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Physical and mechanical properties of denture base acrylic resins: Comparison between CAD/CAM fabrication and water-bath and microwave heat-curing under the effects of thermocycling and disinfection

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Polymers in Medicine, ISSN 0370-0747, eISSN 2451-2699 *Polim Med*. 2026;56(2)

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Funding sources
We thank the São Paulo Research Foundation (FAPESP) for funding the present research (process No. 2024/08721-3).

Conflict of interest
None declared

Received on June 20, 2026
Revised on June 30, 2026
Accepted on September 7, 2026

Published online on November 9, 2026

Abstract

Background. PMMA-based complete dentures remain widely used in clinical practice; however, inherent limitations such as porosity, residual monomer content, and susceptibility to biofilm accumulation may compromise their long-term performance. Although CAD/CAM technology has been introduced to improve prosthesis quality and reduce structural defects, aging processes and routine disinfection protocols may still negatively affect the physical and mechanical properties of denture base materials, highlighting the importance of laboratory simulations of clinical conditions.

Objectives. This study evaluated the influence of thermocycling and different disinfection protocols on the physical and mechanical properties of milled and heat-cured acrylic resins used for denture bases.

Materials and methods. A total of 150 specimens were fabricated (n = 50 per material) using a CAD/CAM-milled resin (Vasden) and 2 heat-cured acrylic resins, processed either by water-bath heat curing (Lucitone) or microwave heat curing (Vipi-Dent). Microhardness, surface roughness, color stability, and water sorption and solubility were measured at baseline (T0), after thermocycling (2000 cycles between 5 ±1°C and 55 ±1°C), and after disinfection (T1). Disinfection protocols included 4% chlorhexidine, 1% sodium hypochlorite, effervescent cleansing tablets, neutral soap, and microwave irradiation. Each material group was subdivided into 5 subgroups (n = 10) according to the disinfection protocol.

Results. Microhardness was significantly influenced by time, material type, and disinfection protocol. Surface roughness was affected by material and disinfection protocol, but not by time. Color stability was influenced by all evaluated factors, with microwave disinfection producing clinically unacceptable changes. Water sorption and solubility increased over time in all materials and were also affected by the disinfection protocol.

Conclusions. Aging and disinfection procedures may alter the physical and mechanical properties of denture base resins, with microwave-polymerized resins and microwave disinfection showing the greatest impact.

Key words: acrylic resins, disinfection, dentures, mechanical tests

Cite as
Wolff CPA, do Santos DM, de Caxias FP, Goiato MC. Physical and mechanical properties of denture base acrylic resins: Comparison between CAD/CAM fabrication and water-bath and microwave heat-curing under the effects of thermocycling and disinfection. [published online as ahead of print on November 9, 2026]. *Polim Med*. 2026. doi: 10.17219/pim/236119

DOI
10.17219/pim/236119

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Introduction

For over 70 years, complete dentures have been restoring function, aesthetics, phonetics, social relationships, interaction, and a more active life for patients.[1–3] Removable complete dentures, produced with polymethyl methacrylate (PMMA) by heat-curing polymerization, either by the bath method or by microwave processing,[4,5] still have adequate physicochemical, aesthetic, and mechanical properties, in addition to a favorable cost, biocompatibility, and ease of manufacture. However, conventional PMMA exhibits polymerization shrinkage and residual monomers, resulting in surface porosity and increased susceptibility to biofilm accumulation.[6–8]

Since the constant pursuit of perfect reproduction of lost anatomical structures demands minute detail, it requires naturalness, anatomical knowledge, manual skills, high-quality materials, minimal alteration during use, comfort, and advanced technology.[9] When all these elements are present, the result is a well-fitted, imperceptible, and durable removable prosthesis, restoring not only function, speech, and aesthetics, but also the complete physical, mental, and social well-being of the patient, who can now smile, eat, talk, and have their overall health and quality of life restored.

In computer-aided design (CAD) and computer-aided manufacturing (CAM) systems, a subtractive method is used in which the acrylic resin disc is compacted under high pressure and heat, reducing the porosity common in conventional resins.[10] Furthermore, another noteworthy modern method for manufacturing prostheses is 3D printing, which deposits layers of acrylic resin and simultaneously photopolymerizes them with ultraviolet light, reducing material waste.[11,12] The result, therefore, is the realization of this pursuit of perfect and technological reproduction of the smallest details, increasingly present and indispensable in the clinical life of the patient and the dentist.

The increase in life expectancy is a relevant point,[1–3] as replacing lost teeth with complete dentures restores comfort in daily life. However, with complete dentures, wear occurs due to cleaning procedures, patient-related factors, and contact with oral fluids, resulting in an irregular surface with minor imperfections and color changes.[13,14] In addition to the factors already mentioned, studies indicate that constant exposure of acrylic resins to disinfectants may interfere with their physical properties,[6–8] since disinfection is performed not only mechanically but also chemically or by microwave energy.[15,16] Examples of chemical disinfection include 4% chlorhexidine, 1% hypochlorite, neutral soap, and sodium bicarbonate-based cleaning tablets. Microwave disinfection for 3 min is also considered an alternative because it is less expensive, simpler, and effective in addressing stomatitis caused by continuous denture use and in reducing microorganisms such as *Candida albicans* and *Staphylococcus aureus*.[17–20] According to previous studies, although the microhardness of acrylic resin decreases, this microwave disinfection protocol has been shown to be more effective at eliminating pathogenic microorganisms.[18–20]

However, it is necessary to consider not only the antimicrobial properties when choosing a disinfection protocol, but also the need to preserve the physical and mechanical properties of the acrylic resin. Laboratory thermocycling and disinfection tests are useful for simulating clinical use and evaluating these changes across different resin types.[21–26] According to Goiato et al.,[27] the usage time and resistance of the complete denture are compromised by the occurrence of porosities, impairing the use of the prosthesis due to trauma caused by contact and also generating irritation in the mucosa due to the accumulation of microorganisms and organic matter on the porous surface, making hygiene difficult.

Given this, this work aimed to compare the physical and mechanical properties (microhardness, surface roughness, color stability, and sorption and solubility) between a resin disc for milling with a CAD/CAM system and water-bath and microwave-polymerized acrylic resins after undergoing thermocycling and different disinfection protocols. The null hypothesis of the study was that there would be no change in microhardness, roughness, color, or sorption and solubility for the milled, water-bath-cured, and microwave-cured acrylic resins.

Materials and methods

Study design

In vitro analyses were performed on samples of heat-cured acrylic resins used in the manufacture of complete denture bases. Microhardness, surface roughness, color stability, and sorption and solubility tests were carried out at two time points: before (T0) and after the samples underwent thermocycling and various disinfection protocols using 4% chlorhexidine, an effervescent tablet, 1% sodium hypochlorite, neutral soap, and microwave energy.

Samples

The samples were made using 3 different types of acrylic resins, each with distinct polymerization methods; the materials, manufacturers, locations, trademarks, and basic chemical compositions are listed below in Table 1.

One hundred and fifty samples were prepared, 50 of which were made of resin discs for milling using a CAD/CAM system, 50 of which were made of water-bath heat-cured resin (Lucitone), and 50 of which were made of microwave energy heat-cured resin (Vipi-Dent), all with the same dimensions: 10 mm in diameter and 3 mm in thickness. Table 2 shows the distribution of samples across the resin groups and their disinfection protocols.

Table 1. Materials, manufacturers, locations, trade names, and basic chemical compositions of acrylic resins used in the manufacture of complete denture bases

Water-bath heat-cured acrylic resin	Dentsply Ind. e Com. Ltda., Brazil	Lucitone 550	Powder: copolymer (methyl-*n*-butyl), methacrylate, benzoyl peroxide, and mineral dyes. Liquid: methyl methacrylate, ethylene glycol dimethacrylate, and hydroquinone.

Table 2. Groups, materials used, and number of samples for each disinfection protocol

Heat-cured acrylic resins

The water-bath heat-cured acrylic resin (Lucitone) was measured according to the manufacturer's instructions, and the measurements were performed at 23 ±2 °C with a relative humidity of 50 ±10%.[14] It was placed in a flask with type III stone plaster (Gesso-Rio, Rio de Janeiro, Brazil). The space for preparing the samples was left by models of extra-hard laboratory silicone discs (Zhermack, Rovigo, Italy) manufactured from a metal mold. The metallic flasks were pressed in a hydraulic press (Midas Dental Products Ltda., Araraquara, São Paulo, Brazil) at a load of 1.25 tons and held for 2 min. After the material polymerized, the flask was immersed in water at 73°C and kept submerged for 90 min. Once the water boiled, it was kept submerged for 30 min.

After de-embedding, the samples were polished with sandpaper of varying grits (280, 320, 600, 1200; Norton, São Paulo, Brazil) for a total of 4 min, followed by polishing with a felt disc and a 0.25-µm diamond solution (Buehler, Lake Bluff, USA).[28] The samples were finished with pumice stone and Spanish white (Vigodent, Rio de Janeiro, Brazil) for 3 min under water cooling.

The microwave polymerization of the acrylic resin (Vipi-Dent) was performed as indicated by the manufacturer, using a specific microwave flask. The preparation, insertion, and pressing were carried out in the same way as for water-bath heat-cured acrylic resins. The microwave programming was done in 3 stages: with a 1300-W oven, the 1st stage was at 30% power for 3 min, the second at 0% power for 4 min, and the 3rd at 60% power for 3 min.[29] After this, the already polymerized samples were subjected to finishing with maxi-cut burs (Vicking, São Paulo, Brazil) to remove excess material, followed by polishing with a sequence of four wet/dry sandpapers (grits 280, 320, 600, 1200) on an APL-4 polisher (Arotec, SP, Brazil), for 1 min for each sandpaper grit.[28]

Milled samples

The samples manufactured using the milling method were designed in software (InlabCAM – Dentsply Sirona, Charlotte, USA) and then cut on a milling machine (MCX5 Dentsply Sirona, Charlotte, USA) to the same dimensions as the previous ones: 10 mm in diameter by 3 mm in thickness. After being milled, the samples were polished with sandpaper of varying grits (280, 320, 600, 1200; Norton, São Paulo, Brazil) for a total of 4 min, followed by polishing with felt and a 0.25-µm diamond solution (Buehler, Lake Bluff, USA).[28] The samples were finished with pumice stone and Spanish white (Vigodent, Rio de Janeiro, Brazil) for 3 min on the surface under water cooling, in the same way as the previous samples.

Sample storage

After preparation and milling, all samples were stored in distilled water in a bacteriological incubator at 37 ±1 °C (CIENLAB Equipamentos Científicos Ltda., Campinas, Brazil) for 24 h before the start of the tests[30,31] to eliminate residual monomer in water-bath- and microwave-cured acrylic resin samples.[32]

Thermocycling

The 150 samples were subjected to a thermocycling test in a thermocycler (Odeme Dental Research, Luzerna,

Brazil) that simulated 2 clinical years of prosthesis use, through 2000 immersion cycles in distilled water for 60 s at temperatures of 5 ±1°C and 55 ±1°C.[33,34]

Storage and disinfection

After thermocycling, the samples were immersed in distilled water at a temperature of 35°C and stored in a hermetically sealed container in a digital bacteriological incubator (CIENLAB Equipamentos Científicos Ltda., Campinas, Brazil) for a period of 60 days, to simulate the clinical conditions of prosthesis use by patients, i.e., in contact with the oral cavity.

During storage, the samples were disinfected every 3 days. After each disinfection,[29] they were removed from the solutions, washed under running water for 1 min, and excess fluid was removed using sterile gauze.

The following products were used for disinfection: 4% chlorhexidine (Vic Pharma, Taquaritinga, Brazil); effervescent tablets (Corega whitening tablets, GKS, Jacarepaguá, Brazil); 1% hypochlorite (compounded); neutral soap (Johnson & Johnson, São Paulo, Brazil); and microwave energy (Brastemp, São Paulo, Brazil).

Samples disinfected with 1% sodium hypochlorite, 4% chlorhexidine, and neutral soap were immersed in the solutions for 10 min and rinsed under running water.[35] In the disinfection with effervescent tablets, the samples were immersed in a container containing 1 effervescent tablet dissolved in 250 mL of warm water for 15 min.[36] In the microwave disinfection protocol, the samples were immersed in distilled water (200 mL), positioned in the center of the microwave oven plate, and subjected to irradiation at 650 W for 6 min.[15–18]

Mechanical and physical properties tests

Knoop microhardness was determined in accordance with American Society for Testing and Materials E384-1131 using a microhardness tester (HMV-2T; Shimadzu Corporation) with a 25-g load for 10 s. Five measurements were performed on the same sample, with a 500 µm spacing between them; the average of these 5 measurements was then calculated to determine the final value for each sample.[35,37]

Surface roughness (Ra)was measured using a profilometer (SJ-401, Mitutoyo, Kanagawa, Japan).[38] The samples were positioned on a holder and the profilometer was used on the surface with a 2-mm-diameter diamond, with settings of λ = 0.08 mm for the cutting wavelength and 0.25 mm for the transverse length at a speed of 0.05 mm/s for the surface roughness characteristic Ra (average roughness which is determined by the arithmetic mean of the absolute values of the ordinates of the roughness profile). The roughness was measured in micrometers (µm).

Color was analyzed by an ultraviolet-visible reflection spectrophotometer (UV-2450, Shimadzu, Japan), and the color change (ΔE) was analyzed by the *Commission Internationale de l'Éclairage* L*a*b* system, using the formula $\Delta E = ((\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2)^{1/2}$.[12] "L" represents brightness from 0 (black) to 100 (perfect white), "a" represents the amount of red (positive values) or green (negative values), and "b" represents the amount of yellow (positive values) or blue (negative values).[39–41]

The sorption and solubility of the samples were analyzed by subjecting them to a desiccation test in accordance with the American Dental Association (ADA) specification.[12] This procedure consists of storing the samples with silica gel in a vacuum environment, inside an incubator at a temperature of 37 ±2°C, followed by daily weighing of the samples on a precision digital balance (BEL Equipamentos Analíticos, Piracicaba, Brazil) until a constant mass is obtained (W1). Afterward, the samples were subjected to accelerated aging (thermocycling) and weighed again (W2). A final desiccation was performed, and their final weight (W3) was recorded. Sorption and solubility were calculated according to the formula:sorption%$(W2 - W3)/W1 \times 100$, solubility % = $(W1 - W3)/W1 \times 100$.[12] All the tests were performed before and after the accelerated aging.

Statistical analyses

Sample size estimation

The variable color change (ΔE*) was selected as the basis for calculating post hoc statistical power because it represents the study's primary outcome and the parameter most directly related to the aesthetic impact of the evaluated disinfection protocols. Furthermore, the ANOVA for ΔE* showed the most robust and well-defined effect among all the outcomes analyzed, allowing for the precise determination of the effect size (Cohen's f) from the F values and degrees of freedom. Therefore, using color change as a reference provides a more reliable and representative estimate of sample size sufficiency, reflecting the materials' clinical performance under different disinfection protocols.

Based on the F values and degrees of freedom obtained in the ANOVA for the factor "disinfection protocol" on color change (ΔE*), Cohen's f effect size was calculated, which was 7.45 (partial $\eta^2 = 0.98$), indicating an extremely high effect. Considering this effect size and the design with five disinfection groups and 10 specimens per group (n = 150), the statistical power (1–β) of the F test was greater than 0.99 for $\alpha = 0.05$. Further theoretical analysis demonstrates that, to detect an effect of this magnitude with 80% power, only two specimens per group would be necessary, reinforcing that the number of samples adopted in this study was more than sufficient.

Data analyses

The data normality was verified using the Shapiro–Wilk test, confirming compliance with the necessary

assumption for the application of ANOVA. Statistical analyses were conducted using Jamovi software (v. 2.2, Jamovi Project, Australia). ANOVA with repeated measures was used to analyze microhardness, roughness, and sorption and solubility, with evaluation time (T0 and T1) as the within-subject factor and resin and disinfection protocol as the between-subject factors. Multiple comparisons were performed using Tukey's test ($p < 0.05$). Color change was evaluated by two-way ANOVA (resin × disinfection protocol), followed by Tukey's HSD test ($p < 0.05$).

Results

Microhardness

The surface microhardness of acrylic resins was significantly influenced by aging time ($F = 35.368$; $p < 0.001$) and by the triple interaction between time, resin types, and disinfection protocol ($F = 2.897$; $p = 0.005$), as shown in Table 3. No significant effects were observed for the time × resin interaction ($p = 0.377$) or the time × disinfection interaction ($p = 0.086$), indicating that these factors, in isolation, do not significantly affect mechanical behavior during aging. Among the main effects, there was a significant difference among the resins ($F = 49.401$; $p < 0.001$), while the disinfection protocols, when analyzed separately, did not show a statistically significant impact ($p = 0.409$), nor did the resin × disinfection interaction ($p = 0.490$).

In the multiple comparisons (Table 4), the milled resin showed a slight reduction in microhardness from T0 to T1 when subjected to 4% chlorhexidine and 1% sodium hypochlorite, whereas the protocols with neutral soap, an effervescent tablet, and microwave maintained stable values over time. The water-bath-cured acrylic resin also showed a slight decrease in microhardness after aging, with larger differences in the effervescent tablet and microwave groups.

Table 3. Analysis of variance (ANOVA) for Knoop surface microhardness values ($p < 0.05$)

Effect	SS	df	MS	F	p-value
Time (T0 vs T1)	19.74	1	19.737	35.368	<0.001
Time × resin type	1.10	2	0.548	0.983	0.377
Time × disinfection protocol	4.65	4	1.163	2.085	0.086
Time × resin type × disinfection protocol	12.93	8	1.617	2.897	0.005
Error (within-subject)	73.10	131	0.558	–	–
Resin type	251.4	2	125.68	49.401	<0.001
Disinfection protocol	10.2	4	2.55	1.001	0.409
Resin type × disinfection protocol	19.0	8	2.38	0.935	0.490
Error (between-subject)	333.3	131	2.54	–	–

Table 4. Mean values (±SD) of Knoop surface microhardness according to resin type, disinfection protocol, and aging time (Tukey test, $p < 0.05$)

Resin	Disinfection protocol	T0 (mean ± SD)	T1 (mean ± SD)
Milled resin	4% chlorhexidine	21.0 ± 1.57 A,a	20.3 ± 1.62 A,b
Milled resin	Effervescent tablets	21.3 ± 1.24 A,a	20.8 ± 1.45 A,a
Milled resin	1% sodium hypochlorite	21.0 ± 1.57 A,a	20.3 ± 1.62 A,b
Milled resin	Neutral soap	21.3 ± 1.24 A,a	20.8 ± 1.45 A,a
Milled resin	Microwave disinfection	21.0 ± 1.53 A,a	21.1 ± 1.29 A,a
Water-bath-cured resin	4% chlorhexidine	20.2 ± 1.43 B,a	19.7 ± 0.77 B,a
Water-bath-cured resin	Effervescent tablets	20.2 ± 1.43 B,a	19.7 ± 0.77 B,b
Water-bath-cured resin	1% sodium hypochlorite	20.2 ± 1.43 B,a	19.7 ± 0.77 B,a
Water-bath-cured resin	Neutral soap	20.2 ± 1.43 B,a	19.7 ± 0.77 B,a
Water-bath-cured resin	Microwave disinfection	20.2 ± 1.43 B,a	19.0 ± 1.33 C,b
Microwave-cured resin	4% chlorhexidine	18.9 ± 0.86 C,a	18.9 ± 1.20 C,a
Microwave-cured resin	Effervescent tablets	18.9 ± 0.85 C,a	18.9 ± 1.20 C,a
Microwave-cured resin	1% sodium hypochlorite	18.9 ± 0.86 C,a	18.9 ± 1.20 C,a
Microwave-cured resin	Neutral soap	18.9 ± 0.86 C,a	18.9 ± 1.20 C,a
Microwave-cured resin	Microwave disinfection	18.6 ± 0.86 C,a	16.7 ± 0.69 D,b

Means followed by the same uppercase letter in the same column and the same lowercase letter in the same row do not differ significantly at the 5% significance level according to Tukey's test ($p < 0.05$).

The microwave heat-cured acrylic resin proved the most susceptible to microhardness reduction induced by thermocycling, an effect that was particularly pronounced after microwave disinfection, resulting in the greatest decrease among all materials evaluated (18.6 → 16.7).

Surface roughness

Surface roughness was significantly influenced by all factors evaluated, except for the main effect of aging time (T0 vs T1), which showed no statistical difference ($p = 0.155$). There were marked effects of resin types ($F = 114.9$; $p < 0.001$) and disinfection protocol ($F = 46.4$; $p < 0.001$), in addition to significant time × resin, time × disinfection, and time × resin × disinfection interactions ($p < 0.001$), as shown in Table 5.

According to the values presented in Table 6, the milled resin showed a slight reduction in roughness from T0 to T1 across all disinfection protocols ($p < 0.05$), maintaining low values (≈0.04 µm) and indicating a stable, clinically smooth surface throughout aging. The water-bath heat-cured resin showed greater variability across methods, with a significant increase in roughness after microwave disinfection (0.0547 → 0.106 µm), whereas neutral soap and 1% sodium hypochlorite produced significant reductions in the T1 value. The microwave heat-cured resin exhibited the highest average roughness among the materials evaluated, with microwave again producing the greatest increase across the entire sample (0.0614 → 0.120 µm).

Color change

Analysis of variance demonstrated that all investigated factors significantly influenced the color change of acrylic resins ($p < 0.001$), as shown in Table 7. Significant effects were observed for resin type ($F = 48.0$), disinfection protocol ($F = 1871.1$), and their interaction ($F = 40.2$),, indicating

Table 5. Analysis of variance (ANOVA) for surface roughness (Ra) values ($p < 0.05$)

Effect	SS	df	MS	F	p-value
Time (T0 vs T1)	1.24×10^{-4}	1	1.24×10^{-4}	2.04	0.155
Time × resin type	0.00437	2	0.00218	35.94	<0.001
Time × disinfection protocol	0.01936	4	0.00484	79.67	<0.001
Time × resin type × disinfection protocol	0.01077	8	0.00135	22.17	<0.001
Error (within-subject)	0.00820	135	6.07×10^{-4}	–	–
Resin type	0.0249	2	0.01247	114.9	<0.001
Disinfection protocol	0.0201	4	0.00504	46.4	<0.001
Resin type × disinfection protocol	0.0105	8	0.00131	12.0	<0.001
Error (between-subject)	0.0147	135	1.09×10^{-4}	–	–

Table 6. Mean values (±SD) of surface roughness (Ra) according to resin type and aging time (Tukey test, $p < 0.05$)

Resin	Disinfection protocol	T0	T1
Milled resin	4% chlorhexidine	0.0472 A,a	0.0415 A,b
Milled resin	Effervescent tablets	0.0508 A,a	0.0415 A,b
Milled resin	1% sodium hypochlorite	0.0472 A,a	0.0415 A,b
Milled resin	Neutral soap	0.0472 A,a	0.0410 A,b
Milled resin	Microwave disinfection	0.0501 A,a	0.0418 A,b
Water-bath-cured resin	4% chlorhexidine	0.0556 B,a	0.0440 B,b
Water-bath-cured resin	Effervescent tablets	0.0547 B,a	0.0502 C,b
Water-bath-cured resin	1% sodium hypochlorite	0.0544 B,a	0.0398 D,b
Water-bath-cured resin	Neutral soap	0.0532 B,a	0.0392 D,b
Water-bath-cured resin	Microwave disinfection	0.0547 B,a	0.106 E,b
Microwave-cured resin	4% chlorhexidine	0.0651 C,a	0.0625 F,b
Microwave-cured resin	Effervescent tablets	0.0626 C,a	0.0597 F,b
Microwave-cured resin	1% sodium hypochlorite	0.0604 C,a	0.0591 F,b
Microwave-cured resin	Neutral soap	0.0636 C,a	0.0630 F,b
Microwave-cured resin	Microwave disinfection	0.0614 C,a	0.120 G,b

Means followed by the same uppercase letter in the same column and the same lowercase letter in the same row do not differ significantly according to Tukey's test at the 5% significance level ($p < 0.05$).

Table 7. Analysis of variance (ANOVA) for color change (ΔE*) values (Tukey test, $p < 0.05$)

Effect	SS	df	MS	F	p-value
Resin type	16.4	2	8.181	48.0	<0.001
Disinfection protocol	1275.8	4	318.962	1871.1	<0.001
Resin type × disinfection protocol	54.9	8	6.861	40.2	<0.001
Residuals	23.0	135	0.170	–	–

that the color stability of the materials depended directly on the disinfectant.

In the multiple comparisons (Tukey – Table 8), it was found that the chemical disinfection protocols – 4% chlorhexidine, neutral soap, 1% sodium hypochlorite, and an effervescent tablet – demonstrated low and similar ΔE* values among the three resins, showing the highest value of 1.86. These values are below the clinical perceptibility threshold, indicating that these solutions did not cause a clinically relevant color change.

In contrast, microwave disinfection proved to be the most critical method, producing the highest ΔE* values in all materials. The microwave-polymerized acrylic resin showed the greatest statistically significant change (ΔE = 10.9) compared to the other two resins studied—the milled resin (ΔE = 7.53) and the water-bath-polymerized acrylic resin (ΔE = 7.65).

When comparing the materials, it was observed that the milled and water-bath-cured acrylic resins showed similar color behavior across most protocols. However, the microwave-cured acrylic resin was more susceptible to color change, exhibiting significantly higher values when exposed to 4% chlorhexidine, neutral soap, and microwave energy.

Sorption and solubility

The sorption and solubility of acrylic resins were significantly influenced by aging time ($F = 19.211$; $p < 0.001$) and by the interaction between time and disinfection protocol ($F = 2.496$; $p = 0.046$), as shown in Table 9. The other interactions were not significant ($p > 0.05$), indicating that, overall, the materials' behavior remains stable across different disinfection protocols. Among the main effects, a significant difference was observed among the resins ($F = 231.32$; $p < 0.001$), indicating that each material has a distinct intrinsic capacity to release components, regardless of the disinfectant used.

Table 8. Mean values (± SD) of color change (ΔE*) according to resin type and disinfection protocol

Resin/disinfection protocol	4% chlorhexidine	Effervescent tablets	1% sodium hypochlorite	Neutral soap	Microwave disinfection
Milled resin	1.77 ±0.31 A,[a]	1.25 ±0.26 A,[a]	1.34 ±0.19 A,[a]	1.16 ±0.25 A,a	7.53 ±0.78 A,b
Water-bath-cured resin	1.79 ±0.29 A,[a]	1.27 ±0.19 A,[a]	1.34 ±0.15 A,[a]	1.17 ±0.23 A,a	7.65 ±0.71 A,b
Microwave-cured resin	1.86 ±0.23 B,[a]	1.31 ±0.17 A,[a]	1.36 ±0.13 A,[a]	1.25 ±0.23 B,a	10.9 ±0.89 B,b

Means followed by the same uppercase letter in the same column and the same lowercase letter in the same row do not differ significantly according to Tukey's test at the 5% significance level ($p < 0.05$).

Table 9. Analysis of variance (ANOVA) for water sorption and solubility values ($p < 0.05$)

Effect	SS	df	MS	F	p-value
Time (T0 vs T1)	0.00128	1	0.00128	19.211	<0.001
Time × resin type	1.14×10^{-4}	2	5.72×10^{-5}	0.857	0.427
Time × disinfection protocol	6.67×10^{-4}	4	1.67×10^{-4}	2.496	0.046
Time × resin type × disinfection protocol	1.65×10^{-4}	8	2.06×10^{-5}	0.309	0.962
Error (within-subject)	0.00902	135	6.68×10^{-5}	–	–
Resin type	0.26820	2	0.134	231.3218	<0.001
Disinfection protocol	0.00313	4	7.83×10^{-4}	1.3498	0.255
Resin type × disinfection protocol	4.19×10^{-4}	8	5.24×10^{-5}	0.0903	0.999
Error (between-subject)	0.07826	135	5.80×10^{-4}	–	–

Table 10. Mean values (± SD) of water sorption and solubility according to resin type and aging time (Tukey test, $p < 0.05$)

Resin	T0 (mean ±SD)	T1 (mean ± SD)
Milled resin	0.326 ±0.18 A,a	0.332 ±0.3 A,b
Water-bath-cured resin	0.258 ±0.08 B,a	0.263 ±0.085 B,b
Microwave-cured resin	0.266 ±0.078 C,a	0.273 ±0.095 C,b

Means followed by the same uppercase letter in the same column and the same lowercase letter in the same row do not differ significantly according to Tukey's test at the 5% significance level ($p < 0.05$).

According to Table 10, all resins demonstrated a slight increase in sorption and solubility values between T0 and T1. The milled resin exhibited the highest values at both times (0.326 → 0.332 mg/cm^2), while the water-bath-cured resin demonstrated the lowest sorption and solubility rates (0.258 → 0.263 mg/cm^2). The microwave-cured resin demonstrated intermediate behavior, but with a consistent increase after aging (0.266 → 0.273 mg/cm^2).

Discussion

The null hypothesis was rejected because the physical and mechanical properties of the resin discs changed after thermocycling and disinfection protocols.

CAD/CAM technology is increasingly present in dental offices and makes daily work easier for dentists and dental technicians, leading to more patients wearing milled complete dentures that will remain in contact with food, fluids, and saliva. In addition, the disinfection of complete dentures for adequate hygiene also raises an important question about the effects of thermocycling and disinfectants on acrylic resin discs milled in a CAD/CAM system compared to traditional heat-cured acrylic resins. It was therefore of utmost importance that this comparative study be carried out to provide the patient with a resin that offers better aesthetics, microhardness, minimal color change, surface roughness, sorption, and solubility, and that guarantees their personal satisfaction.

Although there is a growing trend towards the use of milled resins, they still have limitations, mainly in terms of aesthetics and the adhesion of artificial teeth to the denture bases, 10, which still means that dentures are widely made with conventional acrylic resins, that is, manufactured in dental prosthesis laboratories by heat-curing. There is controversy in the literature over whether milled resins are superior to conventional resins in physical and mechanical properties. While some authors argue that they possess better properties, such as mechanical strength, surface smoothness, and color stability,[10] others claim that their properties are not superior to those of heat-cured resins.[42] These contrasts in results can be explained by the lack of standardization in studies, which can influence the results.[42] In this study, the milled resin showed superior properties, including the highest microhardness among the resins tested; however, it also exhibited more unfavorable properties, such as higher sorption and solubility at T0 and T1 than the other resins. On the other hand, the microwave-cured resin showed the worst performance in this study, with the greatest color change, the lowest microhardness, and the second-highest values for sorption, solubility, and surface roughness.

Several materials for disinfecting acrylic resin prostheses are available in dental practice, as observed in this study. The product or protocol presented to the patient by the professional must be effective at eliminating microorganisms, preserve the physical and mechanical properties of the prostheses,[43] be accessible and low-cost, be palatable, and be residue-free. Therefore, the authors tested various low-cost, easily accessible disinfection protocols for most patients and assessed their effects on the properties of acrylic resins. With the results presented here, clinicians can guide their patients on the best disinfection protocol to preserve the physical and mechanical properties of their complete dentures.

Physical and mechanical properties, such as color, roughness, microhardness, and sorption and solubility, must be preserved throughout the service life of dental prostheses to ensure greater durability. Microhardness reflects the degree of deformation and alteration of the material's three-dimensional stability that occur when the material is dropped or during disinfection of the prosthesis, for example.[32] The roughness of a material is directly related to the accumulation of microorganisms on its surface.[30] Color variation is related to the gradual staining of the prosthesis during clinical use, as patients expose it to disinfectants, dyes, solutions, foods, and liquids.[31] Solubility, in turn, is the maximum amount of a substance that can dissolve in a liquid.[44]

Surface microhardness is a property that contributes to the prosthesis's resistance, ensuring safe functionality for an adequate period and, consequently, greater longevity.[35,37] In general, milled resin showed the highest microhardness values, followed by water-bath-cured resin, while microwave-cured resin exhibited the lowest values, highlighting intrinsic differences among the three materials. Milled resin showed a decrease in microhardness after disinfection with 4% chlorhexidine and 1% sodium hypochlorite. On the other hand, water-bath-cured resin showed a decrease in this property after disinfection with effervescent tablets and microwave energy. The decrease in microhardness at T1 may be caused by the thermocycling process and by changes in physical properties that can occur when acrylic resins are exposed to disinfectants, which degrade their surfaces.[45]

Regarding surface roughness, in general, chemical disinfection protocols (4% chlorhexidine, neutral soap, 1% sodium hypochlorite, and effervescent tablets) showed more stable behavior and better preserved the surface integrity of the resins, while microwave disinfection stood out as the protocol that most compromised roughness, especially for heat-cured resins, reaching values close to the clinical limit associated with increased microbial accumulation established in the literature of Ra = 0.2 µm. [46] Studies indicate that these poorer results with microwave disinfection may be caused by small cracks that can form on the resin surface due to heat generated by the method, as well as by the release of residual monomer, which can lead to additional polymerization and affect the acrylic resin surface.[47]

Color change proved highly variable, as it was influenced by all factors (time, resin, and disinfection protocol). There

is debate in the literature about the clinically acceptable limit for color change. Some authors indicate that ΔE is acceptable up to 3.3,[48] while others indicate that a value of 2.6 is perceptible and that a value above 5.5 is unacceptable.[49] Regardless of which of these two values is considered, all resins presented values from 7.5 onwards with the microwave disinfection protocol, demonstrating that, in terms of color stability, this protocol was inadequate. These values far exceed the clinically acceptable limit, demonstrating that microwave exposure causes visible, intense, and undesirable color alteration. It can be inferred that these microwave disinfection results are related to surface alterations caused by heating the resin, as discussed in relation to surface roughness.

Regarding sorption and solubility, despite the statistical differences observed, all values remained within clinically accepted limits for acrylic resins,[50] indicating adequate stability of the materials over time. Solubility is a property of resins related to the release of unreacted substances, such as residual monomer, plasticizers, and initiators.[51] The increase in solubility over time may be related to the thermocycling process and changes in the polished surface of the resins caused by disinfectant agents. It is worth noting that solubility is an undesirable property in resins because they must be stable in the oral environment.[51]

This in vitro study should be interpreted with caution when extrapolated to clinical practice, as the oral environment differs significantly from the controlled laboratory environment. In a real clinical setting, the presence of salivary components, microorganisms, food, and temperature fluctuations can lead to different results, underscoring the need for clinical studies to confirm the findings presented here. Other studies using other commercial resin brands would also allow comparison between manufacturers and highlight improvements needed for each material.

Conclusions

The physical and mechanical properties of the tested resins can change over time, depending on the disinfection protocol used. Microwave heat-cured resins showed the most significant changes in their properties. The microwave energy method of disinfection had the greatest influence on these properties.

Declaration of Interest

The author(s) declared no potential conflicts of interest.

Acknowledgements

We thank the São Paulo Research Foundation (FAPESP) for the funding for the present research (Process No.: 2024/08721-3).

Data Availability

All data supporting the findings of the current study are included within the manuscript. Extra data will be available upon request.

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