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Surface Roughness and Color Stability

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ABSTRACT

Aim: This study aimed to evaluate the effects of thermal cycling on the surface roughness (Ra) and color stability (ΔE00) of three types of denture base materials: CAD/CAM-milled, 3D-printed, and heat-polymerized acrylic resins.

Material and Method: Seventy-two specimens were fabricated from three denture base materials (n=24 each). Each group was divided into thermally cycled (TC+) and non-cycled control subgroups (TC−) (n=12 each). Surface roughness (Ra) and color change (ΔE00) were measured before and after thermal cycling or control storage. Surface roughness data met normality assumptions and were analyzed using paired t-tests and one-way ANOVA. ΔE00 values were non-normally distributed and analyzed using Mann–Whitney U and Kruskal–Wallis tests. The significance level was set at $p<0.05$.

Results: A statistically significant increase in surface roughness occurred only in the 3D-printed group after thermal cycling ($p=0.047$). CAD/CAM and heat-polymerized materials showed no significant changes. No material exhibited significant color changes following thermal cycling ($p>0.05$). Between-material comparisons revealed that 3D-printed specimens had significantly higher Ra and ΔE00 values at both time points compared with CAD/CAM and heat-polymerized groups. No significant differences were observed between CAD/CAM and heat-polymerized PMMA.

Conclusion: Thermal cycling did not significantly affect color stability but increased surface roughness in 3D-printed denture base materials. Material selection is therefore essential for maintaining long-term surface integrity and esthetic durability.

Keywords: Denture base materials; CAD/CAM acrylic; 3D-printed acrylic; Surface roughness; Color stability.

ÖZET

Amaç: Bu çalışma, üç farklı protez kaide materyalinin CAD/CAM ile frezelenmiş, 3D baskı ile üretilmiş ve ısıyla polimerize edilmiş akrilik rezinlerin yüzey pürüzlülüğü (Ra) ve renk stabilitesi (ΔE00) üzerine termal döngünün etkilerini değerlendirmeyi amaçlamıştır.

Gereç ve Yöntem: Toplam 72 örnek, üç protez kaide materyalinden (her biri için n=24) hazırlanmıştır. Her grup, termal döngü uygulanan (TC+) ve uygulanmayan kontrol alt gruplarına (TC−) ayrılmıştır (her alt grup için n=12). Yüzey pürüzlülüğü (Ra) ve renk değişimi (ΔE00), termal döngü veya kontrol koşullarından önce ve sonra ölçülmüştür. Yüzey pürüzlülüğü verileri normallik varsayımlarını karşılamış olup eşleştirilmiş t testi ve tek yönlü ANOVA ile analiz edilmiştir. ΔE00 değerleri normal dağılmadığından Mann–Whitney U ve Kruskal–Wallis testleri uygulanmıştır. Anlamlılık düzeyi $p<0.05$ olarak belirlenmiştir.

Bulgular: Sadece 3D baskılı grupta termal döngü sonrası yüzey pürüzlülüğünde istatistiksel olarak anlamlı bir artış görülmüştür ($p=0.047$). CAD/CAM ve ısıyla polimerize materyallerde anlamlı bir değişiklik saptanmamıştır. Hiçbir materyalde termal döngü sonrasında anlamlı bir renk değişimi gözlenmemiştir ($p>0.05$). Materyaller arası karşılaştırmada, 3D baskılı örnekler her iki zaman noktasında CAD/CAM ve ısıyla polimerize edilen gruplara kıyasla anlamlı derecede daha yüksek Ra ve ΔE00 değerlerine sahipti. CAD/CAM ve ısıyla polimerize PMMA arasında ise anlamlı bir fark bulunmamıştır.

Sonuç: Termal döngü, renk stabilitesini anlamlı olarak etkilememiş, ancak 3D baskılı protez kaide materyallerinde yüzey pürüzlülüğünü artırmıştır. Bu nedenle, uzun dönem yüzey bütünlüğü ve estetik dayanıklılığın korunmasında materyal seçimi önem taşımaktadır.

Anahtar Kelimeler: Protez kaide materyalleri; CAD/CAM akrilik; 3D baskılı akrilik; Yüzey pürüzlülüğü; Renk stabilitesi.

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Introduction

Complete dentures (CDs) remain a significant restorative option for the growing elderly population, and their demand is anticipated to rise in the coming years.[1] Conventional denture bases fabricated via heat-polymerized poly (methyl methacrylate) (PMMA) techniques have been the gold standard for decades, offering satisfactory physical, biological, and economic properties.[2] The integration of digitally assisted design and manufacturing systems (CAD/CAM) has significantly transformed the manufacturing of complete dentures, replacing the conventional high-temperature, high-pressure molding of PMMA resins with precise, digitally controlled workflows. Compared with traditional techniques, CAD/CAM methods offer reduced production time, fewer clinical visits, lower technique sensitivity, improved mechanical and physical properties, and the ability to store a permanent digital record of the final prosthesis.[3,4] CAD-CAM milled denture bases are manufactured from densely cross-linked, pre-polymerized PMMA blocks, resulting in enhanced mechanical strength, decreased residual monomer content, and greater dimensional accuracy. Several studies have shown that these dentures achieve superior fit and adaptation in critical anatomical areas such as the palatal vault and alveolar crest compared with conventional dentures.[5,6] In parallel, 3D printing has become as a versatile and efficient alternative for denture fabrication due to its rapid prototyping capabilities. However, limitations remain regarding the mechanical properties, interlayer bonding, the stability of color and the surface roughness behavior of additively manufactured denture bases, which may influence their long-term clinical performance.[7,8] In subtractive CAD-CAM milling, dentures are carved from pre PMMA discs that are polymerized industrially under elevated pressure and controlled parameters, producing bases with excellent mechanical properties, favorable surface characteristics, stable color, reduced microbial adhesion, and lower residual monomer release compared with conventionally compression-molded resins. Conversely, additive manufacturing (3D printing) fabricates dentures layer by layer from liquid resin, followed by curing with light, heat, or laser until the CAD-designed form is completed. [9,10] PMMA blocks used in CAD-CAM milling have demonstrated superior surface properties compared with heat-polymerized PMMA; nevertheless, the Ra measurements recorded for every denture base material examined have been reported to remain below 0.2 µm, a threshold considered clinically acceptable.[11] Evaluating the roughness characteristics of additively manufactured PMMA may help clarify differences among denture bases produced through different fabrication techniques.[12] Clinically, maintaining an Ra value near 0.2 µm is important to reduce bacterial retention, with smoother surfaces supporting better hygiene.[2] Maintaining stable color over time is essential for ensuring the long-term esthetic quality of denture materials, as discoloration can compromise appearance and reduce patient satisfaction .[13] Thermal cycling (TC) is a widely used in vitro aging method that alternates specimens between hot and cold water baths, simulating temperature changes inside the mouth caused by food and beverage consumption.[14] This process can generate thermal stresses, microcracking, filler–matrix debonding, and polymer chain degradation, potentially affecting surface roughness and color stability.[15] However, previous studies have reported inconsistent outcomes; some found significant increases in Ra and ΔE values[16,17], while others observed minimal or no changes.[18] Given the limited direct comparisons of additively, subtractively produced , and heat-polymerized acrylic denture base materials, The aim of this study was to investigate the effects of thermal cycling on the surface roughness and color stability of these three materials. The null hypothesis was that TC would not significantly affect Ra or ΔE_{00} values in any group.

Materials and Methods

Three denture base materials (heat-polymerized PMMA, CAD-CAM PMMA, 3D-printed PMMA) were tested. Detailed information regarding their composition and manufacturer is listed in Table I.

Specimen Preparation

A total of 72 disk-shaped specimens (10 mm in diameter and 2 mm in thick) were made from three denture base materials. Subtractive milled PMMA resin and additively produced PMMA, and conventional PMMA resin polymerized using heat. Heat-cured PMMA

Table I. Chemical composition and manufacturer information of the denture base materials and silicone-based soft liner used in the study.

Name of the Material	Chemical Composition	Manufacturer
Heat-polymerized PMMA	95 % polymethyl methacrylate (PMMA)	Ivoclar Pro Base, Ivoclar Vivadent, Liechtenstein
CAD-CAM PMMA	≥ 95 % PMMA base, with dimethacrylate monomers and color pigments/ fibers	Yamahachi Pink Block 30 mm, Yamahachi Dental, Japan
3D-printed PMMA	PMMA-based resin with multifunctional methacrylate monomers and photoinitiators	Alias Dental Denture, Alias Dental, USA

specimens were fabricated using conventional flasking and water-bath curing at 74 °C for 9 h. CAD/CAM specimens were milled from pre-polymerized PMMA blocks using a 5-axis milling machine .

For fabrication of the 3D-printed PMMA denture base resin specimens, an SLA (stereolithography) based 3D printer (Saturn 4 Ultra 16K; Elegoo, Shenzhen, China) was used. This device employs a 405-nm light source and a COB + Fresnel lens collimation system and provides 16K printing resolution. The printer is capable of producing layers with thicknesses between 0.01 and 0.2 mm. Prior to printing, the device was calibrated in accordance with the manufacturer's recommendations. To obtain a homogeneous mixture, the photopolymer resin was manually shaken for 5 min before the printing procedure.The printing parameters were standardized as follows: 0° print angle, 0.05 mm layer thickness, 35 s exposure for the first layer, 2 s exposure for subsequent layers, and 60% UV exposure.

All specimens were finished and standardized by wet grinding using 600 , 800, and 1200 grit silicon carbide abrasive papers (English Abrasives Ltd., London, UK) under constant water irrigation, following ISO 10139-2[19] guidelines to ensure uniform initial surface roughness.

İnitial measurements of surface roughness (Ra) and color parameters (L*, a*, b*) were performed on all specimens prior to aging procedures.Following initial measurements, each material group (n=24) was randomly separated into a non-thermocycled control subgroup (TC−, n = 12) and a thermocycled experimental subgroup (TC+, n = 12). The control subgroup (TC−) was kept in distilled water at 37 °C, while the experimental subgroup (TC+) was subjected to thermal cycling consisting of 6000 cycles between 5 °C and 55 °C in a thermal cycling machine (MODDENTAL, Ankara, Turkey), with a 30-second wait at each temperature and a 5-second transfer time between baths, simulating intraoral thermal stress.

Surface Roughness Measurement

Ra values (µm) for surface roughness were measured using a profilometer (Mahrsurf M300C, Mahr, Göttingen, Germany) with a measurement length of 1.75 mm and a traverse speed of 0.5 mm/s. To ensure measurement reliability, the device was calibrated with a reference calibration block after every 10 specimens. Three measurements were taken at different locations on each specimen, and the arithmetic mean of these three values was taken as the Ra value.

Color Measurement

Color measurements were done using a Minolta CR-21 Chroma Meter (Konica Minolta, Japan) under D65 standard illumination and against a white background. For all specimens, measurements were recorded three times before immersion in the coloring media on day 0, and the mean values were denoted as L0*, a0*, and b0*. Post-aging measurements were recorded and denoted as L1*, a1*, and b1*. The color change was calculated

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}$$

where ΔL′, ΔC′, and ΔH′ are the lightness, chroma, and hue differences between the two measurements, respectively; S L, S C, and S H are the weighting functions for lightness, chroma, and hue; k L, k C, and k H are the parametric factors (set to 1 in this study); and R T is the rotation term that accounts for the interaction between chroma and hue differencesPost-Aging Measurements

After the storage or thermal cycling procedures, surface roughness and color measurements were repeated for all specimens in both subgroups to enable paired statistical comparisons within each group.

As this study used only materials and did not involve human or animal, so ethical approval was not needed.

Data Analysis

Normality of the data was tested with the Kolmogorov Smirnov test and by evaluating skewness and kurtosis values. Normally distributed Ra data were analyzed with paired t-tests for intragroup comparisons and one way ANOVA followed by Tukey or Games Howell post hoc tests for intergroup comparisons. Non-normally distributed ΔE00 values were analyzed using Mann–Whitney U tests for two-group comparisons and Kruskal Wallis tests with Dwass–Steel–Critchlow–Fligner (DSCF) post hoc analysis for multiple grups. Statistical significance was defined at $p<0.05$ for all analyses, which were conducted using SPSS software (version XX.0; IBM Corp., Armonk, NY, USA).

Results

Normality testing showed that surface roughness (Ra) data followed a normal distribution, whereas ΔE_{00} data did not. Accordingly, Ra values were analyzed using parametric tests, and ΔE_{00} values using non-parametric tests.

Surface Roughness (Ra), when all specimens were considered together, no notable difference was found between before aging (0.219 ± 0.05 µm) and after aging (0.226 ± 0.06 µm) values ($p > 0.05$) (Table II, Figure 1). CAD/CAM, before aging (0.194 ± 0.05 µm); after aging (0.189±0.04 µm). No meaningful difference was observed ($p > 0.05$).3D-printed, before aging (0.263 ± 0.03 µm); after aging (0.288 ± 0.05 µm). A significant increase was detected in the thermocycled (TC+) subgroup (0.254 → 0.304 µm, $p < 0.05$), while no change was observed in the control (TC−) subgroup. Heat-polymerized, before aging 0.202 ± 0.04 µm; after aging 0.203 ± 0.04 µm. No meaningful difference was observed ($p > 0.05$). In between-material comparisons, the additively produced group showed significantly greater Ra values than CAD/CAM and heat-polymerized groups both before and after aging ($p <0.05$). No noticeable difference was found

Table II. Mean surface roughness (Ra, µm) values of denture base materials according to thermal cycling (TC), measurement time, and material type.

Material	TC- *(n=36)*					TC+ *(n=36)*					**Overall** *(n=72)*						
	Before *(n=18)*		**After** *(n=18)*		**p** (t)**	**Before** *(n=18)*		**After** *(n=18)*		**p** (t)**	**Before** *(n=36)*		**After** *(n=36)*		**p** (t)**	*p* (Time) *(t)*	
	mean	**SS**	**Ort**	**SS**		**mean**	**SS**	**Ort**	**SS**		**mean**	**SS**	**Ort**	**SS**		**Before**	**After**
CAD/CAM *(n=24)*	^{a}0,192	0,04	^{a}0,192	0,04	-	^{a}0,195	0,05	^{a}0,185	0,05	0,272 (1,16)	^{a}0,194	0,05	^{a}0,189	0,04	0,263 (1,15)	0,884 (0,14)	0,702 (0,39)
3D-printed *(n=24)*	^{b}0,272	0,03	^{b}0,272	0,03	-	^{b}0,254	0,04	^{b}0,304	0,06	0,047 (2,24)	^{b}0,263	0,03	^{b}0,288	0,05	0,049 (2,61)	0,173 (1,40)	0,101 (1,71)
Heat-polymerized *(n=24)*	^{ac}0,192	0,04	^{ac}0,192	0,04	-	0,212	0,04	^{ac}0,213	0,05	0,913 (0,11)	^{ac}0,202	0,04	^{ac}0,203	0,04	0,910 (0,11)	0,227 (1,24)	0,211 (1,29)
Overall *(n=72)*	0,219	0,05	0,219	0,05	-	0,220	0,05	0,234	0,07	0,162 (1,43)	0,219	0,05	0,226	0,06	0,160 (1,42)	0,904 (0,12)	0,292 (1,06)
p (Material) **(*t*)**	*0,000* *(28,06)*		*0,000* *(38,46)*			*0,008* *(6,08)*		*0,000* *(15,23)*			*0,000* *(25,88)*		*0,000* *(33,038)*				

*ANOVA, *: Student's t-test, a, b, c: Different superscript letters indicate statistically significant differences between rows..*

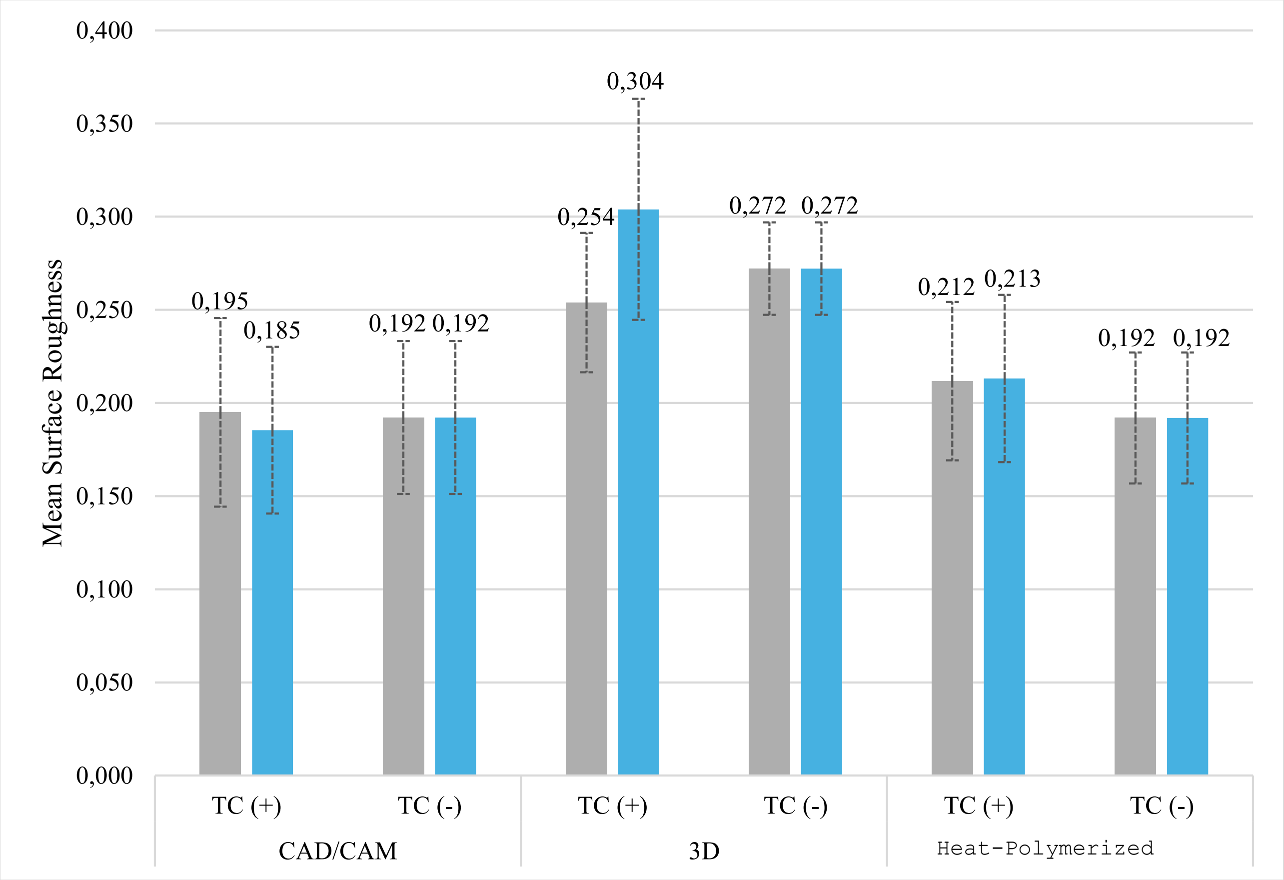

Figure 1. Mean surface roughness (Ra, µm) values of CAD/CAM, 3D-printed, and heat-polymerized denture base materials before (gray bars) and after (blue bars) thermal cycling (TC).

Table III. Mean ΔE_{00} values of denture base materials according to thermal cycling (TC) and material type.

Material	**TC-** *(n=36)*		**TC+** *(n=36)*		**overall** *(n=72)*		**p value (TC effect) (t)**
	Mean	**SS**	**Mean**	**SS**	**Mean**	**SS**	
CAD/CAM *(n=24)*	^{a}0,843	0,57	^{a}0,805	0,51	^{a}0,824	0,53	1,000 (72)
3D -printed *(n=24)*	^{b}2,055	1,31	^{b}1,255	0,36	^{b}1,655	1,03	0,114 (44)
Heat-polymerized *(n=24)*	^{ac}0,802	0,42	^{ac}0,542	0,29	^{ac}0,672	0,38	0,101 (43)
Overall *(n=72)*	1,233	1,02	0,867	0,49	1,05	0,82	0,241 (543)
p value (Material)	0,011 (8,97)		0,000 (14,02)		0,000 (20,65)		

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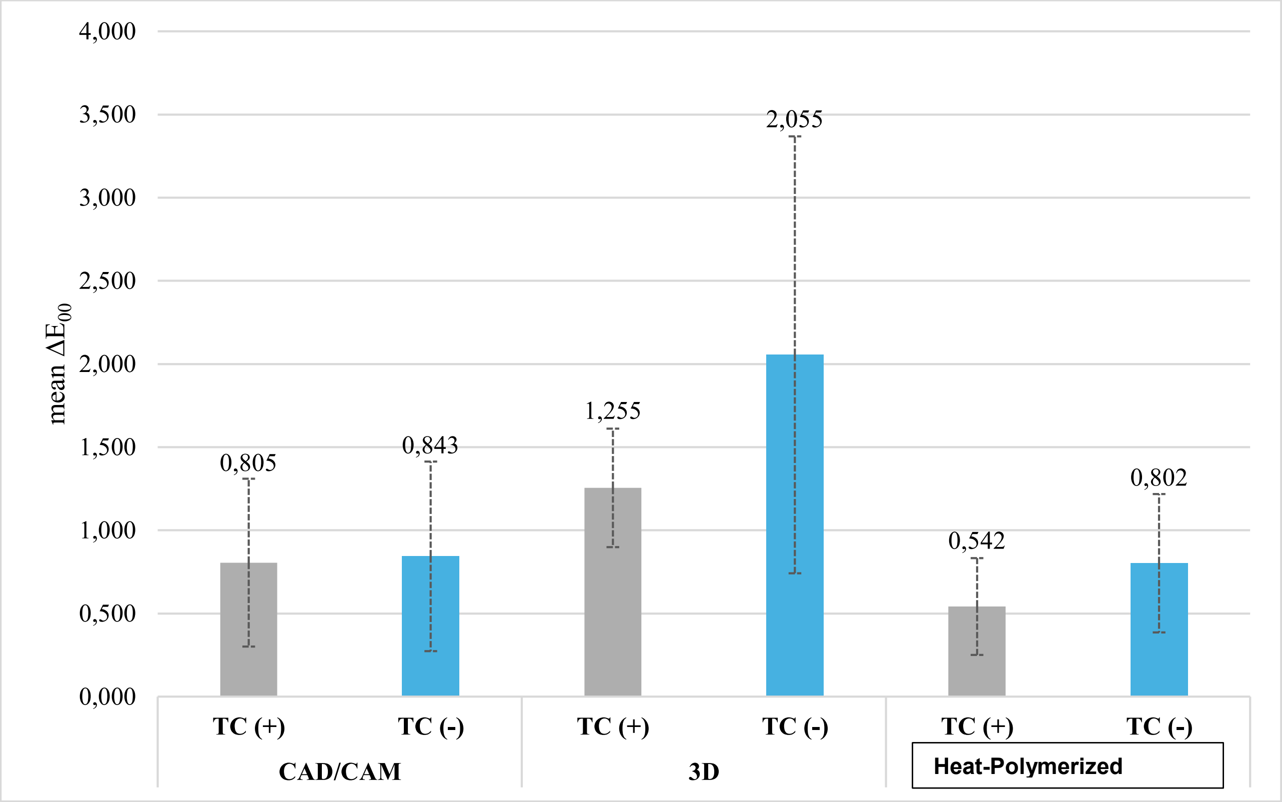

Figure 2. Mean color difference (ΔE₀₀) values of CAD/CAM, 3D-printed, and heat-polymerized denture base materials before (gray bars) and after (blue bars) thermal cycling (TC).

between CAD/CAM and heat-polymerized PMMA.

Color Stability (ΔE₀₀), thermal cycling did not result in a statistically significant change in ΔE₀₀ values for any material when comparing before and after aging measurements ($p > 0.05$) (Table III, Figure 2).CAD/CAM, TC− group (0.843 ± 0.57); TC+ group (0.805 ± 0.51), no meaningful difference between before and after aging ($p > 0.05$).3D-printed, TC− group (2.055 ± 1.31); TC+ group: (1.255 ± 0.36), no meaningful difference between before and after aging ($p > 0.05$). Heat-polymerized, TC− group (0.802 ± 0.42); TC+ group (0.542 ± 0.29), no meaningful difference between before and after aging ($p > 0.05$).

In between-material comparisons, the additively produced group showed the highest mean ΔE₀₀ values both before and after aging, with significantly higher values compared to CAD/CAM and heat-polymerized PMMA ($p < 0.05$). No significant difference was found between CAD/CAM and heat-polymerized groups at either time point.

Discussion

The null hypothesis of this study stated that thermal cycling would not significantly affect the surface roughness (Ra) or color stability (ΔE₀₀) of any tested denture base materials, and that there would be no significant differences among materials. Based on the results, the null hypothesis was partially accepted. Thermal cycling did not produce a statistically meaningful change in ΔE₀₀ values for any material and did not significantly alter Ra in CAD/CAM or heat-polymerized PMMA. However, in the 3D-printed group, Ra significantly increased after thermal cycling ($p < 0.05$). In between-material comparisons, significant differences were observed for both Ra and ΔE₀₀ at each time point, with the 3D-printed group showing the greatest values. CAD/CAM and heat-polymerized PMMA maintained stable surface roughness regardless of thermal cycling, and no meaningful differences were found between them at any time point.

According to previous reports, a surface roughness (Ra) value of 0.2 μm has been described as the clinical threshold above which bacterial adhesion and plaque accumulation are significantly increased.[2] After thermal cycling, CAD/CAM specimens maintained Ra values below this threshold, whereas 3D-printed specimens exceeded it, and heat-polymerized PMMA values were close to the threshold. In particular, the 3D-printed group reached a post-aging Ra value of 0.304 µm, showing a notable potential for increased microbial adherence. These findings show the importance of adequate finishing and polishing procedures, as well as periodic maintenance, particularly for 3D-printed denture bases, to minimize surface roughness in clinical use.

However, CAD/CAM specimens in this study exhibited the lowest Ra results among all tested materials both before and after thermal cycling, which agrees with previous reports attributing this finding to the prepolymerized nature of millable PMMA blocks. Millable PMMA pucks are industrially made under high pressure and temperature, creating a higher degree of polymerization and lower residual monomer content, as well as a more homogeneous structure, all of which contribute to reduced surface irregularities and improved surface quality.[18]

This study's findings regarding higher Ra values in additively manufactured specimens compared to CAD/CAM and heat-polymerized PMMA differ partially from those of Alfouzan et al.[20], who reported no meaningful differences in Ra among milled and 3D-printed denture base materials after thermocycling, brushing, and staining. However, they observed that brushing and staining increased Ra values. These discrepancies may be caused by differences in test protocols, as the present study evaluated only the effect of thermal cycling, while Alfouzan et al.[20] included additional mechanical and chemical challenges.

Studies investigating the influence of thermal cycling (TC) on denture base resins have reported varying results. Some authors have found increased Ra values after TC, attributing this to water absorption and subsequent swelling of the material, which may promote surface irregularities .[21,22] Others, such as Ayaz et al.[23], showed no meaningful changes in the Ra of PMMA or polyamide after TC, In this study, a significant increase in Ra after TC was detected only in the 3D-printed group, with values rising from 0.254 µm to 0.304 µm. CAD/CAM and heat-polymerized PMMA showed no statistically significant changes, and CAD/CAM remained below the 0.2 µm clinical threshold at both time points. These findings suggest that 3D-printed resins may be more susceptible to surface changes under thermal stress, whereas CAD/CAM and heat-polymerized PMMA demonstrate greater stability.

Color variations are typically evaluated using the CIELAB color system, which defines color in three dimensions: L* (lightness–darkness), a* (red–green), and b* (yellow–blue). The overall color difference is calculated as ΔEab, an arithmetic value representing the magnitude of change between two measurements. However, there is considerable debate regarding the ΔEab value that is clinically acceptable or imperceptible to both patients and clinicians. Some individuals can notice color changes as low as 0.5, whereas others may not detect differences as high as ΔEab = 4.[24] According to Douglas et al.[25], ΔEab values <2 indicate color matching, while values >3.3 are considered clinically perceptible in the intraoral environment. More recently, the CIEDE2000 (ΔE00) color difference formula has been shown to provide a better correlation with human visual perception compared to the classic CIELAB formula[26], offering lower and more precise thresholds of acceptability. As reported by Paravina et al.[27], a ΔE00 value of 1.8 represents the acceptability threshold of color differences for dental professionals.[28] In this study, ΔE00 was used for the final analysis to ensure accurate assessment of clinically relevant color changes.

According to Paravina et al[27], a ΔE_{00} value of 1.8 represents the acceptability threshold of color differences for dental professionals, with values at or below this limit considered clinically acceptable. In this study, thermal cycling did not produce statistically significant changes in ΔE_{00} within any material ($p > 0.05$). However, when compared with the 1.8 threshold, all groups except the 3D-printed TC− subgroup demonstrated clinically acceptable color stability both before and after aging. The 3D-printed TC− subgroup exhibited a ΔE_{00} value of 2.055, exceeding the acceptability threshold and indicating a perceptible color change, whereas its TC+ counterpart showed a lower value (1.255), falling within the clinically acceptable range. These findings suggest that while most tested conditions maintained satisfactory color stability, 3D-printed resins may be more prone to perceptible discoloration in certain situations.

PMMA-based removable dentures fabricated using 3D printing technologies is strongly influenced by printer-related technical parameters. The layer-by-layer photopolymerization process may result in interlayer heterogeneity and microvoid formation, which can facilitate pigment penetration and increase susceptibility to discoloration. Moreover, variations in light source wavelength, intensity, and exposure duration directly affect the degree of polymerization; insufficient curing is associated with higher residual monomer content and time-dependent changes in color. Surface oxygen inhibition and increased surface roughness further contribute to staining by promoting plaque and chromogen accumulation. In addition, inadequate or inconsistent post-curing protocols may allow ongoing polymerization and material maturation after fabrication, leading to variability in optical properties over time. Collectively, these observations suggest that printer-specific polymerization efficiency, surface characteristics, and post-processing procedures play a critical role in the long-term color stability of 3D-printed PMMA denture materials and should be carefully standardized to improve clinical performance.[4,7,18]

Literature reports on the color stability of 3D-printed resins are inconsistent. Some investigations have reported that 3D-printed materials can demonstrate superior color performance compared to conventional heat-cured resins[29–31]; for instance, Alfouzan et al.[29] found greater color change in a conventional resin compared to two different 3D-printed resins when exposed to various staining solutions. In contrast, other authors, including Gruber et al.[10] and Arora et al.[3], observed more pronounced discoloration and lower color stability in 3D-printed resins than in milled and heat-cured alternatives. These outcomes have been linked to higher water uptake and surface degradation in 3D-printed polymers, with the latter often associated with a lower concentration of inorganic fillers. Differences in material composition, filler content, post-processing techniques, and experimental aging protocols may account for these contradictory findings.[18]

From a clinical perspective, when surface roughness is over 0.2 µm, bacteria can attach more easily and plaque accumulation, potentially leading to denture stomatitis. Therefore, the higher Ra values observed in 3D-printed resins especially after thermal aging could have implications for hygiene maintenance and patient comfort. Likewise, ΔE00 values above the perceptibility threshold (~1.0) indicate color changes that may be noticeable to the human eye, possibly reducing patient satisfaction with esthetics. The current results suggest that CAD/CAM PMMA offers superior long-term stability, making it preferable in cases where durability and esthetics are prioritized.

This study was limited to a single brand and formulation for each material type, which may not represent the full range of commercial products. Additionally, thermal cycling was performed over 6000 cycles, simulating a defined period of clinical service; longer-term or more aggressive aging protocols may yield different results. Future studies should assess the combined effects of thermal, mechanical, and chemical aging, as well as the impact of different polishing systems, to better replicate clinical conditions.

Conclusion

Based on this in vitro study the main conclusions are presented below:

1. Material type had a significant influence on both surface roughness and color stability.
2. 3D-printed PMMA exhibited the highest surface roughness and color change values, both at baseline and after thermal aging, with a significant post-aging increase in Ra.
3. CAD/CAM-processed PMMA demonstrated the minimal Ra values and the highest color stability, showing no significant changes after thermal aging.
4. Heat-polymerized PMMA showed intermediate performance, with no significant surface or color deterioration following thermal aging.
5. Thermal cycling for 6000 cycles did not significantly affect the surface or optical features of CAD/CAM or heat-polymerized PMMA, but adversely affected surface roughness in 3D-printed specimens.

From a clinical perspective, CAD/CAM-milled

PMMA seems to be the most favorable option when long-term surface integrity and esthetic stability are critical. While 3D-printed PMMA offers manufacturing convenience, its higher surface roughness and lower color stability may limit its durability and hygiene performance over time.

Clinical Significance

Material selection for denture bases should consider not only fabrication efficiency but also long-term clinical performance. The present findings indicate that CAD/CAM-milled PMMA provides superior resistance to surface degradation and color change compared to 3D-printed and heat-polymerized PMMA. This stability is likely to enhance patient comfort, reduce plaque accumulation, and maintain esthetic quality over time.

In contrast, 3D-printed PMMA, despite offering quick and economical production, may require more frequent polishing, repolishing, or replacement because of its higher susceptibility to surface roughness increase and discoloration.

Clinicians should weigh these material properties against patient needs, esthetic expectations, and maintenance capabilities when selecting the appropriate denture base resin.

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