

# Printed Versus Conventional Denture Base Resins: Physical-Mechanical Evaluation After Immersion in Beverages and Cleansers

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## ABSTRACT

*Introduction:* Denture base resins, both 3D-printed (PR) and heat-cured (HR), are exposed to beverages and cleansers that impact their color stability, surface roughness, and microhardness. Understanding these effects is essential for guiding clinical recommendations and optimizing material selection for long-term use. *Objectives:* To evaluate the color change, roughness, and microhardness of PR and HR denture base resins after immersion in beverages and cleansers. *Methods:* PR and HR samples were subjected to 5,000 thermocycling cycles in distilled water, coffee, and green tea, as well as immersion in 1% sodium hypochlorite (NaClO) and effervescent tablets (Corega Tabs®) to simulate 6 months of use. Color change was evaluated using the CIELab and CIEDE2000 systems, surface roughness using Ra and Rz parameters, and microhardness, before and after immersion. *Results:* Distilled water, 1% NaClO, and effervescent tablet caused higher color changes in both PR and HR ( $P>0.05$ ). HR showed increased roughness after immersion in 1% NaClO, effervescent tablet, and coffee ( $P<0.05$ ). All beverages and cleansers affected PR roughness ( $P<0.05$ ). Only 1% NaClO reduced HR microhardness ( $P<0.05$ ). *Conclusions:* Immersion in beverages and cleansers alters the color and roughness of PR and HR, with 1% NaClO causing the most significant impact on their physical and mechanical properties.

## INTRODUCTION

Acrylic resins are widely used to manufacture dental prostheses (in approximately 95% of cases) and devices, including intermaxillary and orthodontic appliances.<sup>1-5</sup> While complete dentures are traditionally made with HR, the development of PR offers a faster and more precise alternative through additive manufacturing.<sup>6-10</sup> Both materials are susceptible to physical and mechanical changes due to oral cavity conditions, including temperature and pH fluctuations, beverage consumption, and exposure to chemical cleansers.<sup>11-16</sup>

PR and HR can be indicated for the same purpose; however, differences in composition and processing yield distinct physical and mechanical properties.<sup>13,14,17</sup> PR has a higher dimensional stability compared to HR due

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to the gradual polymerization of thin layers, enabling more accurate denture bases with better tissue adaptation and retention.<sup>13,14,17</sup> However, PR components exhibit inferior aesthetics and a higher capacity for color change due to the use of monochromatic resins and the formation of gaps between layers, which allow liquid and dye penetration.<sup>18–20</sup>

Beverages such as coffee, tea, and soft drinks alter oral temperature and pH.<sup>8,11,14,16,19–24</sup> Their natural or synthetic pigments accelerate material aging, increasing roughness, reducing microhardness, and causing discoloration or staining.<sup>8,11,14,16,19–25</sup> These changes compromise prosthesis aesthetics, cause patient discomfort, and necessitate replacement.<sup>8,11,14,16,19–24</sup>

Cleaning dentures with chemical substances such as sodium hypochlorite (NaClO) and effervescent tablets also leads to changes in the polymethylmethacrylate (PMMA) through the oxidation of its pigments, the formation of micropores, and surface degradation, which promotes increased roughness and subsequent adsorption of new dyes.<sup>13,26–32</sup>

The literature lacks comparative studies on the effects of different beverages and cleansers on PR and HR. Variations in manufacturing methods, materials, immersion protocols, thermocycling, and beverages make it challenging to understand the physical-mechanical performance of resins and determine precise clinical recommendations. Since these property changes can lead to denture failure and replacement, this study aimed to evaluate the color, roughness, and microhardness of PR and HR denture base resins after immersion in beverages and cleansers, simulating 6 months of use. The null hypothesis tested was that thermocycling and immersions would not alter the physical or mechanical properties of either resin.

## MATERIAL AND METHODS

A total of 150 samples ( $10 \times 6 \times 3.3 \text{ mm}^3$ ) were used in this study, 75 of HR (Clássico, Art. Clássico, Brazil) and 75 of PR (Cosmos denture base resin, Yller Biomateriais S.A., Brazil). Sample size was determined using power analysis in RStudio (version 2022.12.0+353, Posit PBC, USA) with the “power.t.test” package, based on data from Falahchai *et al.*<sup>33</sup> and Selin and Ipek.<sup>34</sup> Input parameters included values of  $4.25 \pm 0.26$  (color change),  $0.12 \pm 0.02$  (surface roughness), and  $17.28 \pm 1.92$  (microhardness), with a significance level of 0.05 and a statistical power of 80%, resulting in a minimum required sample size of 2. To ensure robustness, a sample size of 5 was adopted for each condition, totaling 25 specimens per resin type for each test (color stability, roughness, and microhardness). The test conditions included immersion in distilled water, coffee, green tea, sodium hypochlorite, and effervescent tablet solution.

HR was handled according to the manufacturer’s instructions.<sup>3</sup> After reaching the plastic phase, it was pressed into metal molds with rectangular dies ( $10 \times 6 \times 3.3 \text{ mm}^3$ ) under a 1000 Kgf load for 60 minutes. Polymerization was performed in a wa-

ter bath using an automatic thermocuring machine (Termociler 100, Brazil) at 73°C for 1.5 hours, followed by 30 minutes at 94°C.<sup>3</sup> After removal from the mold, samples were finished and polished using 80, 400, 600, and 1200 grit sandpaper.<sup>3</sup>

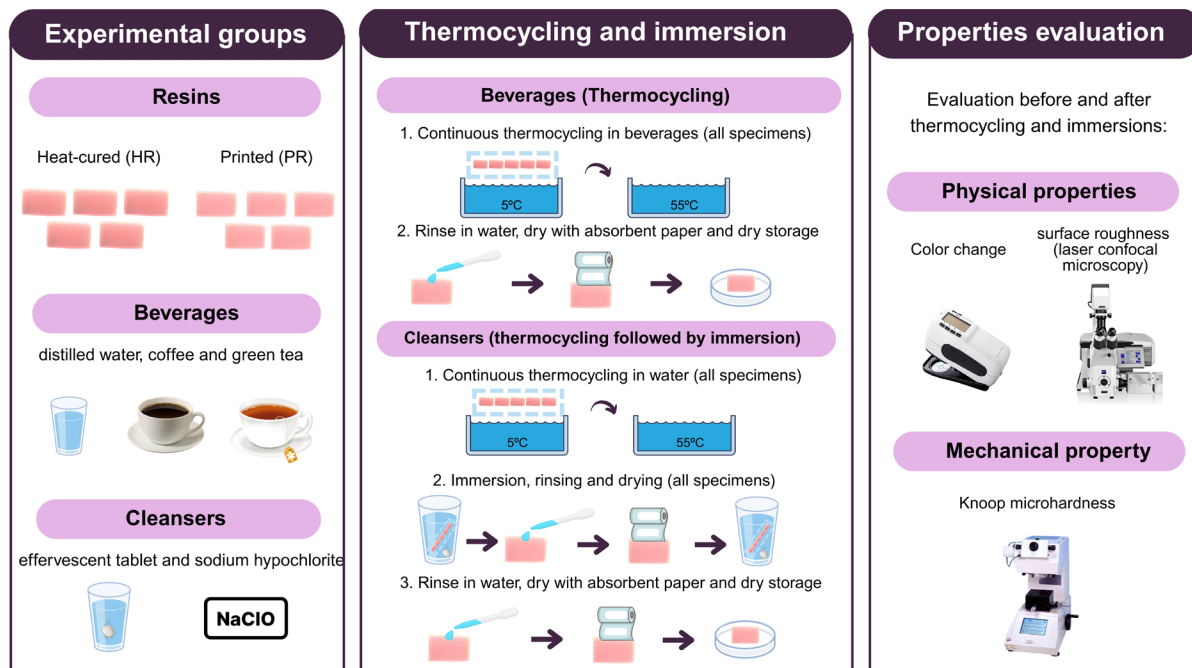
PR samples were made using Cosmos denture base resin (Yller Biomateriais SA, Brazil) on a Foto 6.0 FlashForge printer (Flashforge 3D Technology Co. Ltd., China).<sup>3</sup> The samples were designed in Meshmixer (version 3.5.474, Autodesk, USA), and the .STL file was exported to FlashDLPrint (version 2.2.1, Flashforge 3D Technology Co. Ltd., China) to set printing parameters: 50  $\mu\text{m}$  layer thickness and 0° printing angle.<sup>3</sup> After printing, the specimens were washed with isopropyl alcohol for 5 minutes, dried, and post-cured for 10 minutes in a 2-in-1 Wash and Cure machine (CiclOne, dOne 3D, Brazil). They were then sanded with 80, 400, 600, and 1200 grit sandpaper.<sup>3</sup>

The samples were randomly assigned into groups according to the type of resin (HR or PR) and the immersion solution: distilled water, coffee (Café União®, Brazil), green tea (Chá Leão®, Brazil), 1% NaClO (Suprema®, Brazil), and effervescent tablet solution (Corega Tabs 3 Minutes®, Corega®, Brazil) (Figure 1). The chemical composition of the effervescent tablet includes sodium bicarbonate, citric acid, sodium monopersulfate, sodium carbonate, tetraacetylenediamine (TAED), sodium benzoate, macrogol, sodium lauryl sulfate, flavorings, copovidone, sodium carmellose, and colorants (CI 42090 and CI 73015).

Thermocycling of the PR and HR samples ( $n = 5$ ) was performed using an appropriate equipment (Thermocycling MSCT-3 Plus, Thermocycler, Brazil) under a protocol of 5000 cycles, simulating 6 months of clinical use.<sup>35</sup> The temperature range was set between 5 and 55°C, with a dwell time of 30 seconds and a transfer time of 10 seconds.<sup>35</sup> For the beverage groups (distilled water, coffee, and green tea), the samples were placed in a perforated container to ensure free circulation of the solution, and thermocycling was conducted continuously. Throughout the procedure, the immersion media were regularly monitored and replenished to maintain a constant reservoir volume of 2 litres.

For the cleanser groups (effervescent tablet and 1% NaClO), samples were initially subjected to continuous thermocycling in distilled water, following the same protocol applied to the beverage groups.<sup>35</sup> After thermocycling, samples from each group were immersed collectively in the respective cleansing solution, rinsed with distilled water, dried with absorbent paper, and re-immersed in a freshly prepared solution. This cycle of immersion, rinsing, and drying was repeated until completion of the experimental protocol. Upon conclusion, all specimens were rinsed in distilled water, dried, and immediately evaluated for color change, surface roughness, and microhardness.

Coffee was prepared by pouring 200 mL of distilled water at 90°C over 1 tablespoon of coffee powder in a strainer, and the solution was used immediately. Green tea was prepared by steeping 1 sachet in 200 mL of distilled water at 90°C for 5



**Figure 1:** Diagram of the methodology employed in the study.

minutes and used immediately. Effervescent tablets were dissolved in 200 mL of warm water ( $40 \pm 2^\circ\text{C}$ ) for 3 minutes, according to the manufacturer's instructions, while immersion in 1% NaClO lasted 10 minutes in 200 mL of solution.<sup>15,27,29</sup> A total of 180 cycles simulated daily denture cleaning over 6 months.<sup>15,27,29</sup> Between cycles, samples were washed, dried with absorbent paper, and stored at room temperature.

Color change was analyzed by placing PR and HR samples on a standard white background following ISO/TR Z8642(E). Three color measurements ( $n = 5$ ) were taken before and after immersion using a portable spectrophotometer (Model SP62S, X-Rite Incorporated, USA) in accordance with the CIELab and CIEDE2000 systems.<sup>36-39</sup> Color change was expressed in  $\Delta E_{00}$ . For CIELab, values  $\geq 3.3$  were considered clinically unacceptable.<sup>39</sup> For CIEDE2000, the perceptibility threshold (PT) was set at 1.7, while the acceptability threshold (AT) was 4.1.<sup>36,37</sup> Clinically,  $\Delta E_{00}$  values  $\leq 1.7$  were considered imperceptible,  $1.7 < \Delta E_{00} \leq 4.1$  acceptable, and  $\Delta E_{00} > 4.1$  unacceptable.<sup>36,37</sup>

The CIELab system measures luminosity (L) and the color variations from green to red (a) and from blue to yellow (b). This was complemented by CIEDE2000, which also measures luminosity (L) but includes saturation (C) and hue (H), adjusting for non-linearity in color changes and saturation to better align with human perception.<sup>20,21,26,36-38</sup>

Surface roughness of PR and HR samples ( $n = 5$ ) was evaluated before and after immersion in beverages and cleansers using the LSM 780 laser confocal microscope (Zeiss, Germany). Micrographs were obtained by the reflection method in 3 different regions of each sample (center, 1.7 mm to the right, and 1.7 mm to the left) using a  $10\times$  objective lens and a  $100 \mu\text{m}$  scale. The roughness parameters Ra and Rz were calculated

using ImageJ software (version 1.54, National Institutes of Health, USA).

Knoop microhardness ( $n = 5$ ) was evaluated according to ASTM C1327-08 using a microhardness meter (HMV-2, Shimadzu, Japan) with a 25 Kgf load applied for 5 seconds. Three readings were taken for each sample, and the mean was calculated.

Data analysis was performed using IBM SPSS Statistics software (version 25.0, IBM, USA). Normality was assessed with the Shapiro-Wilk test, and homoscedasticity was evaluated using Levene's test. The following statistical tests were employed for group comparisons: one-way ANOVA with Tukey's *post hoc*, two-way ANOVA with Bonferroni's *post hoc*, and paired t-test.

## RESULTS

Tables 1 and 2 indicate that the color change ( $\Delta E_{00}$ ) measured by the CIELab and CIEDE2000 systems was highest for PR after thermocycling in distilled water, effervescent tablets, and 1% NaClO, with values similar to each other ( $P > 0.05$ ). In contrast, PR exhibited less color change after thermocycling in coffee and tea ( $P < 0.05$ ).

According to the CIELab system, HR exhibited the highest color change after thermocycling in distilled water ( $P < 0.05$ ), with values similar to those found for tea, effervescent tablets, and 1% NaClO ( $P > 0.05$ ). The least change was observed after thermocycling in coffee ( $P < 0.05$ ). For the CIEDE2000 system, the highest color change in HR was noted after immersion in distilled water, effervescent tablets, and 1% NaClO ( $P < 0.05$ ), with no significant differences among these groups ( $P > 0.05$ ). Less change occurred after immersion in tea and coffee ( $P < 0.05$ ).

**Table 1.** Mean ± standard deviation of color change by the CIELab system of printed (PR) and heat-cured (HR) resins after thermocycling and immersion in beverages and cleansers.

Groups		CIELab			
		ΔL	Δa	Δb	ΔE00
PR	Control	-62.46±0.17	-24.32±0.55	-8.04±0.54	-
	Distilled water	-60.52±0.11	-22.87±0.64	-11.44±0.51*	4.76±0.98 <sup>A,a</sup>
	Coffee	-60.16±0.76*	-22.54±1.14	-11.12±0.70*	3.21±0.52 <sup>B,a</sup>
	Tea	-59.97±0.73*	-23.22±1.20	-11.58±0.90*	3.30±0.56 <sup>B,C,a</sup>
	Effervescent tablet	-60.75±1.01*	-22.83±0.25	-11.63±0.87*	4.02±0.36 <sup>A,B,a</sup>
	1%NaClO	-59.81±0.70*	-22.89±0.39	-11.09±0.93*	4.39±0.32 <sup>A,C,a</sup>
HR	Control	-60.56±1.09	-20.37±1.35	-9.89±0.60	-
	Distilled water	-59.59±2.03	-21.10±1.79	-11.83±0.93*	3.98±1.74 <sup>A,B,C,a</sup>
	Coffee	-60.31±1.09	-19.69±1.50	-10.88±0.49*	1.99±0.31 <sup>D,E,b</sup>
	Tea	-59.16±0.60	-20.91±1.18	-11.63±0.71*	2.46±0.56 <sup>A,D,F,b</sup>
	Effervescent tablet	-59.16±1.64	-20.60±2.20	-11.58±0.99*	4.99±1.26 <sup>B,G,a</sup>
	1% NaClO	-59.17±0.66	-20.29±0.58	-11.31±0.37*	3.33±0.15 <sup>C,E,F,G,b</sup>

Legend: 1-way ANOVA and Tukey post hoc (P<0.05). \* Represents statistical difference in relation to the control group (for each variable in the same resin type). 2-way ANOVA and Bonferroni post hoc (P<0.05). <sup>A,B</sup> Same capital letters represent statistical similarity between rows. <sup>a,b</sup> Same lowercase letters represent statistical similarity between resins for each liquid.

**Table 2.** Mean ± standard deviation of color change by the CIEDE2000 system of printed (PR) and heat-cured (HR) resins after thermocycling and immersion in beverages and cleansers.

Groups		CIEDE2000			
		ΔL	ΔC	ΔH	ΔE00
PR	Control	62.46±0.17	25.42±0.98	19.43±1.30	-
	Distilled water	60.32±0.53*	25.83±0.99	26.79±1.97*	2.05±0.18 <sup>A,a</sup>
	Coffee	59.97±0.73*	25.96±1.07	26.53±2.33*	0.93±1.12 <sup>B,a</sup>
	Tea	60.52±0.47*	25.57±0.72	26.37±1.22*	0.22±0.18 <sup>B,a</sup>
	Effervescent tablet	60.59±0.98*	25.62±0.52	29.16±5.64*	2.15±0.21 <sup>A,a</sup>
	1% NaClO	60.44±0.45*	25.80±1.59	27.10±1.20*	2.13±0.51 <sup>A,a</sup>
HR	Control	61.55±1.05	23.89±1.67	23.50±1.21	-
	Distilled water	59.59±1.41*	23.03± 2.80	23.03±2.80	2.76±0.75 <sup>A,a</sup>
	Coffee	59.16±0.60*	23.92±1.37	23.92±1.37	0.98±0.44 <sup>B,a</sup>
	Tea	59.59±2.03*	24.36±2.04	24.36±2.04	1.04±0.40 <sup>B,a</sup>
	Effervescent tablet	59.16±1.64*	23.63±2.39	24.39±0.94	2.88±0.95 <sup>A,a</sup>
	1% NaClO	59.16±1.00*	23.38±1.93	23.38±1.93	2.84±0.96 <sup>A,a</sup>

Legend: 1-way ANOVA and Tukey post hoc (P<0.05). \* Represents statistical difference in relation to the control group (for each variable in the same resin type). 2-way ANOVA and Bonferroni post hoc (P<0.05). <sup>A,B</sup> Same capital letters represent statistical similarity between rows. <sup>a,b</sup> Same lowercase letters represent statistical similarity between resins for each liquid.

The CIELab system showed that thermocycling in distilled water caused a similar color change between HR and PR ( $P=0.408$ ). PR showed a higher color change after thermocycling in tea ( $P=0.0$ ), coffee ( $P=0.008$ ), and NaClO 1% ( $P=1.000$ ) compared to HR. However, by CIEDE2000, both resins (PR and HR) showed similar color changes after immersion in the different beverages and cleansers ( $P=1.000$ ).

Regarding the CIELab variables, both resins exhibited an increase in  $\Delta b$  (blue tone) after thermocycling in beverages and immersion in cleansers ( $P=0.001$ ). Brightness ( $\Delta L$ ) decreased for PR following thermocycling in tea, coffee, 1% NaClO, and effervescent tablets ( $P=0.001$ ). In the CIEDE2000 system, a decrease in luminosity was noted for both resins across all immersion protocols ( $P=0.001$ ), and a change in  $\Delta H$  (hue) was observed only for PR after immersions ( $P<0.005$ ).

In the CIELab assessment, exposure to distilled water, effervescent tablets, and 1% NaClO resulted in clinically unacceptable color changes for both resins. Additionally, the PR resin exhibited clinically unacceptable color changes after exposure to tea. According to the CIEDE2000 system, immersion in distilled water, effervescent tablets, and 1% NaClO led to noticeable changes in HR and PR, but beverages (tea and coffee) did not lead to changes considered clinically unacceptable.

The micrographs (Figures 2 and 3) indicate that the cleansers altered the surface of the HR samples, revealing cracks, defects, and fissures on the surface of the material, as also occurred for PR after immersion in 1% NaClO. Table 3 shows that the initial surface roughness (Ra and Rz) of both resins (RI and RT) was comparable ( $P>0.05$ ). However, immersion of PR in beverages and cleansers led to a significant increase in surface roughness

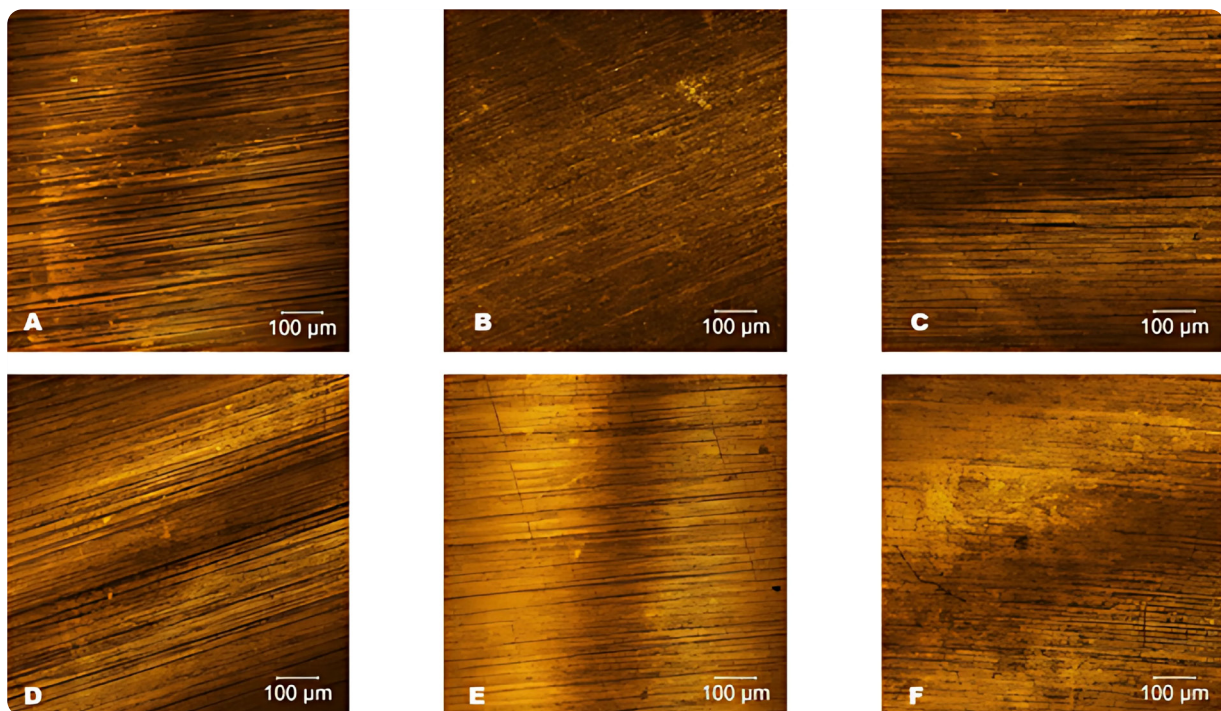
for both Ra and Rz parameters ( $P<0.05$ ), with no statistical differences among them ( $P>0.05$ ). For HR, an increase in surface roughness (Ra) was only noted after immersion in coffee, effervescent tablets, and 1% NaClO ( $P<0.05$ ). The most significant increase in Ra occurred after immersion in 1% NaClO compared to the other beverages and cleansers, which exhibited similar values ( $P>0.05$ ).

Before immersion and thermocycling, HR exhibited higher microhardness compared to PR ( $P<0.05$ ). However, after the interventions, both materials showed similar values ( $P>0.05$ ). Immersion and thermocycling in beverages and cleansers did not result in any significant changes in microhardness for either PR or HR ( $P>0.05$ ), except for HR immersed in 1% NaClO, which showed a slight decrease in microhardness ( $P=0.13$ ) (Table 4).

## DISCUSSION

Thermocycling and immersion of PR and HR in beverages and cleansers affected both the color and surface roughness of the materials, with only the 1% NaClO protocol reducing the microhardness of HR. The null hypothesis that these protocols would not cause changes in the physical and mechanical properties of the resins was rejected.

The color changes observed in both resins after thermocycling and immersion in 1% NaClO and effervescent tablets result from surface degradation of the microstructure (Figures 2 and 3). These changes are consistent with previous reports attributing discoloration to the formation of oxidizable surface groups susceptible to the oxidative action of cleansers,



**Figure 2:** Surface micrographs of printed resin samples (PR) before and after immersion in beverages and cleansers. A: before the experiment; B: after thermocycling in distilled water; C: after thermocycling in coffee; D: after thermocycling in tea; E: after immersion in effervescent tablet; F: after immersion in 1% NaClO.

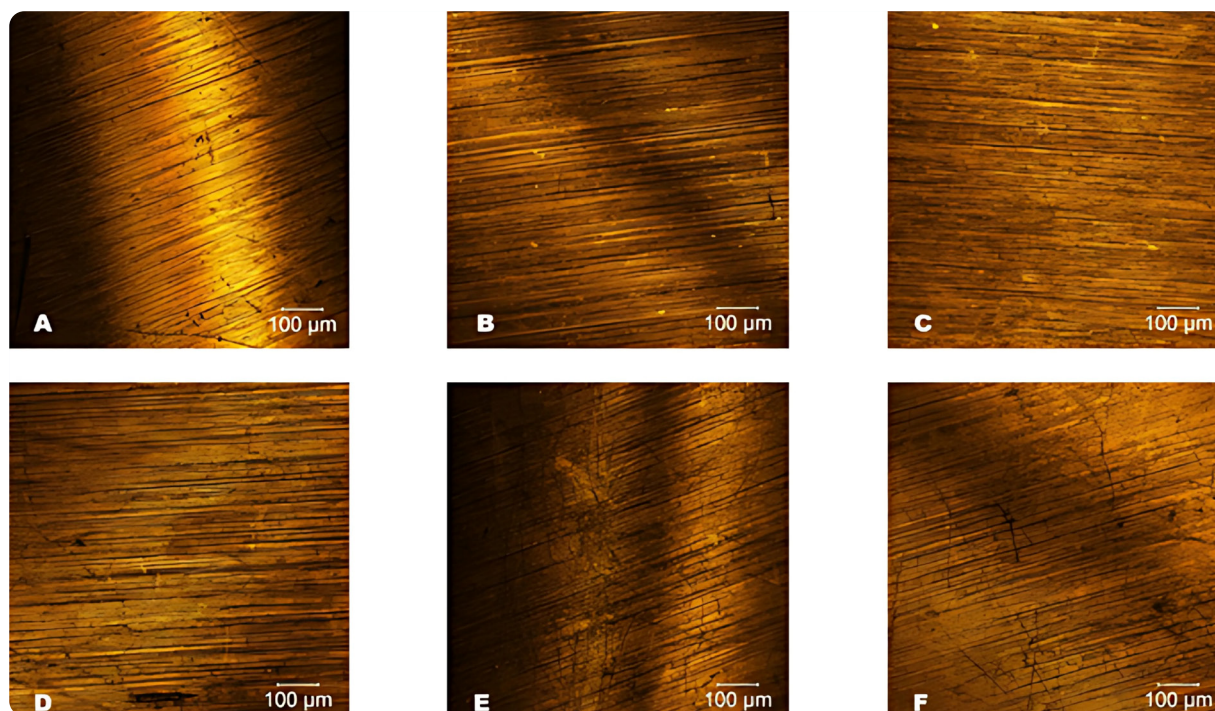


Figure 3: Surface micrographs of heat-cured resin samples (HR) before and after immersion in beverages and cleansers.

**Table 3.** Mean ± standard deviation of roughness (Ra e Rz) of printed (PR) and heat-cured (HR) resins before and after immersion in beverages and cleansers.

Groups	Ra (µm)		Rz (µm)		
	Before	After	Before	After	
PR	Distilled water	0.293±0.001 A,a	0.303±0.002 A,b	0.398±0.002 A,a	0.404±0.003 A,b
	Coffee	0.293±0.001 A,a	0.303±0.003 A,b	0.391±0,001 A,a	0.403±0.004 A,b
	Tea	0.293±0.001 A,a	0.386±0.109 A,b	0.391±0.001 A,a	0.408±0.005 A,b
	Effervescent tablet	0.293±0.001 A,a	0.381±0.113 A,b	0.391±0.001 A,a	0.402±0.006 A,b
	1% NaClO	0.294±0.001 A,a	0.342±0.093 A,b	0.392±0.001 A,a	0.401±0.008 A,b
HR	Distilled water	0.294±0.001 A,a	0.302±0.006 A,a	0.392±0.001 A,a	0.403±0.010 A,a
	Coffee	0.294±0.001 A,a	0.298±0.002 A,b	0.392±0.001 A,a	0.398±0.004 A,a
	Tea	0.293±0.001 A,a	0.295±0.001 A,a	0.391±0.001 A,a	0.396±0.005 B,a
	Effervescent tablet	0.293±0.001 A,a	0.295±0.002 A,b	0.372±0.044 A,a	0.394±0.003 B,b
	1% NaClO	0.293±0.001 A,a	0.503±0.002 B,b	0.391±0.001 A,a	0.402±0.004 A,b

Legend: 2-way ANOVA and Bonferroni post hoc (P<0.05). A,B Same capital letters indicate statistical similarity between rows. t-test (P<0.05). a,b Same lowercase letters indicate statistical similarity between columns for each parameter (Ra or Rz).

liquid penetration within the resin matrix, and the leaching of intrinsic pigments.<sup>13,28-32</sup> The data in table 1 corroborate these findings, as the bluish hue increase in PR and HR detected by CIELab is consistent with oxidation and pigment loss caused by cleanser penetration.<sup>13,29-31</sup> Similarly, the hue changes reported in Table 2 using CIEDE2000 support these observations. In addition, thermal stress from repeated expansion

and contraction of the polymers promotes microcrack formation, which further accelerates structural degradation.<sup>13,29-31</sup>

Alqanas *et al.*<sup>13</sup> also reported color changes in PR and HR, evaluated by the CIELab, after immersion in 5.25% NaClO and effervescent tablets, while Jain *et al.*<sup>29</sup> observed similar changes with effervescent tablets without prior thermocycling. NaClO acts as a plasticizer and oxidizer, while effervescent tablets

**Table 4.** Mean  $\pm$  standard deviation of microhardness of printed (PR) and heat-cured (HR) resins before and after immersion in beverages and cleansers.

Groups		Microhardness (Kgf)	
		Before	After
PR	Distilled water	14.95 $\pm$ 0.90 <sup>A,a</sup>	17.57 $\pm$ 1.54 <sup>A,a</sup>
	Coffee	16.00 $\pm$ 0.74 <sup>A,a</sup>	17.70 $\pm$ 1.13 <sup>A,a</sup>
	Tea	15.90 $\pm$ 2.21 <sup>A,a</sup>	16.62 $\pm$ 2.07 <sup>A,a</sup>
	Effervescent tablet	15.70 $\pm$ 2.35 <sup>A,a</sup>	18.27 $\pm$ 1.46 <sup>A,a</sup>
	1% NaClO	16.45 $\pm$ 0.46 <sup>A,a</sup>	17.07 $\pm$ 2.30 <sup>A,a</sup>
HR	Distilled water	17.99 $\pm$ 0.91 <sup>B,a</sup>	19.23 $\pm$ 1.34 <sup>A,a</sup>
	Coffee	18.65 $\pm$ 1.30 <sup>B,a</sup>	19.11 $\pm$ 0.79 <sup>A,a</sup>
	Tea	18.88 $\pm$ 1.53 <sup>B,a</sup>	17.99 $\pm$ 1.87 <sup>A,a</sup>
	Effervescent tablet	19.37 $\pm$ 1.35 <sup>B,a</sup>	19.15 $\pm$ 1.02 <sup>A,a</sup>
	1% NaClO	19.13 $\pm$ 1.06 <sup>B,a</sup>	17.23 $\pm$ 1.62 <sup>A,a</sup>

Legend: 2-way ANOVA and Bonferroni post hoc ( $P < 0.05$ ). A, B Same capital letters indicate statistical similarity between rows. t-test ( $P < 0.05$ ). a, b Same lowercase letters indicate statistical similarity between columns.

release carbon dioxide (CO<sub>2</sub>) bubbles that interact with resin pigments, promoting discoloration.<sup>13,29-31</sup> Both cleansers penetrate the resin, expanding polymer chains and increasing surface roughness and porosity.<sup>13,29-31</sup> These alterations facilitate the adsorption of dietary pigments, diminishing the aesthetic of the prostheses.<sup>13,29-31</sup>

The comparison of color changes between PR and HR showed that only the CIELab system detected higher changes in PR after immersion in tea, coffee, and 1% NaClO (Table 1), while CIEDE2000 showed no significant differences (Table 2). This discrepancy is due to CIELab's higher sensitivity to microstructural changes, as its linear system captures subtle shifts in color dimensions.<sup>36-39</sup> The thin-layer construction of PR specimens, along with inefficient polymerization, promotes microcrack formation due to thermal expansion, facilitating liquid and dye penetration, which is detectable by CIELab.<sup>13,29-31,39</sup> In contrast, CIEDE2000 accounts for saturation and hue, identifying only changes perceptible to the human eye.<sup>36-39</sup>

In this study, the higher color change observed in PR after immersion in 1% NaClO contrasts with the findings of Alqanas *et al.*,<sup>13</sup> who reported a higher change in HR. The difference may be due to methodological differences; in this investigation, PR samples here were printed at a 0° orientation with an MSLA printer, post-cured for 10 minutes, and subjected to thermocycling. In contrast, Alqanas *et al.*<sup>13</sup> used samples printed at a 90° orientation with DLP and SLA printers, post-cured for 15 minutes, and without thermocycling. The DLP and SLA technologies ensure more uniform polymerization and greater material stability, while the extended post-cure

improves interlayer bonding and color stability.<sup>13</sup> However, the thermocycling applied in this study simulates material degradation in oral conditions,<sup>15</sup> which showed that HR exhibited less color change than PR under these conditions.

Gruber *et al.*<sup>40</sup> also observed less color change in HR than in PR after coffee immersion, similar to this study, which also reported changes after tea immersion (Tables 1 and 2). The hue changes observed in Table 2 are due to the adsorption and penetration of tea anthocyanins and coffee tannins (dyes with low polarity and small molecular size) into the polymeric matrix of the resin.<sup>16,21-24,40</sup> However, the increase in the bluish tone (CIELab) in PR, as shown in Table 1, is attributed to the increase in luminosity detected by both CIELab and CIEDE2000. This suggests that thermocycling induced partial bleaching through color shifts and oxidation of intrinsic and extrinsic pigments due to temperature fluctuations.<sup>36,37,39</sup>

Coelho *et al.*<sup>26</sup> reported PT and AT values of 1.7 and 4.1, respectively, for the CIEDE2000 system. In the present study, both resins exhibited noticeable and acceptable color changes, indicating that their esthetic quality is maintained over a 6-month period under these conditions (Tables 1 and 2). Studies over a longer period could be conducted to predict which material has the greatest esthetic survival and allow its assertive clinical indication.<sup>26,36-39</sup>

The surface degradation of polymers due to cleansers and thermocycling significantly contributes to the formation of peaks and valleys,<sup>13,26,29-31</sup> resulting in increased surface roughness for both PR and HR (Table 3). This enhances microbial adhesion, potentially leading to tissue inflammation and denture

stomatitis in clinical settings.<sup>13</sup> Were investigated Ra, which indicates mean surface roughness, and Rz, which provides the mean height of the surface profile.<sup>25</sup> In this study, PR exhibited higher Ra values (Table 3), consistent with findings from Alfouzan *et al.*<sup>19</sup> and Alqanas *et al.*<sup>13</sup> They suggest that gallic and ascorbic acids from tea, as well as caffeic and acetic acids from coffee, contribute to increased surface roughness by breaking carbon double bonds on the polymer surface.<sup>13,19</sup> In contrast, Takhtdar *et al.*<sup>41</sup> reported no change in roughness for PR after immersion in 1% NaClO and effervescent tablets. This discrepancy may be attributed to their absence of thermocycling, which minimizes material degradation, as well as the use of the DLP printing technique, which enhances layer adhesion and resistance to liquid penetration.<sup>41</sup>

For HR, the 6-month protocol using distilled water and tea did not produce significant changes in surface roughness, in contrast to the findings of Taweel *et al.*,<sup>8</sup> who reported changes in roughness after immersion in tea. This discrepancy may be due to their longer thermocycling duration combined with mechanical brushing (1 year), which leads to higher degradation of the resin surface.<sup>8</sup> In addition, exposure to 1% NaClO resulted in an increase in Ra and a decrease in microhardness for HR. This observation is consistent with the findings of Alqanas *et al.*<sup>13</sup> and Porwal *et al.*,<sup>15</sup> who also noted a decrease in microhardness for HR after immersion in NaClO. The plasticizing effect of NaClO increases its penetration into the polymer matrix, leading to the removal of filler particles and the formation of pores and decreasing microhardness.<sup>13,15</sup>

The findings of this study indicate that PR exhibited higher color change and increased roughness compared to HR after immersion in coffee, green tea, 1% NaClO, and effervescent tablets, with the cleansers causing more significant changes. Although 1% NaClO was used for its rapid disinfection, a 0.25% concentration effective for denture cleansing may induce fewer physical and mechanical changes. Although statistically significant changes in surface roughness and microhardness were observed for both PR and HR, the magnitude of these alterations was relatively minor, suggesting that the physical and mechanical properties of the materials remained stable over the simulated six-month period. In contrast, the color changes observed were more pronounced and may compromise the aesthetic quality of the resins.

This study highlights the limitations of the *in vitro* method, which does not simulate the oral cavity's variables, including pH fluctuations, mechanical cleaning, and mechanical loading. In addition, the samples were dried and stored under dry conditions to prevent potential alterations in material properties due to resin matrix degradation caused by water sorption and solubility. However, this approach does not align with ideal storage recommendations for prosthetic materials and dental prostheses. Future research that extends the evaluation periods, incorporates mechanical cleansing methods, and includes various denture base materials could provide insights into the physicomaterial behavior of these materials, facilitating more informed clinical decisions.

## CONCLUSION

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

1. Thermocycling and immersion in beverages and cleansers led to noticeable color changes in PR and HR, although these remained within clinically acceptable limits.
2. PR exhibited higher color, roughness, and microhardness changes compared to HR.
3. Cleansers caused higher color, roughness, and microhardness changes for both resins compared to beverages.
4. Immersion in the 1% NaClO resulted in higher physico-mechanical changes in HR.
5. The low magnitude of the changes in roughness and microhardness observed over the simulated 6-month period suggests that the functional performance of the materials remained adequate.

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