scientific reports

OPEN

Effect of prolonged brushing with different agents on surface characteristics of conventional and 3D-printed denture resins

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Given the increasing use of three-dimensional (3D) technology, evaluating the effects of prolonged brushing on denture base resins is necessary. This study evaluated the influence of long-term brushing with cleaning/disinfection agents on the surface properties of heat-cured and 3D-printed denture base resins. Resin discs were produced and randomly divided into groups: T0: no brushing; T1: simulated 1-year brushing; T2: simulated 2-year brushing. A soft-bristled toothbrush was used with one of the solutions: dentifrice (Colgate TOTAL®), disinfectant soap (Lifebuoy®), or distilled water (negative control group). Color stability, roughness and hardness (n = 9 each) tests were performed. Surface topography was analyzed by Scanning Electron Microscopy (n = 2). Data were analyzed using the Mann–Whitney U test (α = 5%). For comparison between the resins, the mean values and standard deviations of the variables for the types of resin and brushing times were obtained, controlling the solutions, using two-way ANOVA with Tukey's Post Hoc Test. For both resins, a statistically significant change in color stability was observed in the groups brushed with dentifrice after 2 years. There was an increased roughness in the samples brushed with the same solution. Concerning hardness, a decrease was observed regardless of the solution and the resin, after 2 years of brushing. Differences between resins were found in relation to color change and hardness. Both resins, heat-cured and 3D-printed, presented changes in color stability, increased roughness and decreased hardness after 2 years of brushing with dentifrice. Brushing with disinfectant soap caused the smallest changes in surface properties, which can be an option for brushing dentures.

Keywords 3D printing, Denture base, Simulate brushing, Color, Surface roughness, Hardness

Dental prostheses are commonly produced from polymethyl methacrylate (PMMA), which shows desirable properties, such as good aesthetics, easy handling and processing, adequate mechanical properties, and low toxicity[1–3]. However, in order to improve some flaws in specific characteristics of PMMA, such as low flexural strength, water absorption, low surface hardness, and sustained monomer release for long periods, new technologies have been emerging, such as additive manufacturing (3D printing)[4–8]. Regardless of the processing system, 3D printing technology can cause differences in the surface properties of resins when compared to the conventional method[9].

The surface properties of the denture base resins can favor the adhesion and formation of biofilm on the prostheses, leading to the development of oral diseases[10,11]. Therefore, it is recommended to clean prostheses using combined methods, such as daily brushing with cleaning agents and immersion in disinfectant solutions[12–14]. However, it is necessary to be aware of different solutions that can be used to clean and disinfect the prostheses, such as toothpaste, sodium hypochlorite solutions, chlorhexidine 2%, glutaraldehyde and disinfectant liquid soap[10,15–19], since these solutions can directly impact on the surface properties of the resin and, consequently, on the adhesion and formation of the biofilm[20].

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The brushing of prostheses by patients is predominantly performed using toothpaste due to its pleasant flavor, ease of use, and ability to aid in the removal of debris and biofilms[21]. However, it is known that this cleaning method modifies the surface of the conventional denture base, increasing its roughness and, consequently, influencing the adhesion of microorganisms[22,23]. Denture base resins obtained by the 3D method can also undergo these same modifications with the use of dentifrice. However, there is still controversy in the literature about the real impact of cleaning with dentifrice on dentures obtained by additive manufacturing[24–29]. As an alternative clean solution, studies report the safe use of Lifebuoy® liquid soap, preserving the color stability, roughness, and hardness of denture base and relining resins obtained by the conventional method[19,30–32]. Furthermore, an antimicrobial effect against *Candida albicans* and low cytotoxicity of these resins were observed after immersion in the same solution[19,30]. Considering these studies, it is possible to use antiseptic soaps as a low-cost simple alternative without causing significant changes to properties that are important for the durability of dental prostheses. However, the effects of simulated mechanical brushing with Lifebuoy® soap over different periods on heat-cured resins and those obtained through 3D printing, compared to the effects of dentifrice, have not yet been reported in the literature.

The use of 3D printing to produce dental prostheses has been progressively increasing in the dental market. Therefore, it is essential to evaluate the properties such as color stability, to preserve aesthetics; surface roughness, to minimize microbial accumulation; and material hardness, to ensure strength and masticatory efficiency. These factors contribute to greater durability and improve clinical performance. Furthermore, this work is justified by the attempt to find new cleaning/disinfection agents that have few adverse effects on the three-dimensional materials. Therefore, the objective of this study was to evaluate the effects of long-term brushing associated with cleaning/disinfection agents on the surface properties of denture base resins obtained by the conventional method (heat-cured) and by 3D printing. The null hypothesis stated that the cleaning and disinfection agents would not affect the surface properties (color stability, roughness, hardness, and surface topography) of the resins, and that no differences would be observed between the two processing methods (conventional and 3D printing).

Materials and methods

Preparation of heat-cured and 3D printed samples

The samples of heat-cured acrylic resin (Vipi Wave—Vipi Produtos Odontológicos, Pirassununga, SP, Brazil) were produced using metal matrices with 10 mm of diameter and 1.2 mm of thickness[31,32]. Flasks compatible with microwave with glass plates sandblasted with aluminum oxide were used to standardize the roughness of the samples[33]. The resin was prepared and polymerized according to the manufacturers' instructions. After polymerization, excess material was removed with a Mini-cut tip (Lesfils de August Malleifer SA, Ballaigues, Switzerland)[19,32].

The production of the printed resin samples was based on the protocol described by Shim et al. (2020)[34]. Circular samples with dimensions of 10 mm in diameter and 1.2 mm in thickness were virtually designed using Computer-Aided Design (CAD) software (Meshmixer v.3.5.474; Autodesk, Inc), and the designs were exported in Standard Tessellation Language (STL) format to slicing software (FlashDLPrint version 2.3.0., FlashForge, Zhejian, China, https://enterprise.flashforge.com/), which convert the file into the *.svgx* format for printing. The samples were printed with the FlashForge Hunter 3D Printer (DONE 3D Store, Ltda, Ribeirão Preto, Brazil) with composite material for denture bases fabrication (Cosmos Denture – Pink Color; Yller Biomateriais S.A.). The samples were printed in the 90-degree orientation[34] with layer thickness of 50 µm, and washed with isopropyl alcohol under agitation for 10 min at normal speed (Wash and Curing, Creality, Shenzhen, China). Post-curing was performed with UV light (wavelength: 385 nm and 405 nm) for 10 min at normal speed (Wash and Curing, Creality, Shenzhen, China) following the manufacturer's recommendations. After that, the excess material was removed using tungsten burs (Mini-cut) and the samples were sanded with 150-grit silicon carbide sandpaper under running water[35], to standardize the initial roughness value similarly to heat-cured resin samples.

Immediately after production, all samples (both heat-cured and 3D-printed) were washed in ultrasonic bath using distilled water for 15 min to remove residues obtained during the manufacturing process and then stored in distilled water for 48 h (T0) to release residual monomer[18,36,37]. Surface roughness was measured prior to the tests (Surftest SJ-401, Mitutoyo Sul Americana Ltda, Santo Amaro, SP) with a resolution of 0.01 µm, to select resin discs that had an average roughness between 2.7 and 3.7 µm, to simulate the internal surface of the prostheses[18,38].

Experimental groups and brushing cycles

The samples were randomly divided into experimental groups (Table 1) and subjected to two simulated brushing cycles: T1: the samples were subjected to 10,000 cycles to simulate 1 year of manual brushing; T2: the samples were subjected to 20,000 cycles to simulate 2 years of manual brushing[24,39]. The samples were brushed with one of the following substances: distilled water (negative control group); Lifebuoy® solution at a 0.78% concentration[19];

Solution	T0	T1 (1 year of brushing)	T2 (2 years of brushing)
Distilled water (negative control)	–	10,000 cycles (DWT1)	20,000 cycles (DWT2)
Lifebuoy®	–	10,000 cycles (SST1)	20,000 cycles (SST2)
Dentifrice	–	10,000 cycles (DTT1)	20,000 cycles (DTT2)

Table 1. Experimental groups and brushing conditions:

or dentifrice prepared by mixing toothpaste with distilled water in a 1:1 ratio (Colgate TOTAL® Creme)[25,26]. The brushing cycle was performed on a brushing machine with six test points developed by School of Dentistry of Araraquara, São Paulo State University (UNESP). Soft bristle toothbrushes (Sorriso Original, Colgate-Palmolive, SP, Brazil) were employed[31,40]. The machine was calibrated to perform 60 reciprocal strokes per minute, with a constant vertical load of 200 g being applied on each specimen[31,32,39]. The compartments in which the samples were filled with 100 mL of each solution according to the groups[31,32]. Different toothbrushes were used in each group. In the simulated 2-year brushing process, brushing was interrupted upon reaching 10,000 cycles, the solution was replaced.

Sampling

The number of samples for each test (color stability, roughness and hardness), totaling 378 samples (n = 9 per group), was determined based on previous studies[16,18,19,31,32]. For the assessment of surface topography, two samples of each group were used (n = 28). In total, 406 samples were used in the study.

Color stability

The initial time was the 48-h storage time in distilled water (T0 – Without brushing). The acquisitions of color measurements were performed for all groups at the times T0, T1 and T2 with the samples positioned on a black background[18,31,32] to simulate the oral cavity, using a portable spectrophotometer (Color Guide 45/0, PCB 6807 BYK-Gardner GmbH, Gerestsried, Germany) with a 4 mm aperture, and daylight used as illuminant (D65)[41,42]. A sight line was created and, in all readings, was positioned in the center of the sample to standardize the area. In addition, the readings were performed in the same setting, with controlled lighting. Three color measurements were made, and then the average tristimulus value was calculated. The procedures were performed in triplicate, over 3 different occasions, totaling 9 samples (n = 9) for each experimental condition. To analyze the color differences perceived by the human eye, the calculation of ΔE00 was performed using the CIEDE2000 color difference formula (1:1:1), which is based on the CIELAB color space[43,44]. In this scale, L* refers to luminosity (L* = 0 = black; L* = 100 = white), A* indicates the chroma on the red-green axis (A* ≥ 0 = red and A* ≤ 0 = green), and B* the chroma on the yellow-blue axis (B* ≥ 0 = yellow; B* ≤ 0 = blue). This scale represents the visible color spectrum as perceived by the human eye.

The formula used was:

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

In this formula, ΔL′, ΔC′, and ΔH′ represent the differences in lightness, chroma and hue, respectively. The weighting factors (SL, SC, SH) are coefficients used to adjust the relative contribution of perceived differences in lightness, chroma, and hue. The parametric factors (KL, KC, KH) were set to 1 under standard conditions. RT is the rotation term that accounts for the interaction between chroma and hue in specific regions[45].

For color difference (ΔE00), the obtained values were classified according to the perceptibility and acceptability threshold, which are related to the clinical significance of color changes, as follows: ΔE00 ≤ 1.7: clinically imperceptible changes; 1.7 > ΔE00 ≤ 4.1: clinically acceptable changes; ΔE00 > 4.1: clinically unacceptable changes[46].

Roughness

Before (T0) and after simulated brushing (T1 and T2), the samples' roughness in each group were measured using a roughness meter (Surftest SJ-401; Mitutoyo Sul Americana Ltda, SP, Brazil). The parameter used were resolution of 0.01 μm; cutting length of 0.8 mm; transverse length of 2.4 mm; tip speed of 0.5 mm s – 1 and tip radius of an active diamond tip of 5 μm. Three measurements were performed for each sample, at different sites within a predetermined area that was the same for all samples. Then, the mean values of the three measurements were obtained. The Ra parameter was selected to allow a comparison with other studies, translating the value of the arithmetic mean of all absolute distances of the roughness profile. The procedures were performed in triplicate, on 3 distinct occasions, totaling 9 samples (n = 9) for each experimental condition.

Hardness

The hardness of the samples from each group were determined before (T0) and after simulated brushing cycles (T1 and T2), using a Vickers diamond. The measurements were performed on a Micromet 2100 device (Buehler, IL, USA), with 100 gf for 10 s. The diagonal lengths were read immediately after each advance for a short period, thus avoiding viscoelastic recovery of the diagonals. Three indentations were performed on each sample, and the mean values were calculated. The procedures were performed in triplicate, on 3 distinct occasions, totaling 9 samples (n = 9) for each experimental condition.

Surface topography assessment

The surface topography of the samples was evaluated by Scanning Electron Microscopy (SEM) analysis. Sample from each group (n = 2) was dehydrated, metallized with carbon, and positioned in the microscope (JEOL JSM, 6610LV) to obtain the images. The magnifications for each view were 100x, 250x and 1000x.

Statistical analysis

Initially, the collected data were organized, classified, and arranged in Excel® 2021 software. Then, the descriptive analysis of the data was performed by calculating the summary measures (median and interquartile range, as well as mean and standard deviation). The data were found to have a non-normal distribution using the Shapiro–

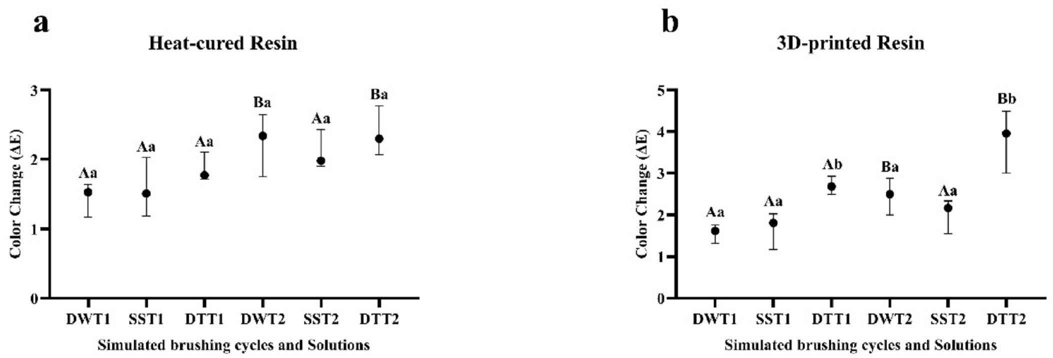

Fig. 1. (**a**) Median values and interquartile range of ΔE for the different cleaning/disinfection agents and simulated brushing period of heat-cured resin ($n = 9$). (**b**) Median values and interquartile range of ΔE for the different cleaning/disinfection agents and simulated brushing period of 3D-printed resin ($n = 9$). Different capital letters indicate significant differences in ΔE values between brushing times T1 and T2 ($p < 0.05$), while different lowercase letters indicate significant differences between cleaning solutions within the same brushing time ($p < 0.05$), according to the Mann–Whitney U test. **DWT1:** 1 year of brushing with distilled water; **SST1:** 1 year of brushing with disinfectant liquid soap solution; **DTT1:** 1 year of brushing with dentifrice; **DWT2:** 2 years of brushing with distilled water; **SST2:** 2 years of brushing with disinfectant liquid soap solution; **DTT2:** 2 years of brushing with dentifrice.

Resin	T1	T2
Heat-cured	1.63 ± 0.34^{A}	2.26 ± 0.48^{A}
3D-printed	1.94 ± 0.66^{A}	2.72 ± 0.94^{B}

Table 2. Mean and standard deviation values of ΔE for the resin types and brushing times with solution control. T1: 1 year of brushing; T2: 2 years of brushing. Different capital letters indicate significant differences in ΔE values between lines ($p < 0.05$), according to the two-way ANOVA with Tukey's Post Hoc Test.

Wilk test. Therefore, the Mann–Whitney U test was chosen as the statistical test, and the SEM images were qualitatively analyzed. The data were analyzed using R software (version 4.3.1, https://www.r-project.org/) with a significant level of 5%. The inferential power was given by the p-value of the Mann–Whitney U test, which was translated into superscript letters of the descriptive values. For comparison between the resins, the mean values and standard deviations of the variables for the types of resin and brushing times were obtained, controlling the solutions, using two-way ANOVA with Tukey's Post Hoc Test. Figures were created using GraphPad Prism (GraphPad Software version 10.5.0, San Diego, CA, USA, https://www.graphpad.com/). However, the *p*-values with statistically significant differences are described in the text.

Results

Color stability

Figure 1 shows the median and interquartile range values of ΔE00 of the heat-cured and 3D-printed resins samples for the different cleaning/disinfection agents and simulated brushing times. In relation to conventional resin (Fig. 1a), it was observed that there was a color change in the samples immersed in water and dentifrice after 2 years of brushing ($p = 0.0054$; $p = 0.03$, respectively). In addition, no differences were detected between the solutions. However, the changes were clinically acceptable. Similarly, in relation to the 3D printed resin (Fig. 1b), it was observed that simulated brushing for T2 with water and dentifrice promoted significant color changes when compared to T1 ($p = 0.001$; $p = 0.008$, respectively). However, the changes were clinically acceptable. In addition, the dentifrice in both times significantly altered the color of the samples compared to the other solutions. For both resins at T1, the samples brushed with distilled water and Lifebuoy® solution showed clinically imperceptible changes. Color stability data are shown in Supplementary Table S1 (Heat-cured resin) and Supplementary Table S2 (3D-printed resin).

For comparison between the resins, the mean values and standard deviations of ΔE for the types of resin and brushing times were obtained, controlling the solutions (Table 2). The results showed a statistically significant difference in T2, with greater color change for the 3D printed resin ($p = 0.04$).

Roughness

Figure 2 shows the roughness' values (median and interquartile range) for the different denture base resins, the cleaning/disinfection agents and the simulated brushing time evaluated. Regarding heat-cured resin (Fig. 2a), it was evident that there was no increase of roughness after 1 year of brushing (T1) for all solutions when compared with T0. In T1, there was a statistically significant difference in the roughness values of the samples brushed

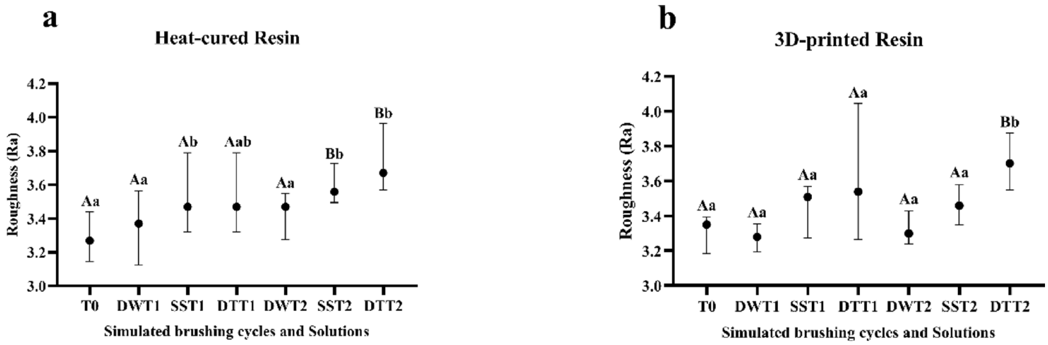

Fig. 2. (**a**) Median values and interquartile range of roughness for the different cleaning/disinfection agents and simulated brushing period of heat-cured resin (n = 9). (**b**) Median values and interquartile range of roughness for the different cleaning/disinfection agents and simulated brushing period of 3D-printed resin (n = 9). Different capital letters indicate significant differences in roughness values at T1 and T2 when compared to T0 ($p < 0.05$), while different lowercase letters indicate significant differences between cleaning solutions within the same brushing time ($p < 0.05$), according to the Mann–Whitney U test. **T0:** No brushing**;** **DWT1:** 1 year of brushing with distilled water; **SST1:** 1 year of brushing with disinfectant liquid soap solution; **DTT1:** 1 year of brushing with dentifrice; **DWT2:** 2 years of brushing with distilled water; **SST2:** 2 years of brushing with disinfectant liquid soap solution; **DTT2:** 2 years of brushing with dentifrice.

Resin	T0	T1	T2
Heat-cured	$3.28 \pm 0{,}18^{A}$	3.47 ± 0.27^{A}	3.59 ± 0.24^{A}
3D-printed	3.29 ± 0.18^{A}	3.45 ± 0.28^{A}	3.50 ± 0.24^{A}

Table 3. Mean and standard deviation values of roughness for the resin types and brushing times with solution control. T0: No brushing; T1: 1 year of brushing; T2: 2 years of brushing. Different capital letters indicate significant differences in roughness values between lines ($p < 0.05$), according to the two-way ANOVA with Tukey's Post Hoc Test.

with disinfectant soap compared to other solutions. In addition, the conventional resin samples immersed in disinfectant soap and dentifrice showed increased roughness after two years of simulated brushing (T2), when compared to T0 ($p = 0.004$; $p = 0.0009$, respectively). At that time, samples immersed in disinfectant soap and toothpaste presented the highest roughness values ($p = 0.04$; $p = 0.01$, respectively). For 3D-printed resin (Fig. 2b), the 2-year simulated brushing (T2) with dentifrice showed an increase in roughness compared to the control group (T0), which was considered statistically significant ($p = 0.0008$). In T1, the groups remained similar. Furthermore, in T2, there was a statistical difference between dentifrice and distilled water ($p = 0.02$) and disinfectant soap ($p = 0.04$). Supplementary Tables S3 and S4 present the roughness data for Heat-cured and 3D-printed resins, respectively.

The comparison between the two resins showed no significant difference in the roughness values (Table 3).

Hardness

Figure 3 shows the median and interquartile range values of hardness for the heat-cured and 3D-printed resins samples, the different cleaning/disinfection agents and the simulated brushing times. After 1 year of brushing (T1), no statistically significant differences were observed for the different solutions, for both resins ($p > 0.05$). However, regarding the conventional resin after 2 years of simulated brushing (T2), distilled water ($p = 0.003$) and dentifrice ($p = 0.0003$) decreased the hardness values compared to T1. In addition, the hardness values of the samples brushed with Lifebuoy® liquid soap solution in T2 were statistically different from the distilled water ($p = 0.0006$) and dentifrice ($p = 0.0003$) groups.

Regarding the 3D-printed resin, the samples brushed with Lifebuoy® liquid soap solution showed statistically higher hardness values than the other groups in T1 ($p = 0.002$). Furthermore, a statistically significant decrease ($p = < 0.0001$) in hardness of all evaluated groups was observed after the 2-year simulated brushing (T2), compared to the control group (T0). Supplementary Table S5 and S6 present the hardness data for Heat-cured and 3D-printed resins, respectively.

Comparing the two resins, the data revealed that the 3D printed resin presented the highest hardness values in all evaluation periods (Table 4).

Surface topography assessment

SEM images of the heat-cured resin samples (Fig. 4) show, in T0, a surface with clearly perceptible irregularities. After 1 year of simulated brushing (T1), the samples brushed with distilled water showed a smoother surface, however, with flaws and cracks along the sample that may influence roughness. This result differs from the

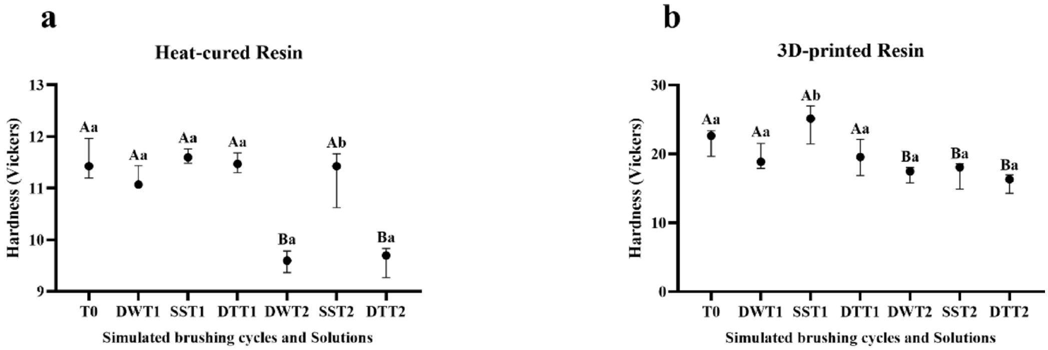

Fig. 3. (**a**) Median values and interquartile range of hardness for the different cleaning/disinfection agents and simulated brushing period of heat-cured resin (n = 9). (**b**) Median values and interquartile range of hardness for the different cleaning/disinfection agents and simulated brushing period of 3D-printed resin (n = 9). Different capital letters indicate significant differences in hardness at T1 and T2 when compared to T0 ($p < 0.05$), while different lowercase letters indicate significant differences between cleaning solutions within the same brushing time ($p < 0.05$), according to the Mann–Whitney U test. **T0:** No brushing**; DWT1:** 1 year of brushing with distilled water; **SST1:** 1 year of brushing with disinfectant liquid soap solution; **DTT1:** 1 year of brushing with dentifrice; **DWT2:** 2 years of brushing with distilled water; **SST2:** 2 years of brushing with disinfectant liquid soap solution; **DTT2:** 2 years of brushing with dentifrice.

Resin	T0	T1	T2
Heat-cured	11.55 ± 0.45^{A}	11.43 ± 0.29^{A}	10.13 ± 0.87^{A}
3D-printed	22.14 ± 2.40^{B}	21.24 ± 3.60^{B}	16.57 ± 1.69^{B}

Table 4. Mean and standard deviation values of hardness for the resin types and brushing times with solution control. T0: No brushing; T1: 1 year of brushing; T2: 2 years of brushing. Different capital letters indicate significant differences in hardness values between lines ($p < 0.05$), according to the two-way ANOVA with Tukey's Post Hoc Test.

groups brushed with liquid soap and toothpaste, which showed greater alterations, with deeper scratches and more heterogeneous topography, mainly for the group brushed with toothpaste. In T2, changes occurred in all groups. Distilled water caused moderate changes, while the liquid soap group showed surface deterioration. The group brushed with dentifrice showed more severe changes, with an apparent rough surface and visible loss of structure. From this, it was found that all agents associated with toothbrushing caused surface changes in conventional acrylic resin, potentially influencing roughness and, subsequently, biofilm adhesion.

In the case of the 3D-printed samples (Fig. 5), surface topography analysis was hindered by the presence of numerous grooves resulting from the polishing process (see the Materials and Methods section). Nevertheless, changes in surface topography were still observed. After 1 year of simulated brushing, the lines became less evident for all solutions, but a surface with loss of structure, with the presence of gaps and cracks, was observed. The 1000 × magnification image of the group brushed with dentifrice revealed an irregular surface and granules throughout the sample. In T2, the images of the samples brushed with distilled water and liquid soap showed staining, likely residue from carbon deposition during preparation for scanning electron microscopy. In the dentifrice group, marked wear and marked irregularity were observed.

Considering the results described above, brushing with the different solutions caused surface changes in both resins. However, the comparison between the two resins was hampered by the polishing performed on the 3D printed resin samples. Future studies using unpolished 3D-printed samples are recommended, as this approach may help overcome the limitations of SEM imaging and allow a more accurate evaluation of the material's topography. Moreover, increasing the sample size per group is advisable.

Discussion

The aim of the present study was to evaluate the influence of simulated mechanical brushing with cleaning/disinfection agents on the color stability, roughness, hardness and surface topography of heat-cured and 3D-printed denture base resins. The null hypotheses were rejected due to changes in these properties after simulated mechanical brushing with cleaning/disinfection solutions. In addition, differences were observed between the two processing methods (conventional and 3D printing).

Regarding color stability, statistically significant changes observed after 2 years of simulated brushing (T2) with water and dentifrice were observed to the heat-cured samples. However, these changes were considered clinically acceptable. Color stability is an important aspect when addressing the esthetics and durability of dental materials for complete and partial dentures[47]. Color change occurs mainly due to the resin's ability to absorb liquid, thus expanding the polymer matrix, separating the polymer chains, resulting in stains or discoloration[2].

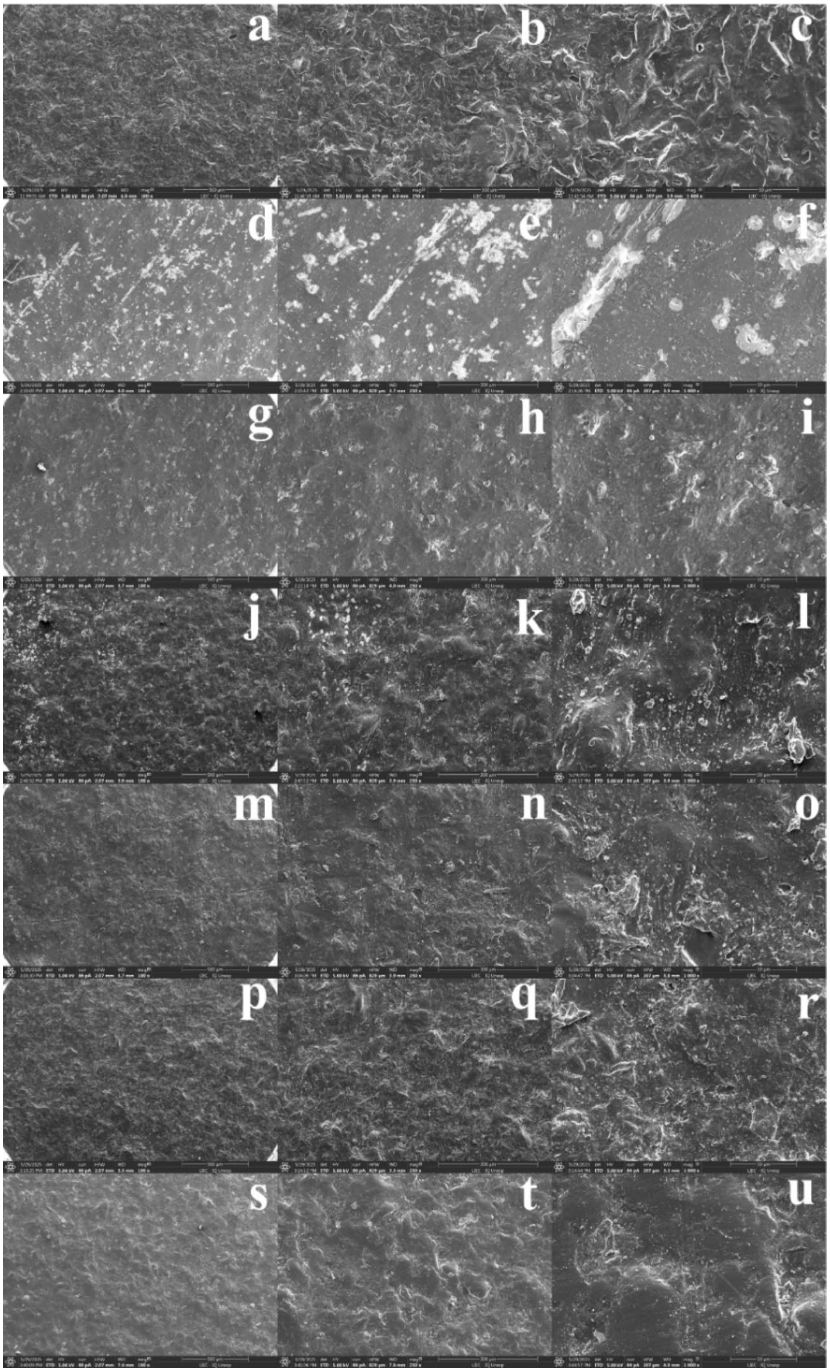

Fig. 4. SEM images of the surface topography of heat-cured resin before and after simulated mechanical brushing with cleaning/disinfection agents (n = 2). (**a, b, c**) Surface topography of the "no brushing group" (T0) at 100x, 250x and 1000x, respectively; (**d, e, f**) 1 year of brushing with distilled water at 100x, 250x and 1000x, respectively; (**g, h, i**) 1 year of brushing with disinfectant liquid soap solution at 100x, 250x and 1000x; (**j, k, l**) 1 year of brushing with dentifrice at 100x, 250x and 1000x, respectively; (**m, n, o**) 2 years of brushing with distilled water at 100x, 250x and 1000x, respectively; (**p, q, r**) 2 years of brushing with disinfectant liquid soap solution at 100x, 250x and 1000x, respectively; (**s, t, u**) 2 years of brushing with dentifrice at 100x, 250x and 1000x, respectively.

This absorption causes the breaking of bonds and gradual deterioration of the structure[48]. In addition, brushing can cause surface erosion, affecting the resin tone, and liquid absorption can increase the adhesion of pigments in denture base resins[49,50]. However, this result cannot be justified based entirely on the liquid absorption theory.

In the present study, a greater color change was observed for the printed resin after simulated brushing with dentifrice. Similarly, Fouda et al. (2023)[29] observed a color change in 3D resins after simulated brushing of 20,000 cycles with dentifrice, exceeding the acceptability limit ($\Delta E00 = 4.68$).

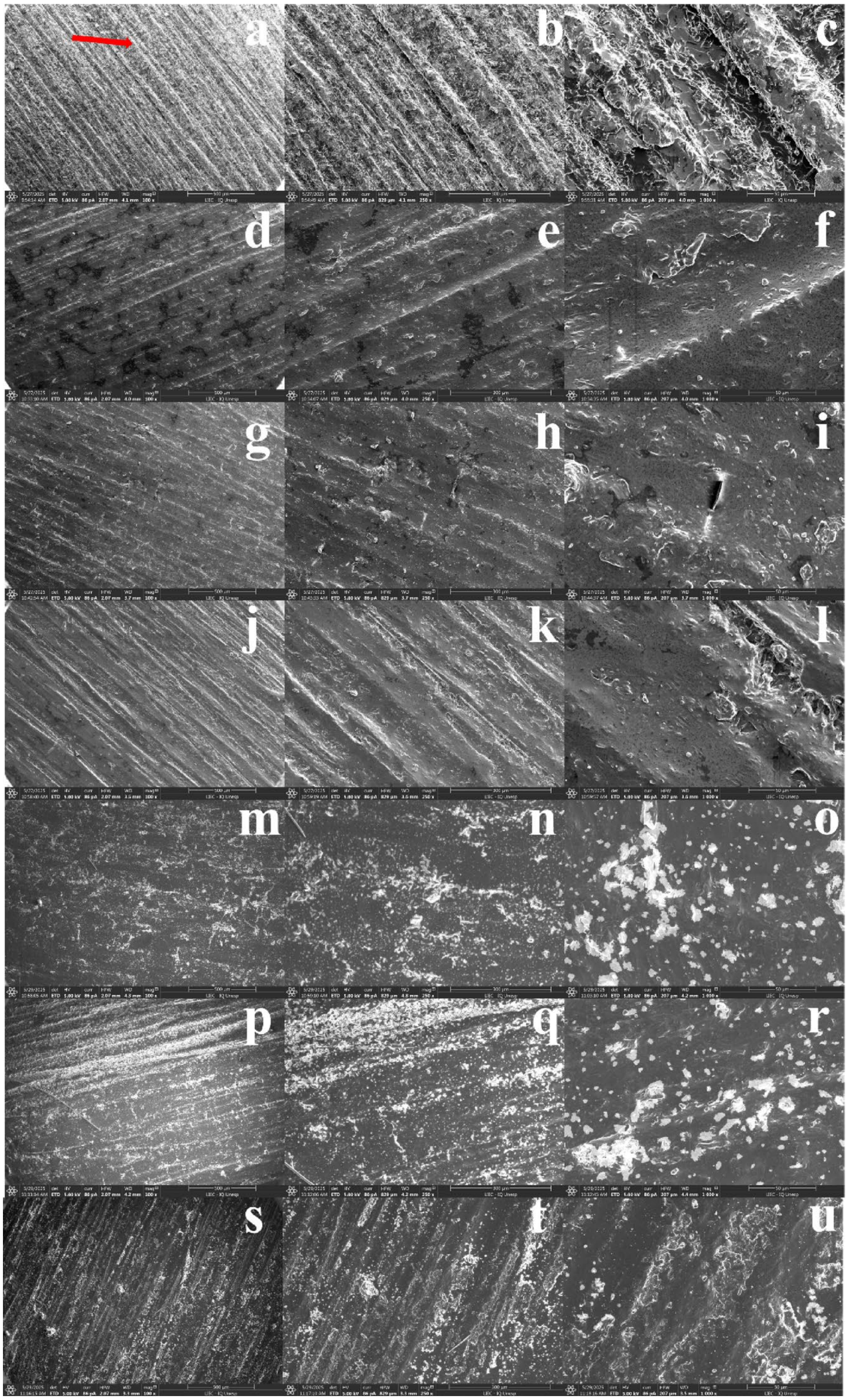

Fig. 5. SEM images of the surface topography of 3D printed resin before and after simulated mechanical brushing with cleaning/disinfection agents (n = 2). The red arrow points to the grooves caused by polishing the samples. (**a, b, c**) Surface topography of the "no brushing group" (T0) at 100x, 250x, and 1000x, respectively; (**d,e, f**)1 year of brushing with distilled water at 100x, 250x, and 1000x, respectively; (**g, h, i**) 1 year of brushing with disinfectant liquid soap solution at 100x, 250x, and 1000x; (**j, k, l**) 1 year of brushing with dentifrice at 100x, 250x, and 1000x, respectively; (**m, n, o**) 2 years of brushing with distilled water at 100x, 250x and 1000x, respectively; (**p, q, r**) 2 years of brushing with disinfectant liquid soap solution at 100x, 250x and 1000x, respectively; (**s, t, u**) 2 years of brushing with dentifrice at 100x, 250x and 1000x, respectively.

Furthermore, it was noticed in the present study that the samples brushed with distilled water and Lifebuoy® solution showed the best results, with clinically imperceptible changes, for both resins in T1. There are no studies in the literature that address simulated brushing of 1 or 2 years with Lifebuoy® soap, making comparisons with other studies impossible. However, Ribas et al. (2022)[31] evaluated the influence of mechanical brushing cycle for 10 s with an antiseptic soap solution on the color stability of heat-cured denture resin and concluded that soap solution did not alter the color of the acrylic resin.

For comparison between the resins, the results showed greater color change for the 3D printed resin in T2. These results agree with other studies[9,51] that demonstrated that the 3D-printed resin exhibited the lowest color stability. These results can be attributed to high water sorption and surface deterioration of the 3D-printed resins. Furthermore, surface deterioration is inversely correlated with filler concentration, and most 3D printed resins contain reduced inorganic fillers[51]. These results are not in agreement with Al-Ameri et al. (2025)[52], who observed a greater color change in the conventional resin. This difference may be related to the treatment of the samples. Al-Ameri et al. (2025)[52] compared the effect of aging by thermocycling on the mechanical properties and color stability of 3D-printed and conventional heat-cured denture base resins.

In conventional resins, surface properties such as roughness can be influenced by the degree of monomer-to-polymer conversion, and this conversion degree depends on the material's processing method, storage time, and composition[53,54]. For 3D-printed resins, roughness can be influenced by the printing angle, which is performed in successive layers. For example, resins printed at 90° have lower roughness than those printed at 45°[34,55]. Furthermore, both brush and immerse in cleaning/disinfection solutions can also alter the surface roughness of resins[31,32]. These are important characteristics to be evaluated, once roughness can influence adhesion and biofilm formation on dental prostheses, causing oral diseases. In the present study, the two evaluated resins showed similar behavior regarding roughness. Brushing with distilled water did not influence the roughness of the samples for both resins, regardless of the evaluated times, corroborating with Fouda et al. (2023)[29]. Furthermore, the highest roughness values were observed after simulated 2-year brushing with dentifrice. Contradictorily, Fouda et al. (2023)[29] observed a decrease in roughness in 3D-printed resin after brushing with dentifrice. These variations in results may be related to the commercial brand of the resin, the manufacturing method, the abrasiveness of the dentifrice, and hardness and material of the employed toothbrushes[56].

The combination of toothbrushes with highly abrasive dentifrices can influence the roughness and wear of denture resin[57]. Pisani et al. (2010)[58], when evaluated the abrasiveness of different dentifrices on thermally activated resins for complete dentures, observed that the conventional dentifrice (Sorriso) increased resin roughness. In addition, it has been seen that brushing without cleaning agents can also cause wear on the resin[59]. Therefore, it is necessary to use toothbrushes with soft bristles for brushing. Furthermore, it would be more interesting to use toothpaste with low abrasiveness and smaller particles when brushing dentures, allowing the polishing of the resin surface, making it less susceptible to biofilm adherence[58,60–63]. In this sense, Lifebuoy® liquid soap could be indicated for printed resins, since it did not cause a significant change in samples' roughness. Ribas et al. (2022)[31] obtained the same results, using 10-s brushing cycles in heat-cured acrylic resin for denture bases.

The comparison between the two resins showed no significant difference in the roughness values, mainly due to the initial standardization of the samples. Therefore, future studies using unpolished samples are necessary to complement the results. For both resins, roughness values were above 3.0 µm. Quirynen et al. (1990)[64] stated that the surface roughness threshold for acrylic resins is 0.2 µm; below this, no significant reduction in bacterial colonization would occur. Significant colonization would occur above 2 µm. Thus, the initial values and those obtained after brushing were well above the clinically acceptable threshold. The development of effective techniques to reduce or prevent microbial proliferation during the laboratory stages of denture fabrication is of great interest. Polishing the internal surface of the denture, for instance, could be beneficial; however, this procedure is usually avoided as it may compromise the retention and stability of the denture.

In general, in the present study, a decrease in the hardness of the samples could be noticed after simulated brushing for 2 years (T2), regardless of the employed solutions, with statistically significant results in both resins. The surface hardness of the sample is an indicator of abrasion resistance. A decrease in hardness can cause greater damage to the resin surface[51]. The hardness' decrease could be explained by the possible plasticizing effect on the surface of polymeric materials caused by aqueous solutions[18,65]. In addition, substances incorporated into the solutions, such as flavorings, oils, and dyes, can modify the resin surface, acting as solvents in thermoplastic materials[66]. Furthermore, regarding the heat-cured resin, the residual monomer evaporation can cause porosity, weaken the mechanical performance of the resin and influence the surface hardness[19,67]. These results do not corroborate those obtained by Nam et al. (2021)[68] and Fouda et al. (2023)[29], which observed no change in the hardness of 3D-printed resins after brushing with distilled water and toothpaste over the same period. However, a post-curing process was carried out for 30 min under UV light in these studies. This method may influence the physical properties of the material, since the longer the post-curing time, the greater the conversion of the monomer, especially on the surface of the resin that will be subjected to brushing[69]. In another study, it was noticed that a 10-s cycle brushing with Lifebuoy® soap did not cause changes in the hardness of acrylic resins[31]. However, direct comparisons cannot be made due to the type of resin and brushing cycle employed in the different studies. Furthermore, there is no evidence in the literature about the use of this soap in the simulated brushing of resins for 3D-printed denture bases. Therefore, further studies are needed.

Comparing the two resins, the data revealed that the 3D printed resin presented the highest hardness values in all evaluation periods, in accordance with the study by Al-Ameri et al. (2025)[52]. The higher hardness values observed for the printed resin may be related to the post-polymerization process, which increases monomer conversion and, consequently, increases the hardness of the material[69]. On the other hand, these results are contrary to the study by Falahchai et al. (2023)[9] in which the surface hardness of the conventional group was significantly higher than that of the 3D-printed group. The difference between the studies may be related to variations in commercial resin brands, compositions and structures, pre- and post-processing procedures, and types of printers and software[70].

The present study showed positive results in relation to the surface properties of denture base acrylic resin after brushing with Lifebuoy solution, in agreement with previous studies[31,32]. Ribas et al.[31] observed that brushing with the soap solution did not change the superficial properties of the denture base resin, but it was able to reduce the *C. albicans* biofilm formed on the samples. The differences observed between dentifrice and disinfectant soap in this study are likely attributable to their distinct compositions. The soap contains active components such as EDTA (ethylenediaminetetraacetic acid), cocamidopropyl betaine, sodium hydroxide, citric acid, triclocarban (which has mechanisms of action very similar to triclosan), curcumin, linalool, among others[31]. Unlike dentifrice, no abrasive agents have been reported in its formulation. The effectiveness of this disinfectant agent, when combined with brushing, offers denture wearers a new cleaning alternative that is both accessible and low-cost.

This study has some limitations that should be acknowledged. As an in vitro investigation, it did not reproduce the complex oral environment, particularly the presence of saliva, intraoral temperature fluctuations, and mechanical stresses, all of which may influence the surface properties and long-term performance of the resins. Additionally, the experimental conditions may not fully reflect the variability of clinical use, such as patient-related factors and differences in hygiene practices. Therefore, further in vivo studies are necessary to validate these findings and to better assess the clinical relevance of the results.

The use of 3D-printed resins in Dentistry is recent, therefore, there is an urgent need for research to evaluate the impacts of hygiene methods on the surface properties of dental materials. Furthermore, different parameters related to the printing process, such as layer height, infill density, printing speed, nozzle temperature, and material type, should also be evaluated in future studies. From this, it is possible to predict more lasting and aesthetic results of prostheses obtained by 3D printing.

Conclusion

Within the limitations of the present study, it may be concluded that the simulated brushing protocol significantly influenced the surface properties of both resins, with more evident effects observed after two years. Dentifrice-brushed samples exhibited the greatest surface alterations, whereas brushing with disinfectant liquid soap produced the least impact on the surface characteristics of both resins. The printed resin showed greater color change, but higher hardness values.

Data availability

Data are provided within the manuscript or supplementary information files.

Received: 7 July 2025; Accepted: 19 September 2025
Published online: 24 October 2025

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Acknowledgements
The authors thanks to Pró-reitoria de Pesquisa (ProPe), for the scientific initiation scholarship granted to carry out this research (PIBIC/Reitoria 9134) and São Paulo Research Foundation (FAPESP) for supporting this study through the grant no. 2021/09624-3.

Author contributions
J.S.O: Acquisition of data, analysis and interpretation of data, drafting the article. H.P.M.M: Acquisition of data, Methodology. R.C.: Acquisition of data, Methodology. B.R.R: Methodology. A.C.F: Methodology. A.L.G.P: Writing—revision. J.H.J: conception and design of the study, Project Administration, Writing – revision & editing. All authors have given approval to the final version of the manuscript.

Funding
This study was funded by the São Paulo Research Foundation (FAPESP), grant no. 2021/09624–3.

Declarations

Competing interests
The authors declare no competing interests.

Ethical approval
The study was conducted entirely in vitro and did not involve human participants or animal subjects; therefore, ethical approval was not required.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-21212-1.

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