Effect of toothbrush/dentifrice abrasion on weight variation, surface roughness, surface morphology and hardness of conventional and CAD/CAM denture base materials

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We evaluated the effect of toothbrush/dentifrice brushing on the weight variation and surface properties of different denture bases. Four denture base materials (conventional heat cure, high impact, CAD/CAM, and polyamide resins) were subjected to toothbrushing abrasion (50,000 strokes). The weight value, surface roughness, and topography of each group were determined before and after toothbrushing. The hardness was measured by the Vickers hardness test. Data were analyzed using ANOVA and Bonferroni tests. After toothbrushing, the weight of the polyamide resin had significantly increased; significant weight losses were observed for conventional heat cure and high impact resins, but none for the CAD/CAM resin. The surface roughness of each group increased significantly owing to the wear caused by toothbrushing. The weight variation and surface roughness were not affected by the hardness. Our results suggested that denture base materials deteriorate after brushing with toothpaste, in which the polyamide resin exhibited lower levels of abrasion.

Keywords: Denture bases, Denture cleansers, Dentifrices, Hardness, Wear

INTRODUCTION

Since 1936, polymethylmethacrylate (PMMA) resin has been widely used as a repair material in dental prosthesis owing to its desirable properties, namely excellent aesthetics, low water sorption and solubility, relative lack of toxicity, repair capabilities, and simple processing techniques1-3). According to the ISO 1567 standard4), denture-base polymers can be classified as heat-polymerizable polymers, auto-polymerizable polymers, thermoplastic blanks, light-activated materials, and microwave cured materials. Recently, the processes for fabricating complete dentures have progressed from conventional methods (compression and injection-molding techniques) to computer-aided design and computer-aided manufacturing (CAD/CAM) and 3D printing. Although there are also more options for the processing of denture resin, there have been no major changes in terms of materials selection.

Denture cleaning is important in order to avoid poor oral mucosal health and extend the durability of partial removable dentures. Without the removal of bacterial and fungal colonization on dentures, biofilm is easily formed. Biofilm accumulation not only causes oral diseases, such as denture stomatitis, periodontitis, and caries, but also systemic diseases such as pleural infection, aspiration pneumonia, and gastrointestinal infection5). In order to maintain the hygiene of removable prostheses, various chemical and mechanical methods have been proposed. The most commonly used denture cleaning methods can be categorized into mechanical and chemical, physical, and associated methods6-8). Denture chemical cleaning involves generating a chemical reaction to kill bacteria using a cleaning agent. Some peroxide-type denture cleansers contain an effervescent composition such as sodium perborate or sodium bicarbonate. These denture cleansers may cause hydrolysis and the decomposition of the polymerized acrylic resin itself and result in bleaching, discoloration of the resin, and loss of aesthetics9). In addition, the surface roughness of PMMA dentures increase significantly due to the active oxygen released by the solution containing hydrogen peroxide10). The surface hardness significantly decreases due to oxidation and conversion from large molecules to small molecules by free radicals10). Thus, chemical denture cleansers should be carefully selected to avoid adverse effects on denture materials. Furthermore, the residues in the denture base are also difficult to remove using this approach2).

On the other hand, mechanical cleaning involves the use of tools or other media to generate forces for cleaning; the most common method of mechanical cleaning is brushing11). Mechanical cleaning also has some disadvantages. If the wrong toothpaste or cleaning products are used, the bristles of the brush and the abrasive particles of toothpaste jointly cause sliding and rolling wear. Thus, the surface of the denture resin can be damaged due to its low hardness and its roughness...
may be increased; in addition, a mass loss may occur\(^6\). Furthermore, Žilinskas et al.\(^12\) investigated the reflection of a heat-polymerized acrylic resin after brushing it with table salt, baking soda, and toothpaste. No significant differences were found between these three methods; all the methods caused material deterioration in the denture base, which reduced the resulting reflection. Therefore, when using mechanical cleaning of dentures, attention should be paid to the media used and the negative effects on the denture surface.

Denture base materials should possess sufficient physical properties, such as hardness, for patient satisfaction. Thus, it can resist forces such as forces due to occlusion and mechanical cleansing, increasing the longevity of the patient’s prostheses.\(^9\) The hardness of the resin is not only determined by the main material but also the polymerization method.\(^14,15\) Measurement of hardness may indicate the possibility of fracture and the longevity of the denture base.\(^10\).

Many methods can be employed to clean the denture base, but none can be considered the most appropriate method. Dental health care professionals’ (DHCPs) usually make recommendations to patients regarding denture cleaning. Axe et al.\(^11\) stated that denture cleansing tablets are more commonly recommended by DHCPs in developed countries, whereas regular toothpastes are mostly recommended in developing countries. However, consumers reported that they mostly used regular toothpastes for denture cleaning irrespective of DHCP’s recommendations. Thus, it is important to understand the effects of surface changes in the denture base after using toothpaste in a clinical setting under daily-use conditions.

Although numerous studies have been carried out to evaluate the effect of denture cleanser on the denture base materials, yet only a few studies have evaluated the newer denture bases such as CAD/CAM products. Some studies have reported the properties of CAD/CAM denture bases such as stainability,\(^16\) bacteria adhesive evaluation,\(^17\) mechanical property,\(^18,19\) monomer released,\(^20\) and accuracy.\(^21\) However, the effect of denture cleanser on the CAD/CAM denture base is still unconfirmed. Therefore, the purpose of this study is to investigate the hardness of denture bases using CAD/CAM and conventional methods. Further, the weight variation and surface properties were measured after simulated toothbrushing.

**MATERIALS AND METHODS**

**Sample preparation**

Four denture base materials were used in this study: Triplex Cold Polymer (TCP), Palapress\(^8\) vario (PV), ThermoSens (TS), and IvoBase CAD (IBC), as listed in Table 1. Each material was polymerized according to the procedures recommended by the corresponding manufacturers. We evaluated five specimens of each denture base material, for a total of 20 specimens. The specimens were prepared using a mold with dimensions of 25×25×2.5 mm. The surface of each specimen was sanded sequentially using 600-grit, 1000-grit, and 1500-grit silicon carbide paper. After sanding, the surfaces were polished with 0.3-µm Al\(_2\)O\(_3\) powder for 120 s. The specimens were ground and polished to ensure uniform roughness for all specimens before simulated toothbrushing. Subsequently, the specimens were subjected to ultrasonic cleaning and were then immersed in a water bath at 37 ºC for 48 min.\(^22\) To observe the size of toothpaste granules, they were obtained from the precipitate of three rounds of centrifugation with a uniform mixture of toothpaste (3 g) and water (30 mL), in which the precipitate was resuspended with 30 mL of water in each round of centrifugation and was then dried in an oven at 65 ºC.

**Brushing simulation**

A toothbrush (H6-A healthy super-soft toothbrush, Healthy\(^8\), Taiwan) was fixed in the toothbrush holder of a testing device (PAT-2012, PROYES testing equipment, Taichung, Taiwan) and moved back and forth over the specimen at 120 strokes per minute and at a displacement of 35 mm. The toothbrush bristles are made of DuPont nylon, and the dimensions of the toothbrush head are 10.0×21.2 mm (width×length). The number of tufts and their distribution in the H6-A toothbrush are 10 tufts and 3 rows. The toothpaste used in this study was Colgate TOTAL\(^8\) Professional Cleansing Toothpaste (Colgate-Palmolive, USA). In this study, we used a

<table>
<thead>
<tr>
<th>Materials</th>
<th>Groups</th>
<th>Manufacturer</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triplex Cold Polymer</td>
<td>TCP</td>
<td>Ivoclar Vivadent, Schaan, Liechtenstein</td>
<td>Powder-Polymethyl methacrylate, catalyst and pigments Liquid- Methyl methacrylate stab., dimeth-acrylate, catalyst and stabilizer</td>
</tr>
<tr>
<td>Palapress(^8) vario</td>
<td>PV</td>
<td>Heraeus Kulzer, Hanau, Germany</td>
<td>Powder-Methylmethacrylate-Copolymer Liquid-Methylmethacrylate and dimeth-acrylate.</td>
</tr>
<tr>
<td>ThermoSens</td>
<td>NY</td>
<td>Vertex-Dental, Headquarters, The Netherlands</td>
<td>The product is based on a compounded mixture of Polyamide and pigments.</td>
</tr>
<tr>
<td>IvoBase CAD</td>
<td>IBC</td>
<td>Ivoclar Vivadent</td>
<td>&gt;90% polymethylmethacrylate</td>
</tr>
</tbody>
</table>
toothpaste and water mixture at a 1:2 weight percentage ratio. Manual brushing was simulated to investigate its effects on different materials. The testing device provides a 200-g vertical load for toothbrushing on each specimen during horizontal movements throughout the tests. The specimens were brushed with a total of 50,000 reciprocal strokes which was considered to simulate denture cleaning for approximately 5 years. The toothbrush and slurry were renewed before testing each specimen. After testing, the specimens were removed from the testing device, rinsed with tap water, cleaned, and gently air-dried.

Weight variation measurements
Each specimen was subjected to ultrasonic cleaning with pure water for 10 min twice before the measurements, and their surfaces were dried with warm air. The weight values of each specimen were measured using a precision balance (Rodwag, AS 220/C/1, Poland) before and after brushing. The weight value of each specimen was only recorded after no changes were observed over five consecutive readings because PMMA absorbs moisture when it comes into contact with water in its immediate environment.

Surface roughness measurements
We used a surface roughness tester (Surftest SJ-410, Mitutoyo, Japan) to measure the surface texture before and after brushing. Each specimen was first placed on a granite platform and then probed with the diamond stylus of the device within the allowed limits of the instrument at a measuring speed of 0.1 mm/s to measure 10 mm. The average of the readings from three different positions in a direction perpendicular to the brushing direction was obtained. This 10 mm measurement is horizontally centered on the specimens and the positions are located at 1/4, 1/2, and 3/4 of the specimens as shown in Fig. 1. Each position was measured three times and the surface roughness of each specimen was based on the average of 9 measurements.

Hardness tests
A hardness test was conducted using a digital micro-hardness tester (Akashi, MVK-H1, India) to investigate the differences in the surface hardness of dentures polymerized using different methods. The Vickers hardness test involves the use of a pyramidal diamond indenter to indent the test material with a load of 50 g. Three specimens from each group were used, and five random positions were picked for measurement. Then, the hardness value was calculated after removing the load as the average of the two diagonals of the indentation. The denture base materials used for the measurement were prepared on the same day of the experiments.

Surface observations
The surface of each specimen was observed before and after 50,000 strokes of brushing. Before the observation, the surfaces were subjected to 10 min of ultrasonic cleaning twice and then blown dry with warm air. All the processed samples were gold-plated (Hitachie-1010, Tokyo, Japan) with a conductive layer. The surfaces were examined using a scanning electron microscope (SEM, JEOL, JSM-6380, Tokyo, Japan) at a voltage of 15 kV.

Statistical analyses
A power analysis was performed to determine the number of specimens needed in different materials. In this study, the minimum number of specimens for each material was determined as \( n = 5 \) in each group at a power of 0.95 and an error probability, \( \alpha \) of 0.05. The mean weight and roughness before and after brushing were analyzed using two-way repeated measures, ANOVA followed by Bonferroni comparison tests. A one-way ANOVA was used to determine the intergroup comparisons of the surface hardness. In this study, SPSS (Version 20, IBM, New York, USA) software was used for statistical analysis and a significance level of 0.05 was used for statistical testing.

RESULTS
Two-way repeated measures ANOVA results (Tables 2 and 3) illustrate that the weight and surface roughness values varied significantly, depending on the denture material used (\( p<0.001 \)) and brushing (\( p<0.001 \)). There were significant interactions between the materials and brushing, indicating that the effects of these two factors were dependent on each other. The mean weight and surface roughness of the denture bases before and after brushing are presented in Table 4. It can be observed that the weight values of both TCP and PV specimens decreased significantly after 50,000 strokes of brushing (both \( p<0.001 \)), whereas those of TS specimens increased significantly (\( p<0.001 \)). The surface roughness of all denture base materials increased significantly after toothbrushing (all \( p<0.05 \)). After multiple comparisons, we determined that the weight values of TCP specimens did not differ significantly from those of PV and IBC specimens (\( p=1.000 \) for both), whereas...
Table 2  Two-way repeated-measures ANOVA results for weight

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean squares</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>2,482,146.062</td>
<td>3</td>
<td>827,382.021</td>
<td>21.668</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Brushing</td>
<td>1,365.860</td>
<td>1</td>
<td>1,365.860</td>
<td>577.649</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Material × Brushing</td>
<td>1,878.496</td>
<td>3</td>
<td>626.165</td>
<td>264.818</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Error (within subjects)</td>
<td>37.832</td>
<td>16</td>
<td>2.365</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Error (between subjects)</td>
<td>610,949.999</td>
<td>16</td>
<td>38,184.375</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 3  Two-way repeated-measures ANOVA for surface roughness

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>728,341</td>
<td>3</td>
<td>242,780</td>
<td>6,698.200</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Brushing</td>
<td>1,377,603</td>
<td>1</td>
<td>1,377,603</td>
<td>6,649.786</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Material × Brushing</td>
<td>727,962</td>
<td>3</td>
<td>242,654</td>
<td>1,171.308</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Error (within subjects)</td>
<td>3.315</td>
<td>16</td>
<td>0.207</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Error (between subjects)</td>
<td>3.318</td>
<td>16</td>
<td>0.207</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 4  Mean weight values and surface roughness for each denture base material before and after 50,000 strokes of toothbrushing

<table>
<thead>
<tr>
<th>Materials</th>
<th>Weight value (Mean±SD) (mg)</th>
<th>Surface roughness (Mean±SD) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Final</td>
</tr>
<tr>
<td>TCP</td>
<td>2,525.8±129.9aA</td>
<td>2,501.8±130.4aA</td>
</tr>
<tr>
<td>PV</td>
<td>2,549.4±178.1aA</td>
<td>2,523.4±179.2bA</td>
</tr>
<tr>
<td>TS</td>
<td>1,924.5±413.5bB</td>
<td>1,930.7±40.7bB</td>
</tr>
<tr>
<td>IBC</td>
<td>2,442.7±160.4aA</td>
<td>2,439.7±161.0aA</td>
</tr>
</tbody>
</table>

Lower case letters - analysis between columns (initial×final, p<0.05).
Upper case letters - analysis between rows (group comparison, p<0.05).

Fig. 2  Morphology of abrasive particle: 5–25 µm size.

Fig. 3  SEM images of the specimen surface.
(a) TCP, (b) PV, (c) TS, (d) IBC. Yellow arrow: micropores.
significant differences were found for the weight values of TS specimens ($p<0.001$) compared with the other three materials. In addition, we performed multiple comparisons of the surface roughness values and found significant differences in the changes in the roughness for almost all the materials ($p<0.001$ for each). However, no significant difference was found between TCP specimens and PV specimens ($p=1.000$).

Figure 2 shows that the dentifrice in the toothpaste exhibited an uneven particle size distribution (5–25 µm) and a rough surface. Figure 3 shows the surfaces of four denture base materials after polishing with Al$_2$O$_3$ powder. It can be observed that the TCP, PV, and TS specimens exhibited a smooth surface, as shown in Figs. 3(a), (b), and (c). In addition, small scratches can be observed on the surface due to polishing. The surface of the IBC specimens had many micropores (yellow arrows) with a size of 5–15 µm, as shown in Fig. 3(d). TCP and PV specimens exhibited similar changes in surface texture after brushing with 50,000 strokes with slurry and had a series of channel-like grooves running parallel to the brushing direction as shown in Figs. 4(a) and (b). Lots of surface scratches could still be found on TS specimens, but they had a relatively smooth surface (Fig. 4(c)). In addition, the micropores of the IBC surface was enlarged and exhibited irregular surface damage, as shown in Fig. 4(d).

The results of the hardness tests are shown in Fig. 5. TCP and IBC specimens exhibited higher hardness values (14.99 Hv and 14.41 Hv), which are significantly higher than that of PV specimens (12.62 Hv). The TS specimens (9.11 Hv) exhibited the lowest hardness, which is significantly lower than those of the other three materials.

**DISCUSSION**

Denture wearers often use a toothbrush with toothpaste for cleaning, which can have many negative effects on denture materials. Many studies have been carried out using conventional and specific pastes as well as toothbrush abrasion devices. However, toothbrushing abrasion is affected by various factors, such as toothbrushing load, number of strokes, type of dentifrice, and type of toothbrush. In addition, the abrasion testing device used in the simulations can also affect toothbrushing abrasion. In this study, a to-and-fro direction was used to simulate tooth brushing in real life as this is similar to the brushing action performed by humans. In previous studies, the number of brushing motions of toothbrushes on the base of the denture was estimated. The results indicate that 20,000 strokes would be equivalent to approximately 2 years of cleaning, and it was estimated that a denture worn for 5 years would endure 50,000 strokes. The premise for obtaining these values is that patients brush their dentures twice a day. However, the actual values are probably higher for some patients who clean their dentures frequently. In this study, the effects of toothbrush/dentifrice abrasion were evaluated for four different denture base materials using conventional and CAD/CAM methods. In order to investigate the wear resistance of these materials, weight variation, surface roughness and hardness as well as SEM observations were carried out.

After polishing with Al$_2$O$_3$ particles, the SEM images obtained showed that TCP, PV, and TS specimens had relatively smooth surfaces without scratches as shown in Figs. 3(a), (b), (c). However, some micropores were observed on the IBC specimens after polishing (Fig. 3(d)). These small micropores were enlarged owing to continued abrasion caused by Al$_2$O$_3$ particles, and they may become areas where bacteria accumulate. Nevertheless, the roughness of each set of materials after polishing was less than 0.2 µm, indicating that they all have good polishing capability for use in oral
environments and reduce biofilm accumulation\textsuperscript{27}. After 50,000 strokes of simulated brushing with toothpaste, the TCP and PV specimens that were subjected to toothpaste abrasion exhibited similar abrasive wear patterns in the brushing direction as shown in Fig. 4.

The results of the weight variation and surface roughness tests revealed a correlation between the denture materials and brushing ($p<0.001$ and $p=0.001$), suggesting that the differences between different denture materials become more apparent with brushing. The relatively high number of residual monomers in auto-polymerizable TCP causes its internal structure to be relatively more fragile compared with other materials. The surface of TCP is thus more susceptible to damage. However, the auto-polymerizable TCP and heat-polymerizable PV specimens did not exhibit significant differences ($p=1.000$) in terms of weight variation or roughness in this study. The selected toothpaste causes the same degree of damage to both materials. A possible explanation is that TCP and PV exhibit similar linear polymer chain structures that improve the durability of the material\textsuperscript{28}.

Among the three PMMA materials, the roughness value of IBC specimens was significantly lower than those of TCP and PV specimens in a post-hoc comparison ($p<0.001$). This shows that even for the same denture base material, different processes still result in different wear characteristics. The CAD/CAM milled IBC can achieve a homogeneous condition due to the industrial manufacturing process. Having fewer defects can effectively prevent the damage caused by abrasive particles on the surface of the denture base, and the CAD/CAM milled process also achieves a relatively high flexural strength\textsuperscript{10}. In the post-weight comparison, TS was determined to be significantly different from the other three materials. The main reason is that TCP, PV, and IBC all exhibited weight loss characteristics. However, TS specimens exhibited positive changes (increase) in weight after brushing abrasion. This occurred because TS is a polyamide that has special properties, such as the ability to easily absorb water, relatively high elasticity, and wear resistance\textsuperscript{29,30}. However, the action of the toothbrush and the abrasive particles still caused the surface roughness of TS specimens to increase from 0.014 µm to 1.95 µm, which in turn increased the exposed surface area and caused the material to continuously absorb water.

Kyoizumi et al\textsuperscript{31} reported that the hardness of the toothbrush bristles, tuft density, and tuft material had minimal impact on the surface roughness of denture resins and that changes in the overall roughness depend on the denture material used. Therefore, the polymerization methods used and the materials’ compositions are factors that can potentially affect the artificial ageing of denture bases. According to the results of the hardness tests conducted in this study, PMMA (TCP, PV, and IBC) materials have roughly similar hardness. Out of these materials, PV and TCP specimens exhibited differences in hardness (Fig. 5) primarily because the hardness of auto-polymerizable resin surfaces generally exhibits a relative increase after 7 days owing to continued polymerization of the resin\textsuperscript{29}. Thus, TCP specimens exhibited the highest surface mean hardness (14.99 Hv). Although the hardness of polyamide (TS) is lower than those of the other three materials, it exhibited weight gain and the lowest increase in roughness owing to its anti-wear properties. Hence, resin hardness was not associated with the observed abrasion tendencies.

Ozyilmaz and Akin\textsuperscript{10} observed that the roughness of the denture base material significantly increased after using four different effervescent denture cleansers for a long time (140 days) compared with using distilled water. Žilinskas et al\textsuperscript{12} evaluated the reflection of denture base materials according to different cleaning methods and found that both mechanical and chemical cleaning methods significantly reduce the surface reflection of denture base materials. In this study, the surface roughness was measured and was used to evaluate the wear resistance of each material. The detector moved across the brushed groove perpendicularly to the direction of toothbrushing movements. Furthermore, if the roughness was measured only on the brushed area, it is possible to obtain a relatively high roughness value comparable with values obtained by other researchers\textsuperscript{6,22,28}. Although chemical and mechanical cleaning methods have yielded significant sterilizing effect on denture bases\textsuperscript{33}, they also produce some negative impacts. Out of these negative impacts, the surface roughness of the material has been mostly investigated because a higher roughness causes adherence and maturation of bacterial biofilm as well as the accompanying diseases\textsuperscript{30}. Therefore, it is important to select suitable denture materials and denture cleanser to ensure a good denture.

This study also has some limitations. The results of \textit{in vitro} studies are generally not consistent with clinical situations. The artificial ageing of denture materials is affected by the temperature and saliva in oral environments. Thermo-cycling was not used in this study to imitate natural temperature changes. Moreover, it is difficult to use testing devices to perfectly simulate the complexities of the manual brushing of dentures with a toothbrush. In the present study, there was no control group. The wear resistance of four different materials was evaluated using toothpaste by obtaining the change in weight variation and surface roughness. The surface roughness values were recorded for each sample; however, these results cannot be used to characterize acrylic surfaces in real situations. Therefore, future studies should be conducted on the ageing processes of different denture materials to determine the differences in their wear resistance to tooth brushing. In addition, the effect of various denture cleaners should also be evaluated such as denture cleanser and specific denture pastes.

**CONCLUSIONS**

Within the limitations of this \textit{in vitro} study, it can be
concluded that out of the PMMA-based materials, IBC exhibited lower weight loss and surface roughness than the conventional TCP and PV. In addition, the conventional TS exhibited the best wear resistance out of the four denture base materials owing to its material properties. After toothbrushing, the surface of PMMA denture base shows groove-like wear which is consistent with the direction of brushing. TCP exhibits the highest hardness but no correlation was found between the hardness and wear of the denture base materials. Based on this study, cleaning with toothbrushes and toothpaste is not recommended for any conventional or CAD/CAM denture base materials. Furthermore, the effects of using specific denture pastes on these denture base materials should be evaluated in a future study.

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REFERENCES


