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# In Vitro Evaluation of the Effect of Thermal and Mechanical Fatigues on the Bonding of an Autopolymerizing Soft Denture Liner to Denture Base Materials Using Different Primers

Hiroyuki Minami, DDS, PhD,[1] Shiro Suzuki, DDS, PhD,[2] Yoshito Minesaki, DDS, PhD,[3] Hisanori Kurashige, DDS, PhD,[1] & Takuo Tanaka, DDS, PhD[4]

[1]Senior Instructor, Department of Fixed Prosthodontics, Kagoshima University Graduate School of Medical and Dental Sciences, Kagoshima, Japan
[2]Visiting Professor, Department of Prosthodontics, University of Alabama at Birmingham, Birmingham, AL
[3]Assistant Professor, Department of Fixed Prosthodontics, Kagoshima University Graduate School of Medical and Dental Sciences, Kagoshima, Japan
[4]Professor, Department of Fixed Prosthodontics, Kagoshima University Graduate School of Medical and Dental Sciences, Kagoshima, Japan

**Keywords**
Denture base material; autopolymerizing soft denture liner; surface pretreatment; adhesion; fatigue process.

**Correspondence**
Dr. Hiroyuki Minami, Department of Fixed Prosthodontics, Kagoshima University Graduate School of Medical and Dental Sciences, 8-35-1, Sakuragaoka, Kagoshima 890-8544, Japan. E-mail: AlteMinami@aol.com

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## Abstract

**Purpose**: This in vitro study evaluated the effect of priming procedures on bonding of an autopolymerizing silicone denture liner (Sofreliner) to a denture base material after fatigue processes using cyclic thermal stressing and repetitive mechanical stressing.
**Materials and Methods**: Denture base specimens were fabricated by use of an autopolymerizing denture base resin and Co–Cr alloy into a cylinder shape 8-mm diameter and 4-mm high. The bonding surfaces of denture base specimens were polished with 600-grit silicon carbide paper. Resin denture base specimens were pretreated with applications of resin primer (Sofreliner Primer or Reline Primer for resin). Metal specimens were pretreated with application of metal primer (Reline Primer for metal) or coated with adhesive resin (C&B Metabond) followed by application of resin primer (Sofreliner Primer). Tensile specimens were fabricated by polymerizing a 2-mm thickness of Sofreliner between a pair of pretreated denture base cylinders. Repetitive mechanical stressing was performed by using a University of Alabama-type wear-testing apparatus as a stress generator. Vertical 75 N load with 15° rotation was applied 66,700, 133,300, 266,700, and 400,000 times, then residual tensile resistance to failure was measured. Seven specimens were fabricated for 16 groups—four cyclic loading groups for four pretreatment groups. Residual tensile resistance to failure of specimens before the fatiguing process and after 5000, 10,000, 20,000, and 30,000 thermocycles were used as reference. The mean values of each group were statistically analyzed by three-way ANOVA and Bonferroni/Dunn test at a 95% confidence level. Failure modes were assessed for all specimens measured.
**Results**: In the denture-bonded groups, residual tensile resistance to failure of Sofreliner Primer-treated group was significantly higher than that of the Reline Primer at each thermocycling interval ($p < 0.0001$) and up to 133,300 times of cyclic loading ($p < 0.0001$). In the metal-bonded groups, residual tensile resistance to failure of the intermediate adhesive resin group was higher than the metal primer-applied group up to 5000 thermocycles ($p < 0.0001$); however, there was no significant difference between them after 66,667 cyclic loads ($p = 0.1698$). Although adhesive resin-coated specimens of metal-bonded groups showed mixed failure, metal primer-applied groups and both denture-bonded groups consistently revealed cohesive failure of the soft denture liner after cyclic loading.
**Conclusions**: Application of Sofreliner Primer for a resin denture base provided better bonding after thermocycle and cyclic load testing than did Reline Primer. Using an intermediate adhesive resin layer on a Co–Cr denture base material improved the bonding for up to 5000 thermocycles; however, it did not affect cyclic loading parameters.

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The use of soft denture liners usually helps to avoid stress concentration[1–6] and to obtain retention for clinical cases with irritated denture-bearing mucosa and/or severe undercut areas.[1,3,4,7]

The bonding of soft denture liners has been evaluated by means of tensile tests,[1,2,6,8–17] shear tests,[3,5,9,10,13,14,18] and peel tests.[4,7,13–15] The longevity of soft lining materials has been evaluated by immersion in water,[2,5,6,9,12,17–19] accelerated weather tests,[16,20,21] and thermal cycling.[7,8,11] Soft denture liners are applied not only to acrylic denture bases, but also to metal denture bases. The application of soft denture liner to a metal denture base is advantageous in reducing the total thickness of the denture base when compared to its application to an acrylic denture base.[22] Furthermore, soft lining materials need to be bonded to rigid metal frameworks for maxillofacial prostheses in postsurgical cases.[23] These treatments are beneficial both for edentulous and postsurgery patients. In addition, soft denture liners sometimes need to be adhered to the metal structure not only for fabricating new prostheses, but also for repairing or relining the present dentures. The autopolymerizing silicone lining materials have improved physical properties[3,19] and are being used routinely in clinical practice. They are usually used for the direct relining technique, as they are easy to manipulate and need no laboratory procedures. A common problem of soft denture liners is the failure of adhesion to denture base materials,[1–8,10,23] which generates a favorable surface for bacterial growth, plaque and calculus accumulations, and stains.[11,23] The bonding strengths of autopolymerizing soft denture liner to denture base resin (0.7 to 0.95 MPa) have been reported.[1–4,7,8,10,8] Regarding the longevity of the materials, bond strengths after 5000 thermal cycles (0.5 to 0.95 MPa)[8] and after 90 days immersion in water (0.4 MPa),[2] have been reported.

A few studies have evaluated the adhesion of soft denture liners to Co–Cr alloy[22] and titanium[23] by use of tensile tests. One study evaluated the adhesion after long-term immersion in water.[22] Researchers have already evaluated the bonding of an autopolymerizing soft denture liner to a fluid resin denture base[24] and a Co–Cr alloy denture base.[25] Some priming procedures provided good adhesion after thermal cycling.[24] The lined denture may be exposed to a severe environment—not only cyclic thermal stressing, but also repetitive mechanical stressing during mastication. However, the service life of adhesive bonding between the soft denture liner and denture base materials under repetitive mechanical stressing has not been tested. It has been hypothesized that the bonding of autopolymerizing soft denture liner to denture base materials after fatigue processes might be affected by priming procedures for denture base materials.

The purpose of this in vitro study was to evaluate the effect of surface pretreatment of denture base materials on the bonding of an autopolymerizing soft denture liner to an acrylic denture base and a Co–Cr denture base after fatigue processes using cyclic thermal stressing and mechanical stressing.

## Materials and methods

Materials used in this study are presented in Table 1. A total of 112 denture base resin specimens and 112 Co–Cr alloy specimens were prepared according to previous studies.[24,25] Denture base resin specimens were made of a fluid resin (Pour Resin, Shofu, Inc., Kyoto, Japan). Polymer/monomer mixture (18 g/10 ml) was poured into silicone rubber molds and left at room temperature for 2 minutes. The mixture was then polymerized for 10 minutes using a polymerizing unit (SSKJ-50, Shofu, Inc.) in 50°C water under a pressure of 0.4 MPa. Denture base resin specimens were stored in 37°C water for 21 days to achieve water saturation before this test, according to a reported testing method.[24] Water saturation was confirmed by weighing the resin specimens every 24 hours using an electronic scale (FR-300, A&D Co., Ltd., Tokyo, Japan) with 0.1-mg accuracy. Co–Cr alloy was cast into cylinder shapes with a vacuum pressure casting system (SLVT-I, Shofu, Inc.) at 1450°C under argon atmosphere.[25] The bonding surfaces of both acrylic resin and Co–Cr denture base specimens were polished with 600-grit silicon carbide paper (Carbimet Paper Discs, Buehler Ltd., Lake Bluff, IL) under water irrigation. All acrylic and Co–Cr denture base specimens were fabricated into cylinders of 8-mm diameter and 4-mm height.

The denture base resin and Co–Cr specimens were arbitrarily divided into two groups of 56 specimens each. The bonding surface of the denture base specimens were pretreated with one of the procedures listed in Table 2. In group MA/P2, which contains metal-bonded specimens with an intermediate resin layer (Table 2), the bonding surfaces of the Co–Cr specimens were air-abraded, and 4-META/MMA TBB adhesive resin (C&B Metabond, Parkell, Inc., Edgewood, NY) was applied in a Teflon mold using a brush-on technique into 0.7-mm thickness. The thickness was confirmed by measuring with a micrometer (PK-1012, Mitutoyo Corp., Kawasaki, Japan). The adhesive resin layer was autopolymerized for 5 minutes (manufacturer's recommendation) and left for 1 hour at room temperature to secure a complete polymerization. The resin layer was ground flat to 0.5-mm thickness with 600-grit silicon carbide paper under water irrigation, and the resin surface was primed with Sofreliner Primer (Tokuyama Corp., Tokyo, Japan).[25]

Soft denture liner was polymerized into a 2-mm thickness layer between a pair of pretreated denture base cylinders in a Teflon mold by using an incubation chamber (MIR-162, Sanyo Electric Co., Ltd., Osaka, Japan) for 10 minutes. Twenty-eight tensile specimens were fabricated for each pretreatment group and stored in 37°C distilled water for 24 hours, then equally divided into four groups and subjected to a cyclic loading test.

Repetitive mechanical stressing was performed by applying cyclic loads by use of a University of Alabama-type wear-testing apparatus[26] as a stress generator. The mechanism of mechanical stressing is presented in Figure 1. One of the denture base cylinders of the tensile test specimen was fixed on the specimen holder. A stainless steel stylus was positioned at the starting point slightly above the top of the denture base cylinder with a starting load of 0 N. The stylus vertically contacted the specimen, and then it rotated clockwise 15° with an increasing load up to 75 N at the end point of the stroke. The process was then repeated. The load was applied 66,700, 133,300, 266,700, and 400,000 times in distilled water at room temperature. The frequency of the loading was 72 times per minute (1.2 Hz), which approximated the chewing rate of humans.[27] Four hundred thousand times of cyclic loading corresponds to a

**Table 1** Materials used

| Material | Product name | Manufacturer | Lot no. | Abbreviation |
|---|---|---|---|---|
| Poly(vinyl siloxane) soft denture liner | Sofreliner (medium soft) | Tokuyama Corp., Tokyo, Japan | 690842 | RL |
| Denture base materials | | | | |
| Fluid denture base acrylic | Pour Resin | Shofu, Inc., Kyoto, Japan | Powder: 048583<br>Liquid: 069633 | D |
| Co–Cr alloy | Cobaltan | Shofu, Inc. | 029603 | M |
| Adhesive resin | C&B Metabond | Parkell, Inc., Edgewood, NY | Powder: ER1<br>Liquid: EL1<br>Catalyst: EK22 | A |
| Adhesive primers | | | | |
| Resin primer | Reline Primer (for resin) | GC Corp., Tokyo, Japan | 0105081 | P1R |
| | Sofreliner Primer | Tokuyama Corp. | 815 | P2 |
| Metal primer | Reline Primer (for metal) | GC Corp. | 0110171 | P1M |

3-year period of intraoral conditions.[26] Therefore, 66,700, 133,300, 266,700, and 400,000 times of cyclic loading simulate 0.5, 1, 2, and 3 years of intraoral conditions. The number of specimens per group was seven, therefore, a total of 112 specimens, which included 56 denture-bonded and 56 metal-bonded specimens for four cyclic loading groups of two pretreatment groups each, were fabricated.

Although shear stresses were generated during cyclic loading, those cycles were not carried to the point of failure. Therefore, the specimens were removed from the stress generator, and the residual strengths of the specimens were evaluated in tension. A specimen holder consisting of an acrylic rod and a screwed stainless steel hook was attached to both the top and bottom surfaces of each tensile test specimen with cyanoacrylate adhesive (Zerotime, Cemedine Co., Ltd., Tokyo, Japan). The specimen assembly was mounted onto a universal testing machine (Instron model 1114, Instron Corp., Canton, MA) using a jig to avoid torque on the specimens during tensile testing. The tensile test was carried out at a 25.4 mm/min (1 inch/min) crosshead speed until failure. The data were collected through a scanner (model 5100 scanner, Vishay Measurements Group, Inc., Raleigh, NC) and recorded into data system software (Strain Smart version 3.1, Vishay Measurements Group, Inc.) throughout the tensile testing at a frequency of ten times per second. As the tensile specimens did not always separate cohesively, it was impossible to identify the actual bonding area. Furthermore, cross-sectional areas could not be detected, as the soft denture liner was being stretched during tensile testing. Therefore, the maximum tensile load during failure was described as residual tensile resistance to failure in newtons (N).

**Table 2** Pre-treatment procedures for bonding surfaces of denture base specimens

| Priming procedures | Abbreviation |
|---|---|
| Acrylic denture base-bonded specimen | |
| Application of Reline Primer (for resin) | D/P1R |
| Application of Sofreliner Primer | D/P2 |
| Co–Cr alloy-bonded specimen | |
| Air-particle abrasion, followed by application of Reline Primer (for metal) | M/P1M |
| Air-particle abrasion and coated with adhesive resin, followed by application of Sofreliner Primer | MA/P2 |

Air-particle abrasion was performed by use of 50-$\mu$m alumina particles under 0.4 MPa for 5 seconds.

Fractured surfaces were observed under an optical microscope (SMZ-10, Nikon Corp., Tokyo, Japan) at a magnification of 10× to assess the failure mode. The assessed failure modes were categorized as cohesive failure of the soft denture liner, adhesive failure between the soft denture liner and the denture base material interface, adhesive failure between the adhesive resin and metal denture base interface, or a combination of the above. Scanning electron microscopy (SEM) (JSM-5510LV, JEOL Ltd., Tokyo, Japan) was used to assess the failure surface in detail.

The standardization of the evaluation method for bonding between soft denture liners and denture base materials after mechanical stressing is preferable. Therefore, the bonding results before fatigue processes and after cyclic thermal stressing, which have been previously reported,[24,25] were quoted as references. Themocycling was carried out by soaking the specimens alternatively in 4°C and 60°C water baths with a 1-minute dwell time at each temperature. The groups before fatigue processes for each surface pretreatment group were used as controls. Ten thousand cycles of cyclic thermal stressing correspond to a 1-year period of intraoral conditions.[28] Therefore, 5000, 10,000, 20,000, and 30,000 cycles of thermal stressing simulate 0.5, 1, 2, and 3 years of intraoral conditions. Additionally, seven D/P1R specimens were fabricated, and residual tensile resistance to failure was measured after 5000 thermal cycles in a similar manner.[24,25]

The mean values of each group were statistically analyzed by three-way ANOVA for respective denture base materials, with surface pretreatments for denture base material, fatigue processes, and simulated intraoral periods as independent factors. Differences among the groups were analyzed by a Bonferroni/Dunn test at a 95% confidence level.

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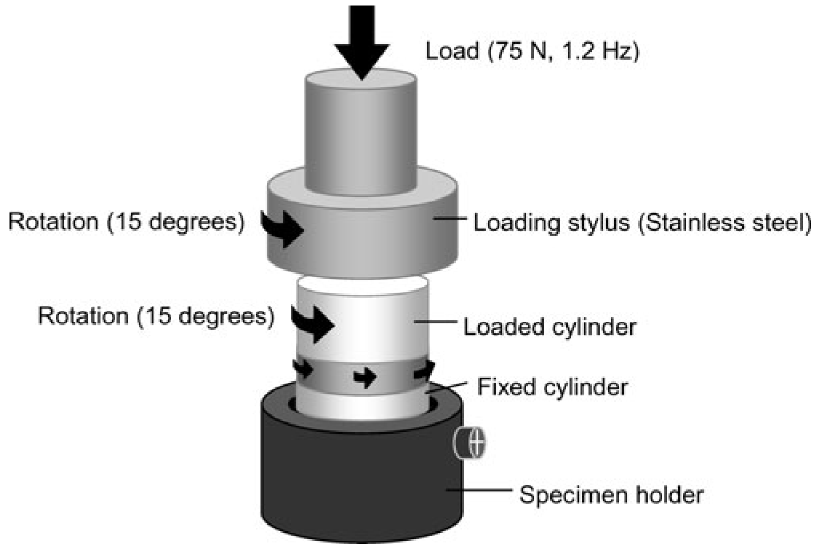



**Figure 1** Schematic diagram of cyclic loading.

## Results

Three-way ANOVA indicated significant differences among surface treatment ($p < 0.0001$), fatigue processes ($p < 0.0001$), and simulated intraoral periods ($p < 0.0001$) for residual tensile resistance to failure of the respective denture base materials. In addition, significant interaction was observed among surface treatment, fatigue processes, and simulated intraoral periods ($p < 0.0001$ for denture-bonded specimen group, $p = 0.0012$ for metal-bonded group). Typical SEM views of specimens showing cohesive failure, cohesive and adhesive failure after thermocycling, and cohesive failure after cyclic loading are presented in Figures 2–4, respectively.

For the denture-bonded specimen groups, residual tensile resistance to failure of group D/P2 (108.2 ± 6.8 N) maintained up to 20,000 thermocycles (103.5 ± 6.2 N) (simulated 2-year period), and group D/P1R (97.6 ± 6.1 N) maintained its residual tensile resistance to failure up to 10,000 thermocycles (86.5 ± 8.4 N) (1 year) (Fig 5); these specimens showed cohesive failure of the soft denture liner (Fig 2, Table 3). Residual tensile resistance to failure of group D/P2 were significantly higher than group D/P1R after 66,700 cyclic loads (61.1 ± 5.1 N for D/P2, 48.1 ± 4.0 N for D/P1R) ($p = 0.0002$) and 133,300 cyclic loads (47.8 ± 5.0 N for D/P2, 32.2 ± 6.1 N for D/P1R) ($p < 0.0001$) (Fig 5). The residual tensile resistance to failure significantly decreased ($p < 0.0001$) after 66,700 cyclic loads (0.5 year) for both groups D/P1R and D/P2 (Fig 5). Although D/P2 specimens after 30,000 thermocycles (70.8 ± 11.7 N) and DP1R specimens after 20,000 thermocycles (49.7 ± 5.8 N) showed cohesive and adhesive failure (Table 3, Fig 3), cyclic-loaded specimens consistently showed cohesive failure of the soft denture liner (Table 3, Fig 4).

For the metal-bonded specimen groups, residual tensile resistance to failure of groups M/P1M (70.0 ± 4.7 N) and MA/P2 (86.5 ± 4.1 N) significantly decreased after both 5000 thermocycles (50.3 ± 4.8 N for M/P1M, 70.2 ± 5.5 N for MA/P2)

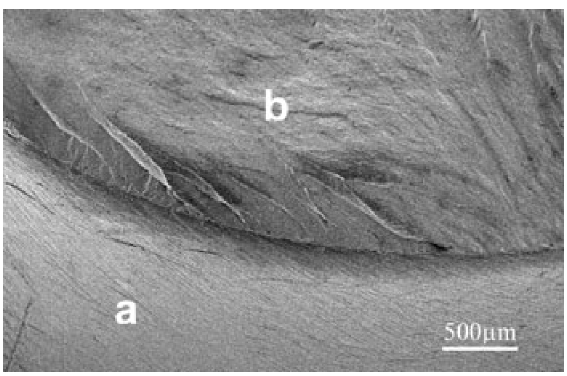



**Figure 2** SEM view of specimen showing cohesive failure. (a) Axial surface of denture base resin specimen; and (b) soft denture liner failed cohesively during tensile testing. Note that the liner remained on the bonding surface of denture base specimen.

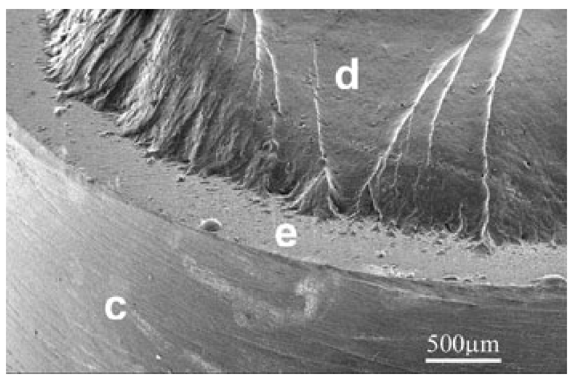



**Figure 3** SEM view of thermocycled specimen showing cohesive and adhesive failure. (c) Axial surface of denture base resin specimen; (d) soft denture liner failed cohesively during tensile testing; and (e) area failed adhesively by thermocycling. Polished surface texture of bonding surface can be observed.

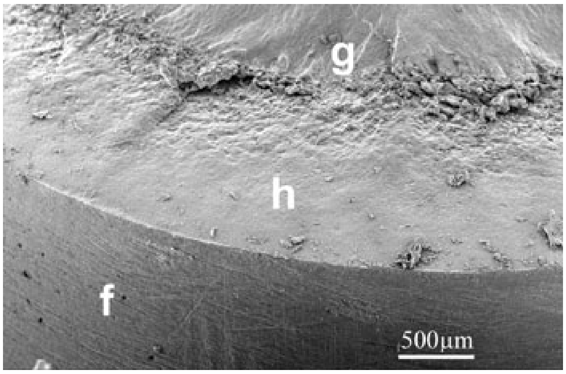



**Figure 4** SEM view of cyclic loaded specimen showing cohesive failure. (f) Axial surface of denture base resin specimen; (g) soft denture liner failed cohesively during tensile testing; and (h) soft denture liner torn up during cyclic loading and failed cohesively. Worn silicone debris remains on it.

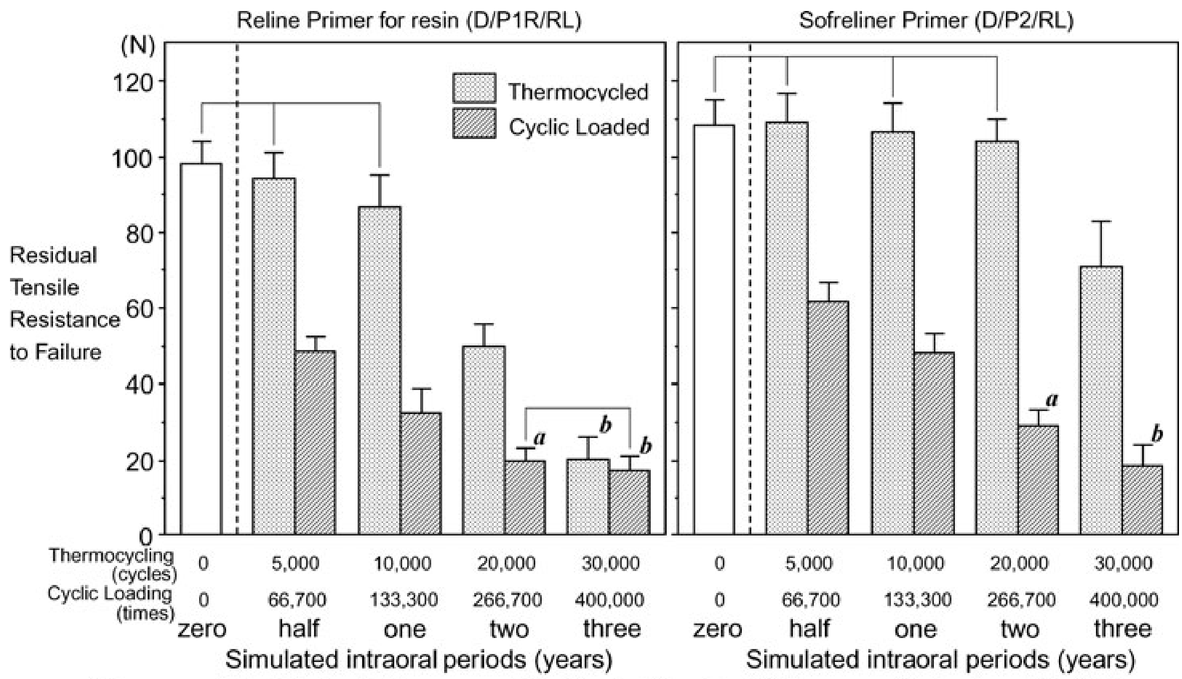
and 66,700 cyclic loads (48.1 ± 3.9 N for M/P1M, 51.3 ± 4.2 N for MA/P2) ($p < 0.0001$) (Fig 6). Although residual tensile resistance to failure of group MA/P2 was significantly higher than group M/P1M after 5000 thermocycles ($p < 0.0001$), there was no significant difference between them after 66,667 cyclic loads ($p = 0.1698$) (Fig 6). Group M/P1M showed cohesive failure of soft denture liner after cyclic loading; however, group MA/P2 showed mixed failure, which consists of cohesive failure of soft denture liner and adhesive failure at the soft denture liner–adhesive resin interface after 133,300 cyclic loads (Table 4).

## Discussion

It is impossible to simulate intraoral conditions completely; therefore, longevity of materials is usually predicted by laboratory tests. This in vitro study was carried out by focusing on thermocycling and cyclic loading as a simulated intraoral environment to evaluate the effect of priming procedures for denture base materials on the bonding longevity between denture base materials and autopolymerizing soft denture liner.

The bonding interface between soft denture liners and denture base materials is mainly subjected to shear and tear stresses during clinical use.[14] Shear stress is generated at the periphery of the bonding interface during tensile testing, as the bonding area remains the same while the soft denture liner stretches.[29] Therefore, the tensile test used in this study was an acceptable method to evaluate the adhesion between both materials.

Specimens were fabricated by polymerizing soft denture liner between a pair of denture base cylinders to enable the tensile testing. Soft denture liner is attached to one side of the denture base in clinical cases, which means half of the liner will be in contact with the soft tissue and exposed to saliva. This fact may lead to the differences in the stress transmission to bonding interface and water absorption of soft denture liner, which may have a large impact on the bonding between the denture base and soft denture liner; therefore, results obtained from the present study may differ from those in clinical situations. The use of heat-polymerizing resin is ideal to simulate the clinical




Values connected with horizontal lines were not significantly different within the same surface treatment ($p > 0.05$).
Values with the same letter were not significantly different within the same intraoral periods ($p > 0.05$).

**Figure 5** Residual tensile resistance to failure of denture-bonded specimens.

**Table 3** Failure modes of denture-bonded specimens

| Specimen | Fatigue process | Simulated intraoral periods (years) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 0.5 | 1 | 2 | 3 |
| | Thermocycling (cycles) | 0 | 5000 | 10,000 | 20,000 | 30,000 |
| | Cyclic loading (times) | 0 | 66,700 | 133,300 | 266,700 | 400,000 |
| Reline Primer (for resin) (D/P1R/RL) | Thermocycling | C | C | C | C/A | C/A |
| | Cyclic loading | | C | C | C | C |
| Sofreliner Primer (D/P2/RL) | Thermocycling | C | C | C | C | C/A |
| | Cyclic loading | | C | C | C | C |

C = cohesive failure of soft denture liner; A = adhesive failure at soft denture liner-acrylic denture base interface;
C/A = cohesive and adhesive failure.

situation, because the porosity and amount of residual monomers in fluid resin are different from those of heat-polymerizing resin, which may affect the bonding between soft denture liner and denture base resin. A fluid resin was chosen because of the ease of specimen fabrication. As fluid resin was polymerized in 50°C distilled water under 0.4-MPa pressure, formation of voids and the amount of residual monomer may have been controlled. Furthermore, resin specimens were stored in distilled water for 21 days to allow water saturation, which likely facilitated residual monomers being released. Some residual monomers, which still existed in resin specimens, may have been released during thermocycling and may have affected the bonding of the soft denture liner.

Residual tensile resistance to failure of denture-bonded specimens were calculated in the range of 1.94 ± 0.12 to 2.15 ± 0.14 MPa for nonthermocycled groups, and 1.88 ± 0.13 to 2.17 ± 0.05 MPa after 5000 thermocycles, by dividing load

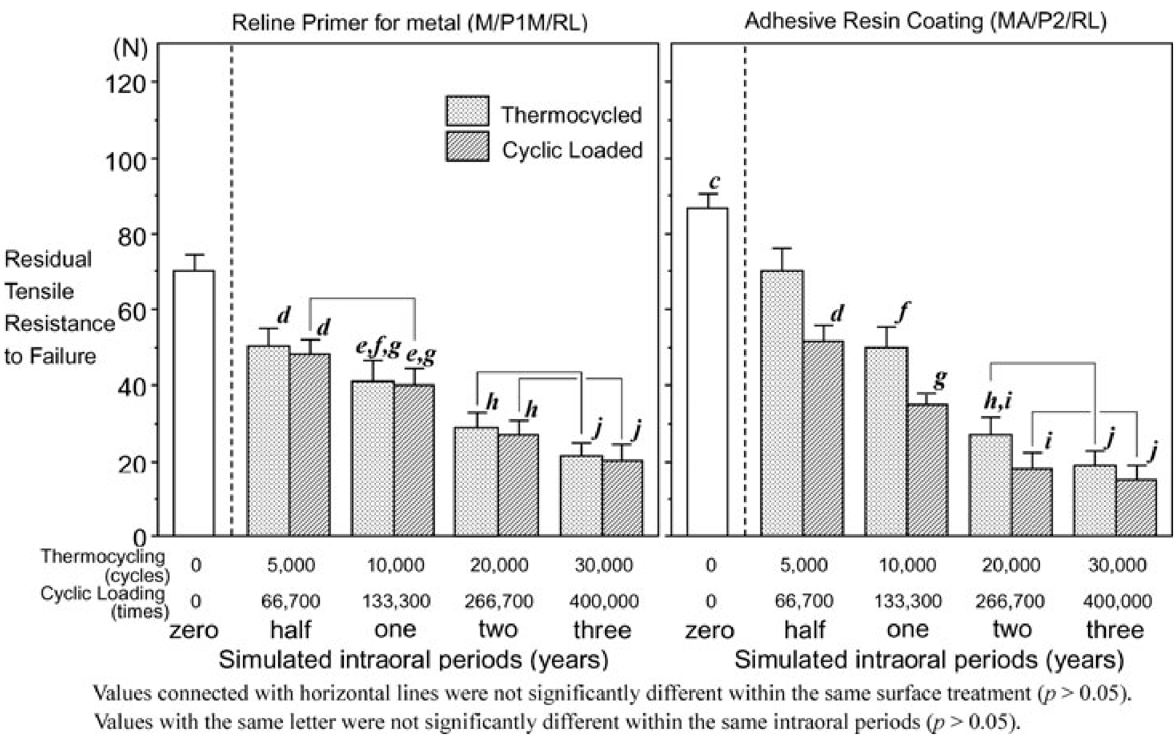



**Figure 6** Residual tensile resistance to failure of Co–Cr alloy-bonded specimens.

by adhesive area. These values were higher than those before thermocycling (0.7 ± 0.01 to 0.95 ± 0.05 MPa)[1-4,7,8,10,18] and after 5000 thermocycles (0.5 ± 0.02 to 0.95 ± 0.05).[8] The variation in values may have been caused by differences in specimen size, specimen configuration, thickness of soft lining material, crosshead speed, type of denture base resin, type of soft lining material, surface preparation, and processing techniques.[14,15]

The effect of thermocycling on the bonding of soft denture liner to denture base materials obtained from the current study partially agreed with previous studies;[7,8] some materials showed an increase in bond strength after 5000 thermocycles by peel test[7] and tensile test.[8] Increased bond strength was probably a result of further polymerization in a hot water bath during thermocycling. Cyclic thermal stress provokes shear stress at the bonding interface between the autopolymerizing resin and denture base material. The thermal expansion coefficients for Co–Cr alloy, denture base acrylic, and silicone materials are $14 \times 10^{-6}$, $70 \times 10^{-6}$, and $150 \times 10^{-6}$, respectively.[30] These differences cause repetitive shrinkage and expansion alternately, and result in a difference of thermal volumetric change between both materials.

The thermocycling also relates to the thermal conductivities and thermal diffusivities of each material. The thermal conductivities of denture base acrylic (0.37) and silicone material (0.72) are much lower than that of chromium (160).[30]

Although the specimen size employed in this study was smaller than those used in previous studies,[8,11-13,17] dwell time at each temperature during thermocycling might not have been long enough to cause temperature change in denture-bonded specimens. Therefore, denture-bonded groups must have required a higher thermocycling number to provoke the degradation of bonding, compared to metal-bonded groups. During thermocycling, the soft denture liner absorbs a certain amount of water.[3] This water absorption may also lead to a considerable amount of dimensional change and result in shear stress at the bonding interface. Furthermore, hydrolytic degradation of the bond occurs when water diffuses into the bonding interface and contacts the adhesive primers, as well as the interfacial degradation caused by the long-term immersion in distilled water.[2,5,6,9,12,17,18] For the metal-bonded specimens, water absorption occurred only in the soft denture liner, but not in Co–Cr alloy specimens. This may have resulted in a greater difference of volumetric change as metal-bonded specimens may have been more affected by thermocycling. As a result, adhesive failure occurred concentrically from the boundary of the adhesive area, and the bonding areas were reduced with the increment of thermocycle numbers.

As lined dentures are exposed to repetitive mechanical stresses during mastication, the current study evaluated the bonding of a soft denture liner after cyclic loading tests. Cyclic loading was applied using the University of Alabama-type wear-test apparatus as a stress generator. The soft denture liner is compressed by a vertical load, and some circumferential shear stress is generated at the bonding interface between the soft denture liner and denture base resin. Furthermore, concentric shear stress may be provoked at the bonding interface by the rotating action. Some thermocycled specimens showed mixed failure consisting of adhesive failure at the boundary of the bonding area and cohesive failure at the inner area (Fig 3); however, cyclic-loaded specimens of groups D/P1R, D/P2, and M/P1M consistently showed cohesive failure of the soft denture liner (Fig 5). SEM observation showed that the soft denture liner might have been concentrically torn off from the periphery by rotating action during cyclic loading, and that the remaining central area was broken during tensile testing. The concentrically torn region of soft denture liner might have expanded during cyclic loading, and resulted in the lower residual tensile resistance to failure. Although the rotation was consistently 15° during cyclic loading, the actual rotating distance results in more intensive shear stress as the diameter of the specimen increases.

Exposure of soft denture liner in an oral environment can affect mechanical properties such as hardness, tensile strength, elongation, and tear resistance. Changes in mechanical properties varied with material type;[2,5-9,17-21] however, autopolymerizing soft denture liner decreased in tensile strength after long-term water storage[21] and increased in hardness after accelerated weather testing.[9] Similar changes might have been provoked in the soft denture liner during cyclic loading. This phenomenon indicates that the adhesive strength between soft denture liner and denture base material is higher than the cohesive strength of soft denture liner.

As silicone soft denture liners have little or no chemical adhesion to denture base materials,[1,4,19] proprietary primers are supplied to achieve the bonding of soft denture liner to denture base materials. The chemical components of both the resin and the metal primers have not been published. It is speculated that adhesive primers may consist of an organic solvent and adhesive monomer, which react with silicone and denture base materials. For resin primers, the differences in organic solvents may affect the infiltration of the adhesive monomer into the denture base resin, and the differences in adhesive monomers may affect the reactivity of the added soft liner. Although Sofreliner Primer worked better for bonding of Sofreliner after thermocycling up to 133,300 cyclic loads, it may not work well for the bonding of other soft lining materials. As the metal primer used was not the proprietary primer for the soft liner tested, the reactivity of the adhesive monomer included in the metal primer might not have been sufficient for the soft denture liner tested.

The MA/P2 specimens showed cohesive and adhesive failure after 133,300 cyclic loads. In adhesive failure, the failure occurred between soft denture liner and adhesive resin. Although adhesive resin coating (group MA/P2) was effective up to 5000 thermocycles compared to the metal primer (group M/P1M), it was not effective at resisting cyclic loading. The adhesive resin used for group MA/P2 is a methyl methacrylate (MMA)-based material; it can be categorized as an autopolymerizing resin.[31] Therefore, the adhesive resin layer may contain residual monomer,[32] which may have inhibited the polymerization of the soft denture liner and accelerated the debonding of the soft denture liner. Therefore, adhesion between the soft denture liner and adhesive resin received intensive damage during cyclic loading and might have resulted in adhesive failure as well as cohesive failure of the soft denture liner.

Maximal bite forces of complete denture wearers have been reported with values of approximately 80 N,[33] 100 N,[34] 150 N,[35,36] and 250 N.[37] Furthermore, approximately 300 N from

**Table 4** Failure modes of Co–Cr alloy-bonded specimens

| | Fatigue process | Simulated intraoral periods (years) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 0.5 | 1 | 2 | 3 |
| | Thermocycling (cycles) | 0 | 5000 | 10,000 | 20,000 | 30,000 |
| Specimen | Cyclic loading (times) | 0 | 66,700 | 133,300 | 266,700 | 400,000 |
| Reline Primer (for metal) (M/P1M/RL) | Thermocycling | C | C | C | C/$A_1$ | C/$A_1$ |
| | Cyclic loading | | C | C | C | C |
| Adhesive resin coating (MA/P2/RL) | Thermocycling | C | C | C | $A_2$ | $A_2$ |
| | Cyclic loading | | C | C/$A_3$ | C/$A_3$ | C/$A_3$ |

C = cohesive failure of soft denture liner; $A_1$ = adhesive failure at soft denture liner-metal denture base interface; $A_2$ = adhesive failure at adhesive resin-metal denture base interface; $A_3$ = adhesive failure at soft denture liner-adhesive resin interface; C/$A_x$ = cohesive and adhesive failure.

removable partial denture wearers without occlusal support between opposing premolars or molars, and 420 N from partial denture wearers with occlusal support have also been mentioned.[37] It is quite difficult to determine the value of loads that are supported with unit area of denture base. As the value of 75 N for cyclic loading used in this study is a specified value representing the bite force of normal dentition, this value must be the upper limit for repetitive mechanical stressing.

The hypothesis was partially accepted, as the residual tensile resistance to failure of groups primed with Sofreliner Primer was higher compared to those primed with Reline Primer up to 133,300 cyclic loads; however, the residual tensile resistance to failure remarkably decreased after 66,700 cyclic loads for all groups. Therefore, it was clarified that cyclic loading with shear stress at the bonding interface was one of the factors which provoked the degradation of the bonding interface between the soft denture liner and denture base materials. Furthermore, clinical degradation of lined dentures may be accelerated by the interaction of both cyclic thermal stressing and repetitive mechanical stressing. Therefore, the new cyclic loading method and/or apparatus should be developed to evaluate bonding under conditions more closely approximated to clinical situations.

## Conclusions

The following conclusions were drawn within the limitations of this in vitro study:

1. For denture-bonded groups, application of Sofreliner Primer to the adhesive surface provided better bonding after thermocycling. It was also effective in improving the bonding for up to 133,300 cyclic loads ($p < 0.0001$).
2. For Co–Cr alloy-bonded groups, the intermediate adhesive resin layer improved the bonding up to 5000 thermocycles ($p < 0.0001$); however, it was not effective against cyclic loading.
3. Cyclic loading and cyclic thermal stressing are important factors that affect the bonding between soft denture liner and denture base materials.
4. For all specimen groups, residual tensile resistance to failure significantly decreased after 66,700 (simulated 0.5-year intraoral period) cyclic loads ($p < 0.0001$).
5. Denture-bonded groups (groups D/P1R and D/P2) and metal primer-applied group (group M/P1M) consistently showed cohesive failure of soft denture liner after cyclic loading.

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