Digital wear analysis of different CAD/CAM fabricated monolithic ceramic implant-supported single crowns using two optical scanners

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Abstract

Purpose: To digitally evaluate the volumetric wear of four different implant-crown materials and their antagonists after artificial aging using an intraoral scanner (IOS) device and a laboratory desktop scanner. Materials and Methods: A total of 48 implants were restored with monolithic crowns divided according to restorative material: lithium disilicate (LDS), zirconia (ZR), polymer-infiltrated ceramic network (PICN), and porcelain fused to metal (PFM). Each specimen was scanned using a desktop scanner (LAB; iScan D104, IMETRIC 3D) and an IOS (TRIOS 3, 3Shape) before and after chewing simulation (1,200,000 cycles, 49 N, steatite antagonist, 5°C to 50°C). The obtained STL files were superimposed, and the volumetric loss of substance of the crowns and their antagonists was quantified (Materialise 3-matic). Kruskal-Wallis, Spearman rho, and paired t tests were used to analyze the data (α = .05). Results: The means of volume loss for each restorative material varied between 0.05 ± 0.06 mm³ (ZR with IOS) and 3.42 ± 1.65 mm³ (LDS with LAB). The wear of the antagonists was significantly lower (P < .05) for ZR than the other groups. Increased wear of the crowns was highly correlated with increased wear of their antagonists (rₛ = 0.859). When comparing the wear measurement using the two scanning devices, no difference in mean volume loss was found (IOS: 1.81 ± 1.81 mm³; LAB: 1.82 ± 1.78 mm³) (P = .596). Conclusion: Polished ZR was the most wear-resistant material and the least abrasive to the respective antagonist among the tested ceramics. For the quantification of wear, this IOS device can be used as an alternative to desktop scanners. Int J Prosthodont 2021. doi: 10.11607/ijp.7430

Introduction

Wear is defined as the deterioration or loss of substance by continuous use¹. As the human teeth are in use on a daily basis, the wear of dental tissues such as enamel and dentine is of relevance². Apart from natural tooth substance, the wear behaviour of dental materials is of
great interest to ensure their longevity and stability of the antagonist dentition. This assumes a particular importance when restoring dental implants. As previously reported, the reduced proprioception of an implant may lead to higher forces during function and possibly higher wear of the reconstruction and their antagonists ³–⁵.

Traditionally, implant-supported restorations were fabricated with a metallic framework and veneered with a porcelain or glass-ceramic, also known as porcelain-fused-to-metal (PFM) restorations. Newer fabrication methods using computer-assisted designing and computer-assisted manufacturing (CAD/CAM) led to the introduction of new glass- and oxide-ceramic materials, which offer improved material strength and allow for the production of monolithic ceramic restorations ⁶. Such types of restorations can be bonded to titanium inserts or titanium bases, and are directly screw-retained on the implants. Their popularity is growing as they provide a simplified fabrication method and might offer good mechanical stability ⁷–⁹. However, there seems to be little evidence on the wear of the implant-borne monolithic restorations bonded to titanium inserts.

In the past, the wear of dental substances and restorations was evaluated visually either intraorally or on a cast plaster model ¹⁰–¹³, which tends to be subjective ¹⁴. A more objective evaluation was introduced with the invention of computer-controlled measuring devices, which allowed analysis in an indirect laboratory setting. For this, an impression and replica of the respective site were made, and thereafter scanned for analysis. This indirect methodology comes with several drawbacks such as the amount of time necessary for scanning or the need for fabrication of replicas when analysing in-vivo ¹⁵. Furthermore, the process might introduce errors during impression taking or replica casting and, therefore, reduce the accuracy of the wear analysis ¹⁶.

The scanning of an object with an industrial optical scanner could provide a more time- and cost-efficient method to assess a volume change in all three dimensions. With the evolution of optical scanning technologies in recent years, such lab-side scanners were shown to achieve a scanning resolution of below 10 µm ¹⁷,¹⁸. While this trueness is still inferior to the
established profilometry techniques, it may be high enough to evaluate the annual wear of enamel (average of 30 \( \mu m \)) or restorative materials (eg. 20 \( \mu m \) for monolithic zirconia).

In a clinical setting, the possibility to monitor the wear of both dental substances and dental restorations is highly desirable. The notion to use intraoral scanning (IOS) devices for the quantification of dental wear is therefore enticing, especially since the newer generation of scanners show a trueness close to that of their lab-side counterparts. Some recent publications show first advancements to use intraoral scanners and compare-software to evaluate wear. Yet, there is no consensus on a standardised fully digital workflow for measuring dental wear that can be applied both in-vitro and in-vivo.

Therefore, the aim of the present study was to digitally evaluate the volumetric loss of substance of 4 different implant-restorative materials and their antagonists after artificial aging and chewing simulation. As a second objective, the use of an intraoral scanning device for wear analysis was validated by comparing it to an industrial laboratory desktop scanner.

The null hypotheses were: 1) the restorative material does not influence the volumetric loss of substance of crowns and respective antagonists after artificial aging; 2) the type of scanning device does not influence the volumetric loss of substance outcome.

**Material and methods**

A total of 48 implant-supported single crowns were divided into 3 test groups and 1 control-group (n=12), according to the restorative material (Table 1): 1) lithium disilicate (LDS) (e.max CAD, Ivoclar Vivadent); 2) zirconia (ZR) (Lava Plus, 3M ESPE); 3) polymer-infiltrated ceramic network (PICN) (VITA Enamic, VITA Zahnfabrik); 4) porcelain-fused-to-metal (PFM, control group) (Esteticor CC, Cendres&Métaux + VITA VM13, VITA Zahnfabrik). The sample size was defined based on the number of specimens necessary to test the mechanical stability of the different materials. The detailed information is presented in a previous publication.
The regular-diameter bone-level type implants with an internal conical connection of 7.5° (CONELOG, diameter 4.3 mm, length 13 mm; Camlog Biotechnologies GmbH, Basel, Switzerland) were embedded according to ISO standard 14801. The implants in the test groups were restored with identical CAD/CAM-fabricated monolithic crowns bonded to titanium base abutments (CONELOG Titanium Base for CAD/CAM, Camlog Biotechnologies GmbH, Switzerland), while in the control group manually casted and veneered crowns were fabricated on a gold-abutment (CONELOG Gold-Plastic Abutment, Camlog Biotechnologies GmbH, Switzerland). After milling, all the crowns of the test groups were either crystallized (LDS), sintered (ZR) or left unaltered (PICN). In order to keep all specimens identical, no glaze layer was applied onto the ceramic materials. The metallic framework for the crowns of the PFM group was cast using the lost-wax technique and a precious metal alloy (Estheticor CC, Cendres+Metaux SA., Switzerland). After casting, a compatible feldspathic veneering ceramic was applied (VITA VM13, VITA Zahnfabrik, Germany). A detailed description of the specimen preparation is reported in a previous publication.

After mounting, the crowns were high gloss polished according to the restorative materials properties. For group LDS, a sequential polishing kit (OptraFine ceramic polishing kit, Ivoclar Vivadent, Lichtenstein) was used. The coarse grit finisher was followed by the fine grit polisher and the high gloss polisher along with its diamond polishing paste (HP paste, Ivoclar Vivadent, Lichtenstein). Each crown was polished for 2 minutes using a handpiece at 15’000 rpm. For group ZR, diamond polishing discs of three descending grain sizes were used (StarGloss diamond polisher for ceramic, Edenta dental, Au, Switzerland) for 30 seconds each at 15’000 rpm. For high gloss polishing, a diamond polishing paste (Dura-Polish DIA, Shofu inc., Kyoto, Japan) along with a Robinson brush was used for 30 seconds at 15’000rpm. For group PICN, a dedicated polishing set to the respective material was used (VITA Enamic Polishing set technical, VITA Zahnfabrik, Germany). Each polisher was used according to the manufacturer’s instruction (pre-polisher for 1 minute at 8’000 rpm with low contact pressure; high-gloss polisher for 1 minute at 6’000 rpm with low contact pressure).
For group PFM, the veneered crowns were polished using diamond polishing discs (StarGloss diamond polisher for ceramic, Edenta dental, Switzerland) and then a final firing was performed.

After polishing, all specimens were cleaned with isopropanol and air-dried (Fig.1).

Data acquisition

The specimens were powdered according to the manufacturers recommendations (30-cm distance, short bursts) with a thin layer of scanning powder (Helling 3D, Helling GmbH, Heidgraben, Germany) to avoid optical imprecisions caused by the different light refraction of the tested materials during the scanning process. Each specimen was scanned using a desktop reference scanner (LAB) (IScan D104i, Imetric 3D, Courgenay, Switzerland) with a reported precision by the manufacturer of less than 10 µm. A calibration of the scanner was performed directly before scanning all specimens. Furthermore, the ball-shaped steatite antagonists were scanned using the same protocol. Additionally, each specimen was scanned with a handheld optical scanner designed for intraoral use (IOS) (TRIOS 3, 3Shape A/S, Copenhagen, Denmark). The scanning was done using the scan pathway recommended by the manufacturer for all specimens, starting on the palato-incisal edge area and then capturing the palatal, interproximal and vestibular areas.

After the scanning, the specimens and antagonists were cleaned using steam evaporation and alcohol and submitted to the aging. After the aging was complete, the same scanning protocol was repeated for all the surviving specimens and respective steatite antagonists.

Chewing simulation

The specimens were artificially aged using simultaneous thermocycling (5° to 50°C, dwelling time 120 seconds) and mechanical loading (1,200,000 cycles, 49 N, 1.67 Hz) to simulate 5
years of intraoral use. As an antagonist to simulate natural human enamel ball-shaped steatite with a diameter of 6 mm was used in the chewing simulator (CS-4.9, SD Mechatronic, Feldkirchen, Germany). According to ISO 14801, the specimens were loaded at a 30° angle to the implant long axis. The steatite indenter was placed 2 mm below the incisal edge on the palatal aspect of the crowns and the vertical displacement of the indenter was set to 1 mm per chewing cycle.

**Wear Analysis**

The obtained STL files of each specimen before and after aging were cropped at the implant-abutment interface with an industrial inspection software (GOM Inspect, GOM GmbH, Braunschweig, Germany) to facilitate superposition. The modified STL data pairs were then transferred into a 3D modelling software (3-matic, Materialise, Leuven, Belgium). The data was superimposed using a local-best-fit protocol applied to the untouched outer surfaces of the crowns. After superimposition, an area of approximately 24 mm² involving the indentation was selected and the volumetric loss of substance between the STL files was quantified (3-matic, Materialise, Belgium) (Fig. 2). The same protocol was used to analyse the STL data obtained from the intraoral scanning (IOS) device. Furthermore, the scanning data from the steatite antagonists (LAB) before and after aging was treated with the same software protocol to quantify the volume loss of the simulated tooth structure.

**Statistical analysis**

The data of the volumetric loss of substance was computed in a statistical software (IBM SPSS Statistics v22; IBM Corp, NY, USA). The normality of the data was analysed with Shapiro-Wilk, and as one group (ZR) did not present normal distribution, Kruskall-Wallis test followed by the Dunn-Bonferroni adjusted post-hoc test was performed to compare the groups. Spearman’s Rho test was used to correlate the values measured on crowns and on
antagonists. A paired t-test assessed differences of volumetric loss of substance between
the scanning devices. The significance level was set at $\alpha = 0.05$ for all tests.

**Results**

Specimens which did not survive to the entire artificial aging procedures were excluded from
the present analysis, as they did not represent the same aging time and were, thus, not
comparable to the remaining specimens. Reasons of failure are reported in a separate
publication 26. Therefore, 12 (LDS), 8 (ZR), 7 (PICN) and 11 (PFM) samples could be
analysed. The means of volume loss for each restorative material varied between 0.05±0.06
mm$^3$ (ZR with IOS) and 3.42±1.65 mm$^3$ (LDS with LAB) (Table 2, Fig. 3). When the volume
loss of the crowns was measured with intraoral scanning device (IOS) no significant
differences were found between PFM and LDS ($p \geq 0.05$), however the remaining
comparisons revealed to be significantly different ($p < 0.05$). For the laboratory desktop
scanner (LAB), the differences of the wear given in median values were statistically
significant among all groups ($p < 0.05$). The volume loss of the antagonists was significantly
lower ($p < 0.05$) for ZR than the other groups, while no differences were detected among the
remaining groups ($p \geq 0.05$) (Fig. 4). Augmented wear values of the crowns were highly
correlated to augmented wear of their respective antagonists ($r_s = 0.859$).

When comparing the wear measurements of the specimens using the two scanning devices,
no difference of the mean volume loss was found (IOS: 1.81±1.81 mm$^3$, LAB: 1.82±1.78
mm$^3$) ($p = 0.596$) (Fig. 3).

**Discussion**

This investigation showed, that different restorative materials exhibited different
amounts of wear and also led to different wear of antagonists. Independent of the analysis
method, zirconia revealed the least wear volume, followed by PICN, while lithium disilicate
and PFM resulted in higher loss of substance. Furthermore, the antagonists presented a significantly less wear when opposed to zirconia, as compared to opposing the other materials. Thus, the first null hypothesis was rejected. Moreover, no differences of the outcomes were found when the two scanners were compared. Therefore, the second null hypothesis could not be rejected.

In terms of restorative material wear, polished zirconia exhibited the least amount of wear in the present study. This result is in accordance with other in-vitro studies investigating wear of ceramics \(^{36-38}\). A systematic review investigating in-vitro wear of polished monolithic zirconia showed minimal wear behaviour of both the material and the antagonist \(^{39}\). The standardization of in-vitro conditions might contribute to these outcomes, as an ideal polishing protocol can be achieved. Furthermore, short-term clinical evidence also confirms minimal material wear of polished zirconia \(^{40-42}\). In the present study, no glaze layer was applied onto the zirconia, as there is evidence that glaze negatively affects wear behaviour when compared to polished zirconia \(^{37,38}\). The occlusal surface of a zirconia restoration ideally should remain unglazed but high-gloss polished, while glaze can be used on the oral and buccal walls for aesthetic purposes \(^{41}\).

The lithium-disilicate and PFM crowns showed extended amount of volume loss in the areas of functional loading, in contrast to others in-vitro \(^{42-44}\) and in-vivo \(^{45-48}\) studies that revealed reduced wear for these materials. A possible explanation for the increased wear of lithium-disilicate in the present study might be the timing of the polishing protocol that was used or the absence of a glaze firing. In this study, the specimens were polished only after crystallization and it can be hypothesized that an additional polishing at an uncrystallized stage may lead to a smoother surface finish once crystallized. The surface topography plays an important role, as an initially rough material surface may lead to increased antagonist wear and roughness which in turn may lead to more wear of the restorative material. A study investigating the effect of different polishing protocols showed a high surface roughness for lithium-disilicate after crystallization firing. However, the authors were able to polish the
lithium-disilicate material to a very smooth surface using a similar polishing protocol to the one used in the current study. Nevertheless, the increased wear in the current study may suggest that the smooth surface obtained after polishing cannot be maintained after continuous mechanical loading. This hypothesis is in accordance with a recent study that showed a significant increase in surface roughness of lithium-disilicate after aging and cyclic wear testing, as well as increased antagonist wear. Regarding the omission of a glaze firing, it has been suggested that the smoothness of the glaze layer is lost quickly after intraoral use or occlusal adjustment. According to the manufacturer, the application of a glaze layer is optional, while an approach by solely polishing the reconstruction is also approved. For standardisation purposes, only the polishing procedure was applied in the present study.

In the current study, the PICN presented less wear than the lithium-disilicate or PFM materials. These results are controversial and partly in contradiction to previous investigations. The reduced hardness of PICN would justify an increased wear when compared with glass ceramic materials. However, some authors also report findings suggesting decreased wear of hybrid ceramics when compared with glass ceramics. It may be hypothesized that the internal structure of the PICN material is not homogenous and that differences in microstructure lead to the highly differing results. This assumption, however, needs to be evaluated in future research.

It has been reported that high ceramic hardness is correlated to higher antagonist wear. However, a systematic review on the subject found that the surface topography (e.g., roughness) of the ceramic material is of greater importance than the material strength in regards to antagonist wear. The results in the present study support previous findings, indicating that unglazed but high gloss polished zirconia leads to decreased antagonist wear. There was no difference in terms of antagonist wear between the other materials tested in the present study. However, the relatively low wear of the PICN crowns is opposed by the increased wear of its antagonists. This result is in accordance with a recent study showing
good restorative material stability but increased antagonist wear \(^{54}\). Other authors have also found that the hybrid nature of this material leads to an increased surface roughness after aging \(^{51}\) and chewing simulation \(^{50}\). A reason for this could be that the organic polymer matrix is less resistant during function, and therefore leaves the ceramic microstructure exposed which in turn leads to wear of the antagonist.

Most interestingly, in this present study, no difference between the two scanning devices was found. It must be stated however, that these findings might not be generalized to larger scanning areas (e.g. full arch), or other LAB/IOS devices. It has been shown that smaller objects (e.g. single restorations) can be digitized more precisely due to lower accumulation of errors \(^{21}\). Nonetheless, a recent review on measuring wear of dental materials highlighted the advantages of direct IOS devices compared to indirect replica techniques \(^{59}\). It may be hypothesized that clinical monitoring of dental wear could help to establish the presence of parafunctional activity, reveal undesired excessive occlusal contacts or follow patients with an active medical condition (e.g. bulimia). Furthermore, the collection and assessment of such data should be as quick and cost-efficient as possible so it may be used routinely. Previous authors analysed the sensitivity of intraoral scanning devices for measuring early erosive wear \(^{60}\). While the average loss of dental substance due to erosive destruction was minimal (10 \(\mu\)m) and therefore difficult to reliably monitor, larger defects above that threshold could be detected consistently \(^{60}\). Other authors have also stated that intraoral scanners may be considered a viable clinical tool to monitor wear \(^{24}\).

Lastly, with further evolution of the IOS technology, the accuracy and viability for monitoring wear with intraoral scanning devices is expected to increase.

Still, profilometry has been shown to be a highly accurate means and may be considered the golden-standard technique to map the surface topography of a given object \(^{61}\). In this study, a methodology using optical scanners was applied instead of profilometry, which may be considered as a limitation of this investigation. However, a recent study compared white light profilometry with intraoral scanning and found the differences to be
within the expected inaccuracy of measurement \(^{24}\). Another possible limitation of the present study is the use of steatite to simulate human enamel. In the literature, several different antagonist materials next to steatite are reported, such as human enamel \(^{62,63}\), bovine enamel \(^{53,64}\) and stainless steel \(^{65}\). While steatite has been described as being more porous and thus more abrasive than human enamel \(^{66}\), it is still widely used by many authors \(^ {30-33}\). An important aspect is the fact that steatite allows for standardisation of the antagonist, whereas human enamel samples are inherently different from each other.

This study evaluated the wear behavior of different restorative materials, however, other mechanical properties as fracture resistance, color stability or bonding capability may also play a decisive role on the material selection for implant-borne restorations supported by titanium bases. The evolution of intra-oral scanning technology and the possibility for direct in-vivo measurements may present new opportunities to assess wear in future clinical research. A validation of this methodology when applied to larger scanning areas may be as well necessary.

**Conclusion**

Polished zirconia was the most wear resistant material and the less abrasive to the respective antagonist among the tested ceramics. For the quantification of surface wear, IOS devices can be used as an alternative to laboratory / desktop scanners. Clinical monitoring of wear using IOS devices will, hence, gain in importance in the future.

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References


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<table>
<thead>
<tr>
<th>Group</th>
<th>Material</th>
<th>Product name</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDS</td>
<td>Lithium disilicate glass ceramic</td>
<td>IPS e.max CAD, Ingots A16S</td>
<td>Ivoclar Vivadent (Schaan, Liechtenstein)</td>
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<td>ZR</td>
<td>Tetragonal zirconia</td>
<td>Lava Plus, Disc 98S-25</td>
<td>3M ESPE (St. Paul, MN, USA)</td>
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<td>PICN</td>
<td>Polymer infiltrated ceramic network</td>
<td>VITA Enamic, Ingots IS-16S</td>
<td>VITA Zahnfabrik (Bad Säckingen, Germany)</td>
</tr>
<tr>
<td>PFM</td>
<td>Palladium-based precious metal alloy</td>
<td>Esteticor CC</td>
<td>Cendres&amp;Métaux (Bienne, Switzerland)</td>
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<tr>
<td></td>
<td>Feldspathic ceramic</td>
<td>VITA VM13, powder &amp; liquid</td>
<td>VITA Zahnfabrik (Bad Säckingen, Germany)</td>
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**Table 1: Specification of the restorative materials used.**

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<th>Scanning device</th>
<th>Restorative materials (mm³)</th>
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<td></td>
<td>LDS</td>
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<td>Crown</td>
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<td>3.42 ± 1.65</td>
</tr>
<tr>
<td>IOS</td>
<td>3.40 ± 1.65</td>
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<tr>
<td>Antagonist</td>
<td></td>
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<tr>
<td>LAB</td>
<td>1.45 ± 0.54</td>
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**Table 2: Means ± SD of the wear according to restorative material and scanning device.**
Fig. 1: Prepared specimens before artificial aging. From the left: Specimen of group PFM, LDS, ZR and PICN.

Fig. 2: Digital wear analysis. a) superimposition of the initial scan (grey), the scan after chewing simulation with LAB (blue) and IOS (red). b) isolation of the volume of interest c) lateral view of the volume loss.
Fig. 3: Boxplot of the volume loss of the specimen according to restorative material.

Different uppercases represent a statistical difference between restorative materials for LAB scanner, while different lowercase represent a statistical difference between restorative materials for IOS scanner (p < .05).

Fig. 4: Boxplot of the volume loss of the steatite antagonist with respective restorative material. Different letters represent a statistical difference between restorative materials (p < .05).