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Original Article

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Cleaning solutions and liner type: *in vitro* bond strength on three-dimensional printed denture bases: the effects of cleaning solutions on prosthesis bases

Soluções de limpeza e tipo de reembasador: resistência à tração *in vitro* de bases de próteses impressas em 3D: os efeitos das soluções de limpeza nas bases de próteses

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Resumo

Introdução: Este estudo teve como objetivo investigar a resistência à tração da união de materiais de reembasamento rígidos e resilientes (soft) aderidos a bases de próteses impressas em três dimensões (3D) e avaliar o impacto de várias soluções de limpeza sobre essas propriedades. **Material e método:** Espécimes de bases de próteses impressas em 3D foram reembasados com materiais de reembasamento rígidos ou resilientes. As amostras foram então tratadas com cinco agentes de limpeza diferentes: hipoclorito de sódio, peróxido de hidrogênio, água destilada, ácido acético e um limpador químico de próteses comercial. A resistência à tração da união na interface reembasamento-base foi medida utilizando uma máquina de ensaio universal. Os dados foram analisados através de ANOVA de duas vias (α=0,05). **Resultado:** O material de reembasamento rígido exibiu uma resistência à tração da união significativamente superior em comparação ao resiliente. Entre os agentes de limpeza, o limpador químico de próteses exibiu a maior resistência à tração (24,89 ± 2,68 MPa), enquanto o hipoclorito de sódio exibiu o valor mais baixo (17,20 ± 1,81 MPa). **Conclusão:** Para bases de próteses impressas em 3D, materiais de reembasamento rígidos proporcionam maior resistência à tração da união do que os resilientes. Além disso, a escolha do agente de limpeza influencia significativamente a integridade da união; especificamente, o hipoclorito de sódio pode afetar adversamente a resistência à tração. A seleção de um protocolo de limpeza adequado é essencial para aumentar a longevidade de próteses impressas em 3D reembasadas.

Descritores: Soluções de limpeza; reembasadores de próteses; resistência à tração da união.

Abstract

Introduction: This study aimed to investigate the tensile bond strength of hard and soft reline materials bonded to three-dimensional (3D)-printed denture bases and to evaluate the impact of various cleaning solutions on these properties. **Material and method:** Specimens of 3D-printed denture bases were relined with either hard- or soft-liner materials. The samples were then treated with five different cleaning agents: sodium hypochlorite, hydrogen peroxide, distilled water, acetic acid, and a commercial chemical denture cleaner. The tensile bond strength at the liner-base interface was measured using a universal tensile testing machine. Data was analyzed using two-way ANOVA (α=0.05). **Result:** The hard-liner material exhibited significantly superior tensile bond strength compared to the soft-liner. Among the cleaning agents, the chemical denture cleaner exhibited the highest tensile bond strength (24.89 ± 2.68 MPa), while sodium hypochlorite exhibited the lowest value (17.20 ± 1.81 MPa). **Conclusion:** For 3D-printed denture bases, hard liner materials provide greater tensile bond strength than soft liners. Furthermore, the choice of cleaning agent significantly influences bond integrity; specifically, sodium hypochlorite may adversely affect tensile strength. Selecting an appropriate cleaning protocol is essential to improve the longevity of relined 3D-printed prostheses.

Descriptors: Cleaning solutions; denture liners; tensile bond strength.

INTRODUCTION

Denture liner materials, which are available in both soft and hard forms, are used to enhance the comfort of dental prostheses and to ensure an optimized fit within the oral cavity. These materials help distribute pressure, prevent irritation, and maintain the stability of dentures in the mouth for extended periods. There is a wide variety of denture liners in terms of their application methods, intended purposes, and chemical compositions[1].

Hard-liner materials are employed in clinical settings to re-establish the fit of removable dentures that have lost adaptation, thereby eliminating the need to fabricate new prostheses. Their major advantage lies in providing a chairside solution within a single appointment, coupled with a practical application procedure. However, they often lack the superior physical properties of heat-cured acrylic resins, a limitation often attributed to the high amount of residual monomers remaining after polymerization[1,2]. Although not ideal in terms of physical properties, their ease of use makes them a practical option in daily dental practice.

In contrast, soft-liner materials are frequently indicated for patients with removable dentures that have undercut areas, for the fabrication of epitheses and obturators, and in cases of atrophic ridges, owing to their flexibility. This flexibility allows forces to be evenly transmitted to the underlying ridges and mucosa. However, the benefits of these materials can only be realized if a strong and durable bond with the denture base is achieved[3]. A weak bond may lead to the separation of the liner from the base, resulting in prosthesis instability and crack formation. Once this bond has been established, maintaining its integrity over time is essential.

The cleaning solutions used by patients, due to their chemical constituents, may weaken this bond, leading to surface roughness and discoloration of the liner materials. Such roughness can facilitate bacterial and fungal adhesion, potentially resulting in Candida-associated infections, as well as structural degradation of both the dentures and the liner materials[4]. Conversely, these cleaning solutions provide a convenient hygiene method for geriatric patients with diminished manual dexterity and are able to penetrate inaccessible micropores more effectively than mechanical cleaning[5]. It is essential to conduct scientific research to examine the influence of cleaning agents on the adhesion between denture liners and 3D-printed prosthesis bases.

In addition to conventional denture fabrication methods, digital systems have emerged as an alternative approach for prosthesis production. These systems are preferred because they reduce errors associated with laboratory and technician processes, shorten production times, and enhance patient comfort[6].

This study aimed to assess the impact of various cleaning solutions on the strength of bonding of hard-and soft- liners put to 3D-printed denture bases. The study was designed to test two null hypotheses:

1. The type of relining material (hard vs. soft) would have no significant effect on the tensile bond strength of 3D-printed denture bases.

2. The type of cleaning solution used would have no significant effect on the tensile bond strength of the relined 3D-printed denture bases.

MATERIAL AND METHOD

Experimental Design and Specimen Preparation

This study examined the impact of various cleaning agents on the tensile bond strength of hard and soft reline materials. A virtual specimen of the denture base (Saremco Dental AG, Rebstein, Switzerland), sized 10×10×20 mm, was designed using open-source CAD software (Meshmixer; Autodesk Inc., San Rafael, USA) and exported for 3D printing.

A power analysis (G*Power v3.1.9.2) for a two-way ANOVA (fixed effects, special, main effects, and interactions) was conducted with $\alpha = 0.05$, power $(1-\beta) = 0.95$, and an effect size $f = 0.25$. The results indicated that a total of 200 specimens were required, with 20 specimens randomly assigned to each of the ten experimental groups (2 liner types× 5 cleaning solutions). Randomization was achieved using a computer-generated random number table.

The designs were transferred to a Max UV 3D printer (Asiga, Sydney, Australia). Each specimen was fabricated at a 50-µm layer thickness. Following the manufacturer's guidelines, the printed bases were cleaned in an ultrasonic bath (Sonorex RK; Bandelin, Berlin, Germany) containing 99% isopropyl alcohol for 10 minutes. Post-polymerization was completed in a UV unit (DentaFab, Istanbul, Turkey) for 30 minutes.

Relining Procedures

To ensure standardization, two auxiliary designs (22 × 10 × 3 mm and 10 × 10 × 3 mm) were created in Blender (Amsterdam, Netherlands). The longer design served as a mould, while the shorter design was 3D-printed and seated within the mould to create a uniform cavity for the liner. This approach standardized the liner thickness at 3 mm and minimized operator-related bias[7].

- **Soft Liner Application:** The heat-polymerized silicone-based soft liner (Molloplast B, Detax, Ettlingen, Germany) was applied according to the manufacturer's protocol. The material was packed with a sterile spatula, covered with a polyethylene film, and placed under a muffle press. Specimens were pressed for 4 minutes to remove excess, followed by 100 kp of pressure for 15 minutes. Polymerization was performed by immersing the muffle in a cold-water bath, gradually heating it to 100°C, and maintaining this temperature as per the curing cycle. After gradual cooling, specimens were deflasked and mechanically polished with pumice and a soft brush (Figure 1a).

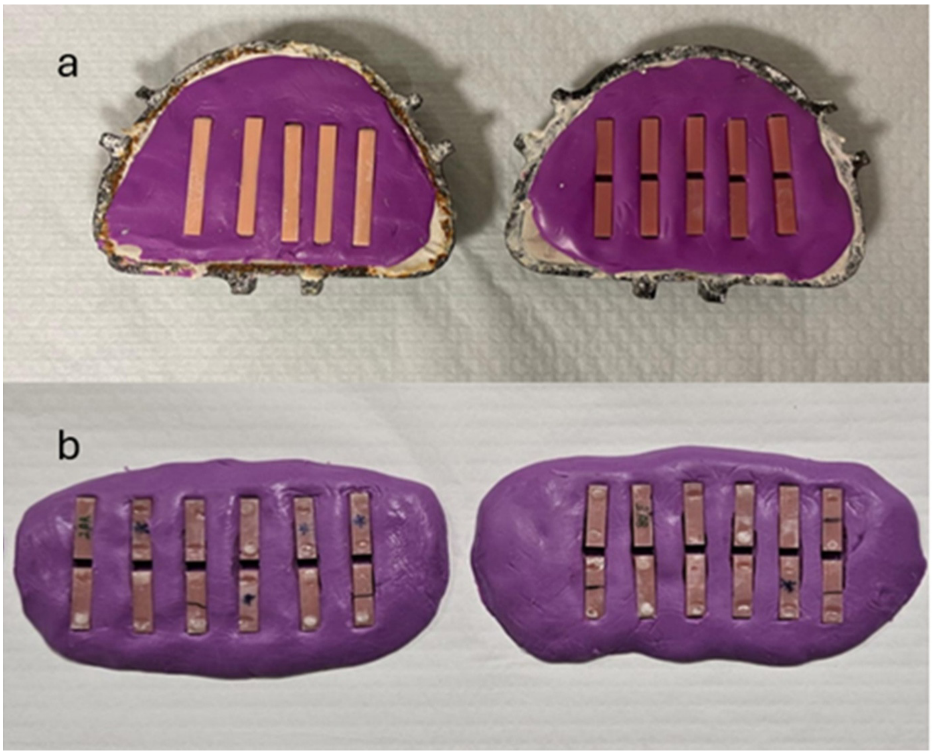

Figure 1. (a) Soft liner samples are taken to the Muffle; (b) Moulding of hard liner samples.

- **Hard Liner Application:** The hard reline material (Ufi Gel Hard, VOCO GmbH, Cuxhaven, Germany) was applied following the manufacturer's chairside instructions. The provided conditioner was applied to the bonding surfaces for 30 seconds. The material was mixed at a liquid-to-powder ratio of 1 ml to 3 ml. The mixture was packed into the mould, excess material was removed, and polymerization was carried out in a pressure vessel at a controlled temperature of 40°C. Finishing was performed using hand instruments and specialized polishing disks (Figure 1b).

Experimental Timeline and Protocols

To simulate clinical conditions and ensure procedural consistency, the following chronological sequence was followed:

Initial Stabilization: After relining, all specimens were stored in distilled water at 37°C for 24 hours to ensure complete stabilization.

Cleaning Protocols (Immersion): Specimens were divided into five subgroups: distilled water (Group C), 1 wt% NaOCl (pH=10.9) (Group N), 5 wt% CH_3COOH (pH=2.4) (Group A), 3 wt% H_2O_2 (pH=4.5) (Group H), and a commercial denture cleanser (COREGA® TABS®; pH=7.2) (Group T). Thirty immersion cycles of 3 minutes each were performed over 6 days, simulating 180 days of daily clinical use. Specimens were rinsed and kept in distilled water between cycles[8-11].

- **Thermal Aging:** Immediately following the cleaning protocols, specimens underwent 10,000 thermal cycles (5°C to 55°C) with a 30-second dwell time to simulate long-term intraoral thermal stress[12].

Tensile Bond Strength Testing

Within 24 hours of aging, specimens were subjected to tensile stress using a universal testing machine (Shimadzu, Kyoto, Japan) at a crosshead speed of 5 mm/min. The maximum load before failure was recorded in Newtons (N). Tensile bond strength (MPa) was calculated by dividing the maximum load by the cross-sectional area of the interface (mm^2) (Figures 2a-2b).

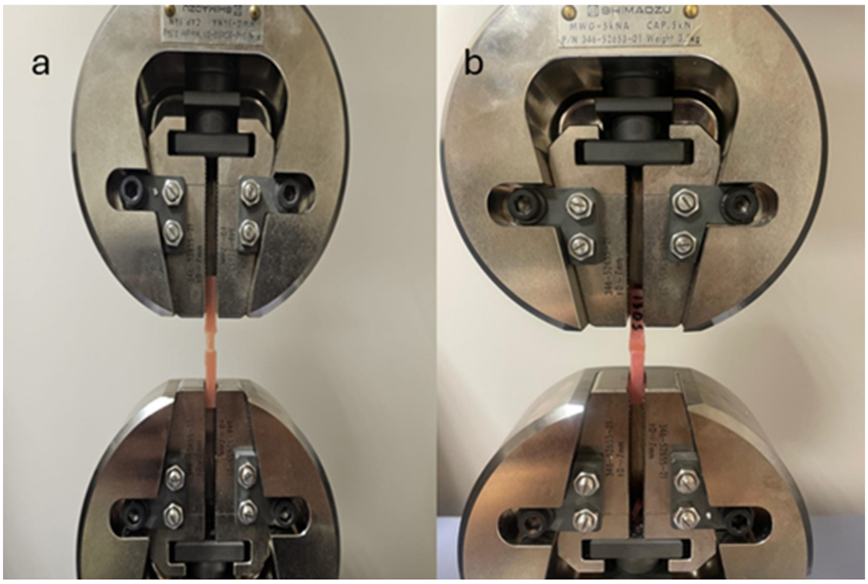

Figure 2. (a) Tensile test on soft liner applied samples; (b) Tensile test on hard liner applied samples.

Examination of Failure Modes of Specimens Under Stereomicroscope

To determine the failure mode, each specimen was examined under a stereomicroscope (SZX10, Olympus, Tokyo, Japan) at 25× magnification and categorized as adhesive, cohesive, or mixed. Adhesive failure was defined as separation occurring along the interface between the 3D-printed denture base and the liner with no residual liner material remaining on the bonding surface, whereas cohesive failure was characterized by a fracture occurring entirely within either the denture base or the liner material. Mixed failure was classified as a combination of both modes, where the bonding surface exhibited both adhesive and cohesive characteristics.

Statistical Analysis

Data normality was confirmed via the Shapiro-Wilk test. A two-way ANOVA was utilized to analyze the effects of liner materials, cleaning solutions, and their interaction on bond strength. Post-hoc comparisons were performed using the Tukey test ($\alpha = 0.05$).

RESULT

Two-way ANOVA revealed significant differences in tensile bond strength based on both the liner material and the cleaning solution ($p < 0.001$). The mean values and standard deviations are summarized in Tables 1 and 2.

Table 1. Two-way ANOVA Test for the Effect of Liner and Solution Tensile Bond Strength

	Type III Sum of Squares	**Df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Line	4962272.858	1	4962272.858	742.047	.000	.796
Solution	141879.998	4	35469.999	5.304	.000	.100
Line * Solution	123161.993	4	30790.498	4.604	.001	.088
Total	15064631.078	200				

*R Squared = .804 (Adjusted R Squared = .795)

Table 2. Descriptive Statistics of Tensile Bond Strength (MPa)

	Material	
Cleaning Solution Hard	Soft	Total
Group C 39.39±1.89$^{a.b}$	5.19±1.35^{d}	22.29±1.93^{A,B}
Group N 29.91±5.47^{c}	4.48±0.62^{d}	17.20±1.81^{C}
Group H 33.45±3.85$^{b.c}$	4.71±0.78^{d}	19.15±1.46^{B,C}
Group A 34.72±8.13$^{b.c}$	5.21±0.82^{d}	19.97±1.99^{A,B,C}
Group T 44.74±6.91^{a}	5.05±1.03^{d}	24.89±2.68^{A}
Total 36.44±2.41^{x}	4.94±0.97^{y}	20.69±1.07

A-C: There is no difference in tensile bond strength within the vertical column denoted by the same letter. a-d: No difference between cleaning solution and liner materials interactions with the same letter. x,y: There is no difference in tensile bond strength within the horizontal column denoted by the same letter.

Specimens relined with hard liners (36.44±2.41 MPa) exhibited significantly higher tensile bond strength than those relined with soft liners (4.94± 0.97 MPa) ($p < 0.05$). Regarding the cleaning solutions, Group T (commercial cleanser) combined with the hard liner achieved the highest values (44.74± 6.91 MPa). Overall, Group T specimens showed the highest total tensile bond strength (24.89 ±2.68 MPa), while the lowest values were observed in Group N (sodium hypochlorite) (17.20±1.81 MPa). Within the soft-liner groups, no significant differences were detected between the various cleaning solutions ($p > 0.05$). The absolute lowest bond strength was recorded in Group N within the soft-liner category (4.48±0.62 MPa). Detailed multiple comparisons are presented in Table 2.

The predominant failure mode was adhesive. However, Hard liner groups also showed mixed and adhesive failures. Soft liner groups only showed adhesive failures. (Table 3) (Figures 3a-3b). No cohesive failure was observed in the tested specimens.

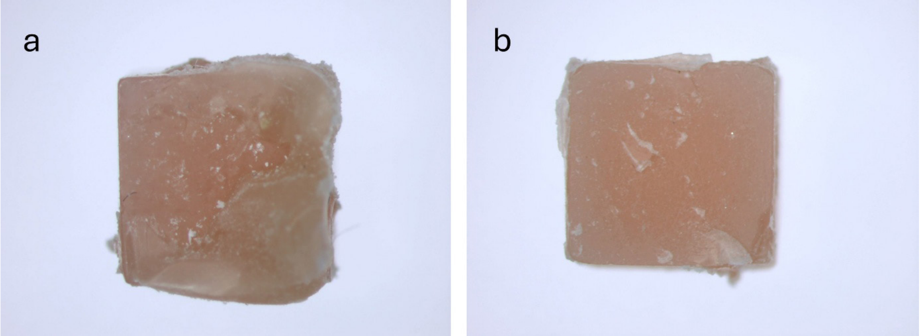

Figure 3. (a) Mixed failure between liner and denture base specimen; (b) Adhesive failure between liner and denture base specimen.

Table 3. Modes of failure in each group of specimens

		Failure Modes		
Materials	**Cleaning Solution**	**Adhesive**	**Cohesive**	**Mix**
Hard Liner	Group C	2	0	18
	Group N	9	0	11
	Group H	7	0	13
	Group A	5	0	15
	Group T	1	0	19
Soft Liner	Group C	20	0	0
	Group N	20	0	0
	Group H	20	0	0
	Group A	20	0	0
	Group T	20	0	0

DISCUSSION

The impact of using soft and hard liner materials on 3D-printed denture bases remains a subject of investigation. In this study, we assessed the tensile bond strength of these materials and evaluated the effects of various cleaning solutions on their performance. The first null hypothesis—stating that liner type would not affect the tensile bond strength—was rejected, as soft liners showed significantly lower values than hard liners. Similarly, the second hypothesis—that different cleaning solutions would alter these outcomes—was supported, as the solutions produced significantly varied results in bond integrity.

Thermocycling has been shown to detrimentally affect the physical characteristics of soft liners, including their tensile and shear bond strength, in nearly all reports[13]. In the present study, the specimens underwent thermocycling to simulate intraoral conditions. The reported reduction in tensile bond strength after thermocycling may be ascribed to the water immersion of the soft liner; during this process, plasticizers are leached, leading to increased water sorption. As water penetrates the junction between the soft liner and the denture base, it induces swelling and interfacial tension. Consequently, the viscoelastic properties and the hardness of the soft liner are altered, reducing its cushioning effect. This allows external loads to be transmitted more directly to the acrylic interface, thereby diminishing the material's resistance to degradation and fracture[14,15].

Regarding biofilm removal, sodium hypochlorite (NaOCl) is among the most effective agents due to its ability to dissolve organic matter[16,17]. However, our results indicate that the alkaline nature of NaOCl may also enhance water solubility and accelerate bond degradation. In this study, Group N (NaOCl) exhibited significantly greater losses in bond strength across all intervals compared to other agents, which is consistent with previous reports suggesting that the chemical action of NaOCl can compromise the structural integrity of the liner-base interface.

Another cleaning solution evaluated was acetic acid. Previous research indicated that 4% acetic acid produces pronounced surface roughness across all immersion periods[18]. Storage in various acidic environments, compared with the control (deionized water), has been shown to increase surface roughness[19]. Increased roughness renders these surfaces more prone to plaque accumulation, staining, and antagonistic wear[20]. When tensile bond strengths were compared, Group A (19.97 ± 1.99 MPa) exhibited a lower value than Group C (22.29 ± 1.93 MPa), consistent with its higher solubility.

Alkaline peroxides generate hydrogen peroxide in water, which subsequently decomposes to release oxygen. This released oxygen plays a crucial role in cleaning through both chemical and physical mechanisms. However, our results suggest that higher peroxide content and the ensuing oxygen release can also promote hydrolysis and surface degradation[21]. In the tensile bond strength tests, Group H (19.15 ±1.46 MPa) showed lower values than Group C, potentially due to the denture cleaner's penetration into the polymer network. This penetration expands intermolecular spaces, leading to a consequent reduction in interfacial resistance[22,23].

Specimens treated with soft liners (4.94± 0.97 MPa) exhibited much lower bond values than those with hard liners (36.44± 2.41 MPa). This is consistent with current permanent resins, where the bond strength of soft liners is inherently lower due to their silicone-based structure and higher plasticizer content. Dimensional changes due to water uptake are expected; therefore, storing dentures in water is recommended to prevent shrinkage[24]. However, water also acts as a plasticizer that can reduce hardness and transverse strength. Our study found that distilled water (Group C) yielded the highest bond-strength values (22.29±1.93 MPa), indicating that it may preserve material durability better than harsh chemical cleaners when disinfection is not required.

When the solutions were compared in terms of tensile bond strength, specimens immersed in distilled water showed the highest values (22.29 ± 1.93 MPa). For permanent 3D-printed resins, storage in distilled water is commonly recommended when disinfection is not required. Because cleaning is challenging, soft liners are particularly susceptible to plaque accumulation[25]. In the present study, distilled-water immersion yielded the highest bond-strength values, indicating that distilled water does not reduce material durability and may better preserve it relative to chemical cleaners.

Specimens immersed in NaOCl exhibited significantly lower bond strength values compared to those treated with other agents, consistent with previous reports[26,27]. Accordingly, distilled-water storage is reasonable for the maintenance of 3D-printed dentures in the absence of specific disinfection needs. Nevertheless, patients often store removable dentures in tap water, which can vary in hardness (Ca^{2}_{+}/Mg^{2}_{+}), chlorine content, and pH[28]. To limit deposits and improve hygiene, an effervescent denture-cleaning tablet may be considered according to the manufacturer's instructions,29 while ensuring compatibility with the denture base material.

Previous studies have reported no statistically significant changes in retention loss among tap water, Protefix, and Corega over various immersion periods[27,29]. Similarly, Mahboub et al.[30]

investigated the effects of Corega and NaOCl solutions on the tensile and shear bond strength of soft liners, concluding that immersion in Corega did not weaken the bond between the liners and the acrylic resin. Regarding the present findings, although Group T (24.89 ±2.68 MPa) exhibited higher tensile bond strength values, no statistically significant difference was detected in comparison to Group C (22.29 ±1.93 MPa). These results suggest that the chosen cleaning procedure for removable dentures must be compatible with the denture base material to preserve its physical characteristics

This in-vitro study has several limitations that should be acknowledged. First, the experimental design did not include chewing (fatigue) cycles, which could potentially influence interfacial wear and long-term degradation. Only a single tensile test was performed for each specimen. Although thermocycling was utilized to simulate temperature fluctuations, the 3D-printed denture base was not evaluated under masticatory loading or in the presence of artificial saliva, both of which are critical variables that may influence clinical outcomes. Furthermore, while a year-equivalent immersion protocol was applied, the synergistic effect of repeated mechanical cycling combined with cleanser exposure might further alter bond strength over time. Future research should incorporate chewing simulations, salivary media, and longitudinal testing, including scanning electron microscopy (SEM) analysis, to better characterize failure modes and interfacial changes.

CONCLUSION

In conclusion, both the liner material and the cleaning solution play a significant role in the durability of dentures produced by 3D printing. Furthermore, the cleaning solutions significantly affected tensile strength of the material. These findings provide important insights into the maintenance and long-term use of dentures in clinical practice. Although the commercially available denture cleanser tablet (Corega) induces changes in tensile strength, its performance is comparable to that of immersion in distilled water. Based on these results, clinicians can provide informed recommendations regarding the selection of cleaning solutions following the application of liner materials.

AUTHORS' CONTRIBUTIONS

Conceptualization: Emel Arslan, Halil Nuri Ozdemir; Data Curation: Emel Arslan, Halil Nuri Ozdemir, Hatice Sevmez; Formal Analysis: Emel Arslan; Investigation: Emel Arslan, Halil Nuri Ozdemir, Hatice Sevmez; Methodology: Emel Arslan, Halil Nuri Ozdemir, Hatice Sevmez; Project Administration: Emel Arslan; Resources: Emel Arslan, Halil Nuri Ozdemir; Software: Emel Arslan, Halil Nuri Ozdemir; Supervision: Emel Arslan, Hatice Sevmez; Validation: Emel Arslan; Visualization: Emel Arslan, Halil Nuri Ozdemir; Writing – Original Draft Preparation: Emel Arslan, Halil Nuri Ozdemir, Hatice Sevmez; Writing – Review & Editing: Emel Arslan, Halil Nuri Ozdemir, Hatice Sevmez.

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CONFLICTS OF INTERESTS

The authors declare no conflicts of interest.

DATA AVAILABILITY

The datasets generated and/or analysed during the current study are not publicly available due [The data is not publicly available as additional analyses are currently being carried out] but are available from the corresponding author on reasonable request.

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