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Original Article

In vitro wear of four ceramic materials and human enamel on enamel antagonist

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Running title: Wear of four ceramics and enamel

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In vitro wear of four ceramic materials and human enamel on enamel antagonist
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Abstract

The purpose of the present study was to evaluate the wear of four different ceramics and human enamel. The ceramics used were lithium disilicate glass (e.max Press), leucite-reinforced glass (GN-Ceram), yttria-stabilized zirconia (Aadva Zr), and feldspathic porcelain (Porcelain AAA). Hemispherical styli were fabricated with these ceramics and tooth enamel. Flattened enamel was used for antagonistic specimens. After 100,000 wear cycles of a two-body wear test, the height and volume losses of the styli and enamel antagonists were determined. The mean and standard deviation for eight specimens were calculated and statistically analyzed using a non-parametric (Steel-Dwass) test ($\alpha = 0.05$). GN-Ceram exhibited greater stylus height and volume losses than Porcelain AAA. E.max Press, Porcelain AAA, and enamel styli showed no significant differences, and Aadva Zr exhibited the smallest stylus height and volume losses. The wear of the enamel antagonist was not significantly different among GN-Ceram, e.max Press, Porcelain AAA, and enamel styli. Aadva Zr resulted in significantly lower wear values of the enamel antagonist than GN-Ceram, Porcelain AAA, and enamel styli. In conclusion, leucite-reinforced glass, lithium disilicate glass, and feldspathic porcelain showed wear values closer to those for human enamel than did yttria-stabilized zirconia.

Keywords: Wear, Ceramics, Enamel

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Introduction

Dental ceramics have been widely used in prosthodontic treatments to satisfy the aesthetic demands of patients (1). Computer aided design/computer assisted manufacturing (CAD/CAM) systems use a variety of ceramic blocks, such as lithium disilicate glass, leucite-reinforced glass, and yttria-stabilized zirconia. Also, there is a heat-press fabrication system that uses a custom block made of lithium disilicate glass (2,3). These ceramic materials have better mechanical properties, especially flexural strength and fracture toughness, when compared to feldspathic porcelains (4,5).

Wear between ceramic restorations and tooth substrates at the occlusal contact area is of great concern to many clinicians. Some dental porcelains are not the material of choice because of their abrasiveness (6-9). Reduction of opposing tooth substrates from abrasive restorative materials may cause broken incisal anatomy, tooth hypersensitivity or unbalanced occlusion (10). Enamel wear caused by antagonistic enamel and ceramic crowns has been investigated in vivo (11-15). Although such clinical studies are useful, they are also time consuming. Therefore, it is important to preclinically estimate which types of materials are suitable for opposing teeth as a crown restoration.

Several wear testing methods have been developed in order to investigate the wear characteristics of restorative materials (16,17). The wear of enamel against porcelains in a three-body wear test was much smaller than that in a two-body wear test (18). Zirconia exhibited less enamel wear than porcelain and lithium disilicate glass (19). Lithium disilicate glass was not only resistant to wear, but was also wear friendly to enamel antagonist surfaces (20). In a previous study using bovine enamel, no significant difference was found between the wear values for opposing enamel caused by lithium disilicate glass and enamel (21). A glazed porcelain caused more antagonist enamel wear than polished zirconia (22). An experimental fine and nano-scale-crystal-sized leucite glass reduced tooth wear (23).
However, the available information on the wear of enamel/leucite-reinforced glass, enamel/lithium disilicate glass, and enamel/enamel pairs was limited. A systematic study was desired in order to compare wear characteristics between various ceramics and an enamel antagonist by means of the same simulation method, as opposed to fragmentary information. Objective data comparing enamel-to-ceramics (24-26) and enamel-to-enamel wear (27,28) are preclinically useful for choosing an occlusal material for restoratives.

The purpose of the present study was to evaluate the wear of four different ceramics (leucite-reinforced glass, lithium disilicate glass, yttria-stabilized zirconia, and feldspathic porcelain) and human enamel, as well as the wear of opposing enamel by means of a two-body wear simulation. The null hypothesis was that there would be no difference in the wear of the ceramics and enamel.

**Material and methods**

**Preparation of stylus head**

The materials used in the present study are listed in Table 1. A 3.175-mm (1/8-inch) diameter hemispherical tip made of stainless steel was used for the master model of the stylus head. The shape of the master model was duplicated with two CAD/CAM systems (GN-Ceram and Aadva Zr), a lost-wax and heat-press system (e.max Press), and a powder/liquid porcelain firing system (Porcelain AAA). The stylus heads were polished with a polishing paste (Zircon-Brite, Dental Ventures of America, Corona, CA, U.S.A.) and a felt wheel. As a control, the cusps of extracted human molar teeth were ground with custom-shaped rotary instruments (Carborundum Point, Shofu, Kyoto, Japan) to standardize the stylus head (22), and were then polished with silicone mounted polishing points (M2 and M3, Shofu). Before wear testing, a representative stylus head for each test group was observed with a color laser...
3D profile microscope (VK-8500, Keyence, Osaka, Japan), and the arithmetic average roughness (Ra) was determined.

**Wear test**

Two-body wear tests were carried out using a wear-testing device (Higuchi, Nagasaki, Japan) according to a method developed at the University of Alabama (18,29-34). The proximal surface of human premolar teeth was ground flat with 2000 grit silicon carbide paper and was used for enamel antagonist. As the stylus head vertically contacted the enamel-antagonist surface in water, it rotated clockwise 15° (with increasing load up to 75 N), and then counter-rotated to the starting position (Fig. 1). In this test, 100,000 wear cycles were applied with a frequency of 1.2 Hz. Eight specimens were fabricated for each test group.

The worn surfaces were subjected to multiple scans by color laser profile microscopy (VK-8500, Keyence) at a magnification of 100×, and the height and volume losses of the stylus and enamel antagonist were determined. The height losses of the stylus and the enamel antagonist were defined as the distance from the original surface of the specimen to the deepest point of the indentation generated by the wear test. The volume loss of the stylus was calculated as follows (29) (Fig. 2):

\[
\text{Volume loss of stylus} = \pi/6 \times h \left(3c^2 + h^2\right)
\]

\[
c = \sqrt{h(2r-h)}
\]

\[h: \text{height loss of stylus head}\]
\[r: \text{radius of stylus head} = 1.5875 \text{ mm}\]

The volume loss of the enamel antagonist was determined using analysis software (VK shape analysis application VK-H1W, Keyence).

**Statistical analysis**
The mean and standard deviation for eight measurements of Ra on one sample were calculated. After the homoscedasticity assumption was confirmed through Levene’s test, Ra values were analyzed by ANOVA at a statistical significance of 0.05.

The mean and standard deviation for eight specimens were calculated for the wear values (height and volume losses of the stylus and enamel antagonist). After the homoscedasticity assumption was analyzed by Levene’s test, the wear values were compared using a non-parametric (Steel-Dwass) test at a statistical significance of 0.05.

**Scanning electron microscopy**

After completion of the wear tests, a replica of the specimen surface was made using a polyvinylsiloxane impression material (Exafine, GC, Tokyo, Japan) and an epoxy resin (Diemet-e, Erkodent Erich Kopp, Pfalzgrafenweiler, Germany). The surfaces were sputter coated with gold (Ion Coater IB-3, Eiko Engineering, Mito, Japan) and then observed using scanning electron microscopy (SEM; S-3500N, Hitachi, Tokyo, Japan) at a magnification of 50×.

**Results**

The Ra values of all stylus heads were not statistically different (Table 2). The maximum height loss of the stylus was obtained for the GN-Ceram, e.max Press, and enamel styli, and the values were not significantly different. Although no significant differences were found between the e.max Press, Porcelain AAA, and enamel styli, GN-Ceram exhibited significantly greater height loss ($P = 0.0491$) and volume loss of the stylus ($P = 0.0082$) as compared to Porcelain AAA. Among the styli that were evaluated, Aadva Zr exhibited the minimum height and volume losses.
The height losses of the enamel antagonists against the GN-Ceram, e.max Press, Porcelain AAA, and enamel styli exhibited no significant differences (Table 3). There were no significant differences between Aadva Zr and e.max Press, but Aadva Zr exhibited significantly lower values than the GN-Ceram (P = 0.0117), Porcelain AAA (P = 0.0117), and enamel styli (P = 0.0166). The use of the Aadva Zr stylus resulted in the smallest volume loss of the enamel antagonist. No significant differences were detected among the GN-Ceram, e.max Press, Porcelain AAA, and enamel styli.

In a series of representative SEM images of worn stylus surfaces, GN-Ceram, e.max Press, and Porcelain AAA exhibited a clear edge wear facet, whereas Aadva Zr and enamel did not (Fig. 3). GN-Ceram exhibited the coarsest surface with concentric wear patterns, followed by e.max Press and Porcelain AAA. GN-Ceram and e.max Press exhibited a small convex bump at the center of the wear surface. No clear facet was observed on the contact area of the Aadva Zr stylus. The worn surface of the enamel stylus was smooth, and exhibited a small concave dimple centered within the peripheral wear facet.

With regard to the worn surfaces of enamel antagonists, GN-Ceram exhibited the coarsest surface, with a concentric wear pattern (Fig. 4). GN-Ceram and e.max Press exhibited a small concave dimple centered within the peripheral wear facet. Enamel antagonists against e.max Press and Porcelain AAA exhibited concentric wear patterns, whereas the worn surface of Aadva Zr was smooth and quite small. The area worn by the enamel stylus was smooth and exhibited a small convex dimple centered within the peripheral wear facet.
Discussion

The present study revealed that the substrates of the styli (leucite-reinforced glass, lithium disilicate glass, yttria-stabilized zirconia, feldspathic porcelain, and human enamel) influenced the wear loss of the stylus and enamel antagonist. Therefore, the null hypothesis was rejected.

In vivo enamel-to-enamel wear has been reported to be 38 μm over 1 year (11) or 10 μm over 6 months (14). The wear loss of enamel over 3 years in the molar region (105 μm) was more than that in the premolar region (54 μm) (12). Accordingly, the 107-μm height loss of the enamel stylus against the enamel antagonist at 100,000 wear cycles could be converted to approximately 3 years in the molar region.

The wear of other material combinations was also evaluated in accordance with the method validated in the literature (18,36). The in vitro wear test can be regarded as a tool for comparing the loss of restorative materials and the enamel antagonist in a shorter period than that required for a clinical study. In the wear test, 100,000 wear cycles at 1.2 Hz took approximately 23 hours. A force of 75 N was used, based on a report that this is similar to a typical biting force (34).

Standardization of the enamel by grinding preparation influenced the wear properties (19,24,25). We standardized the enamel cusp without modifying the cusp tip in order to quantify enamel wear and minimize the changes in the wear properties based on a previous study (22). As a result (Table 2), the standard deviations for the enamel stylus were relatively high, which is in agreement with in vivo observations (12). Although the variations of enamel may be overcome using control materials such as steatite (25), the microstructure of enamel is essentially different from that of isotropic materials.

Fabrication of a replica is a useful technique for decreasing artifacts, such as cracks that occur when cutting and evacuating an enamel specimen for SEM observation. In addition,
the replica method enables repeated observation of a worn surface for any number of wear cycles without damaging the stylus head (18).

GN-Ceram contained leucite (K$_2$O·Al$_2$O$_3$·4SiO$_2$) in a glass matrix and was characterized by the high crystallinity of the leucite (71%) (4). The surface texture of the styli changed during the wear test (Figs. 3a and 4a). The reason that GN-Ceram exhibited the coarsest surface with concentric wear patterns may be that the leucite crystals possess higher wear resistance than the glass matrix.

Generally, feldspathic porcelains contain leucite crystals, cracks, and voids in the glass matrix, and their worn surfaces became rough and abrasive (9). Interestingly, the enamel antagonist against Porcelain AAA exhibited concentric wear patterns (Fig. 4d), but the worn porcelain AAA stylus was smooth (Fig. 3d). This suggests that fragments from the porcelain contribute both to the wear of the ceramic itself and to the creation of third-body abrasive particles (22,35). Therefore, we speculate that third-body abrasive particles of porcelain, rather than the porcelain itself, ground the enamel surface.

The wear loss of enamel by e.max Press was equivalent to that of enamel-to-enamel wear in vivo (13) and to that reported for an in vitro study using a sliding wear test (17). These reports are supported by the present data, indicating that the wear values of e.max Press-to-enamel and enamel-to-enamel wear exhibited no significant difference. Numerous several-micron-length needle-like crystals of lithium disilicate (Li$_2$Si$_2$O$_5$) exist in the e.max Press ceramic (2). The complex microstructure of lithium disilicate with glass and the crystalline needles plow and deform the enamel surface, resulting in an abrasive surface (Fig. 3b), and enhanced friction (3). The concentric wear pattern on the enamel surface (Fig. 4b) may have resulted from the crystalline needles of e.max Press.

The enamel wear against polished yttria-stabilized zirconia is lower than that against enamel cusp (27,28). Yttria-stabilized zirconia caused less wear on the antagonistic enamel
than a feldspathic porcelain and e.max Press (19). The present results for enamel wear against Aadva Zr, enamel, Porcelain AAA, and e.max Press agree with the results in these reports.

An ideal material possesses the same wear resistance as enamel and has no potential to abrade the opposing tooth structure (35,36). Aadva Zr appeared to have a much higher wear resistance than enamel and no potential to excessively abrade opposing enamel. GN-Ceram, e.max Press, and Porcelain AAA exhibited similar wear resistance to human enamel and abraded opposing enamel as much as the enamel stylus. The high standard deviations for enamel-to-enamel wear suggest that the living body will tolerate some variation of wear characteristics, but yttria-stabilized zirconia seems to exceed this tolerance. Therefore, a speculation that may be added to the literature is that the ideal material should not exceed the tolerance of natural tooth enamel.

The physical and microstructural characteristics, chemical degradation, and surface roughness of ceramics affect wear between ceramics and enamel (9). For example, yttria-stabilized zirconia ground with 100-µm diamond bur caused higher enamel antagonist wear than polished zirconia (26). Furthermore, a number of factors, including food, saliva, pellicle, tooth position, occlusion, biting force, sliding, parafunction, and bruxism, influence intraoral wear (14,17,36-38). The in vitro wear testing used in the present study does not reflect all of the factors that clinically occur. Therefore, long-term clinical data will be required in order to clarify the wear for different ceramics and an enamel antagonist in the future. When ceramic restoratives and adjacent intact teeth support the occlusal force together, clinicians should periodically carefully examine the wear facet.

Within the limitations of the present study, the following conclusions are drawn. Leucite-reinforced glass (GN-Ceram), lithium disilicate glass (e.max Press), and feldspathic porcelain (Porcelain AAA) exhibited wear values comparable to human enamel. The wear
resistance of Porcelain AAA against enamel was higher than that of GN-Ceram. Yttria-stabilized zirconia (Aadva Zr) exhibited the greatest wear resistance and the lowest abrasion of the enamel antagonist.

Conflicts of interest – The authors declare no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References


**Figure legends**

*Fig. 1.* Schematic diagram of the wear-test device used in the present study.

*Fig. 2.* Schematic diagram of the stylus head used in the calculation of volume loss.

*Fig. 3.* Scanning electron micrographs of worn stylus surfaces after 100,000 wear cycles. a: GN-Ceram, b: e.max Press, c: Aadva Zr, d: Porcelain AAA, e: enamel.
Fig. 4. Scanning electron micrographs of worn surfaces of enamel antagonists after 100,000 wear cycles. a: for GN-Ceram, b: for e.max Press, c: for Aadv Zr, d: for Porcelain AAA, e: for enamel.
Table 1  
*Materials and tooth enamel used for stylus head.*

<table>
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<tr>
<th>Name (Color)</th>
<th>Abbreviation</th>
<th>Type of ceramic</th>
<th>Manufacturer</th>
<th>Lot No.</th>
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<tr>
<td>GN-Ceram Block (A3)</td>
<td>GN-Ceram</td>
<td>leucite reinforced glass</td>
<td>GC,</td>
<td>1107291</td>
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<tr>
<td>IPS e.max Press Ingots (LT A3)</td>
<td>e.max Press</td>
<td>lithium disilicate glass</td>
<td>Ivocler Vivadent AG,</td>
<td>R78685</td>
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<td></td>
<td></td>
<td>Schaan, Liechtenstein</td>
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<tr>
<td>Aadva Zirconia Disk (ST)</td>
<td>Aadva Zr</td>
<td>yttria-stabilized zirconia</td>
<td>GC</td>
<td>1112011</td>
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<tr>
<td>Super Porcelain AAA (E3)</td>
<td>Porcelain AAA</td>
<td>feldspathic porcelain</td>
<td>Kuraray Noritake Dental,</td>
<td>0D318</td>
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Table 2

*Arithmetic average roughness (Ra) of stylus head before wear test, and loss of stylus after wear test.*

<table>
<thead>
<tr>
<th>Stylus head</th>
<th>Ra Mean (SD)</th>
<th>Height loss (µm) Mean (SD)</th>
<th>P value*</th>
<th>Volume loss** (mm³) Mean (SD)</th>
<th>P value</th>
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<td>GN-Ceram</td>
<td>0.5 (0.1)a</td>
<td>152.8 (15.4)a</td>
<td>0.0083</td>
<td>0.11 (0.02)a</td>
<td>0.0083</td>
</tr>
<tr>
<td>e.max Press</td>
<td>0.4 (0.1)a</td>
<td>142.0 (26.0)ab</td>
<td>0.0491</td>
<td>0.10 (0.03)ab</td>
<td>0.0083</td>
</tr>
<tr>
<td>Aadva Zr</td>
<td>0.5 (0.2)a</td>
<td>6.1 (3.2)</td>
<td>0.0082</td>
<td>0.23×10⁻³ (0.18×10⁻³)</td>
<td>0.0082</td>
</tr>
<tr>
<td>Porcelain AAA</td>
<td>0.6 (0.2)a</td>
<td>93.6 (29.2)b</td>
<td>0.0315</td>
<td>0.05 (0.03)b</td>
<td>0.0315</td>
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<tr>
<td>enamel</td>
<td>0.5 (0.1)a</td>
<td>107.4 (79.2)ab</td>
<td></td>
<td>0.08 (0.08)ab</td>
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Identical letters in each column indicate values that are not statistically different (p>0.05).

*P values of different pairs determined by non parametric (Steel-Dwass) comparison (P<0.05).

**Approximate values calculated from height loss of stylus.
Table 3

*Loss of enamel antagonist after wear test.*

<table>
<thead>
<tr>
<th>Stylus head</th>
<th>Height loss (µm)</th>
<th>Volume loss (mm³)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>P value*</td>
</tr>
<tr>
<td>GN-Ceram</td>
<td>196.9 (46.4)a</td>
<td>0.0117</td>
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<tr>
<td>e.max Press</td>
<td>133.9 (35.7)ab</td>
<td>0.33 (0.12)a</td>
</tr>
<tr>
<td>Aadva Zr</td>
<td>104.6 (24.3)b</td>
<td>0.07 (0.03)</td>
</tr>
<tr>
<td>Porcelain AAA</td>
<td>186.0 (40.7)a</td>
<td>0.0166</td>
</tr>
<tr>
<td>enamel</td>
<td>184.3 (42.4)a</td>
<td></td>
</tr>
</tbody>
</table>

Identical letters in each column indicate values that are not statistically different ($p>0.05$).

*P values of different pairs determined by non parametric (Steel-Dwass) comparison ($P<0.05$).
c: radius of worn surface
h: height loss of stylus head
r: radius of stylus head