used to evaluate R_a of materials within each polishing-time interval pair and different polishing techniques within each material-time interval pair, while Friedman or repeated measures ANOVA were used to evaluate R_a at different time intervals within each material-polishing pair. ΔE_{00} was assessed with 2-way ANOVA ($\alpha = 0.05$).

Results: Other than VA-after polishing ($p = 0.055$), tested materials had significantly different R_a within each polishing-time interval pair ($p \leq 0.038$). When R_a differences among different polishing techniques within each material-time interval pair were considered, CS had differences after coffee thermal cycling, CT had differences before polishing and after coffee thermal cycling, and VS had differences within each time interval ($p \leq 0.038$). When R_a differences among different time intervals within each material-polishing pair were considered, significant differences were observed among all pairs ($p \leq 0.016$), except for CS-VA ($p = 0.695$) and VS-VA ($p = 0.300$). ΔE_{00} values were affected by material and polishing technique interaction ($p = 0.007$).

Conclusions: R_a of CS was similar to or lower than the R_a of other materials, regardless of the time interval or polishing technique. CP mostly led to lower R_a than other polishing techniques, whereas VA resulted in a high R_a regardless of the material-time interval pair. Polishing reduced the R_a, while coffee thermal cycling was found to have

a small effect. Among tested material-polishing pairs, only CS-VA had moderately unacceptable color change when previously reported threshold values were considered.

KEYWORDS
additive manufacturing, coffee thermal cycling, polishing, stainability, surface roughness

Along with subtractive manufacturing, additive manufacturing has been introduced into dentistry due to the advancements in computer-aided design and computer-aided manufacturing (CAD-CAM) technologies.[1] A wide range of restorative materials are applicable by using CAD-CAM technologies[2] such as resin-based materials.[3] Resin nanoceramics, which can be subtractively manufactured combine the advantages of composites and ceramics as they consist of nanohybrid filler materials dispersed in urethane dimethacrylate matrix.[3,4] In terms of additive manufacturing of resin-based materials, composite resins that are indicated for fixed definitive prostheses are among the latest restorative materials introduced.[5]

Having a smooth external surface is essential for the long-term use of a prosthesis[3] as surface roughness (R_a) might lead to plaque accumulation and discoloration.[6] Clinically acceptable R_a of dental materials have been reported as 0.2 μm.[7–9] Manufacturers recommend either glazing or polishing for smoother surfaces[4]; however, conventional furnace glazing is not recommended for materials with resin matrices.[10] An alternative method to improve the R_a of resin-based materials may be using surface sealants that act as surface glazes by filling the microporosities on the prosthesis surface.[10] However, the information on the effect of surface sealants on resin nanoceramics[3,4,6,10] or additively manufactured composite resins is sparse.

Even though previous studies have investigated additively manufactured composite resins indicated for definitive prostheses,[5,11–22] the knowledge on their R_a and stainability[22] is limited. In addition, to the authors' knowledge, the combined effect of different polishing techniques and long-term aging on these properties has not been documented. Because restorative materials are subjected to thermal changes intraorally with different discoloring media, the present study aimed to evaluate the effect of three different polishing techniques (conventional polishing with a 2-step polishing kit and two different surface sealants) and coffee thermal cycling on the R_a and stainability of two additively manufactured composite resins and to compare to those of a subtractively manufactured resin nanoceramic. The null hypotheses were that (1) material type would not affect the R_a before polishing, (2) polishing technique and time interval (before polishing, after polishing, and after coffee thermal cycling) would not affect the R_a among tested materials, (3) material type and time interval (before polishing, after polishing, and after coffee thermal cycling) would not affect the R_a among different polishing techniques within tested restorative materials, (4) material type and polishing technique would not affect the R_a among different time intervals within tested restorative materials, and (5) polishing technique and material type would not affect the stainability of tested restorative materials.

MATERIALS AND METHODS

An overview of the present study is shown in Figure 1. Three A1 shaded CAD-CAM materials (Cerasmart; GC Corp (CS), Crowntec; Saremco Dental AG (CT), and VarseoSmile Crown Plus; Bego (VS)) indicated for definitive fixed prostheses were used to fabricate a total of 90 rectangular-shaped (14 × 12 × 1 mm) specimens (Table 1). For the fabrication of CS specimens, CAD-CAM blocks were wet-sliced into 1 mm-thick specimens by using a precision cutter (Vari/cut VC-50; Leco Corporation). For the fabrication of CT and VS specimens, a rectangular plate with desired final dimensions was designed using a software program (Meshmixer v3.5.474; Autodesk Inc) in standard tessellation language (STL) format. This STL file was imported to a nesting software program (Composer v1.3.3; Asiga) and positioned horizontally on the build platform. After the supports were automatically generated, the support arrangement was repeated 10 times for standardization. Layer thickness was set to 50 μm and specimens were printed using a digital light processing-based 3D printer (MAX UV; Asiga). An alcohol-soaked cloth (95% Ethanol Absolut; Grogg Chemie AG) was used to remove residual resin on CT specimens. After drying specimens with an air syringe, they were placed in a xenon polymerization device (Otoflash G171; NK Optik) for polymerization under nitrogen oxide gas atmosphere (4000 lighting exposures). Then, specimen surfaces were sandblasted with 50 μm glass beads (Rolloblast; Renfert) at 1.5 bar and supports were removed with a cut-off wheel (Keystone Cut-off Wheels; Keystone Industries).[23] VS specimens were initially cleaned in an ultrasonic bath that contained reusable ethanol solution (95% Ethanol Absolut; Grogg Chemie AG) followed by thorough cleaning in an ultrasonic bath that contained fresh ethanol (95% Ethanol Absolut; Grogg Chemie AG). After air-drying the specimens, supports were removed by using the same cut-off wheel, and surfaces were sandblasted with 50 μm glass beads (Rolloblast; Renfert) at 1.5 bar until the whitish layer that appeared after cleaning had disappeared. Thereafter, specimens were polymerized in the same xenon polymerization device under nitrogen oxide gas atmosphere (3000 lighting exposures).[24] After fabrication, the final thicknesses of all specimens were controlled by using a micrometer (Digimatic QuantuMike IP65; Mitutoyo).

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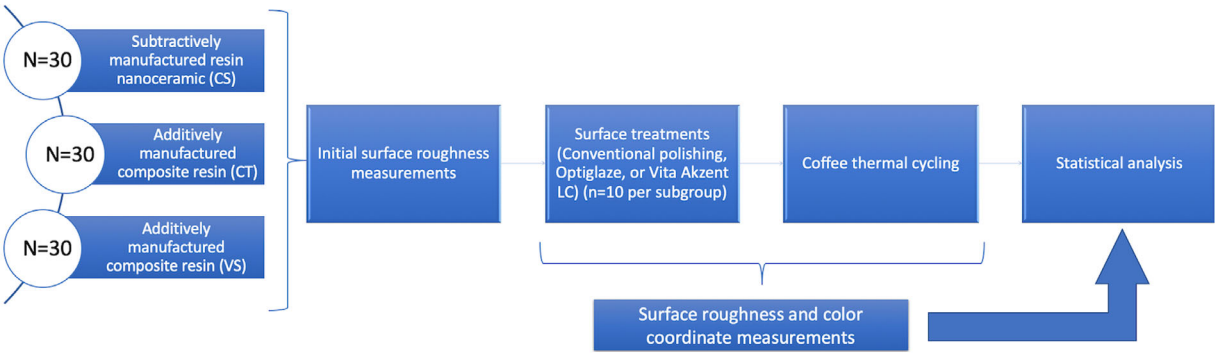

FIGURE 1 Overview of the study design.

TABLE 1 List of CAD-CAM materials used in this study.

Material	Type	Composition	Manufacturer
Cerasmart (CS)	Subtractively manufactured resin nanoceramic	71% Silica (20 nm) and barium glass nanoparticles (300 nm), Bis-MEPP, UDMA, DMA	GC Corp, Tokyo, Japan
Crowntec (CT)	Additively manufactured composite resin	Esterification products of 4,4′-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, pyrogenic silica, initiators. Total content of inorganic fillers (particle size 0.7 μm) is 30–50 wt%.	Saremco Dental AG, Rebstein, Switzerland
VarseoSmile Crown Plus (VS)	Additively manufactured composite resin	Esterification products of 4,4′-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, methyl benzoylformate, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide, 30–50 wt%—inorganic fillers (particle size 0.7 μm)	Bego, Bremen, Germany

Initial R_a values were measured by using a non-contact optical profilometer (FRT MicroProf 100, equipped with a CWL 300 μm sensor, resolution of 3 nm in z-dimension; Fries Research & Technology GmbH).[8] R_a of 6 linear traces (3 horizontal and 3 vertical), which had a length of 5.5 mm, a pixel density of 5501 point/line, and were 1 mm apart, was determined with an integrated software program (Mark III; Fries Research & Technology GmbH) according to the International Organization for Standardization 4287 standard (ISO Standard Reference) with a cutoff value (Lc) of 0.8 mm. The 6 R_a values were averaged per specimen.

Each set of specimens was then randomly divided into three (Excel; Microsoft Corp) depending on the polishing technique used; conventional polishing (control-CP) or application of a surface sealant (Optiglaze; GC Corp (OG) or Vita Akzent LC; Vita Zahnfabrik (VA)) ($n = 10$). Only one surface of the specimens was polished. Specimens of the CP group were manually polished with a 2-stage polishing kit (Diatech; Coltène AG) and a polishing paste (Zircon Brite; Klasse 4 Dental GmbH) applied at 5000 rpm for 90 s with each polishing bur. One surface of the specimens of OG and VA groups was sandblasted with 50 μm Al_2O_3 particles (Cobra; Renfert) (1.5 bar for OG and 2 bar for VA). After sandblasting, specimens were steam cleaned for 15 s and air-dried. Sandblasted surfaces were then treated with a ceramic primer (Ceramic Primer II, GC Corp), and a thin layer of OG or VA was applied with a soft brush in one direction to eliminate air bubbles.[10] Twenty seconds after application,[10] a light-polymerization unit (GC Labolight Duo; GC Corp) was used for polymerization (5 min for OG and 3 min for VA). One specimen was polymerized at once and each specimen was placed in the mid-point in the center of the chamber. After polymerization, all specimens were cleaned in distilled water (Eltrosonic Ultracleaner 07-08; Eltrosonic GmbH) for 15 min and stored in 37 ± 1°C distilled water for 24 h under light-proof conditions. After 24 h, R_a measurements were repeated.

A spectrophotometer (CM-26d; Konica Minolta),[7] which had a medium area view, 2° human observer characteristics, and Commission International de l'Eclairage (CIE) D65 illumination was used to measure the baseline color coordinates (L*, a*, and b*) defined by CIE on a gray backing. Optical contact between the specimens and the backing was ensured with the use of saturated sucrose solution, and the spectrophotometer was calibrated prior to each measurement. One operator (G.C.) performed three measurements for each specimen in a temperature and humidity-controlled room, and the values were averaged.

Specimens were subjected to 10,000 cycles (SD Mechatronik Thermocycler; SD Mechatronik GmbH) at 5–55°C in a coffee solution with a dwell time of 30 s and a transfer

TABLE 2 Descriptive statistics of surface roughness (in μm) values of each material based on polishing protocols and time intervals.

Material	Before polishing		Polishing protocol	After polishing		After coffee thermal cycling	
	Mean ± standard deviation	Median (Min–Max)		Mean ± standard deviation	Median (Min–Max)	Mean ± standard deviation	Median (Min–Max)
	0.27 ± 0.09	0.24^{b} (0.18–0.50)	CP	0.16 ± 0.04	0.15^{ABab} (0.12–0.23)	0.1 ± 0.01*	0.10^{Aa} (0.08–0.11)
CS	0.23 ± 0.10	0.20^{b} (0.13–0.50)	OG	0.10 ± 0.04^{A}	0.11^{a} (0.04–0.16)	0.14 ± 0.05^{A+}	0.14^{ab} (0.05–0.21)
	0.24 ± 0.03	0.24^{a} (0.19–0.26)	VA	0.31 ± 0.24	0.23^{Aa} (0.12–0.91)	0.28 ± $0.11^{AB\hat{}}$	0.26^{a} (0.08–0.48)
Total	0.24 ± 0.08	0.24^{A} (0.13–0.50)					
	0.49 ± 0.24^{+}	0.40^{b} (0.28–1.01)	CP	0.29 ± 0.26	0.17^{Ba} (0.09–0.87)	0.19 ± 0.11	0.12^{Ba*} (0.09–0.38)
CT	0.5 ± 0.19_{b*}	0.5 (0.26–0.78)	OG	0.35 ± 0.13^{Cab}	0.35 (0.21–0.58)	0.31 ± 0.12^{Ba}	0.30^{+} (0.17–0.56)
	0.6 ± 0.28_{b+}	0.6 (0.31–1.16)	VA	0.33 ± 0.14^{a}	0.31^{A} (0.17–0.59)	0.40 ± 0.17^{Bab}	0.40^{+} (0.17–0.70)
Total	0.53 ± 0.24	0.49^{C} (0.26–1.16)					
	0.37 ± 0.06^{c+}	0.36 (0.29–0.49)	CP	0.12 ± 0.02^{a*}	0.11^{A} (0.10–0.17)	0.16 ± 0.01^{b*}	0.16^{B} (0.14–0.19)
VS	0.29 ± 0.06^{b*}	0.26 (0.23–0.41)	OG	0.20 ± 0.06^{Ba+}	0.21 (0.11–0.30)	0.21 ± 0.10^{Aa*+}	0.21 (0.10–0.43)
	0.31 ± 0.04^{a*+}	0.31 (0.25–0.39)	VA	0.28 ± 0.12^{a+}	0.28^{A} (0.11–0.48)	0.26 ± 0.12^{Aa+}	0.25 (0.13–0.52)
Total	0.32 ± 0.06	0.31^{B} (0.23–0.49)					

Abbreviations: CP, conventional polish; CS, Cerasmart; CT, Crowntec; OG, Optiglaze; VA, Vita Akzent; VS, VarseoSmile Crown Plus.
Different superscript uppercase letters indicate significant differences among materials within each polishing-time interval pair (Kruskal Wallis or 1-way ANOVA), while lowercase letters indicate significant differences among different time intervals within each material-polishing pair (Friedman or repeated measures ANOVA). Different uppercase symbols indicate significant differences among polishing techniques within each material-time interval pair (Kruskal Wallis or 1-way ANOVA) ($p < 0.05$).

time of 10 s. A fresh filtered coffee solution was brewed every 12 h by dissolving a tablespoon of coffee (Kaffeehof GmbH) in 177 mL of water.[7,25] After coffee thermal cycling, specimens were initially brushed 10 times with toothpaste (Nevadent Complex 3; DENTAL-Kosmetik GmbH) and Federal Drug Administration-certified toothbrushes, which had soft bristles[7] and changed in every 10 specimens, under running water to clean the coffee extracts, and then ultrasonically cleaned in distilled water for 10 min and dried. R_a and color coordinate measurements were repeated after coffee thermal cycling. CIEDE2000 color difference formula (KL, KC, and KH were set to 1)[25–27] was used to calculate color difference (ΔE_{00}) values. Scanning electron microscope (SEM) images of an additional specimen from each material-polishing pair were taken (LEO 440; Zeiss) at 14 kV and ×1000 magnification to observe surface topography at each time interval.

Normality of data was evaluated by using the Shapiro Wilk test. While comparing the R_a of different materials within each polishing-time interval pair, either Kruskal–Wallis (before polishing, CP-after polishing, CP-after coffee thermal cycling, and VA-after polishing) or 1-way analysis of variance (ANOVA) (OG-after polishing, OG-after coffee thermal cycling, and VA-after coffee thermal cycling) tests were used. Considering that tested specimens were separated only by their material type before polishing, pooled data from 30 specimens in each group were used to analyze the R_a before polishing. To compare the R_a obtained with different polishing techniques within each material-time interval pair, either Kruskal–Wallis (CS-before polishing, CS-after polishing, and all CT pairs) or 1-way ANOVA (CS-after coffee thermal cycling and all VS pairs) tests were used. To compare the R_a at different time intervals within each material-polishing pair, either Friedman (all CS pairs and CT-CP) or repeated measures ANOVA (CT-OG, CT-VA, and all VS pairs) with material type, time interval, and the interaction between these factors as covariates were used. ΔE_{00} values were evaluated by using 2-way ANOVA with material type, polishing technique, and the interaction between these factors as covariates. All analyses were performed with software (SPSS v23; IBM Corp) at a significance level of $\alpha = 0.05$. Perceptibility and acceptability of color differences (ΔE_{00} units) were evaluated with reported thresholds (not perceptible: ≤0.8, perceptible but clinically acceptable: ≤1.8, moderately unacceptable: ≤3.6 clearly unacceptable: ≤5.4, and extremely unacceptable: >5.4 units).[28]

RESULTS

Significant differences in R_a were observed among all materials within each polishing-time interval pair ($p \leq 0.038$), except for VA-after polishing ($p = 0.055$). Before polishing, CT had the highest and CS had the lowest R_a values ($p < 0.001$). After polishing, CT had a higher R_a than VS when CP was used ($p < 0.001$). Among OG-applied specimens, CT had the highest and CS had the lowest R_a values after polishing ($p \leq 0.009$). After coffee thermal cycling, CS had the lowest R_a among CP-applied specimens ($p \leq 0.019$). Among OG-applied specimens, CT had the highest R_a ($p \leq 0.028$). Among VA-applied specimens, CT had higher R_a than VS ($p = 0.047$).

For CS and CT, a significant difference among different polishing techniques was observed after coffee thermal

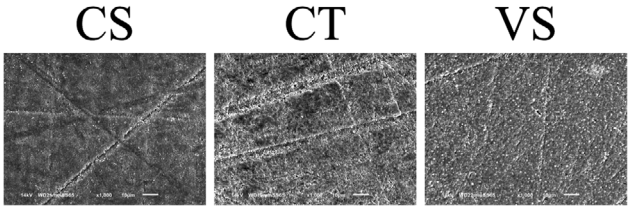

FIGURE 2 Representative scanning electron microscope images of each material before polishing. CS, Cerasmart; CT, Crowntec; VS, VarseoSmile Crown Plus.

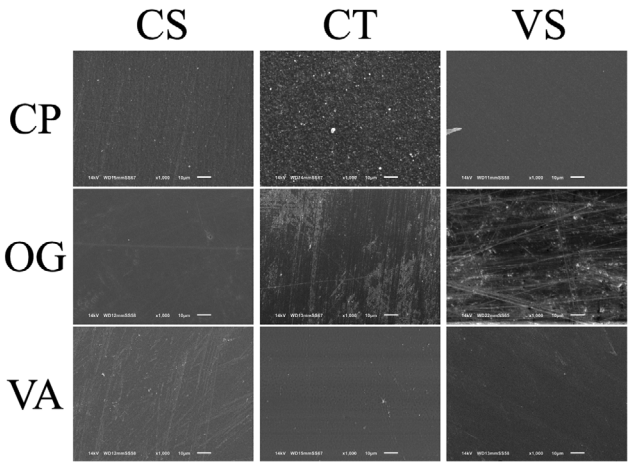

FIGURE 3 Representative scanning electron microscope images of each material-polishing pair after polishing. CP, conventional polish; CS, Cerasmart; CT, Crowntec; OG, Optiglaze; VA, Vita Akzent; VS, VarseoSmile Crown Plus.

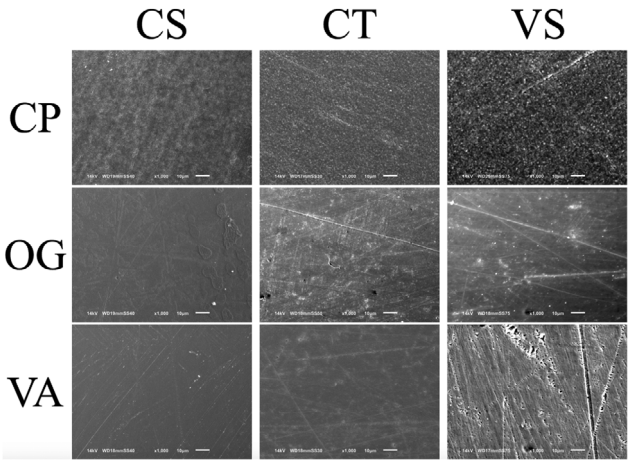

FIGURE 4 Representative scanning electron microscope images of each material-polishing pair after coffee thermal cycling. CP, conventional polish; CS, Cerasmart; CT, Crowntec; OG, Optiglaze; VA, Vita Akzent; VS, VarseoSmile Crown Plus.

TABLE 3 Mean ± standard deviation ΔE_{00} values within each material-polishing pair.

	CS	CT	VS
CP	0.47 ± 0.34^{Aa}	0.89 ± 0.18^{Aa}	1.98 ± 0.18^{Bb}
OG	0.99 ± 0.42^{Ba}	1.04 ± 0.60^{Aa}	1.38 ± 0.59^{Aa}
VA	1.04 ± 0.35^{Ba}	1.52 ± 0.84^{Aa}	1.77 ± 0.68^{ABa}

Abbreviations: CP, conventional polish; CS, Cerasmart; CT, Crowntec; OG: Optiglaze; VA: Vita Akzent; VS: VarseoSmile Crown Plus.
Different superscript uppercase letters indicate significant differences in columns, while different superscript lowercase letters indicate significant differences in rows ($p < 0.05$).

cycling ($p < 0.001$). CS-CP and CT-CP had the lowest ($p \leq 0.039$) and CS-VA had the highest ($p \leq 0.004$) R_a within those materials. For VS, significant differences were observed within each time interval ($p \leq 0.038$). VS-CP had the lowest R_a after polishing ($p \leq 0.003$). After coffee thermal cycling, VS-VA had higher R_a than VS-CP ($p = 0.043$).

For CS, significant differences among different time intervals were observed when CP and OG were used ($p < 0.001$). CS-CP had higher R_a before polishing than after coffee thermal cycling ($p < 0.001$). CS-OG had higher R_a before polishing than after polishing ($p < 0.001$). For CT, significant differences among different time intervals were observed with all polishing techniques ($p \leq 0.016$). CT-CP had the highest R_a before polishing ($p \leq 0.017$). CT-OG had higher R_a before polishing than after coffee thermal cycling ($p = 0.030$), while CT-VA had higher R_a before polishing than after polishing ($p = 0.013$). For VS, significant differences among different time intervals were observed when CP and OG were used ($p < 0.001$). VS-CP had the highest R_a before polishing and the lowest R_a after polishing ($p \leq 0.001$). VS-OG had the highest R_a before polishing ($p \leq 0.030$) (Table 2).

Figures 2–4 are the SEM images of each material-polishing pair at different time intervals. Significant lines and pores were evident on surfaces before polishing, regardless of the material. However, CT had a coarser appearance, while CS and VS had a similar surface topography, which is in line with the R_a values before polishing. Even though some of the material-polishing pairs had lines and pores after polishing, those were less prominent than before polishing. Coffee thermal cycling had a greater effect on the surfaces of CT and VS because specimens of CT and VS mostly had rougher surfaces after coffee thermal cycling.

Two-way ANOVA showed that the interaction between material type and polishing technique ($p = 0.007$) and these variables as main factors ($p \leq 0.024$) affected ΔE_{00} values. Polishing techniques affected the ΔE_{00} values of CS ($p = 0.002$) and VS ($p = 0.020$), while only CP affected the ΔE_{00} values among tested materials ($p < 0.001$). CS-CP had lower ΔE_{00} values than those of CS-OG and CS-VA ($p \leq 0.012$). VS-VA had lower ΔE_{00} values than those of VS-CP ($p = 0.022$). Within CP specimens, VS had the highest ΔE_{00} values ($p \leq 0.042$) (Table 3).

DISCUSSION

The first null hypothesis was rejected considering that material type significantly affected baseline R_a values. None of the specimens tested had R_a smaller than the clinically

acceptable threshold of 0.2 μm[8] before polishing. However, the mean R_a of CS (0.24 μm) may be considered acceptable given that a difference of 0.04 μm can be clinically negligible. In addition, CS had the lowest R_a and the smoothest surface among tested materials before polishing (Figure 2), which could be because CS was the only prepolymerized material tested. The degree of polymerization of CS may be higher and residual monomer content may be lower than CT and VS as millable CAD-CAM pucks are fabricated under high pressure and temperature.[9] Previous studies comparing additively and subtractively manufactured materials have also reported similar findings.[8,9] Nevertheless, this hypothesis needs to be supported by studies on the degree of conversion of tested materials.

The second null hypothesis was rejected, because significant differences in R_a were observed across materials when the same polishing technique was used within each time interval. Regardless of the polishing technique or time interval, CT had R_a that was either similar to or higher than the R_a of other materials. In addition, other than after coffee thermal cycling R_a of CT-CP pair, CT constantly had mean R_a values greater than the clinically acceptable threshold, whereas most of the other material-polishing pairs had acceptable R_a values. Therefore, it can be speculated that CT was less polishable than other tested materials. The unfavorable R_a of CT may be related to its chemical composition. Even though both CT and VS were additively manufactured composite resins with similar compositions, slight differences between the two materials might have led to these results. R_a values of CS also support this hypothesis regarding the effect of chemical composition, it being the only prepolymerized material; CS either had R_a values similar to or smaller than those of additively manufactured composite resins among tested polishing-time interval pairs.

The effect of different polishing techniques on the R_a of materials varied within each material-time interval pair, which led to the rejection of the third null hypothesis. CP pairs had R_a values that were either similar to or lower than those of OG and VA pairs within each material, regardless of the time interval. In addition, most of the CP pairs had mean R_a values smaller than 0.2 μm. Favorable results of CP specimens were more prominent when after coffee thermal cycling values were considered. This could be because OG and VA are sealants that are chemically bonded to specimen surfaces. Even though aging by coffee thermal cycling does not involve direct physical contact with the specimen surface, it might have deteriorated the coating due to thermal changes. SEM images (Figures 3 and 4) support this hypothesis as after polishing, surfaces of OG and VA applied specimens were smoother, whereas prominent fissures and lines were visible after coffee thermal cycling, particularly for CT and VS. In addition, regardless of the material-time interval pair, VA-applied specimens had higher mean R_a values than 0.2 μm. Thus, VA application might lead to higher plaque accumulation on tested materials. However, to the authors' knowledge, the present study was the first to test VA, and both these results and this interpretation need further support. A previous study on the effect of different polishing techniques on resin-matrix ceramics concluded that after thermal cycling, R_a of CS did not change depending on the polishing technique,[10] which may be related to the difference in aging. Nevertheless, both the present study and a study by Çakmak et al.[10] reported clinically acceptable R_a for the CS-OG pair after aging.

Other than CS-VA and VS-VA pairs, significant differences were observed among different time intervals within each material-polishing. Therefore, the fourth null hypothesis was rejected. Tested polishing techniques mostly resulted in either significantly or nonsignificantly lower mean R_a values after polishing compared with before polishing, which was also reported in previous studies.[8,9] No material-polishing pair other than VS-CP had significantly higher R_a value after coffee thermal cycling compared with that of after polishing and none of the tested material-polishing pairs had higher R_a values after coffee thermal cycling than before polishing. However, after coffee thermal cycling mean R_a values of CS-VA, CT-OG, CT-VA, and VS-VA pairs were above the clinically acceptable threshold; thus, these specimens can be considered as more prone to coffee thermal cycling. After coffee thermal cycling mean R_a value of VS-OG specimens was 0.21 μm and the authors believe that this pair can also be considered clinically acceptable.

Significant differences were observed in ΔE_{00} values among tested material-polishing pairs, which led to the rejection of the fifth null hypothesis. However, when these values were further evaluated according to previously reported thresholds,[28] it was observed that only the VS-CP pair had moderately unacceptable color change (ΔE_{00} = 1.98). Among the remaining material-polishing pairs, CS-CP had imperceptible color change (ΔE_{00} = 0.47), while other pairs had acceptable color change as ΔE_{00} values ranged from 0.89 (CT-CP) to 1.77 (VS-VA) units. The implemented coffee thermal cycling procedure in the present study is an excessive simulation of coffee consumption and it may be speculated that for an individual who consumes 1 cup of coffee per day, the test arrangement in the present study simulates potentially over couple decades of coffee consumption. Based on these results, the authors believe that tested material-polishing pairs are resistant to discoloration caused by coffee thermal cycling. However, it should also be noted that no universal perceptibility and acceptability threshold values have been reported. In addition, a previous study on the stain susceptibility of another additively manufactured composite resin reported unacceptable ΔE_{00} values when 1 mm-thick specimens polished with polishing disks were immersed in coffee for 12 and 24 days.[22] Given the contradictory results between the present study and one by Alharbi et al.,[22] and the scarcity of knowledge on the optical properties of additively manufactured composite resins, future studies with different test settings are needed to elaborate the resistance of these materials to discoloration in the long-term. Another interesting finding was the fact that CS had ΔE_{00} values that were either similar to or lower than those of additively manufactured composite resins. Even though CT and VS specimens were

light-polymerized according to manufacturers' instructions, longer durations of polymerization may decrease the residual monomers and increase the resistance of these materials to discoloration.

Coffee thermal cycling could not completely simulate intraoral situations as some factors, for instance, saliva, were not included. In addition, because both sides of the specimens were subjected to coffee thermal cycling, ΔE_{00} values may have increased more than expected, because only the outer surfaces of prostheses are exposed to discolorants intraorally. Coffee was selected due to its accelerating effect on discoloration with its acidic components.[7] However, staining solutions may affect the results.[22] In addition, other optical properties such as translucency should be further investigated. Even though the present study focused on the recently introduced additively manufactured composite resins, only 3 CAD-CAM materials were tested. Also, different polishing techniques may change the results.[4] Finally, no mechanical aging such as cyclic loading or brushing, which could deteriorate specimen surfaces and affect tested parameters, was performed. Other clinically relevant properties like microhardness, water absorption, surface wettability, and biofilm adherence should be further investigated to broaden the knowledge on the applicability of tested additively manufactured composite resins when polished with different techniques.

CONCLUSIONS

Polishing technique and time interval affected the surface roughness of tested materials. Cerasmart had the lowest roughness before polishing and had either similar or lower values than other tested materials within each time interval regardless of the polishing technique. Surface roughness of tested materials among different polishing techniques was affected by material type and time interval affected. Conventional polishing mostly led to lower roughness than the other polishing techniques, which were mostly below 0.2 μm. However, Vita Akzent led to unacceptable roughness regardless of the material-time interval pair. Surface roughness of materials among different time intervals was affected by material type and polishing technique. Polishing reduced the roughness of all materials regardless of the technique; however, Crowntec and Vita Akzent applied specimens had mean roughness values higher than 0.2 μm. Coffee thermal cycling mostly did not affect after-polishing roughness values. Stainability of tested materials was affected by material type and polishing technique. However, among tested material-polishing pairs, color changes were acceptable, and only conventionally polished VarseoSmile Crown Plus specimens had moderately unacceptable color changes when previously reported threshold values were considered. Of additively manufactured resins, Crowntec had smaller color changes with all tested polishing techniques, which were also similar to that of Cerasmart.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest. The authors do not have any financial interest in the companies whose materials are included in this article.

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