Laboratory methods for evaluating the wear of denture teeth and their correlation with clinical results

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\textbf{A B S T R A C T}

Objective. To correlate different laboratory wear simulation protocols for three denture tooth materials with clinical wear results of the same materials.

Methods. Three denture tooth materials were evaluated for which clinical wear data of posterior denture teeth were available: DCL (double cross-linked PMMA with organic fillers; Ivoclar Vivadent), experimental material EM (double cross-linked PMMA with organic fillers; Ivoclar Vivadent), and NFC (PMMA with inorganic nanofillers, Candulor). The clinical data on the three denture tooth materials (10 subjects for each material) came from clinical studies conducted at three different locations. The investigators sent the impressions to one center where they were analyzed with the same methodology and by the same operator. Four different wear simulation protocols were evaluated in a chewing simulator (Willytec) with integrated thermocycling (5°C/55°C) and 8 specimens for each group: (A) molar denture tooth against premolar denture tooth with 1 mm sliding, lifting, 5 kg load; (B) standardized conical ceramic stylus (Ø2.3 mm); (C) standardized ball-shaped ceramic stylus (Ø6 mm); (D) standardized conical stylus (Ø2.3 mm) cut with a special bur from the denture tooth material to be tested. For the protocols B, C and D, the stylus slid under a load of 3 kg for 3 mm on the flat specimen without lifting. All the tests were run for 100,000 chewing cycles. The maximum vertical wear of the material and stylus was quantified on replicas of improved white stone with the etkon es1 scanner and the match 3D software.

Results. The ranking of the materials according to mean clinical vertical wear after 1 year was as follows: DCL = EM > NFC. The ranking of the materials according to the mean vertical wear was as follows (ANOVA post hoc Tukey B, p < 0.05): group A: NFC > DCL = EM; group B: NFC > DCL > EM; group C: NFC > DCL = EM; group D: DCL = EM > NFC.

Significance. Only the results of the experimental setup with standardized antagonists of the same denture tooth material against flat specimens were similar to the clinical wear results with a comparable relative difference in mean vertical wear between the materials. When evaluating denture teeth for wear in the laboratory, a protocol should be applied that matches the clinical wear results.
1. Introduction

Wear of denture teeth is still regarded as a clinical problem, as excessive wear can be observed clinically after only a short period of time, however, not in all patients [1]. Age and gender are potential risk factors with men showing more wear than women and younger patients more than older ones. There are some peculiarities with regard to patients who wear complete dentures. Edentulous patients show increased wear rates compared to dentate patients, as the receptors of the periodontal ligament, which control the chewing forces, are missing; the occlusal forces are regulated only by the masticatory muscles [2]. Edentulous patients have a higher chewing frequency than dentate patients [3]. In dentate patients, males have higher chewing forces than female patients but such a difference has not been detected in edentulous patients [4].

In recent years, new denture tooth materials have been introduced into the market, which claim to be more wear-resistant. Wear resistance has been primarily investigated in vitro with wear simulators. Different wear devices and methods are available that use different wear simulation concepts. Some methods (Minnesota, Alabama, OHSU, Zurich) are specified by the ISO Technical Specification on two-body and three-body wear [5]. According to the FDA guidelines for laboratory test devices, most of the simulators available are not designed to be effectively used for the purpose mentioned [6]. The methods in question were originally developed to test the suitability of composite resins for the direct restoration of posterior teeth. The different methods follow different wear concepts and approaches and therefore vary widely with regard to the main wear-influencing factors, such as load, abrasive medium, number of cycles, force actuator, shape and material of the stylus. The results cannot be directly compared as was shown by the blind round robin test on different dental materials (composite resins, ceramic, amalgam) examined with 5 different methods (ACTA, Alabama, Ivoclar, Munich, OHSU, Zurich) [7,8]. The variability of the test results varied tremendously between the methods.

The same methods that are used to test resin composites for wear have been used to test denture tooth materials, without analyzing the suitability of the method for denture teeth. Some of these methods use metal [9], ceramic [10–12], denture teeth [13] or human teeth [14,15] as the antagonist material; some use an abrasive medium which can be artificial (e.g. PMMA particles) [16] or natural (e.g. millet or poppy seeds) [17]. Another approach is to assess the wear resistance by subjecting the materials to a toothbrushing device [18] or to carbide abrasive paper [19]. As far as the wear of denture teeth is concerned, the results are contradictory. Furthermore, they do not correlate to clinical data. For instance, the results of the nano-filled composite tooth NFC in some simulations indicate a higher wear resistance compared to a denture tooth material that is based on PMMA [12]. However, the same authors have recently published data that showed a high wear rate of the NFC material in vitro [20].

It would be ideal if each denture material could be evaluated clinically with valid wear-quantifying methods. However, due to the technical difficulty of accurately measuring 3-dimensional (3D) changes, there are few studies that have analyzed the wear of artificial teeth in vivo [1,21–27].

The objective of the present study was to develop a laboratory wear method for denture tooth materials whose results correlate with clinical wear data. For this purpose three different denture tooth materials were selected for which clinical wear data are available. The three materials have different chemical compositions (Table 1). One material (NFC) contains silica fillers, while the other two materials (DCL, EM) contain prepolymer fillers. The clinical wear data derived from clinical studies that were conducted at three centers. Four different experimental methods were applied:

1. Molar tooth against premolar.
2. Flat specimen against standardized conical ceramic stylus.
3. Flat specimen against standardized ball-like ceramic stylus.
4. Flat specimen against standardized conical stylus made of the same denture tooth material.

Two null hypotheses were formulated:

1. There is no significant difference between the three materials with regard to clinical wear.
2. None of the laboratory wear methods will match the clinical results on wear.

2. Materials and methods

2.1. Clinical wear data on denture teeth

For the clinical wear data on denture teeth, cast replicas from clinical trials that investigated the three denture tooth materials NFC, DCL and EM were analyzed. The study with the NFC material was carried out at the University of Innsbruck, Austria, that with the materials DCL and EM at the University of Buffalo, USA. The compositions of the three materials are listed in Table 1. All three denture tooth materials were evaluated with the same study protocol:

- Complete maxillary and mandibular dentures.
- Impression of the posterior teeth with a customized tray and silicone impression material (Virtual heavy and light body, Ivoclar Vivadent) after the denture adaptation phase (baseline) and after 12 months of clinical service.
- Pouring of impressions with improved dental stone (Fuji Super Hard Rock, white, GC Corp., Japan).

| Table 1 – Denture tooth materials and composition. |
|---|---|---|
| Denture tooth | Manufacturer | Composition |
| NFC | Candulor | UDMA, DMA, silanized silica fillers, UDMA/PMMA-prepolymer |
| DCL | Ivoclar Vivadent | PMMA, MMA, DMA, PMMA-prepolymer |
| EM | Ivoclar Vivadent | PMMA, MMA, DMA, PMMA-prepolymer |
- Quantification of wear with an etkon es1 laser scanner (see below).
- Occlusal mapping of the attrition zones of posterior teeth (each first molar and first and second premolar).
- Average of maximum vertical loss of the attrition zones of molars and premolars per subject. Statistical unit is the subject.
- Wear quantification was carried out by the same investigator who applied the same methodology and technique.

The wear data for each subject were averaged out so that the statistical unit was the subject. A detailed description of the wear quantification process is published elsewhere [1].

For each material, 12-month wear data of 10 subjects were available for analysis. For the DCL group, the mean age of the subjects was 69 (±11) years, for the EM group 62 (±12) years and for the NFC group 69 (±8) years. There were 6 male and 4 female subjects in the DCL group and 7 male and 3 female subjects in the other two groups.

2.2. Laboratory wear methods

The three denture tooth materials, for which clinical data after 12 months of service were available, were subjected to different wear simulation approaches. For the simulated wear, a commercially available simulator called Willytec (SD Mechatronik, Feldkirchen-Westerham, Germany) was used. This chewing simulator operates with dead weights that are mounted on bars, which are lowered with a stepper motor. The weight can be varied between 1 and 11 kg. Additionally, a lateral movement, which is also driven by the stepper motor, can be integrated into the wear method. Both the vertical and horizontal axes are computer-controlled. The chewing simulator comprises eight chambers so that eight specimens can be tested at the same time. Simultaneous flooding and evacuation of each chamber with water at different temperatures (thermocycling, 5 °C/55 °C) is available.

2.2.1. Experiment 1: Denture tooth against denture tooth

For this experiment the same tooth shape and size was selected for all three denture tooth materials (Ortholingual, Ivoclar Vivadent). To obtain a more or less standardized sliding path, maxillary denture tooth molars were slid against maxillary premolars, whereby the buccal cusp of the premolar slid 1 mm on the buccal cusp of the molar (Fig. 1). Less favorable sliding paths and tooth contacts would have been produced, if one had opted for a molar/molar occlusion simulation. To obtain a three-point contact in centric occlusion, the denture teeth were fixed in an occludator. The contact points were checked with black articulation foil (Hanel, Germany). The specimens were subjected to the following wear simulation protocol (group A):

- 100,000 chewing cycles, 5 kg weight, 1 mm lateral movement with lifting of the antagonist, simultaneous thermocycling (5 °C/55 °C, 105 s per temperature phase).

2.2.2. Experiment 2: Flat specimen against ceramic antagonist

Flat specimens (n = 8) were cut from the bulk of the denture tooth material and luted into SEM holders. Before the specimens were tested, they were kept dry at a temperature of 37 °C for 24 h. Next, the specimens were polished with 600 grit SiC, 1200 grit SiC and 2500 grit SiC grit by means of a polishing device (Phoenix 4000, Buehler GmbH, Düsseldorf, Germany). The antagonists were made of pressed IPS Empress leucite-reinforced ceramic (Ivoclar Vivadent) with two different geometries (Fig. 2):

- Conical shaped antagonist with a radius of 0.6 mm at a height of 200 μm from the cuspal tip to the base (1.18 mm at a height of 600 μm) (group B).
- Ball-like antagonist with a radius of 6 mm (in relation to the entire sphere) (group C).
To ensure standardization, wax patterns of both stylus shapes were produced by a specialized company (Eichenberger AG, Rheinach, Switzerland).

The antagonists were glazed twice at a temperature of 870°C and luted to aluminum SEM holders with resin cement (Dual Cement, Ivoclar Vivadent). They were polymerized with light for 40 s with an Astralis 5 curing light (650 mW/cm²). They were additionally cured for 10 min in a polymerization device (Spectramat, Ivoclar Vivadent).

The specimens were subjected to the following wear simulation protocol:

- 100,000 chewing cycles, 3 kg weight, 3 mm lateral movement without lifting of the antagonist, simultaneous thermocycling (5°C/55°C, 105 s per temperature phase).

2.2.3. Experiment 3: Flat specimen against antagonist of the same denture tooth material
Flat specimens were prepared in the same way as in the previously described test. The antagonists were drilled out of bulk denture tooth material with a diamond-coated bur (Komet, Germany) to obtain the same shape as that of the conical ceramic antagonists described in the previous section (Fig. 3). For this purpose blocks were prepared in a cylindrical shape. The material was prepared with the antagonist bur with a straight dental handpiece (KaVo, Germany) at slow speed (2000 r/min) and water cooling. After the preparation of the shape, the antagonists were polished with Ivoclar polishing paste (Ivoclar Vivadent) and a polishing wheel.

The specimens were subjected to the following wear simulation protocol:

- 100,000 chewing cycles, 3 kg weight, 3 mm lateral movement without lifting of the antagonist, simultaneous thermocycling (5°C/55°C, 105 sec per temperature phase) (group D) (Fig. 4).

2.3. Quantification of wear
After completing the wear generating procedure, impressions of the material were made using a low viscosity vinyl polysiloxane material (Virtual light, Ivoclar Vivadent). After 4 h, replicas of the impressions were fabricated with white improved dental stone (Type IV, Fuji Superhard Rock, GC Corporation, Japan) using a vacuum, vibrator and two bars of pressure.

The plaster replicas were analyzed by means of a commercially available laser scanning device (etkon es1, Straumann CADCAM, Gräfelfing, Germany) and the appropriate match-3D software. The measuring principle is explained in detail elsewhere [28]. For the quantification of the material loss of the molars and premolars, baseline and follow-up scans were superimposed by referencing the scans and matching the objects with the match-3D procedure until a standard deviation of less than 15 μm was obtained (8000 iterations, minimum 1200 points per matching procedure) (Fig. 5). On the flat specimens, the area around the wear facet was used as the reference for the quantification of material loss. The maximum vertical material (and antagonist loss) (99% quantile) was automatically calculated by the software.

2.4. SEM analysis
From each experiment, two specimens were selected for SEM analysis. The specimens were sputter coated (BAL-TEC
SCD 500, Leica Microsystems, Switzerland) and subsequently analyzed with the SEM VP DSM (Zeiss, Germany). The flat specimens were examined at ×25 and ×90 magnification and the molar and premolar teeth as well as the ceramic antagonists at varying magnifications (×40–×200), according to the region of interest.

2.5. Statistical analysis

As both the in vivo wear and in vitro wear showed not normal distribution, the data were log-transformed to achieve quasi normality. An analysis of variance (ANOVA) with post hoc Tukey B was carried out (p < 0.05) to evaluate whether the wear of a material were significantly different from that of another material. To determine whether gender was equally distributed between the three test groups of the clinical trials, a cross-table was created and assessed with the chi-square test (p < 0.05).

3. Results

3.1. Clinical results

In the clinical studies, the vertical loss of the NFC material was about 35% less than that of the other two materials. According to the ANOVA (p < 0.05), the ranking of the materials was as follows (high wear–low wear): DCL = EM > NFC (Table 2). The coefficient of variation was significantly less for NFC compared to DCL and EM. There was no statistically significant difference between the three clinical test centers with regard to gender and age of the subjects.

3.2. Laboratory test results

When molars were tested against premolars, NFC showed significantly more wear of molars and premolars than DCL and EM (Table 3, group A). However, the vertical loss of all three materials was very similar.

In the vertical wear tests involving flat specimens against the two different ceramic antagonists—NFC showed statistically significantly higher wear rate, independent of the shape of the antagonist (Tables 4 and 5, groups B and C). For the ball-like antagonist there was no difference between DCL and EM (Table 5, group C). However, in the tests with the conical antagonists, DCL showed more vertical wear than EM (Table 4, group B).

When flat specimens were tested against standardized antagonists made of the same material, NFC showed significantly less wear than DCL and EM both with regard to the specimens and the total wear (Table 6, group D). The results for specimen and antagonist wear showed no significant difference between DCL and EM. Compared to the other three

| Table 2 - Mean and median maximum vertical loss (µm) of denture teeth of 10 subjects for each material after 12 months of clinical service. Maximum vertical loss of pooled data from first and second premolars and first molars. |
|---|---|---|---|---|---|---|
| N | Statistics | Median (µm) | Mean (µm) | Standard deviation | CV (%) | Minimum | Maximum |
|---|---|---|---|---|---|---|
| DCL | 10 | b | 180 | 225.9 | 109.4 | 48 | 153.3 | 443.6 |
| EM | 10 | b | 219 | 211.2 | 100.2 | 47 | 78.7 | 411.6 |
| NFC | 10 | a | 140 | 140.2 | 39.9 | 28 | 76.4 | 203.4 |
Table 3 – Mean vertical wear (μm) of three denture tooth materials when molars are opposed to premolars (group A).

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Statistics</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>CV (%)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molar</td>
<td></td>
<td>DCL 8 a</td>
<td>107.4</td>
<td>5.9</td>
<td>5</td>
<td>103.9</td>
<td>116.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EM 8 a</td>
<td>116.6</td>
<td>11.9</td>
<td>10</td>
<td>95.8</td>
<td>133.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NFC 8 b</td>
<td>144.5</td>
<td>24.4</td>
<td>17</td>
<td>101.7</td>
<td>173.5</td>
</tr>
<tr>
<td>Molar + premolar</td>
<td></td>
<td>DCL 8 a</td>
<td>199.0</td>
<td>8.4</td>
<td>4</td>
<td>189.0</td>
<td>207.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EM 8 a</td>
<td>224.4</td>
<td>28.5</td>
<td>13</td>
<td>200.5</td>
<td>333.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NFC 8 b</td>
<td>277.6</td>
<td>42.0</td>
<td>15</td>
<td>191.8</td>
<td>333.2</td>
</tr>
</tbody>
</table>

Table 4 – Mean vertical wear (μm) of three denture tooth materials when flat specimens are opposed to conical ceramic antagonists (group B).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N</th>
<th>Statistics</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>CV (%)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen DCL 8</td>
<td></td>
<td>b</td>
<td>310.3</td>
<td>63.3</td>
<td>20</td>
<td>220.1</td>
<td>405.7</td>
</tr>
<tr>
<td>Specimen EM 8</td>
<td></td>
<td>a</td>
<td>153.8</td>
<td>25.8</td>
<td>17</td>
<td>118.0</td>
<td>196.5</td>
</tr>
<tr>
<td>Specimen NFC 8</td>
<td></td>
<td>c</td>
<td>556.9</td>
<td>42.0</td>
<td>7</td>
<td>494.8</td>
<td>602.8</td>
</tr>
<tr>
<td>Specimen + antagonist</td>
<td></td>
<td>DCL 8 b</td>
<td>336.6</td>
<td>74.2</td>
<td>22</td>
<td>225.8</td>
<td>456.0</td>
</tr>
<tr>
<td>Specimen + antagonist</td>
<td></td>
<td>EM 8 a</td>
<td>167.5</td>
<td>26.9</td>
<td>16</td>
<td>130.6</td>
<td>204.4</td>
</tr>
<tr>
<td>Specimen + antagonist</td>
<td></td>
<td>NFC 8 c</td>
<td>642.1</td>
<td>62.8</td>
<td>10</td>
<td>560.8</td>
<td>734.1</td>
</tr>
</tbody>
</table>

Table 5 – Mean vertical wear (μm) of three denture tooth materials when flat specimens are opposed to ball-like ceramic antagonists (group C).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N</th>
<th>Statistics</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>CV (%)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen DCL 8</td>
<td></td>
<td>a</td>
<td>60.0</td>
<td>8.8</td>
<td>15</td>
<td>49.9</td>
<td>78.6</td>
</tr>
<tr>
<td>Specimen EM 8</td>
<td></td>
<td>a</td>
<td>53.6</td>
<td>6.7</td>
<td>12</td>
<td>46.0</td>
<td>62.6</td>
</tr>
<tr>
<td>Specimen NFC 8</td>
<td></td>
<td>b</td>
<td>200.9</td>
<td>20.1</td>
<td>10</td>
<td>168.3</td>
<td>219.9</td>
</tr>
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<td>Specimen + antagonist</td>
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<td>DCL 8 a</td>
<td>66.6</td>
<td>8.6</td>
<td>13</td>
<td>59.2</td>
<td>85.5</td>
</tr>
<tr>
<td>Specimen + antagonist</td>
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<td>EM 8 a</td>
<td>62.3</td>
<td>5.8</td>
<td>9</td>
<td>53.7</td>
<td>69.6</td>
</tr>
<tr>
<td>Specimen + antagonist</td>
<td></td>
<td>NFC 8 b</td>
<td>231.1</td>
<td>21.4</td>
<td>9</td>
<td>197.7</td>
<td>253.1</td>
</tr>
</tbody>
</table>

Table 6 – Mean vertical wear (μm) of three denture tooth materials when flat specimens are opposed to standardized antagonists of the same material (group D).

<table>
<thead>
<tr>
<th>Specimen (μm)</th>
<th>N</th>
<th>Statistics</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>CV (%)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen DCL 8</td>
<td></td>
<td>c</td>
<td>285.5</td>
<td>63.2</td>
<td>22</td>
<td>215.5</td>
<td>422.0</td>
</tr>
<tr>
<td>Specimen EM 8</td>
<td></td>
<td>b</td>
<td>238.2</td>
<td>33.8</td>
<td>14</td>
<td>197.1</td>
<td>295.6</td>
</tr>
<tr>
<td>Specimen NFC 8</td>
<td></td>
<td>a</td>
<td>142.3</td>
<td>9.5</td>
<td>7</td>
<td>129.1</td>
<td>156.0</td>
</tr>
<tr>
<td>Specimen + antagonist (μm)</td>
<td></td>
<td>DCL 8 b</td>
<td>871.2</td>
<td>144.8</td>
<td>17</td>
<td>746.0</td>
<td>1193.6</td>
</tr>
<tr>
<td>Specimen + antagonist (μm)</td>
<td></td>
<td>EM 8 b</td>
<td>818.2</td>
<td>110.1</td>
<td>13</td>
<td>701.0</td>
<td>972.1</td>
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<tr>
<td>Specimen + antagonist (μm)</td>
<td></td>
<td>NFC 8 a</td>
<td>562.2</td>
<td>43.7</td>
<td>8</td>
<td>495.9</td>
<td>648.7</td>
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</tbody>
</table>

Experiments, the total wear was the highest for all three materials. The coefficient of variation of the group with the NFC specimens was lower compared to the other two materials. The same was observed for the clinical wear.

In a comparison of the laboratory wear results with those from the clinical studies, only the results of the third experiment (group D) reflected the clinical wear results. Interestingly enough, the relative difference in mean vertical wear between NFC and the other two materials was in the same range as that of the clinical results (between 30 and 35%).

3.3. SEM analysis

Figs. 6–8 show SEM pictures of each of the three materials and of each of the four experiments (Figs. a–d). The pictures are grouped according to the three materials.

For the specimens of group A, the wear facets of the EM material showed more grooves than those of the NFC material. This may have been caused by the homogeneity of the filler/matrix combination. The EM material is only filled with organic UDMA prepolymer whose physical properties differ very much from those of the PMMA matrix. During polishing, the prepolymer appeared more resistant and did not wear in the same way as the matrix and as a result, the fillers got exposed. The NFC material, however, is composed of different fillers whose surface texture behaved very homogenously during loading. During polishing the surface was more or less smooth. It is worth mentioning that for the NFC material, the premolar showed some distortion of the material at the margin of the wear facet (Fig. 8b).

The specimens of group B showed more wear and more grooves in the material than those of group A. During the initial loading phase with the sharp ceramic antagonist, the material surface was exposed to high forces and shear stresses. During the lateral movement, the hard inorganic filler particles were pressed out of the matrix. They roughened the antagonist, which accelerated the wear loss of the denture tooth material. In the homogenous material
DCL, the fillers were shown to have been torn out of the matrix during the wear simulation. This was probably caused by the fatigue process of the filler/matrix during the lateral movement combined with high pressure by the sharp antagonists. Only small grooves were visible on the ceramic antagonist.

Group C: In contrast to the experiment of group B with a sharp ceramic antagonist, both the material and the ceramic ball of the experiment of group C showed little damage or wear. With EM and NFC only small grooves are visible on the SEM pictures. Only small grooves are discernible on the ceramic antagonist.

Group D: The formation of grooves in the denture tooth material was similar to that observed with the ball-like ceramic antagonist. The surface of EM showed more damage than that of DCL and NFC.

4. Discussion

Clinical results showed that the material with silica fillers (NFC) underwent less wear than the other two materials that contain pre-polymer fillers. Furthermore, the coefficient of variation was significantly lower in the NFC group compared to the other two groups. Therefore, the probability of subjects with NFC denture teeth showing very high wear is lower compared to those with DCL or EM denture teeth. Most likely the factors of age and gender are not responsible for the differences between the three test groups, as they did not significantly differ with regard to these two variables. However, it cannot be excluded that other patient factors (food habits, chewing habits, chewing force) may have influenced the results.

The Willytec simulator was set up to exert a certain type of wear in the second and third experiment of the present study. That is, no lifting of the stylus occurred. Rather a permanent back-and-forth 3 mm long sliding movement was produced. This type of wear usually results in material fatigue. Important material parameters in this case include the elastic modulus, strain-to-break and type of filler [7]. A low elastic modulus leads to a large contact area and low contact stresses. Materials with high strain-to-break values are usually more resistant to fatigue. Once the filler particles have been worn away,
they can cause three-body abrasion, enhancing the wear rate. The contact becomes permanent, since debris is entrapped between the antagonist and material surface. Thus, the larger and the harder the composite filler particles are, the higher the “self-abrading” effect. It may become especially pronounced if the stylus material (ceramic) is much harder than the denture material to be tested. IPS Empress is a leucite-reinforced ceramic material whose important tribological parameters, such as hardness, wear surface evolution and frictional coefficients, are similar to those of human enamel [29]. The OHSU wear method has shown that the wear of composite materials generated by a ceramic stylus is similar to that produced by a stylus made of human enamel and trimmed to the same shape [30]. The experimental design and wear protocol that was chosen for the second and the third experiment were inspired by the OHSU wear method [31] and the method developed at the University of Munich. The latter method involves a wear simulator that is similar to the one used in the present study, with pneumatic cylinders as force actuators [32]. In both wear methods, a ball-like stylus slides over flat specimens for 100,000 unidirectional or 50,000 bi-directional movement cycles respectively. Bi-directional sliding causes more wear than unidirectional sliding [33].

The wear method experiments with the ceramic stylus had been included in the present study as they represent a common approach for wear testing due to ease of stylus fabrication (see above). The authors are aware that the wear protocols that involve denture tooth material against a ceramic stylus do not reflect the clinical studies that evaluated teeth of complete dentures. And indeed, the results of the groups with the ceramic stylus did not match with the clinical results. If the denture teeth had been tested against a natural dentition both the clinical results as well as the correlation between clinical and laboratory wear could have been different.

Wear simulation devices and methods are limited by the fact that they follow one or two tribological concepts. They cannot simulate the complex jaw movements and force-regulating processes that occur in the mouth during mastication. Furthermore, they do not include saliva, which

![Fig. 7 - (a) DCL against DCL (group D); (b) DCL tooth against DCL tooth (group A); (c) DCL against sharp ceramic (group B); (d) DCL against ball-like ceramic (group C).](image-url)
Fig. 8 – (a) NFC against NFC (group D); (b) NFC tooth against NFC tooth (group A); (c) NFC against sharp ceramic (group B); (d) NFC against ball-like ceramic (group C).

acts as a lubricant, thus reducing the surface friction [34]. Clinically tooth wear occurs as the combined result of two- and three-body wear and affected by the individual patient effects (nutrition, parafunctions, antagonists, etc.). Therefore, a direct correlation between the in vivo and in vitro wear tests may not be possible. The main aim of in vitro studies on wear is to understand the wear mechanism, rank of restorative materials with regard to their wear resistance. For laboratory wear tests, it would be unreasonable to reproduce the stomatognath system in each and every detail, because the more complicated the system is, the more delicate is the controlling process and the harder the interpretation of the results. Moreover, wear processes have to be simulated in a time-lapse process, which means that the load, frequency and sliding paths need to be regulated in a none-physiological way to produce results within a short time period. A test device for wear has to be qualified for the intended purpose and it has to yield reproducible results and it must require little maintenance [6]. It must be able to control and reproduce force, force impulses, sliding paths and the frequency of force impulses.

The methods that are run with the device have to simulate one or two processes that occur in the mouth.

Of all the experimental designs to evaluate denture teeth for wear, only the one where flat specimens were exposed to antagonists produced results that correlated with the clinical wear of the same materials. Furthermore, the relative difference in vertical wear was comparable with the clinical results. When the anatomically shaped denture teeth were used, the results did not reflect the clinical results. One explanation for this finding is that it is difficult to mount the teeth in exactly the same way with the same occlusal contact points. Slight deviations alter the wear patterns and the wear results. The buccal cusps of maxillary molar teeth were exposed to the buccal cusps of maxillary premolars, as a more or less even distribution of three occlusal contact points could be reached with this configuration. When the buccal cusps of mandibular molars were exposed to the linguval cusps of maxillary molars, the distribution of the contact point was less favorable.

The shape of the conical antagonist was chosen on the basis of previous wear investigations. Krejci et al. [35]
systematically investigated the shape and size of palatal cusps of upper third molars. They found that a ball radius of 0.6 mm 200 \( \mu \text{m} \) of the y-axis is an ideal radius close to that of natural cusps. The ball-like shape of the other ceramic antagonist was chosen because it constitutes an integral part of the OHSU wear method [31].

If flat specimens were used, the anatomical factor was eliminated. If the stylus was not lifted during the simulation process, uncontrolled force impulses were avoided as it was the case in configurations that involved lifting of the stylus. The anatomical standardization of the opposing antagonists represented another prerequisite. However, no correlation with clinical wear results was found when standardized ceramic antagonists were used, regardless of the type of stylus mounted: conical or ball-shaped. The ball-shape stylus generated significantly less wear on all three materials than the conical ceramic stylus. This result is in line with other studies [36,37] and can be explained by the fact that a ball-shaped stylus has a greater contact area between the stylus and the material than a sharp one and therefore produces less fatigue stress on the material. Ceramic materials generated more wear on materials with glass fillers than on those that contained only prepolymers. Interestingly enough, the coefficient of variation for the NFC material was considerably lower compared to that of the other two materials in all the experiments involving flat specimens. This result corresponds with the clinical findings.

The difference of the ranking between the three materials of group A and group D can be explained by the different ways in which force was exerted on the material. In group A the antagonist was lifted which was not the case in group D. Due to the acceleration of the antagonist before it gets into contact with the specimen, the PMMA based materials attenuate the force impulse because of their elasticity and toughness. This is less the case with the more brittle NFC material and its inorganic fillers. When the antagonist is not lifted, the force can be built up more homogenously and the brittleness is less important.

When a ceramic material is used as the antagonist, more wear of the denture tooth materials can be expected due to the hardness of the ceramic; especially a brittle material like NFC is less wear-resistant toward ceramic. In contrast to solely PMMA-based materials, composite materials like NFC cannot diminish high force impulses during loading. A ceramic material is not an appropriate material for evaluating the wear of denture teeth if complete dentures are to be examined. In partial dentures the antagonist material can be different. But the variability can be very high, depending on the material used: high gold alloys, non-precious alloys, ceramics, composites or natural tooth material. Clinical studies have shown that a denture tooth material containing inorganic fillers, which was incorporated in partial dentures, exhibited higher wear than the same denture tooth material in complete dentures [25,26,38]. However, the type of antagonist material (enamel, ceramic, metal, resin veneer) did not influence the results. The laboratory test with a ceramic material as the antagonist (groups B and C) cannot be assumed to reflect the clinical situation with denture teeth opposing human teeth or restored teeth. Presumably, denture teeth with inorganic fillers are also more wear-resistant in conjunction with partial dentures compared to complete dentures. The laboratory test with ceramic antagonists, however, showed more wear for the composite tooth compared to the PMMA tooth.

One study examined the influence of the antagonist material on the wear of denture teeth [39]. The study evaluated the wear of 8 denture tooth materials using 3 different antagonist materials (denture polymer tooth, stainless steel, magnesium silicate ceramic material “steatite”) in a chewing simulator (flat specimens, 50,000 cycles, 1 mm lateral movement, 50N load with lifting). This study also evaluated two materials (NFC, DCL) which were a part of the present study. If the antagonist was the denture material, no difference was found between NFC and DCL. If steel was the antagonist, NFC showed more wear than DCL and if steatite was the antagonist it was vice versa, which is in line with the present study. However, the difference between both materials was 82% in mean vertical wear, which does not reflect the clinical results for both materials. Generally, the lowest overall material wear was measured for artificial tooth antagonists with a low variability between the different denture materials and the highest for steatite, which showed more discriminatory power. The wear results of denture teeth that had been exposed to steel antagonists were between those of the denture teeth that had been exposed to the other two antagonist materials. However, the aim of a wear method is not to discriminate between materials but to reflect the clinical wear of the materials. Therefore, material A may show a higher wear rate than material B in the laboratory experiment. However, in a clinical evaluation, the two materials may not differ at all in their wear rates.

Another laboratory study that evaluated the NFC and DCL material came to the opposite conclusion, showing that NCL had undergone significantly more wear than DCL (about 2.7 times more vertical wear) [13]. In this study 4 different materials were evaluated (ceramic tooth, NFC, IPN-resin, DCL). Premolar denture teeth were used, which had been shortened by 0.5 mm. The antagonist was the buccal cusp of a lower first denture premolar. The teeth were loaded 600,000 times with 5 kg in the Willytec chewing simulator. Astonishingly enough, the ceramic teeth exhibited twice as much wear as the DCL teeth. Clinical experience has shown that ceramic teeth are more wear resistant than resin or PMMA teeth. In another publication by the same authors, however, NFC showed 71% less wear than DCL [12]. In this study the stylus was not a denture tooth but ceramic balls (steatite) with a diameter of 6 mm, which is in line with the study by Hahnel et al. [39].

The laboratory wear method that matched the clinical results is a standardized and easy-to-perform lab test. Most probably, composite-based denture tooth materials as a whole are more wear-resistant than PMMA-based denture tooth materials, both in vitro and in vivo. However, the actual wear loss of other composite-based materials may be equal to that of the NFC material or between that of NFC and DCL, depending on the composition of the material. Nevertheless, this holds true only for complete dentures. In partial dentures (with retaining elements or supported by implants) the wear rate might be higher, but it may be assumed that composite-based denture teeth are also more wear resistant than PMMA
based denture teeth. However, clinical studies with accurate wear measurements of replicas have yet to prove this.

5. Conclusions

When evaluating denture teeth for wear in the laboratory, a protocol should be applied that matches clinical wear results. The mean vertical wear of the material as well as the total wear (material and stylus) was quite different for the different test protocols. When the laboratory wear results were compared with those from the clinical studies only the test protocol with the stylus prepared from the same material and run against flat specimens yielded results that matched the clinical results. Furthermore, the relative difference in mean vertical wear between the results of the experimental methods was in the same range as the findings of the clinical study.

As far as the null hypotheses are concerned the first hypothesis was rejected as NFC material showed significantly less wear than DCL and EM. The second hypothesis was also rejected as one of the four tested wear methods resulted in the same ranking of the three materials as it was the case for the clinical wear.

For the in vitro/in vivo comparison of the ranking of the materials more denture tooth materials, however, should be evaluated for wear both clinically and in the laboratory. Furthermore, wear of the denture tooth materials should not only evaluated after 1 year but also after 2, 3 and 4 years to see whether the material ranking will be stable over time.

REFERENCES


