

RESEARCH AND EDUCATION

Surface roughness and stainability of CAD-CAM denture base materials after simulated brushing and coffee thermocycling

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ABSTRACT

Statement of problem. Denture bases machined from prepolymerized materials have become popular. However, information on the effect of simulated brushing and coffee thermocycling (CTC) on their surface roughness and stainability is lacking.

Purpose. The purpose of this in vitro study was to compare the effect of simulated brushing and CTC on the surface roughness (R_a) and stainability of computer-aided design and computer-aided manufacturing (CAD-CAM) denture base materials and a heat-polymerized denture base material.

Material and methods. Forty disk-shaped specimens were prepared from 3 CAD-CAM denture base resins (AvaDent, AV; Merz M-PM, M-PM; and Polident d.o.o, Poli) and a heat-polymerized polymethylmethacrylate resin (Promolux, CV) ($n=10$). R_a values of the specimens were measured by using a noncontact profilometer after conventional polishing. The color coordinates were also measured over a gray background with a spectrophotometer. Specimens were then consecutively subjected to simulated brushing for 20 000 cycles, CTC for 5000 cycles, and another 10 000 brushing cycles. R_a and color coordinates were measured after each interval. Color differences (ΔE_{00}) were calculated by using the CIEDE2000 formula, and the data were analyzed by using 2-way analysis of variance and Tukey honestly significant difference tests ($\alpha=0.05$).

Results. The time interval had a significant effect on R_a ($P<.001$) as brushing cycles resulted in higher values than those at baseline and after CTC ($P<.001$). However, the differences between brushing cycles ($P=.143$) and between the baseline and after CTC ($P=.994$) were not significant. The interaction between the material type and time interval was significant for ΔE_{00} ($P=.016$). The only significant difference in ΔE_{00} values was observed between M-PM and CV after all treatments were completed ($P=.029$).

Conclusions. Brushing increased the R_a of all materials when compared with the baseline. All materials showed similar stainability throughout the brushing and CTC processes. However, M-PM CAD-CAM denture base resin underwent a greater color change after all treatments were completed than conventional denture base resin. All color changes can be considered clinically small, considering reported perceptibility and acceptability thresholds. (J Prosthet Dent 2022;■:■-■)

Polymethylmethacrylate (PMMA) is considered as the standard for the fabrication of complete dentures because of its ease of processing and repair, low cost,

biocompatibility, polishability, and acceptable physical and optical properties.¹⁻⁴ Flasking and packing is still the most preferred technique for the fabrication of

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Clinical Implications

Even though the tested CAD-CAM denture base materials had acceptable stainability, because of increased surface roughness after long-term brushing, plaque accumulation and color changes may eventually occur with complete dentures fabricated with these materials.

complete dentures with heat-polymerized PMMA.³ However, with the advancements in computer-aided design and computer-aided manufacturing (CAD-CAM) technologies, complete dentures can now be fabricated from prepolymerized acrylic resin blocks,⁵ with improved physical properties and tissue adaptation as polymerization shrinkage is avoided.^{6,7}

The maintenance of complete dentures is essential to prevent oral infections such as denture stomatitis⁸ and also systemic infections such as pleural infection, aspiration pneumonia, and gastrointestinal infection.^{9,10} Even though there are different chemical, mechanical, and combined methods of cleaning a complete denture, brushing has been preferred because it is inexpensive, straightforward, and effective.^{11,12} However, previous studies have reported the wear of denture base material from brushing.^{9,12,13} Increased surface roughness (R_a) has been associated with plaque accumulation and biofilm formation,^{4,14} and previous studies on the R_a of denture base materials have referred to an R_a of 0.2 μm as the clinically acceptable threshold.^{1,2,4}

Denture base stainability is important, as color change may indicate material damage and aging,^{1,15} which may impair the esthetics and eventually lead to the replacement of the denture.^{16,17} Color may change because of beverages, foods, water sorption, stain accumulation, and roughness.¹⁵ In addition, denture base materials are frequently exposed to hot and cold beverages, which cause thermal stress and subsequently surface degradation.^{7,18} Even though separate effects of thermocycling^{1,3,4,7,15,18} and brushing^{9,10,12,13,19} on the optical and mechanical properties of denture base materials have been studied, the authors are aware of only 3 studies²⁰⁻²² on the combined effect of these parameters. However, none of those studies were based on the behavior of the surface of subtractively manufactured denture resins when brushing and coffee thermocycling (CTC) were combined. Therefore, the present study aimed to investigate the R_a and stainability of 4 different PMMA denture base materials (3 prepolymerized and 1 conventional) exposed to brushing and CTC. The null hypotheses were that the R_a and color of CAD-CAM denture resins would not be affected by material type or time interval.

MATERIAL AND METHODS

A total of 40 $\text{Ø}10 \times 2$ -mm disk-shaped specimens ($n=10$) were fabricated from 3 different CAD-CAM PMMAs (AvaDent; Global Dental Science [AV], Merz M-PM; Merz Dental GmbH [M-PM], and Polident d.o.o; Polident [Poli]) and a heat-polymerized PMMA resin (Promolux; Merz Dental GmbH [CV]). The number of specimens in each group was determined based on the results of similar previous studies that reported significant differences.^{7,20,22} To fabricate CAD-CAM PMMA resin specimens, a $\text{Ø}10$ -mm cylinder was designed in standard tessellation language (STL) format by using a software program (Meshmixer v3.5.474; Autodesk Inc). CAD-CAM PMMA disks were milled with a milling unit (Wieland Zenotec mini, V6.12.04; Wieland Dental +Technik GmbH & Co KG) from this design file. The cylindrical specimens were then sliced with a precision cutter (Vari/cut VC-50; Leco Corp) under water cooling to obtain the 2-mm-thick specimens. Wax patterns (2×10 mm) were prepared for the fabrication of conventional heat-polymerized PMMA resin specimens and conventionally heat processed (74°C for 8 hours of heat polymerization) according to the manufacturer's recommendation.³ After deflasking, the specimens were trimmed, and all specimens were smoothed with silicon carbide abrasive papers (600-grit) under running water. Digital calipers (Model number NB60; Mitutoyo American Corp) were used to measure the dimensions to ensure a uniform final thickness (2 ± 0.03 mm).¹

All specimens were polished conventionally by applying a slurry of pumice in water (Pumice fine; Benco Dental) for 90 seconds at 1500 rpm²³ and finished with a polishing paste (Fabulustre; Grobet USA) for an additional period of 90 seconds.⁴ Before measurements, all specimens were ultrasonically cleaned in distilled water for 10 minutes (Eltrosonic Ultracleaner 07-08; Eltrosonic GmbH) and dried with a paper towel.

A noncontact optical profilometer (FRT MicroProf 100 with H0 sensor; Fries Research & Technology GmbH) was used to measure the R_a (μm) of each specimen.²⁴ Six linear traces (3 horizontal and 3 vertical), 1 mm apart, were recorded for each specimen. The transverse length of a trace was set at 5.5 mm, the pixel density was 1000/mm,²⁴ and the resolution was 1 μm . A cutoff wavelength L_c value of 0.8 mm was used. The average R_a of traces was determined with a software program (Mark III; Fries Research & Technology GmbH).²⁴ The mean R_a (μm) for each specimen was calculated and used for statistical analysis.

Color parameters (L^* , a^* , b^* color space system) defined by the Commission International de l'Éclairage (CIE) were measured on a gray backing for each specimen. A digital spectrophotometer (CM-26d; Konica Minolta) with an illumination aperture of 8 mm, which

uses the CIE standard (2-degree) human observer characteristics and CIE D65 illuminant in its color estimations, was used to measure the color parameters.³ Before each measurement, the spectrophotometer was calibrated according to the manufacturer's recommendation. A saturated sucrose solution was used for the optical contact between specimens and backing. Three measurements were recorded for each specimen, and the mean values of these measurements were calculated. All color measurements were performed by the same clinician (M.S.) in a temperature- and humidity-controlled room with daylight.

After baseline R_a and color measurements, specimens were subjected to 20 000 cycles of artificial brushing (40 000 strokes, each cycle considered as a linear back and forth brushing action at a frequency of 1.5 Hz) with an automatic brushing machine (Bürstmaschine linear LR1; Syndiac Engineering) and Federal Drug Administration (FDA)-certified toothbrushes,²⁵ which had soft bristles.^{19,21} A total brushing time of 20 000 cycles (40 000 strokes) was considered to replicate denture cleaning of approximately 4 years, as 10 000 strokes have been reported to represent 1 year of denture cleaning.^{10,26,27} The brushing machine had 6 separate slots to attach 6 brush heads at the same time. A toothbrush was mounted to the brush holder of the brushing machine, and the bristles of the brush directly faced the specimen surface. A soap slurry was prepared by using alkali-free soap (Sibonet pH 6.5; Burnus GmbH) and distilled water (ratio of 1 part of soap to 3 parts of distilled water by weight).²⁸ The soap was ground and mixed with distilled water with a homogenizer (T25 digital Ultra Turrax; IKA) as a medium to replicate a denture cleaning agent. The soap slurries were prepared immediately before use and were poured into each chamber of the brushing machine until the surface of the specimens was covered. The toothbrushes and slurry were replaced every 10 000 cycles for each specimen.²⁹ A vertical load of 1.96 N was applied on each specimen during the horizontal movement of the brushes, and the test was performed at room temperature (23 °C). After brushing, the specimens were removed from the brushing machine, rinsed with distilled water, and gently air dried.

The specimens were then subjected to 5000 thermocycles (SD Mechatronik Thermocycler; SD Mechatronik GmbH) at 5°C and 55°C in a coffee solution with a dwell time of 30 seconds and a transfer time of 10 seconds.^{30,31} A tablespoon of coffee (Intenso Roasted and Grounded; Kaffeefhof GmbH) was dissolved in 177 mL of water to prepare the filtered coffee solution, which was freshly made every 12 hours.³⁰ After CTC, the specimens were brushed 10 times with toothpaste (Colgate Total Pro Breath Health; Colgate-Palmolive) under running water to clean the coffee extracts, ultrasonically cleaned in distilled water for 10 minutes, and dried.¹ The specimens

were then subjected to another 10 000 brushing cycles (20 000 strokes) with the same protocol.

The R_a and color coordinates were remeasured after the first brushing cycle (20 000 cycles), after 5000 cycles of CTC, and after the second brushing cycle (10 000 cycles). Color difference (ΔE_{00}) values were calculated with the CIEDE2000 color difference formula.³² The parametric factors of K_L , K_C , and K_H were set to 1.^{31,33,34} All R_a and color coordinate measurements were randomized by using a software program (Excel; Microsoft Corp).

Two-way ANOVA and Tukey HSD post hoc tests were used for the descriptive statistical analyses of the data after log conversion with a statistical software program (IBM SPSS Statistics, v23; IBM Corp), with the material type and time interval being the main factors ($\alpha=0.05$). ΔE_{00} values were further evaluated in terms of perceptibility and acceptability by using 50% perceptibility (1.72 units) and 50% acceptability (4.08 units) thresholds for denture base acrylic resin materials.¹⁶

RESULTS

The time interval had a significant effect on the R_a ($P<.001$), whereas the effect of PMMA type ($P=.062$) and the interaction between these factors ($P=.36$) were not significant. R_a values after brushing cycles (first and second) were higher than those at baseline and after CTC ($P<.001$), whereas the differences between brushing cycles ($P=.143$) and between the baseline and after CTC ($P=.994$) were not significant (Table 1).

The interaction between time intervals and material type significantly affected ΔE_{00} values ($P=.016$), while main effects were not significant ($P\geq.17$). Table 2 summarizes the ΔE_{00} values of each material between consecutive time intervals, as well as between the baseline and after the second brushing cycle, after log conversion. Among the materials tested, only the difference between M-PM and CV was significant after all treatments were completed ($P=.029$). The changes in the color coordinates (L^* , a^* , and b^*) of all materials tested after each procedure are given in Figures 1 and 2.

DISCUSSION

The time interval had a significant effect on the R_a of the resin tested, and the color of the denture resins was affected by the material type and the time interval. Therefore, the null hypotheses were rejected.

In the present study, baseline and after CTC R_a values of all materials were similar to or slightly higher than 0.2 μm ($\leq 0.21 \mu\text{m}$),^{1,2,4} consistent with previous studies.^{1,4,7} However, R_a values after both brushing cycles were higher than the clinically acceptable threshold¹⁵ for all materials ($\geq 0.34 \mu\text{m}$). Therefore, the tested denture base materials appear to be susceptible to deterioration after long-term use considering that the total brushing cycles

Table 1. Mean \pm standard deviation values of surface roughness after log conversion of raw data (mean \pm standard deviation values of raw data)

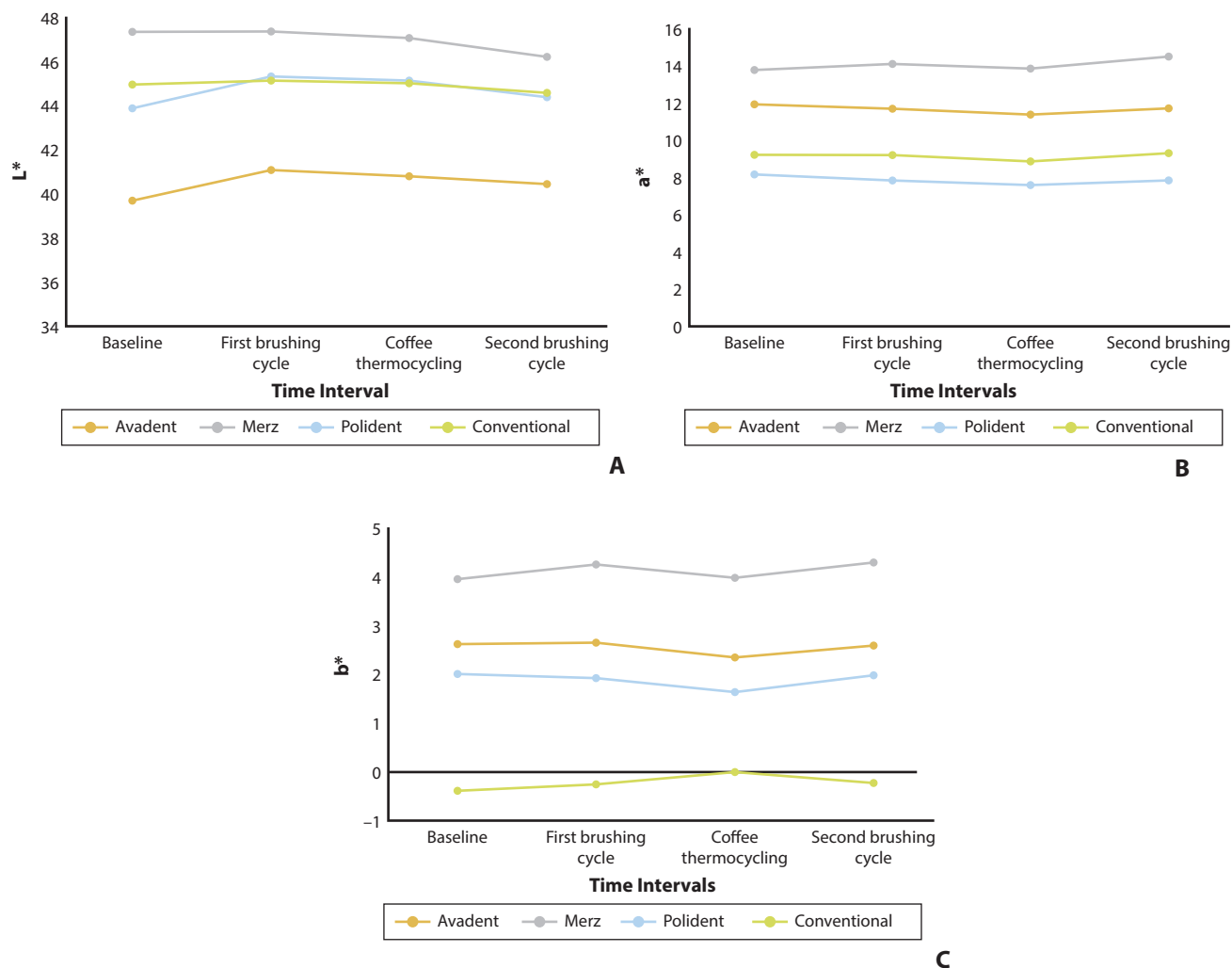
Time Interval	Material			
	AV	M-PM	Poli	CV
Baseline	-1.79 \pm 0.16 ^a (0.17 \pm 0.03)	-1.59 \pm 0.19 ^a (0.21 \pm 0.04)	-1.61 \pm 0.27 ^a (0.21 \pm 0.07)	-1.75 \pm 0.14 ^a (0.18 \pm 0.03)
First brushing cycle	-0.91 \pm 0.22 ^b (0.41 \pm 0.1)	-0.87 \pm 0.25 ^b (0.43 \pm 0.11)	-1.04 \pm 0.26 ^b (0.37 \pm 0.1)	-1.11 \pm 0.27 ^b (0.34 \pm 0.1)
Coffee thermocycling	-1.79 \pm 0.35 ^a (0.18 \pm 0.06)	-1.63 \pm 0.2 ^a (0.20 \pm 0.04)	-1.65 \pm 0.29 ^a (0.20 \pm 0.05)	-1.61 \pm 0.27 ^a (0.21 \pm 0.06)
Second brushing cycle	-0.9 \pm 0.14 ^b (0.41 \pm 0.06)	-0.83 \pm 0.18 ^b (0.44 \pm 0.08)	-0.81 \pm 0.26 ^b (0.46 \pm 0.12)	-0.93 \pm 0.25 ^b (0.41 \pm 0.11)

AV, AvaDent; CV, conventional heat-polymerized; M-PM, Merz M-PM; Poli, Polident d.o.o. Different superscript letters indicate significant differences ($P < .05$).

Table 2. Mean \pm standard deviation values of ΔE_{00} values after log conversion of raw data (mean \pm standard deviation values of raw data)

Time Interval	Material			
	AV	M-PM	Poli	CV
Baseline–first brushing cycle	-0.19 \pm 1.34 ^{Aa} (1.31 \pm 0.81)	-0.56 \pm 0.66 ^{Aa} (0.68 \pm 0.38)	0.15 \pm 0.72 ^{Aa} (1.4 \pm 0.75)	-0.72 \pm 0.73 ^{Aa} (0.61 \pm 0.47)
First brushing cycle–coffee thermocycling	-0.36 \pm 0.28 ^{Aa} (0.72 \pm 0.19)	-0.6 \pm 0.53 ^{Aa} (0.62 \pm 0.29)	-0.63 \pm 0.71 ^{Aa} (0.65 \pm 0.42)	-0.3 \pm 0.54 ^{Aa} (0.85 \pm 0.52)
Coffee thermocycling–second brushing cycle	-0.43 \pm 0.66 ^{Aa} (0.84 \pm 0.49)	-0.36 \pm 0.64 ^{Aa} (1.09 \pm 0.56)	-0.11 \pm 0.64 ^{Aa} (0.97 \pm 0.71)	-0.04 \pm 0.53 ^{Aa} (0.85 \pm 0.39)
Baseline–second brushing cycle	-0.35 \pm 0.57 ^{Aab} (0.81 \pm 0.4)	0.15 \pm 0.48 ^{Aa} (1.28 \pm 0.53)	-0.38 \pm 0.51 ^{Aab} (0.76 \pm 0.38)	-0.95 \pm 0.64 ^{Ab} (0.47 \pm 0.33)

AV, AvaDent; CV, conventional heat-polymerized; M-PM, Merz M-PM; Poli, Polident d.o.o. Different superscript letters indicate significant differences (uppercase letters for columns and lowercase letters for rows) ($P < .05$).

**Figure 1.** Color change in specimens after each treatment. A, L* values. B, a* values. C, b* values.

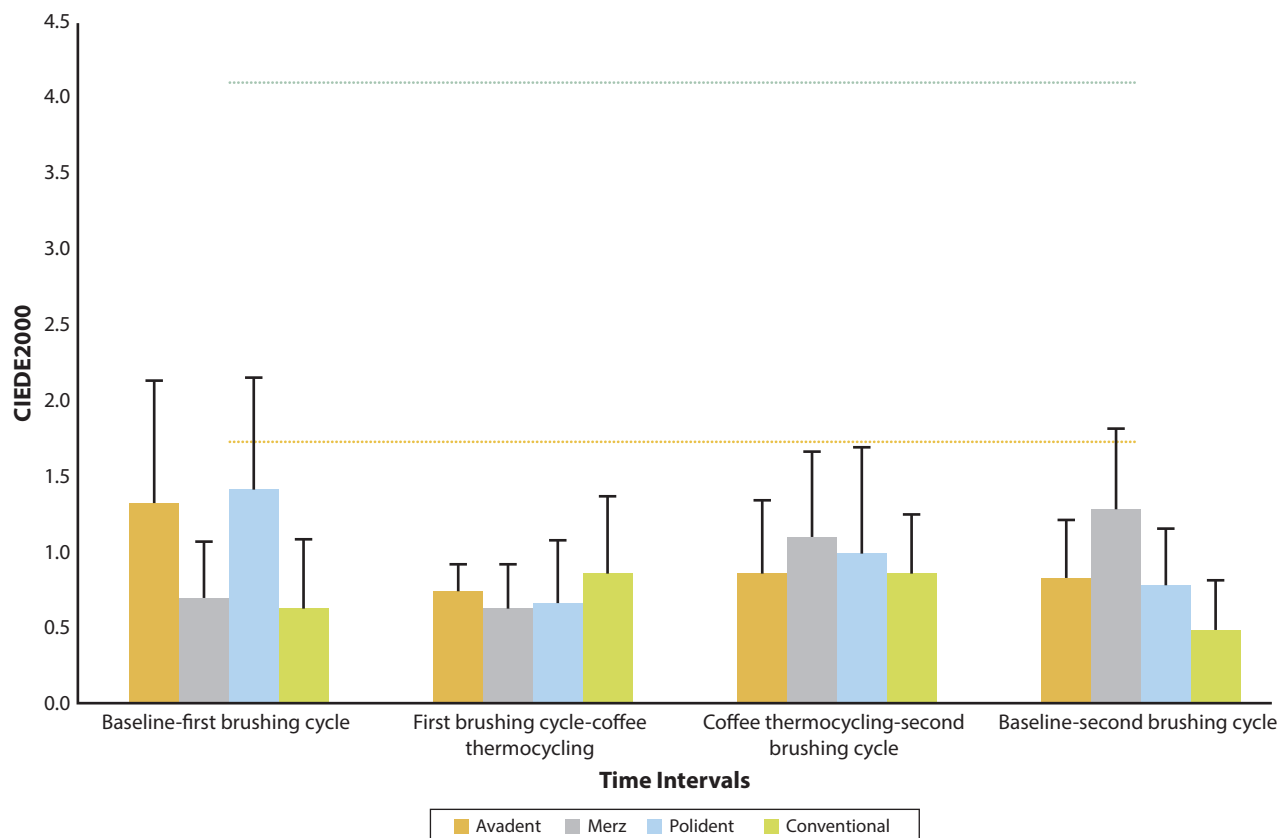


Figure 2. Color differences between time intervals for each material. Green dotted line perceptibility threshold (1.72 units). Red dotted line acceptability threshold (4.08 units).

represented approximately 6 years of clinical use.^{10,26,27} This deterioration needs to be further analyzed with studies investigating the flexural strength, microhardness, and plaque accumulation of denture base materials.

Brushing statistically increased the R_a of all tested denture base materials. However, specimens had similar R_a when the 2 brushing cycles were compared. Previous studies have also reported increased R_a values after brushing.^{10,12-13,19,22} Shinawi¹⁹ investigated the effect of number of strokes (40 000 and 60 000) on the R_a of Poli and reported that a higher number of strokes increased the R_a significantly, inconsistent with the results of the present study. The difference may be that the brushing medium (soap slurry versus dentifrice) differed and that the 2 groups were compared without thermal aging in Shinawi's¹⁹ study. Chang et al¹⁰ investigated the R_a of 4 different denture base materials before and after thermocycling, concluding that brushing increased the R_a , regardless of the material type. However, the authors¹⁰ also stated that CAD-CAM denture base had higher roughness than conventional PMMA before thermocycling, whereas conventional PMMA had higher roughness after brushing. In the present study, the type of denture base material had no effect on R_a , possibly because different materials were tested. Alfouzan et al²²

investigated the R_a of additively or conventionally manufactured denture base resins after consecutive thermocycling, brushing, and staining in different coloring solutions.²² The authors concluded that brushing resulted in higher R_a than at baseline, while repeated brushing had a significant effect on R_a . Considering these contradictory findings and the limited number of brushing strokes applied in R_a studies on additively or subtractively manufactured denture base materials, future studies should investigate the effect of the number of brushing cycles and strokes on the surface properties of CAD-CAM denture base materials.

In the present study, CTC did not result in significant differences in R_a when compared with baseline values. This result was consistent with those of previous studies that investigated the R_a of CAD-CAM denture base materials before and after thermocycling.^{4,7} However, R_a values after both brushing cycles were higher than those after CTC for all materials tested. To the authors' knowledge, only 1 other study has investigated the effect of CTC on the R_a of subtractively manufactured denture base materials and reported a significant increase.¹ However, the study by Alp et al¹ did not involve brushing and investigated different denture base materials. Even though the effect of thermocycling on the R_a

of denture base materials has been previously investigated, contradictory results were reported.^{4,7,18} Therefore, the findings of the present study should be substantiated with *in vivo* studies.

ΔE_{00} values between each consecutive time interval and between baseline and after the second brushing cycle were similar within each material. However, among the materials tested, a significant difference was observed between M-PM and CV when ΔE_{00} values between the baseline and after the second brushing cycle were compared. This result contradicts the findings of a previous study¹ in which the type of CAD-CAM denture base material did not affect ΔE_{00} after only CTC. Nevertheless, none of the materials tested in the present study showed higher ΔE_{00} ($\Delta E_{00} \leq 1.4$) than the perceptibility threshold of 1.72.¹⁶ This imperceptible color change may be associated with the stabilization of water absorption into denture base resins and the hydrophobic nature of coffee, which prevents polar coffee colorants from penetrating deep into the PMMA matrix.³⁵ Another explanation might be the coffee dissolves back into the solution after reaching a certain thickness.²⁰ However, considering that no universally accepted thresholds are available for acrylic resins¹ and different threshold levels have been used,^{15,20} these results should be interpreted carefully. To the authors' knowledge, no study has investigated the effect of brushing on the stainability of subtractively manufactured denture base resins. Therefore, the results of the present study could not be compared with those of previous studies.

Gruber et al³ compared the stainability of different denture base resins after different aging processes. No significant differences were reported among subtractively and conventionally manufactured resins after thermocycling and after coffee immersion, consistent with the study by Al-Qarni et al⁵ and the present study. In contrast, Dayan et al¹⁵ concluded that subtractively manufactured denture base material had higher stainability than that manufactured conventionally when immersed in coffee. Even though Dayan et al¹⁵ also tested M-PM, the conventional resin in their study was different from that in the present study. Alfouzan et al²⁰ evaluated the stainability of denture base resins (2 additively and 1 conventionally manufactured) after brushing and coloring liquid immersion, reporting significant differences among the materials tested. In addition, the repetition of brushing and immersion led to a lower color difference when compared with those calculated after the first stage of the procedures.²⁰ These differences between the present study and the study by Alfouzan et al²⁰ may be related to the differences in the materials, testing procedures, and color difference formulae used.

Among the materials tested, AV and Poli showed a similar trend in terms of lightness, as the first brushing

cycle increased the L^* values of both materials and consequent procedures slightly reduced this value. However, the lightness of M-PM showed a constant decrease starting from the first brushing cycle until the last cycle, whereas CV had a constant lightness throughout the brushing. The redness of all materials did not change significantly throughout the procedures. However, M-PM had a higher a^* difference than the other materials after the second brushing cycle. The yellowness of the materials showed the most drastic change in between consecutive stages. The first brushing cycle increased the b^* values of M-PM and CV, whereas its effect on AV and Poli was negligible. CTC increased the yellowness of only CV, while the b^* values of other materials decreased. The second brushing cycle decreased the yellowness of only CV, while the b^* values of other materials increased. Nevertheless, authors are unaware of a study on the clinically perceptible and acceptable thresholds for color coordinate differences. Therefore, these results should be interpreted carefully.

Limitations of the present study included the lack of an a priori power analysis. However, significant differences were observed among test groups, and the number of specimens was based on previous studies.^{7,20,22} In addition, only 1 type of the CAD-CAM fabrication method was tested. However, additive manufacturing is a promising technique for the fabrication of denture base materials^{20,22} that needs to be studied. This *in vitro* study could not completely simulate *in vivo* conditions affecting the parameters tested, such as the presence of saliva. In addition, both surfaces of the specimens were subjected to thermocycling. Although, clinically, only polished surfaces are exposed to staining liquids, lower color changes in the materials tested may be expected clinically. Only 1 type of the toothbrush and a soap slurry was used for simulated brushing. However, previous studies have shown the effect of dentifrices on R_a .¹¹⁻¹³ In the present study, specimens were subjected to CTC to evaluate their stainability from acidic components (tannin and chlorogenic acids), and coffee was found to accelerate discoloration.³⁶ However, different staining solutions may lead to different results.¹⁵ Future studies involving broadened parameters such as different dentifrices, toothbrushes, and staining solutions are needed to corroborate the findings of the present study and learn more about the materials tested.

CONCLUSIONS

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

1. Compared with the baseline values, brushing increased the R_a of all denture base materials tested. However, CTC did not affect the R_a significantly.

2. Tested denture base materials showed similar color changes in between consecutive time intervals. Only M-PM had a greater color change than CV when the difference between the baseline and after test procedures was compared. However, all color changes can be considered small considering the perceptibility and acceptability thresholds.

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Gülce Çakmak: Investigation, Methodology, Data curation, Project administration. **Mustafa Borgia Donmez:** Writing – original draft, Writing – review & editing. **Sevda Atalay:** Writing – original draft. **Marcella Paula de Silva:** Investigation, Data curation. **Manrique Fonseca:** Writing – original draft. **Martin Schimmel:** Conceptualization, Project administration. **Burak Yilmaz:** Project administration, Supervision, Writing – review & editing.

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<https://doi.org/10.1016/j.prosdent.2022.06.006>