Chapter 4

A comparison of three different methods for the quantification of wear in vitro of dental materials
Abstract

Objective: Different approaches are utilized to quantify the wear generated on flat specimens with a wear simulator. However, there are no systematic studies comparing different wear quantification methods with a series of materials that exhibit different wear rates.

Methods: Sixteen restorative materials, including 14 composites (belleGlass, Chromasit, Estenia, Esthet-X, Four Seasons, Heliomolar RO, Heliomolar HB, Herculite XRV, InTen-S, Point 4, SureFil, Targis cured at 95°C and 130°C, Tetric Ceram) as well as an amalgam (Amalcap) and a ceramic (Empress) material, were subjected to attrition wear against standardized Empress antagonists in the Willytec wear simulator (120,000 cycles, 5 kg, 1.6 Hz). The volume and maximal vertical loss were quantified directly on the specimens with a profilometry device (Perthometer) and the FRT MicroProf optical sensor. After the fabrication of plaster replicas, the loss was also determined with a 3D laser scanning device. For the statistical analysis, the data were subjected to a logarithmic transformation. Intraclass correlation was calculated to measure the agreement among all three methods, while limits of agreement were used to compare one method against another.

Results: There was a very good agreement between all three quantification methods for both volume and vertical loss. The mechanical sensor measured consistently higher values compared to the optical sensors for the volume loss (correction factor 0.95), whereas for the vertical loss consistently lower values were obtained (correction factor 1.17). However, the ranking of the materials was only marginally influenced by the quantification method.

Significance: All three sensors are suitable for the quantification of wear facets. Due to speed and simplicity, the laser sensor has great advantages over the two other sensors.
Introduction

Wear resistance is a prerequisite for a dental material to be accepted by both dentists and patients. A high wear resistance contributes to the longevity of a dental material and thus establishing durable aesthetics and function of the restored teeth. On the contrary, a high wear rate may be related to the elongation of antagonists, tilting and movement of teeth and other dysfunctions. In spite of being frequently mentioned in the literature as possible consequences, there is little evidence that occlusal wear of enamel or restorative materials as such leads to dysfunction of the temporomandibular joint, muscle pain or periodontal disease [1-4]. Even heavy loss of tooth substance due to wear is compatible with health as the stomatognathic system is highly adaptive to changes.

Randomized clinical studies, including an adequate number of subjects and a quantitative wear measurement method, would be desirable to evaluate the wear of dental materials. Clinical wear studies require a high professionalism in the selection of subjects, the operative procedures and wear analysis and the results are available only after years of clinical observation. Therefore, purpose-designed devices were developed to simulate the masticatory movements so that the wear of different materials can be assessed in a short period of time. A number of different devices and systems were developed [5]. A round robin test including ten dental materials subjected to wear processes in five different wear simulators resulted in diverging results as regards the ranking of the materials [6].

Different methods are available for the quantification of wear. It is essential to distinguish between “accuracy” and “precision” to qualify these systems. The former describes the systematic as well as the random deviations related to a “true” value, while the latter describes only the random deviation and can be equated with the term “reproducibility”. Accuracy is measured by using standard surfaces or standard objects with defined dimensions and compare the results with each other while precision is analyzed by repeating the measurements on the same object.

For the quantification of material loss, volumetric, mechanical and scanning electron-optical procedures have been used in dentistry to date [7,8]. As early as in 1978, a three-coordinate measuring device with a non-contact vertical measuring microscope was used to quantify the wear of direct fillings on plaster models; the precision of the z-values was calculated to be 15 µm [9]. In 1983 the first computer-controlled three-coordinate measuring device using a Commodore computer and a mechanical sensor for occlusal mapping was introduced [10] and used for both in vitro and in vivo
measurements [11]. However, this system required reference points like modified brackets for mechanical adjustment. Its precision was calculated to be 0.3 ±6.6 µm. This approach was further optimized by using a mechanical digital measuring device, overlapping software and special specimen holders [7]; the precision of this device of 10 measurements was calculated to be 0.1 ±0.7 µm. However, the precision in the z-direction on oblique surfaces was less accurate, measuring approx 8 µm [12]. Other developments, which did not require specific reference points to allocate the follow-up to the baseline model, employed an MTS universal testing machine and an adequate computer program [13] or a measuring microscope with autofocus functions, which automatically measure the z-coordinates [14]. In 1991 a matching routine for 3D data was developed on the basis of the VISILOG software package [15] and used in conjunction with a scanning procedure, which is conducted by means of a mechanical sensor (profilometer) [8]. In mid-1990 it was possible to develop an optical measuring system which enabled the research worker to efficiently quantify the wear of both in vitro and in vivo specimens by using a triangulation laser sensor, a computer-controlled specimen stage and a sophisticated matching software with subpixel interpolation and a scanning speed of 5000-10,000 surface points per second [16]. The precision in the z-direction was calculated to be between 5 and 10 µm.

As early as in 1993, it was proved that mechanical sensors do not measure the real volume loss of standardized hemispherical deepenings [12]. In 1998 Mehl reported in his postdoctoral thesis that there was no difference in vertical and volume loss of 10 wear facets generated in a chewing simulator and measured by either a mechanical (Perthometer) or an optical sensor (Laserscan 3D) [17]. A publication that systematically compares different methods for the quantification of wear in different dental materials or systematically assesses the accuracy of systems for wear quantification has not been found to date.

The aim of the present study was to compare the measurements of vertical and volume loss obtained with a Laserscan 3D and an FRT MicroProf optical sensor with those obtained with a mechanical sensor (Perthometer). The measurements were carried out in the wear facets of 16 dental materials, which were subjected to a wear generating process in a wear simulator. The hypothesis was that there is practically no difference in neither the vertical nor the volume loss between the three quantifying methods.
Material and methods

The rationale for selecting the composite materials was based on criteria such as material composition (microfiller, fine particle hybrid), wear rate, clinical success record and indication (composites for direct and indirect restorations) (Table 1). In addition to these products, a ceramic and an amalgam material were chosen for comparison. Table 1 lists the materials with their batch number and composition. The composite resins for direct restorations were directly placed in an SEM holder (s. Figure 1a; ring with a hole: Ø 8 mm, depth 2 mm; No. 2455-202, Laubscher AG, Täuffelen, Switzerland) and polymerized with an Astralis 5 polymerization light (560 mW/cm²) (Ivoclar Vivadent, Schaan, Liechtenstein) for 120 s and additionally cured in the Spectramat (Ivoclar Vivadent) for 10 min. The specimens of Empress and the composite resins for indirect restorations (Targis, belleGlass, Estenia) were fabricated according to the manufacturer’s instructions and luted into the SEM holders by means of the Variolink II composite resin (Ivoclar Vivadent). The ceramic material was additionally conditioned with ceramic etching gel and Monobond S (Ivoclar Vivadent). For the measurement with the profilometry device, 8 notches were drilled into the periphery of the sample using a round bur; the notches served as reference points for the superimposition of the profiled surfaces.

Before the samples (n=8) were tested, they were kept dry at a temperature of 37°C for 24 hours. After storage, 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 samples were mounted in a chewing simulator that is commercially available from Willytec (Gräfelfing, Germany). The antagonists were made of pressed IPS Empress ceramic (Ivoclar Vivadent) and were glazed two times at a temperature of 870°C. The radius of the conical shaped antagonist was 1.18 mm at a height of 600µm from the cuspal tip to the base. This geometry was chosen to mimic the curvatures of the palatal cusp of upper first molars of young adults (unpublished data). The antagonists were luted to aluminium SEM holders with resin cement (Dual Cement, Ivoclar Vivadent), which was light-cured for 40 s with an Astralis 5 curing light, and then cured for an additional 10 minutes in a polymerization device (Spectramat, Ivoclar Vivadent).
<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Abbreviation</th>
<th>Manufacturer</th>
<th>Batch</th>
<th>Composition (weight%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Amalcap Plus</td>
<td>Am</td>
<td>Ivoclar Vivadent</td>
<td>C25527</td>
<td>Ag (70.1), Sn (18), Cu (11.9), powder:Hg = 1=0.97</td>
</tr>
<tr>
<td>2</td>
<td>Artemis</td>
<td>Art</td>
<td>Ivoclar Vivadent</td>
<td>RZB041</td>
<td>Dimethacrylates, mixed oxides (6), Ba-Al-F-Si glass (60), YbF$_3$ (11.5)</td>
</tr>
<tr>
<td>3</td>
<td>belleGlass enamel</td>
<td>BelG</td>
<td>KerrLab</td>
<td>911422</td>
<td>BisGMA, TEGDMA, borosilicate 0.6µm (77)</td>
</tr>
<tr>
<td>4</td>
<td>Chromasit S4</td>
<td>Chro</td>
<td>Ivoclar Vivadent</td>
<td>C15082</td>
<td>UDMA, decamethacrylates, stabilizers, catalyst, copolymer (56), SiO$_2$ 40nm (10), pigments (&lt;0.2)</td>
</tr>
<tr>
<td>5</td>
<td>Empress TC1</td>
<td>Emp</td>
<td>Ivoclar Vivadent</td>
<td>C35146</td>
<td>SiO$_2$ (59-63), Al$_2$O$_3$ (17-21), K$_2$O(10-14), Na$_2$O(3.5-65), pigments (&lt;5): B$_2$O$_3$, BaO, CaO, CeO$_2$, TiO$_2$</td>
</tr>
<tr>
<td>6</td>
<td>Estenia Enamel E2</td>
<td>Est</td>
<td>Kuraray</td>
<td>202CA</td>
<td>BisGMA, UDMA, triethyleneglycol DMA Glass ceramic 1.5µm (76), Al$_2$O$_3$ 20nm (16)</td>
</tr>
<tr>
<td>7</td>
<td>Esthet-X Enamel</td>
<td>EsX</td>
<td>Dentsply</td>
<td>8000230</td>
<td>BisGMA, dimethacrylates, Ba-Al-F-B-Silicate 1µm, SiO$_2$ (glass filler 77)</td>
</tr>
<tr>
<td>8</td>
<td>Heliomolar HB</td>
<td>HMHB</td>
<td>Ivoclar Vivadent</td>
<td>SG2-73-3</td>
<td>Bis-GMA, dimethacrylates, copolymer (45), SiO$_2$ 40nm (20.2), YbF$_3$ (10.6)</td>
</tr>
<tr>
<td>9</td>
<td>Heliomolar RO</td>
<td>HM</td>
<td>Ivoclar Vivadent</td>
<td>29157</td>
<td>BisGMA, UDMA, decandiol dimethacrylate, copolymer (47), SiO$_2$ 40nm (20.2), YbF$_3$ (10.6)</td>
</tr>
<tr>
<td>10</td>
<td>Herculite XRV</td>
<td>Her</td>
<td>KerrHawe</td>
<td>006671</td>
<td>Bis-GMA, dimethacrylates, Ba-Al-F-B-Silicate glass (79)</td>
</tr>
<tr>
<td>11</td>
<td>InTen-S</td>
<td>InT</td>
<td>Ivoclar Vivadent</td>
<td>D51683</td>
<td>Dimethacrylates, barium glass (39), copolymer (40), YbF$_3$ (3)</td>
</tr>
<tr>
<td>12</td>
<td>Point 4</td>
<td>P4</td>
<td>KerrHawe</td>
<td>A3012294</td>
<td>BisGMA, dimethacrylates, Ba-silicate (76)</td>
</tr>
<tr>
<td>13</td>
<td>SureFil</td>
<td>SuF</td>
<td>Dentsply</td>
<td>990615</td>
<td>BisGMA, urethane modified, Ba-Al-F-Bor-silicate 0.8-10µm (82), SiO$_2$ (8)</td>
</tr>
<tr>
<td>14</td>
<td>Targis S1</td>
<td>Tar95</td>
<td>Ivoclar Vivadent</td>
<td>C05051</td>
<td>UDMA, BisGMA, Decandiol-DMA, Ba-Al-Si-glass 1µm (72), SiO$_2$ 40nm (5)</td>
</tr>
<tr>
<td>15</td>
<td>Targis S1</td>
<td>Tar130</td>
<td>Ivoclar Vivadent</td>
<td>C05051</td>
<td>UDMA, BisGMA, Decandiol-DMA, Ba-Al-Si-Glass 1µm (72), SiO$_2$ 40nm (5)</td>
</tr>
<tr>
<td>16</td>
<td>Tetric Ceram</td>
<td>TetC</td>
<td>Ivoclar Vivadent</td>
<td>C16761</td>
<td>BisGMA, UDMA, triethyleneglyco-DMA, barium glass 1µm (50.6), Ba-Al-F-B-silicate 1µm (5), SiO$_2$ 40nm (5), spherical mixed oxide 0.2µm (5), YbF$_3$ (17)</td>
</tr>
</tbody>
</table>

Table 1: List of materials, batch number, and composition
A weight of 5 kg was put on each test chamber and the sliding movement was set at 0.7 mm. The frequency of the antagonist movement was 1.6 Hz. A total of 120,000 cycles of unidirectional antagonist movements were carried out. Thermocycling at a frequency of 320/120,000 load cycles and a temperature range between 5°C and 55°C was included in the wear testing. The thermocycling system consists of magnetic valves as well as a heating and cooling system, which are controlled by programmable logic controllers (PLC’s). After completing the wear generating procedure, impressions of the material were made using a low viscosity vinyl polysiloxane material (President light, Coltène, Altstätten, Switzerland). After four hours, replicas of the impressions were fabricated with white super hard plaster (Fuji Superhard Rock, GC Corporation, Tokyo, Japan) using a vacuum, vibrator and pressure device (2 bar) (Figures 1a, 1b).

![Figure 1 - (a) Composite specimen in SEM holder after 120,000 cycles in the chewing simulator - eight notches as reference points for the Perthometer matching software. (b) Plaster replica of the same specimen as in a.](image)

**Profilometry**

The specimens were directly measured with a profilometry device (Perthometer C5D, Mahr, Göttingen, Germany), a PRK drive unit (Mahr), a FRW-750 measuring sensor and Dentmes (version 2.1) matching software, which was developed at the University of Erlangen by Paulus, Neugebauer and Kunzelmann [8,15]. The specimens were mounted on an XY cross table with a computer-controlled microstepper. Before and after the wear generating process, an area of 4.5 mm x 4.5 mm was scanned in each specimen, using a diamond needle of 10µm in diameter and a distance between the tracks of 50 µm and a speed of 0.2 mm/s. The scanning of a wear facet took about 34 minutes. The specimens were all scanned perpendicular to the wear facet.
generated by the lateral movement of the Empress stylus. Before each measurement of a series of 8 specimens, the Perthometer was calibrated with the calibration standard PEN-10-1 (Mahr). The maximal vertical loss was set at 1.25 mm. The theoretical precision is 1 µm in the z-direction and 1.25 µm in the x/y-direction. For the matching procedure, three corresponding points (reference points) in each picture were chosen. Based on these corresponding points, the programme calculated the differences of the position of the specimens with automatic enhancement of the positions and interpolation for higher accuracy. After the pictures had been placed on top of each other, the matching algorithm showed the differential picture. The profiled surfaces were superimposed and the vertical and volumetric differences were calculated with the help of the software (Figure 2).

![Difference picture](image)

**Figure 2**: Difference picture of the same specimen in Fig. 1a generated by the Match 3D software of the Perthometer device.

**Laserscan 3D**

The plaster replicas were analysed by means of a commercially available laser scanning device (Laserscan 3D, Willytec) and the appropriate match-3D software [16]. In principle, a light beam, which has a width of 22 µm and is created by a laser diode, is projected onto a surface and a CCD chip under a triangulation angle of 25°, thus encoding the height of every surface point within the lateral displacement of the light beam on the CCD chip. The specimen was moved along the y-direction on a microstepper motor. After each step, the CCD image of the light line is stored in a frame grabber. A digital signal processor allows the storage and measurement of
8.33 frames (580 lines) per second, which results in a scanning rate of approx. 5000 surface points per second. The precision of 3D data acquisition in flat samples was tested to be 2.9 µm (±0.5) [16], a precision of 5-8 µm can be assumed in samples with a wear facet. The vertical resolution is 2-5µm, 30µm in the y-direction and less than 30 µm in the x-direction; objects with a vertical difference of up to 20 mm can be measured [18]. The time required to scan a flat specimen of 1 cm in diameter is about 20 seconds. However, up to eight specimens can be scanned in a row, thus facilitating the process; for that purpose the SEM holders are put on a special plastic holder, which is fixed on the rotation table of the 3D Laserscan. All eight samples can be stored in one file. The area around the wear facet was used as reference for the quantification of material loss and the procedures “fit plane”, “subtract plane” and “statistics” were used for the 3D calculation of the material loss (Figure 3). The maximal vertical loss (99% quantile) was calculated by the software. The rationale for utilizing the 99% quantile was to eliminate extreme values caused by fine dust particles and other discrepancies.

Figure 3: Difference picture of the same specimen in Fig. 1b generated by the Match 3D software of the Laserscan 3D device. The redder the area, the higher is the vertical loss.

**FRT MicroProf**

The vertical loss (deepest point of wear facet) and volume loss were also measured with an optical sensor called FRT MicroProf® (Fries Research & Technology GmbH, Bergisch-Gladbach, Germany). This device is typically used in fields such as process control, quality assurance as well research and development whenever detailed information about topography, roughness or contour is required. So far, this device
has been used in industries like wafer and semiconductor production, car and electronics, machinery and optical equipment (www.frt-gmbh.com) as well as in the rubber industry [19]. Using this device, the first author of this study developed a software program for automatic gap detection in cylindrical fillings [20]. Furthermore, it is used for automatic measurement of the roughness of dental material surfaces. The measuring principle of the device can be described as follows: Using a special optical sensor (CWL), the sample is illuminated by focused white light. An internal, passive optical measuring head with a strong wavelength dependency of its focal length splits the white light into different colours (corresponding to different wavelengths). A miniaturized spectrometer detects the colour of the light reflected by the sample and determines the vertical position on the sample surface by means of an internal calibration table. The device enables measurements with a resolution of 10 nm in height and 1-2 µm in lateral width using a measuring frequency of up to 1000 Hz. The maximum slope angle is 30° and the working distance is 5 mm. According to a testing protocol provided by the company, measurements with the optical sensor and a reference standard (KNT 2060/01, No. 0934) with three grooves of different depth (0.987 µm, 3.855 µm, 8.914 µm) revealed a deviation of the measured value from the reference value of 0.3 %, 1.1 % and 0.7 %. The detector is provided with a computer controlled stage to which the samples are attached. The xy-position is measured with rotary encoders enabling deviations of less than 0.5 µm as measured by the company. The integrated software consists of two parts: ACQUIRE for scanning the objects and MARK III for data analysis.

For wear quantification, the original specimens were scanned with the sensor using a frequency of 300 Hz, a xy-precision of 4 µm and different layers according to the depth of the wear facet (a single layer covers about 300 µm in height). About 20 minutes were required to scan a flat specimen with an area of 3 mm x 3 mm using the above-mentioned resolution. After deleting extreme values (“spikes”) and eliminating the obliqueness of the specimen, the deepest point was determined by using the operation “smallest value”. Afterwards, a profile was laid over the wear facet down to the minimal point and the difference in the z-direction from the plateau to the deepest point was measured directly within the profile created. The volume loss was measured by first determining the plane where most points had the same z-value. This can be done by calculating a histogram with the z-distribution. The value with the highest frequency was chosen and defined as zero-point. The volume loss
can be determined from this zero-point by using the operation “filling volume” (Figure 4).

Figure 4: Difference picture of the same specimen as in Fig. 1a, generated by the Mark III software of the FRT MicroProf device. The darker the area, the higher is the vertical loss.

**Quantification of waviness with an optical sensor**

As the Empress stylus produces grooves along the lateral movement (Figures 4 and 10a), it was of special interest to quantify the waviness of the wear facet. The grooves could be an explanation for the possible differences between the optical and mechanical sensors. The waviness is defined as the first order of shape discrepancy [21]. The mean waviness Wa was measured in all specimens by means of the MARK III program of FRT MicroProf by isolating the inner part of the wear facet.

**Statistical methods**

A useful tool to assess the agreement between two methods of measurement is to plot the difference versus the average of two measurements, as proposed by Bland and Altman [22]. However, since in the present study the size of these (absolute) differences tended to increase with the value of measurements (both in terms of average values and variance), it was not possible to calculate limits of agreement that are applicable to the whole range of measurements. Therefore, a log-transformation of the data of both vertical and volume loss was carried out and the limits of agreement for the differences of logarithms of measurements were calculated, i.e. the limits of agreement for the logarithm of the ratio of two
measurements was determined. In other words, by exponentiating these limits, the limits of agreement for the ratio of two measurements can be obtained. These limits are calculated in such a way that they contain about 95% of the ratios. The log-transformation was successful in the present study, since both the median and the variability of these ratios remained constant over the whole range of measurements, even (at least approximately) for the Chromasit material, which produced much higher values than the other materials. In order to compare the methods two by two, the limits of agreement for the ratios of two measurements were calculated and plotted. The centre of these limits is an estimate of the median of these ratios and can be used as an estimate of a multiplicative correcting factor. Note that in order to get a better estimate of the variability of these ratios, the pooled data were used (i.e. the data of the three methods). In addition, an intraclass correlation coefficient was calculated to determine the extent of agreement (or reliability) among the three methods. This coefficient may be interpreted as the percentage of the variability in the measurements which is not caused by the discrepancies among the methods. The intraclass correlation coefficients were calculated from the log-transformed data. Associated confidence intervals were calculated assuming a "fixed systematic error" [23], which implies that the focus was placed only on these three specific methods and that the results are not to be generalized to other methods. The materials were ranked by vertical and volume loss according to the averages of log-transformed data. Spearman's rho was used to identify the correlations between vertical and volume loss, as well as between waviness and the ratio of two measurements of vertical loss.

Results

Agreement between the three methods

The maximal vertical and volume loss of each material and each test method is presented in Figures 5 and 6 as box plot graphs in the original scale (16 materials, 128 specimens). The different materials are arranged according to their median from the lowest wear to the highest wear as measured with the Laserscan 3D.
Figure 5: Volume loss \((10^7 \mu m^3)\) of 16 dental materials after 120,000 chewing cycles in a chewing simulator quantified with three different methods (sequence arranged according to the median value of the Laserscan 3D measurement).

*Abbreviations see Table 1*

Figure 6: Vertical loss (\(\mu m\)) of 16 dental materials after 120,000 chewing cycles in a chewing simulator quantified with three different methods (sequence arranged according to the median value of the Laserscan 3D measurement).

*Abbreviations see Table 1*
The three methods showed a high level of agreement. The intraclass correlation coefficient equalled 0.99 (95 % CI=[0.98;0.99]) for the variable volume loss and 0.94 (95 % CI=[0.91;0.97]) for the variable vertical loss. For the variable volume loss, this means that 99 % of the variability observed between the various measurements was due to the "true variability" between the entities measured and only 1 % of that variability was due to the discrepancies between the measurement methods. For the variable vertical loss, 6 % of the variability was due to the discrepancies between the measurement methods. Although intraclass correlation depends on the range of measurements, it is worth noting that the correlation remained very high if the Chromasit material, which showed the highest values of both volume loss and vertical loss, was eliminated from the analysis (see Table 2). The Laserscan 3D and FRT MicroProf methods produced results that were very close to each other. The ratio of the measurements obtained from these two methods was on average 1.005 for volume loss and 0.988 for vertical loss (Table 3). By contrast, the profilometry method produced always slightly higher volumetric wear values for all materials, while the maximal vertical wear values were always slightly lower. These differences were particularly pronounced in the material that showed the highest wear of all (Chromasit).

<table>
<thead>
<tr>
<th>All materials</th>
<th>ICC</th>
<th>95% Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log volume</td>
<td>0.99</td>
<td>0.98-0.99</td>
</tr>
<tr>
<td>Log vertical</td>
<td>0.94</td>
<td>0.91-0.97</td>
</tr>
<tr>
<td><strong>Without Chromasit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log volume</td>
<td>0.99</td>
<td>0.98-0.99</td>
</tr>
<tr>
<td>Log vertical</td>
<td>0.93</td>
<td>0.89-0.96</td>
</tr>
</tbody>
</table>

Table 2: Intraclass correlation (ICC) and confidence intervals (log-transformed data) for three wear quantifying methods with and without the Chromasit material.

<table>
<thead>
<tr>
<th>Ratio volume</th>
<th>Lower limit–centre of interval–upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perthometer/Laserscan 3D</td>
<td>0.82 - 1.05 - 1.34</td>
</tr>
<tr>
<td>Laserscan 3D/FRT MicroProf</td>
<td>0.79 - 1.01 - 1.28</td>
</tr>
<tr>
<td>Perthometer/FRT MicroProf</td>
<td>0.82 - 1.05 - 1.34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ratio Vertical</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Perthometer/Laserscan 3D</td>
<td>0.73 - 0.86 - 1.02</td>
</tr>
<tr>
<td>Laserscan 3D/ FRT MicroProf</td>
<td>0.84 - 0.99 - 1.17</td>
</tr>
<tr>
<td>Perthometer/FRT MicroProf</td>
<td>0.72 - 0.85 - 1.01</td>
</tr>
</tbody>
</table>

Table 3: Limits of agreement between two quantifying wear methods.
Only the graphs for the comparisons between Laserscan 3D and the Perthometer are shown since the graphs for the other two comparisons are very similar. In Figures 7 and 8, the top panel shows the raw data and the graph on the bottom the log-transformed data. On the horizontal axis, the average of the two measurements is plotted for each entity measured and on the vertical axis the difference between these two measurements is shown. The numbers plotted on the graphic refer to the numbers of the different materials (see Table 1). The limits of agreement are plotted as dotted lines on the bottom part of the Figures, together with the ratio of the two measurements of each entity measured. The central dotted line is an estimate of the median of these ratios in the whole sample. A solid horizontal line at the level "ratio=1" was added to the graph as reference line, which would indicate no differences between the measurements. When the plotted graphs were evaluated, it was evident at first glance that the values of the Chromasit material were much higher than those of the other materials. It was assumed that, as a probable consequence, the differences in the measurements of the Chromasit material were much larger than those of the other materials but only when the results of the Perthometer/Laserscan 3D and those of the Perthometer/FRT MicroProf were compared with each other. Similar to Table 3, it is noticeable that most of these differences were negative for volume loss, which means that the Perhometer produced higher values than the Laserscan 3D or the FRT MicroProf.

It is possible to divide the variable volume loss by 1.05 and the variable vertical loss by 0.85 or to multiply the volume loss by 1/1.05=0.95 and the vertical loss by 1/0.85=1.17 in order to compensate for the bias of the Perhometer method. Obviously, no correction is needed between the Laserscan 3D and FRT MicroProf methods.

The ranking of the materials was only marginally influenced by the quantification method (Table 4). An inversion was noted between Laserscan 3D and FRT MicroProf for both vertical and volume loss and two inversions for Laserscan 3D and Perhometer for both variables.
Correlation between vertical and volume loss

As could be expected from the material rankings for volume and vertical loss (which were very similar for the variables Log volume and Log vertical), the correlations between the variables Log volume and Log vertical were very high for each method (with Spearman's rho being 0.96, 0.95 and 0.96 for the Laserscan 3D, FRT MicroProf and Perthometer methods respectively) (Figure 9).
Table 4: Ranking of the materials from lowest to highest wear according to the means of the log-transformed data of volume and vertical material loss - differentiated according to the quantification method (Abbreviations see Table 1).

![Volume Pertheometer - Volume Laser](image1)

Figure 8: Volume loss measured by Laserscan 3D versus that measured by Pertheometer. Plot above: absolute differences between both methods; plot below: limits of agreements referring to ratios of two measurements. The numbers refer to the materials listed in Table 1. (Explanation of lines see text).

![Volume Pertheometer / Volume Laser](image2)
Figure 9: Scatter diagram of the log-transformed data of vertical and volume loss measured with the Laserscan 3D.

Waviness of wear facets
The mean waviness (Wa) for the pooled materials was 19.7 (±8.3) µm with a range between 6.2 and 47.7 µm. Figure 10a shows the 3D picture of a wear facet of a material with high wear and Figure 10b shows a profile of the same wear facet. The Spearman's rho correlation coefficient between vertical loss (log-transformed data) and Wa was 0.81 for Laserscan 3D, 0.82 for FRT MicroProf, and 0.80 for the Perthometer. Although the scatter diagram between both vertical loss and Wa showed a favourable level of correlation (Figure 11), Wa was not (or rarely) correlated with the ratios Perthometer/Laser and Perthometer/FRT (with Spearman's rho being 0.17 and 0.19 respectively). Negative correlations were found between Wa and the differences of two measurements (not log-transformed), with Spearman's rho being -0.36 for the differences Perthometer/Laserscan 3D and -0.43 for the differences Perthometer/FRT MicroProf (this analysis was performed without the Chromasit material). However, these negative correlations were simply the consequence of the fact that the difference between two vertical loss measurements decreased with the number of measurements performed as well as of the fact that Wa was strongly correlated with vertical loss. By taking the differences in the log-transformed data into account, the trend was removed, and as a consequence, Wa was no longer correlated with the ratios of measurements.
Figure 10 – (a) Detail of a wear facet of a specimen that showed great vertical material loss. Note the grooves in the wear facet. Picture was made with FRT MicroProf.
(b) Profile of the specimen of Fig. 1a. Note the grooves within the profile especially pronounced in the deeper part.

Figure 11: Scatter diagram of log-transformed data of vertical loss (µm) (measured by Laserscan 3D) and mean waviness Wa.

Discussion
In the present study 16 restorative materials, including 14 composites, an amalgam and a ceramic material, were evaluated with regard to wear using three different methods for the quantification of wear. The statistical analysis showed that there was a good agreement between the three evaluated sensors and that the ranking of the
materials was practically not affected by the measuring device used to quantify the wear facets.
While the volume loss measured by the mechanical sensor was consistently higher compared to the measurements of the optical sensors, the opposite applies to the maximal vertical loss, as the mechanical sensor measured consistently lower vertical loss values than did the optical sensors. As the laser scanner cannot be used to scan original specimens because it penetrates into semi-transparent composite or ceramic materials and therefore produces incorrect values, it is necessary to cover the surface of the specimens with powder or varnish or to fabricate replicas. In his postdoctoral thesis, Mehl covered the plaster models of tooth surfaces with CEREC powder, Met-L-chek Develop and PTFE Spray 650 and then measured the thickness of the covering agent. He discovered that it was not possible to cover complex structures with a uniform layer. Therefore, the use of plaster replicas has been advocated. Modern impression taking techniques involving addition silicone polyvinylsiloxane materials and epoxy resin based replica materials have already proven to be highly accurate for the SEM analysis of microstructures of dental substances [24-26]. Plaster has been proven as an appropriate replica material that provides the required accuracy in several studies [27,28]. Our own experiments regarding the reproducibility of the replica technique revealed that the variation is less than 0.4% of the mean value when impressions of the same specimen were poured out 10 times with plaster and analyzed for vertical and volume loss with the Laserscan 3D or when ten different impressions were taken from the same specimen, poured out with plaster and subsequently analyzed. Another indication for the high accuracy of the replica technique is the fact that there was a very good agreement between the Laserscan 3D and the FRT MicroProf the former using plaster replicas and the latter measures directly on the specimen.
For both optical sensors, the area around the wear facet which was not subjected to wear was used as reference area to calculate both the vertical and volume loss. Except for thermocycling, no additional stress, such as tooth brushing or chemical degradation, was applied to the flat specimens. Therefore, it can be assumed that this area was not altered during the wear generating process, which lasted about 21 hours. The main purpose for constantly changing the water during the wear process is to eliminate worn material particles.
The accuracy of the 3D Laserscan and matching software to calculate vertical differences between unprepared teeth (n=15) and the same teeth with crown
preparation was tested to be 10.9 (±1.9) µm [16,17]; even if great z-differences are present, the accuracy of the Laserscan 3D should be narrower than 12 µm. No comparative measurement of wear facets with other optical sensors has been reported in the literature. The precision of the Laserscan 3D device for the measurement of slopes that have an angle of less than 60° was measured to be about 3 µm [16,17].

The data of the present study indicated a high level of agreement between the FRT MicroProf, whose accuracy in the z-direction is less than 50 nm, and the Laserscan 3D. However, the level of agreement between the Perthometer and the Laserscan 3D or FRT MicroProf is much lower. If it is assumed that the FRT MicroProf detects the deepest point with highest accuracy, good accuracy can be attributed to the Laserscan 3D, but not to the Perthometer.

The FRT MicroProf is an excellent tool whenever detailed information about the topography of small objects is required or automatic quality routines have to be analyzed. In dentistry, it has recently been reported that the device is used for automatic gap detection in cylindrical cavities [20] and automatic quantification of the surface roughness of dental materials [29]. The device may also be used for the quantification of wear. However, this method is not suitable for routine usage as the scanning process is very time-consuming if a large measuring field needs to be scanned in a high resolution. Furthermore, the vertical maximal height is restricted to 300 µm (it can be increased to 3 mm by scanning the object in various layers) and a matching software program is not yet available. The measuring time can be reduced with a newly developed sensor, which provides an identical resolution and allows layers of up to 600 µm to be measured.

Different phenomena may explain the differences in the data when scanning the wear facet with a mechanical sensor. The tracking force of the sensor results in a sliding movement of the sensor and a slight displacement of it (down-hill slope force). Elastic distortions strains counteract the bending of the sensor. The result, however, is a force which results in a position of the needle that does not correspond with the point to be measured. At steep angles the rounded head of the sensor is not in contact with the deepest point of the surface. Instead, the point is laterally displaced, which results in wrong z-values. Hewlett et al evaluated the accuracy of three-dimensional digitising systems on standard precision spheres made of steel with a radius of 6.35 mm by calculating the deviation of z-values from measured points and calculated points as a function of the spheres’ slope [30]. The z-values steadily
increased with increasing slopes. However, only at a slope angle of 40° was a 10 µm difference calculated. This difference approached 42 µm at a slope angle of 80°. Yet, the precision values increased steadily approaching 45 µm at 40° and 100 µm at 70°, showing high within-run variability. However, as the surface of steel is very smooth, the forces making the diamond needle to slide over the surface are more pronounced than on composite surfaces, which are much rougher, especially those modified by the Empress stylus. This resulted in rough wear facets depending on the material.

Contrary to these results, Mehl reported in his postdoctoral thesis an increase in the z-values when measuring a v-shaped DeLong standard measure with a profilometer compared to a 3D laser scanner [17]; the vertical values measured with the profilometer were up to 100 µm higher compared to the real values.

With regard to volumetric wear, the profilometer measured consistently higher values compared to the laser device. Mehl measured plaster replicas of metal plates with hemispheres of different sizes and compared the volume measured by both sensors [17]. Due to the displacement of the mechanical sensor, a systematic error occurs because the sliding of the needle on the hemisphere results in higher z-values. Thus, the measured volumes of the hemispheres showed higher values than were actually present. The same holds true when measuring concave forms (wear facets) instead of convex forms (hemispheres). This is due to the fact that when the diamond needle, which scans the surface of the specimen, moves from the flat surface to the wear facet, it slides over the edge of the facet into a steep angle and the high down-hill slope force results in higher z-values. This was also detected by Pelka et al. when measuring standard measures with different sphere deepenings [12]. They calculated the difference in volume to be 10% on average. In the present study, this value was 3.7% on average. The authors describe other possible error sources for the mechanical sensor, such as (1) loss of data acquisition during the movement of the stage due to the inertia of the microstepper motor and the stage resulting in an amplification of the object to be measured, (2) distortion of the needle while scanning steep angles, resulting in a displacement of the needle and the acquisition of incorrect z-values, (3) the geometrical shape of the needle which creates problems especially in the scanning of slopes with angles greater than 45°. Mehl also compared the volumetric wear measured by the optical and mechanical sensor on wear facets of 4 different compomer materials (Dyract and 3 experimental compomers, n=2) generated in a chewing simulator with 55 N, a sliding movement of 8 mm, steatite stylus (Ø 2.5 mm) and quantifying the volumetric wear of a defined
5 mm part of the wear facet at different chewing cycles (500-51,000) [17]. Furthermore, he analyzed the mean vertical, maximal vertical and volume material loss of wear facets of 5 different composite materials (n=2), which had been subjected to 5000 chewing cycles using the above described parameters. No significant differences in the volumetric wear between both methods at any of the measuring points were measured in the compomer materials. However, the curves indicate slight differences between both test methods. For the composite materials, there was a tendency of the mechanical sensor to produce higher values than the optical sensor. The volume losses ranged from 5 to 30x10^7 µm^3, whereas in the present study the range was between 4.3 and 203x10^7 µm^3 (as measured by the laser). However, the mechanical sensor measured less volume loss than the optical sensor did in 13 of the 128 specimens, 4 of which i.e. those with the most pronounced discrepancies, were found in the Chromasit group (Figure 6).

As far as the maximal vertical loss is concerned, in 8 of the 10 composite specimens the vertical loss measured by the mechanical sensor was higher compared with the loss measured by the optical sensor and in the other 2 it was vice versa (range of vertical loss of the 10 composite specimens: 50-140 µm), whereas in the present study the mechanical sensor consistently measured a lower vertical loss than both optical sensors in all specimens except for 2 specimens (difference range for all 128 specimens: -21 µm to +359 µm 3D-Laser/Perthometer and -20 µm to +338 µm FRT MicroProf/Perthometer).

A fundamental difference between the optical and mechanical sensor is the fact that the optical sensor scans the object without touching it, thus preventing any interaction between sensor and the surface to be measured, as this may also alter the results. It is assumed that the vertical wear data calculated by means of the Laserscan 3D device is close to the real vertical loss of the specimen [205], the consistent discrepancy measured by the Perthometer in the present study may be explained in principle by the waviness and the algorithm of the matching software. As the Perthometer is profiling the wear facets perpendicular to the wear facet and to the waves generated by the Empress stylus, the mechanical sensor is profiling an area with different categories of mean waviness Wa, which was measured to be between 6.2 and 47.7 µm. Figures 7a and 7b show the pronounced waviness of a wear facet of a material with high wear, whereas materials with a low wear had a lower mean waviness with a much smoother surface. It can be assumed that the mechanical sensor cannot detect such narrow grooves in the area of the deepest points and as
the data of the peaks within the deep wear facets are interpolated during the scan, a loss of information with regard to the deepest point of the wear facet may occur. This may explain why the mechanical sensor measures consistently less vertical loss than the optical sensor and may also explain why the differences increase with increasing waviness and vertical loss, although the statistical analysis based on ratios rather than on absolute differences did not reveal a significant correlation between the increase of waviness and the difference in vertical loss measured by the optical sensors and the mechanical sensor. This may be due to the fact that the differences were correlated with the values of measurement and the waviness was also correlated with the values of the measurements.

Another explanation for the difference might be the occurrence of voids in the region of the deepest points. These voids may be created by the Empress stylus or the stylus opened voids that were already present in the material due to the manual fabrication of the specimens. The detailed analysis of some of the specimens with discrepancies revealed such voids, which were obviously not detected by the mechanical sensor. The high deviations between the mechanical sensor and the optical sensors measured in the material with the highest wear (Chromasit, >500 µm vertical loss) may be due to the fact that the tracing arm is not correctly guided over the wear facet with deep wear, which was observed during the scanning process. This results in an uncontrolled slipping down movement with inaccurate measurements.

The differences of the data of the present study compared to those of the study by Mehl may be explained by the following points: (1) When using the mechanical sensor, Mehl used a lateral displacement of 25 µm compared to 50 µm in the present study, which might have resulted in a higher accuracy of the sensor; (2) the wear facets were quite different to those of the present study, as they included less steep angles, broader facets, less waviness of the surface and less vertical loss, which altogether might have resulted in a higher accuracy of the mechanical sensor; (3) Mehl did not use the matching software that was used in the present study.

Conclusions

- All three sensors were suitable for the quantification of wear (volume and vertical loss) generated on flat samples. The ranking of the materials was practically not influenced by the quantification method.
• Irrespective of the quantification method, both volume and vertical loss were highly correlated with each other, thus making it unnecessary to measure both variables for screening materials for wear resistance.

• For volumetric wear the mechanical sensor measured consistently higher volumes than the optical sensors, while for the maximal vertical loss the mechanical sensor measured consistently lower values.

• The data acquisition with the Laserscan 3D is far more rapid than with the mechanical sensor or the FRT MicroProf. However, the Laserscan 3D requires the fabrication of plaster replicas.

References


