Two-body wear of resin and ceramic denture teeth in comparison to human enamel

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\textbf{ABSTRACT}

\textbf{Objectives.} To evaluate the two-body wear resistance of different artificial denture teeth when opposed to steatite ceramic balls in a dual-axis chewing simulator.

\textbf{Methods.} Artificial denture teeth including the ceramic tooth Bonartic CT\textsuperscript{®}, the composite resin tooth Condyloform II NFC\textsuperscript{®}, the acrylic resin teeth Bonartic TCR\textsuperscript{®}, Orthognath\textsuperscript{®}, Polystar Selection\textsuperscript{®}, SR Orthotyp DCL\textsuperscript{®}, and Vitapan Cuspiform\textsuperscript{®}, and human maxillary premolars were tested in a chewing simulator. Wear resistance was analyzed measuring vertical substance loss and volume loss using profilometry and an optical macroscope after various chewing cycles (49 N, up to 1,200,000 cycles). Data were statistically analyzed using one-way analysis of variance (ANOVA) followed by the Fisher test (LSD) at $p \leq 0.05$.

\textbf{Results.} After 1,200,000 chewing cycles the mean vertical substance loss and volume loss for the composite resin teeth (117 $\mu$m and 0.144 mm$^3$) were significantly lower than for all acrylic resin teeth (149–166 $\mu$m and 0.220–0.292 mm$^3$) ($p \leq 0.05$), but higher than for ceramic teeth (36 $\mu$m and 0.029 mm$^3$) and for enamel (56 $\mu$m and 0.033 mm$^3$) ($p \leq 0.05$). No significant differences were found among the acrylic resin teeth for both parameters ($p > 0.05$).

\textbf{Significance.} The composite resin showed improved in vitro two-body wear resistance compared to modern acrylic resin denture teeth; however, it showed less wear resistance than ceramic teeth and human enamel. Ceramic teeth should be preferred over natural teeth when occlusal stability is considered a high priority.

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1. Introduction

Wear resistance is one of the most important physical properties of artificial teeth that are used in removable partial or complete dentures. Excessive wear might cause loss of vertical dimension of occlusion, loss of masticatory efficiency, faulty tooth relationship, and fatigue of masticatory muscles [1,2]. Materials used for denture tooth fabrication determine the wear resistance to a great extent [3]. Acrylic resins and ceramics are commonly used for artificial teeth. Ceramic teeth have been considered the most wear resistant [3]. However, due to their brittleness, the mismatch in coefficient of thermal expansion and the high modulus of elasticity, ceramic teeth are more likely to fracture and crack from the denture base than resin teeth [1–3].

Convenient handling, better toughness, and better compatibility with the acrylic denture base give the acrylic resin teeth advantages compared to ceramic teeth [1,3]. Therefore in removable dentures, resin denture teeth are usually used more frequently than ceramic teeth. Recently, several new types of
resin denture teeth have been developed in order to retain the positive characteristics of acrylic resin teeth while improving their wear resistance. These teeth are made of cross-linked acrylics and micro-filled composite resins [4]. Cross-linked acrylic denture teeth have been developed by utilizing various polymer technologies including blend polymer, interpenetrating polymer networks (IPN) [5], and double cross-linking (DCL) to increase the resistance to crazing and wear.

The purpose of this in vitro study was to evaluate the two-body wear resistance (vertical loss and volume loss) of ceramic denture teeth, composite teeth, and five different resin teeth and to compare them with the wear resistance of human enamel in a dual-axis computer controlled chewing simulator. The hypothesis of this study was that there is no difference among these artificial denture teeth and human enamel.

### 2. Materials and methods

#### 2.1. Description of the dual-axis chewing simulator

The wear test was performed in a dual-axis chewing simulator (Willytec, Munich, Germany) [6]. It has eight identical sample chambers and two stepper motors which allow computer-controlled vertical and horizontal movements between two antagonistic specimens in each specimen chamber. The masticatory cycle in this study consisted of three phases: contact with a vertical load of (49 N), horizontal sliding of 0.3 mm, and separating the teeth and their antagonistic material. The masticatory load curve is programmed by the combination of horizontal and vertical movements. The computer unit controls the mechanical motion and the water flow of cold and warm water baths for the thermal cycling of the specimens.

#### 2.2. Materials and teeth preparation

For this study, eight maxillary first premolars from each of seven different denture teeth were prepared (Table 1). In addition, eight maxillary first human premolars were also used in this study as control group, which were stored in 0.1% thymol solution and used within 1 month after extraction. All teeth were embedded in auto-polymerizing acrylic resin (Technovit 4000, Heraeus-Kulzer, Wehrheim, Germany) using custom-made copper holders with a diameter of 15 mm. A custom-made surveyor was used to ensure that the occlusal surface of the buccal cusp was aligned rectangularly to the long axis of the specimen holder. Then, the buccal cusps of each tooth specimen were abraded with 2500 grit abrasive paper and finished with 4000 grit abrasive paper to a depth of 0.5 mm to achieve a flat area of about 2.5 mm × 3 mm for loading during the wear test. The wear test was performed on the flat surface of the buccal cusp (Fig. 1). Steatite ceramic balls (Höchst Ceram Tec, Wunsiedel, Germany) with a diameter of 6 mm were used as antagonistic specimens to simulate enamel abraders.

### 2.3. Wear testing and measurements

The teeth and the steatite ceramic balls were mounted in the chewing simulator and the teeth were loaded with total of 1,200,000 chewing cycles. The parameters of the wear test are listed in Table 2. The effective weight of each antagonistic steatite ball was 5 kg, which corresponds to a loading force of 49 N [7]. After 120,000, 240,000, 480,000, 840,000, and 1,200,000 loading cycles, an impression of each loaded tooth surface was taken using a polyether impression material (Permadyne, 3 M Espe, Seefeld, Germany). Then replicas were made using Styrcast 1266 (Emerson & Cuming National Starch & Chemical, Westerlo, Belgium).

Vertical substance loss of the teeth was measured with a custom-made mechanical profilometer. The profilometer consisted of a stepper-motor and a feeler arm (Typ 1920, Pretec, Bienne, Switzerland) with a stylus (5 mm diameter) at the tip, which was movable in a vertical direction at a resolution of 0.02 μm. The replica was fixed in the profilometer, and then the vertical feeler arm with its stylus was positioned on the
non-abraded portion of the flat area of the buccal cusp of the replica. The replica was moved horizontally by the stepper-motor, while the vertical deflection of the stylus was recorded (contact scanning). The profilometer was connected to an x-y-recorder (X–Y Schreiber L800, Linseis, Selb, Germany), which reproduced the enlarged surface profiles (magnification 20×). This process was repeated three times at a parallel line with a distance of 0.1 mm in the mesio-distal direction from mid-line. The deepest point of the profile represented the vertical substance loss. The wear area was analyzed with an optical macroscope (Makroskop M 420, Heerburg, Switzerland), which was connected to a digital camera (Leica DC 100, Leica Microsystems, Bensheim, Germany). The radius of wear area was directly measured using the software Leica IM 50 (Leica Microsystems) at a magnification of 25×. Since the differences in radius of wear area, measured from buccal-lingual direction and mesio-distal direction, were very small (ranging from 0 to 0.025 mm), it was assumed that the shape of the wear area was round. So volume loss could be mathematically calculated in sufficient approximation as a spherical segment using the following formula for a spherical segment: 
\[ V = \frac{\pi}{6} h (3r^2 + h^2). \]
\( V \) = volume loss in mm³, \( h \) = vertical loss in mm, \( r \) = radius of wear in mm. One-way analysis of variance (ANOVA) was used to analyze the data. Multiple pair-wise comparison of means was performed by the Fisher test (LSD) at \( p \leq 0.05 \).

For qualitative analysis of the abraded contact surfaces the specimens were sputter-coated with gold by an ion-sputter instrument (SCD 030, Balzer Union, Liechtenstein), and evaluated at a magnification of 2000 using a scanning electron microscope (SEM, Philips XL 30 CP, Philips, Germany) operating at 10 kV.

3. Results

The mean vertical substance loss and the mean volume loss of the test groups after the various chewing cycles are shown in Tables 3 and 4. All resin teeth tested showed statistically more wear than human enamel, while the ceramic teeth exhibited less wear than enamel although this difference was not statistically significant. After 120,000 chewing cycles, there was no statistically significant difference in the vertical substance loss and the volume loss between enamel and composite resin teeth \( (p > 0.05) \). Although statistical differences were not completely identical for vertical substance loss and volume loss during the various experimental periods, after 1,200,000 chewing cycles, all the tested resin teeth including the composite

<table>
<thead>
<tr>
<th>Groups</th>
<th>120,000</th>
<th>240,000</th>
<th>480,000</th>
<th>840,000</th>
<th>1,200,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>38 ± 13 B</td>
<td>41 ± 15 B</td>
<td>46 ± 16 A</td>
<td>53 ± 16 A</td>
<td>56 ± 17 A</td>
</tr>
<tr>
<td>P-Bon</td>
<td>16 ± 5 A</td>
<td>20 ± 6 A</td>
<td>28 ± 7 A</td>
<td>31 ± 10 A</td>
<td>36 ± 11 A</td>
</tr>
<tr>
<td>C-NFC</td>
<td>50 ± 14 BC</td>
<td>65 ± 12 C</td>
<td>84 ± 20 B</td>
<td>102 ± 27 B</td>
<td>117 ± 30 B</td>
</tr>
<tr>
<td>R-IPN</td>
<td>68 ± 23 CD</td>
<td>87 ± 26 D</td>
<td>113 ± 25 C</td>
<td>136 ± 21 C</td>
<td>149 ± 26 C</td>
</tr>
<tr>
<td>R-Ort</td>
<td>76 ± 11 CD</td>
<td>96 ± 18 DE</td>
<td>121 ± 18 C</td>
<td>141 ± 23 C</td>
<td>159 ± 23 C</td>
</tr>
<tr>
<td>R-TCR</td>
<td>74 ± 11 CD</td>
<td>89 ± 18 DE</td>
<td>118 ± 19 C</td>
<td>143 ± 26 C</td>
<td>160 ± 32 C</td>
</tr>
<tr>
<td>R-DCL</td>
<td>88 ± 31 E</td>
<td>108 ± 29 E</td>
<td>129 ± 34 C</td>
<td>147 ± 27 C</td>
<td>163 ± 28 C</td>
</tr>
<tr>
<td>R-Vit</td>
<td>62 ± 17 CD</td>
<td>80 ± 23 CD</td>
<td>107 ± 33 C</td>
<td>134 ± 39 C</td>
<td>166 ± 47 C</td>
</tr>
</tbody>
</table>

\( ^a \) Means with the same capital letter within one row are not statistically different at \( p \leq 0.05 \) (Fisher test).
Table 4 – Mean volume loss and standard deviations of the tested teeth after various chewing cycles in mm³ (N=8)*

<table>
<thead>
<tr>
<th>Groups</th>
<th>120,000</th>
<th>240,000</th>
<th>480,000</th>
<th>840,000</th>
<th>1,200,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>0.014 ± 0.01 AB</td>
<td>0.017 ± 0.011 AB</td>
<td>0.022 ± 0.014 A</td>
<td>0.029 ± 0.017 A</td>
<td>0.033 ± 0.019 A</td>
</tr>
<tr>
<td>P-Bon</td>
<td>0.004 ± 0.003 A</td>
<td>0.007 ± 0.004 A</td>
<td>0.013 ± 0.008 A</td>
<td>0.020 ± 0.013 A</td>
<td>0.029 ± 0.015 A</td>
</tr>
<tr>
<td>C-NFC</td>
<td>0.026 ± 0.012 AB</td>
<td>0.042 ± 0.015 BC</td>
<td>0.070 ± 0.034 AB</td>
<td>0.108 ± 0.056 B</td>
<td>0.144 ± 0.069 B</td>
</tr>
<tr>
<td>R-IPN</td>
<td>0.050 ± 0.029 C</td>
<td>0.077 ± 0.041 D</td>
<td>0.120 ± 0.051 B</td>
<td>0.175 ± 0.056 C</td>
<td>0.220 ± 0.073 C</td>
</tr>
<tr>
<td>R-Ort</td>
<td>0.057 ± 0.014 CD</td>
<td>0.092 ± 0.027 DE</td>
<td>0.138 ± 0.037 B</td>
<td>0.191 ± 0.052 C</td>
<td>0.242 ± 0.061 C</td>
</tr>
<tr>
<td>R-TCR</td>
<td>0.066 ± 0.023 CD</td>
<td>0.097 ± 0.035 DE</td>
<td>0.160 ± 0.051 B</td>
<td>0.216 ± 0.078 C</td>
<td>0.273 ± 0.104 C</td>
</tr>
<tr>
<td>R-DCL</td>
<td>0.079 ± 0.048 D</td>
<td>0.119 ± 0.060 E</td>
<td>0.166 ± 0.080 C</td>
<td>0.201 ± 0.075 C</td>
<td>0.249 ± 0.081 C</td>
</tr>
<tr>
<td>R-Vit</td>
<td>0.036 ± 0.017 BC</td>
<td>0.067 ± 0.032 CD</td>
<td>0.121 ± 0.061 B</td>
<td>0.197 ± 0.098 C</td>
<td>0.292 ± 0.136 C</td>
</tr>
</tbody>
</table>

* Means with the same capital letter within one row are not statistically different at p ≤ 0.05 (Fisher test).

Resin teeth had statistically significantly higher vertical substance loss and volume loss than enamel and ceramic teeth (p ≤ 0.05). However, the composite resin teeth showed significantly less vertical substance loss and less volume loss than all acrylic resin teeth (p ≤ 0.05), while no statistical difference was detected among the acrylic resin teeth (p > 0.05).

The SEM observations of the abraded surface of the resin and composite resin teeth after 1,200,000 chewing cycles in the chewing simulator are presented in Fig. 2. The size of the irregular inorganic filler particles in group C-NFC varied greatly but was well distributed in the matrix (Fig. 2A). For group R-IPN, a few PMMA beads were missing from the matrix (Fig. 2B). The teeth exhibited the inclusion of spherical particles, presumably PMMA beads in the matrix. In group R-Vit, the spherical PMMA beads could be clearly identified and were homogeneously distributed in the matrix. Some cracks could be seen on the wear surface between the organic filler agglomerates and the resin matrix. In contrast to composite teeth, the organic fillers and resin matrix were worn to the same extent, but the resin matrix showed micro-cracks.

Fig. 2 – SEM observation of the wear surfaces of the resin teeth. Original magnification ×2000. (A) Composite teeth NFC®; (B) Polystar Selection®; (C) Orthognath®; (D) Bonartic TCR®; (E) SR Orthotyp DCL®; and (F) Vitapan Cuspiform®.
4. Discussion

Wear of tooth hard tissues and restorative materials under clinical conditions is rather a complicated phenomenon in contrast to other mechanical and physical properties of materials [6]. The primary mechanisms are first, attritional wear by welding under pressure of surface asperities and subsequent shearing of such welds to give superficial damage of occlusal contact surfaces; second, abrasive wear by abrasive particles in the food or the wear debris loss from a surface through the mechanical cutting action (rubbing or friction) of a secondary material, which is in relative motion to the first surface, and third, erosion by the mechanical removal of food flow from a surface [6]. The discriminating characteristics controlling the wear rate of materials include the friction coefficient, surface roughness, the elastic modulus, and shear strength of both antagonistic materials [3,8].

One recent study compared 10 different dental restorative materials in five wear simulators with a round robin test [8]. The result showed that among the five wear simulators one wear simulator named as IVOCLAR (vertical loss) was the best with the respect to the coefficient of variation. The variables relating to the same method largely agreed with one another (volumetric and vertical wear). This computer-controlled chewing simulator presented [9] the simultaneous simulation of wear mechanics and temperature change. Therefore, in this study, this kind of two-body chewing simulator was used to compare the wear resistance of several artificial teeth. The teeth were loaded with total of 1,200,000 cycles, which is equivalent to 5 years of clinical service [6]. Thermal cycling was used as artificial aging to obtain an increasing wear effect [10–12].

In this study, the two-body wear approach was used as a consequence of direct contact between the test material and its antagonist, and this can be described as mixed wear of adhesion, attrition and fatigue [3]. Steatite ceramic balls with a diameter of 6 mm were used as the antagonistic material since this ceramic has been reported to be a suitable substitute for enamel in wear tests [13,14]. This ceramic material as antagonist produced a similar wear rate on different composites as enamel antagonists [15]. The chosen diameter of 6 mm is more comparable to the size and shape of a molar cusp [9] than flat specimens used as antagonist materials in other studies [8,16].

In the present study, ceramic denture teeth (group P-Bon) exhibited less wear than enamel although no statistical difference was found between the two groups. This may be explained by the type and hardness of the antagonistic steatite ceramic, which has a similar wear rate as enamel antagonists [13,14]. In addition, ceramic is more sensitive to fatigue wear due to flaws in its structure than to attritional wear due to its crystalline matrix. This result is in agreement with another in vitro study [16] in which ceramic teeth showed more wear resistance than human enamel, while two low-fusing ceramics showed a tribological similarity to dental enamel after glazing [17].

In an effort to retain the positive clinical characteristics of acrylic resin teeth while achieving improved wear resistance, composite and cross-linked acrylic resin denture teeth have been developed. In the current study, there was no statistically significant difference in either vertical substance loss or volume loss between groups enamel and C-NFC after 120,000 chewing cycles (p > 0.05). These results indicate that the initial wear resistance of the composite resin teeth was not statistically different from that of enamel. However, after 1,200,000 cycles, all resin teeth including group C-NFC showed a statistically significantly higher vertical substance loss and volume loss than enamel. In the abrasion mechanism of composite resin materials, the size, shape, volume and hardness of fillers, the bonding between fillers and polymer matrix, and the polymerization dynamics, all have an effect on the wear characteristics [8]. During the wear process of composite resin, inorganic filler particles are exposed after the softer resin matrix is abraded, which causes a high friction coefficient and leads to high internal shear stresses in the polymer matrix. This process corresponds with an increased sensitivity to wear which might have accelerated the wear of composite resin teeth during long-term testing. Therefore, the composite resin teeth showed more wear than enamel after long-term chewing simulation, which is in agreement with the SEM photos after 1,200,000 chewing cycles and also an in vivo study reporting the wear patterns of the filled composite resin after 4.5-year of clinical service [18]. So it might be concluded that the composite resin teeth (group C-NFC) of this study showed a high initial wear resistance. However, long-term wear resistance of the composite teeth still needs improvement to be comparable with that of natural tooth enamel.

Several studies indicated that micro-filled composite teeth possess superior wear resistance compared to conventional acrylic resin teeth with lineal polymer chain structures although data vary depending on study designs [19,20]. The components of the materials influence physical parameters, such as flexural strength, fracture toughness, Vickers hardness, modulus of elasticity, etc., which may influence the wear resistance [3,8]. Recently, various polymer technologies including blend polymer, interpenetrating polymer networks [5], and double cross-linking have been used to improve the mechanical properties of modern acrylic resin teeth. However, the wear resistance of all acrylic resin teeth was still statistically lower than that of the composite resin teeth (group C-NFC).

In this study group R-Ort (conventional polymethyl methacrylate denture teeth) showed vertical substance and volume substance losses, which did not differ from those of other modern acrylic resin teeth after 1,200,000 chewing cycles. The result indicates that denture teeth made of polymers with a high degree of cross-linking (IPN, DCL, TCR) are not consistently more wear-resistant than conventional acrylic resin teeth. It also suggests that no definite relationship exists between the chemical composition and the wear resistance of denture teeth [21,22]. One study that compared five brands of acrylic resin teeth with a toothbrush abrasion machine concluded that modified resin teeth did not show superiority over conventional acrylic resins [23] although several previous studies suggested that modern denture teeth with a high degree of cross-linking and composite resin teeth were more wear-resistant than conventional acrylic teeth [19,24,25]. As a result, the hypothesis that there is no difference among these artificial denture teeth and human enamel has to be rejected.
From the wear results of this in vitro study, when the antagonistic materials are enamel or ceramic, ceramic teeth should be preferred for removable dentures over acrylic resin or composite resin teeth from the viewpoint of wear resistance and the intent to keep the vertical distance of occlusion. However, when the antagonistic materials are modern acrylic resins or composite resins, modern acrylic resin or composite resin teeth might be a good choice for removable dentures, due to the similarity in wear properties. Further studies are needed to evaluate the wear resistance of the resin teeth tested when opposed to the materials of similar wear characteristics.

5. Conclusions

Within the limits of this study, the following conclusions are drawn:

1. Ceramic denture teeth demonstrated a two-body wear similar to human enamel.
2. All acrylic resin and composite resin teeth tested showed statistically higher wear than human enamel. However, the composite resin showed improved wear resistance compared to modern acrylic resin denture teeth.
3. The acrylic resin teeth showed differences in their wear resistance which were not statistically significant.

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