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Wear behavior between zirconia and titanium as antagonist on fixed dental prostheses

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Short title: Wear between titanium and zirconia antagonist
Abstract

The aim of this in vitro study was to investigate the wear behavior of the abrader when tetragonal zirconia polycrystal (TZP), cp-titanium (CpTi) and Ti-6Al-4V alloy (TiAlV) were used for the antagonist on fixed dental prostheses. Both hemisphere abrader specimen and flat substrate specimens were prepared using TZP, CpTi and TiAlV. Two-body wear tests were performed in distilled water, and wear volume of the abrader specimen was measured to evaluate the wear behavior. In addition, a scanning microscopic observation and an electron probe micro-analysis were performed to elucidate the underlying mechanism of the wear. The wear volume of CpTi and TiAlV abrader specimen showed approximately twenty times larger than that of TZP abrader specimen against all substrate specimens. This is due to the differences in hardness between the ultra-hardness of TZP and comparatively low hardness of CpTi and TiAlV. The wear volume of CpTi and TiAlV abrader specimen against TZP substrate was significantly smaller than CpTi and TiAlV substrates despite the hardness of TZP was much larger than those of CpTi and TiAlV. This phenomenon may be based on the adhesive wear mechanism. Elements of Ti, Al and V originating in the TiAlV substrate were detected adhering to the abrader CpTi specimen. These results suggest that fixed dental prostheses of CpTi and TiAlV are susceptible to wear against not only TZP but also CpTi and TiAlV in contrast to TZP fixed dental prostheses.

Key words: two-body wear, antagonist, zirconia, TZP, titanium, fixed dental prostheses
1. Introduction

Tetragonal zirconia polycrystals (TZP) are widely used in the dental field as materials for fixed dental prostheses (FDPs) due to their white color, mechanical and chemical properties. Though TZP frameworks have been veneered with translucent feldspathic or glass ceramic materials for esthetics, the chipping in the veneering materials was frequently reported [1].

In order to overcome the chipping problem, it is possible today to produce TZP for FDPs without veneering ceramic, called monolithic TZP reconstructions. It is also reported that the monolithic TZP reconstructions had less enamel wear characteristics compared to porcelain antagonist [2-4]. In addition, the manufacturing costs could be reduced by automatic designing and milling to a full-anatomical contour by computer-aided design and manufacturing (CAD/CAM) technologies. The technique-sensitive veneering process would no longer be necessary, thus guaranteeing a more consistent quality of the restorations. Accordingly, monolithic TZP reconstructions with only polishing have been used even though opaque (non-translucent) TZP. Several manufacturers offer the TZP materials that improved the esthetic by adding coloring pigments [5].

Utilizing of cp-titanium (CpTi) and Ti-6Al-4V alloy (TiAlV) has been also increasing for FDPs as the alternative material of precious alloys. In addition, CpTi and TiAlV has been used as the superstructure of oral implant system, because FDPs with the same composition as the fixture (implant body) materials could be avoid the galvanic action between the superstructure and fixture with using the dissimilar metals for each.

However, one concern associated with the use of monolithic TZP is the possible abrasiveness of CpTi and TiAlV on the restorations for FDPs. When these materials were used for the antagonist, excessive wear could occur. In particular, as severe wear of FDPs made from CpTi and TiAlV is expected when TZP is used as an antagonist due to large differences in hardness between the two types of material. This has raised serious concern that
the wear may lead to metal allergy originating in metal-wear debris [6-9] when these materials used for the FDPs. Therefore, the wear behavior between TZP and CpTi (TiAlV) as an antagonistic material on the FDPs would be of interest clinically.

Concerning the human enamel wear, several investigators have demonstrated that, in general, dental ceramic substrates cause greater abrasive wear of human enamel compared with dental alloys [10-12], even though the wear mechanism is unclear. However, less is also known about the wear behavior of TZP for dental applications. While some basic studies of zirconia–zirconia combinations have shown catastrophic wear [13], others have demonstrated excellent wear resistance [14, 15], mainly due to different test conditions. Recently, it was reported the wear behavior of TZP against CpTi and/or TiAlV under the assumption of wear between TZP implant abutments and Ti retaining screws [16]. They reported that CpTi and TiAlV were more susceptible to wear by both TZP and CpTi (TiAlV) in contrast to TZP. This report, however, did not evaluate the wear behavior of antagonists for FDPs. Furthermore, there were no reports about the wear behavior between TZP and titanium as an antagonist on FDPs.

The aim of this in vitro study was focused on the wear behavior of the abrader when the TZP, CpTi and TiAlV were used for the antagonist on FDPs using a two-body wear test.

2. Experimental details

2.1. Materials

Three kinds of materials, yttria-stabilized tetragonal zirconia polycrystal (Y-TZP, TZ-3YB-E, sintered density of 6.07g/cm³, Tosoh, Tokyo, Japan), commercially pure titanium (CpTi, grade 4, Tokyo Titanium, Saitama, Japan) and Ti-6Al-4V alloy (TiAlV, grade 5, Tokyo Titanium, Saitama, Japan) were used in this study as shown in Table 1. Each material was used for the abraders or the substrates that was corresponding to abraders as shown in Figure1-b and Figure 2-a.
2.2 Making of the abrader specimen

The abrader specimen with cylinder in shape having one hemispherical end (10 mm in length and 5 mm in diameter with a radius of curvature of 5 mm) was prepared using a CAD/CAM machine (DENTAL CAD/CAM GN-1, GC, Tokyo, Japan). These specimens were finally polished with 6-μm diamond pastes.

2.3 Making of the substrate specimen

Disks of 13 mm in diameter and 1 mm in thickness were prepared as the substrate specimens, and these specimens were also polished with 6-μm diamond pastes. Both abrader and substrate specimens showed mirror-like surfaces with less than 0.1 μm of surface roughness (Ra).

2.4 Wear test and measurement of abrader wear volume

Wear tests were performed using an experimental wear simulator as shown in Figure 1 according to pervious study [16, 17]. As seen in Figure 2a, each abrader specimen was moved back and forth on the substrate specimen over a distance of 3 mm for 30,000 cycles at a speed of 90 cycles /min and with a vertical load of 10 N. The test was carried out at room temperature with distilled water circulated through a water chamber in order to remove abrasion debris.

After 30,000 cycles of wear test, the worn surfaces of abrader specimens were observed using a scanning microscope (SEM, SU-6600, HITACHI, Hitachi, Japan) as shown in Figure 2b. Subsequently, the wear area (S) of the abrader specimen was measured using an image analyzer (HDS-N1, HIROYA, Tokyo, Japan), finally the wear volume (V) was calculated (Figure 2c). Five specimens were used for each combination.
2.5 Electron probe micro-analysis (EPMA)

A characteristic X-ray image analysis of the abrader specimens was performed to identify abraded particles that had adhered to the abrader specimens from the substrate specimens using an electron probe micro-analyzer (EPMA, JXA-8200, JEOL, Tokyo, Japan).

2.6 Statistical analysis

For the statistical analysis, an analysis of variance (ANOVA) was used for the wear volume in the wear test, followed by the Scheffe test for a post hoc comparison between groups.

3. Results

3.1 SEM observation of worn surfaces of abrader specimens

Representative SEM images of worn surfaces of abrader specimens are shown in Figures 3-5.

When TZP was used as abrader specimens (Figure 3), comparatively small circles caused by the wear against TZP, CpTi and TiAlV substrates were observed under low magnification (left). Small grains that were originated by a row material of the TZP were randomly observed under high magnification (right, arrows).

When CpTi was used as the abrader specimens (Figure 4), the diameter of worn surfaces was larger than that of TZP abraders (Figure 3), and the wear morphologies were altered depending on the substrate specimens. In addition, the peripheral morphology of the abraded circles was different against between TZP substrate and CpTi substrate, that is, a very sharp periphery was recognized when TZP was used as the substrate specimen (arrow in Figure 4 upper). On the contrary, when CpTi was used as the substrate specimen (arrow in Figure 4 middle), irregular peripheries were observed, suggesting that some fractions of the substance had been pulled off.
When TiAlV was used as the abrader specimens (Figure 5), the wear morphologies had a same tendency as the CpTi abrader specimen, despite the size of abraded circle was larger than CpTi abrader.

3.2 Wear volume of abrader specimens

The wear volume of abrader specimens against various substrate specimens were shown in Figure 6 and 7. Significantly small wear area was recognized in TZP abraders compared to CpTi and TiAlV abraders. The wear behavior of substrate specimens showed the same tendency as those of abrader specimens except the comparative large wear volume on TiAlV abrader compared to CpTi abrader against TZP substrates.

Figure 6 shows wear volume of TZP abrader specimens against various substrate specimens. A quite small wear volume was recognized against all substrates, and no significant difference in wear volume was recognized among the substrates.

Figure 7 shows wear volume of CpTi and TiAlV abrader specimens against various substrate specimens. The wear volume of CpTi and TiAlV abraders showed approximately twenty times larger than those of TZP abrader specimen (Figure 6). The wear volume of CpTi and TiAlV abraders against TZP substrate was significantly smaller than against CpTi and TiAlV substrates (P<0.05). The wear volume of TiAlV abrader specimen showed the large wear volume same as that of CpTi abraders. The wear volume of TiAlV abrader specimen against TZP substrate was significantly smaller than against CpTi and TiAlV substrates (P<0.05).

Table 2 shows multiple comparisons between groups on the wear volume of abrader specimens. The wear volumes of TZP abraders were significantly smaller than those of CpTi and TiAlV abraders. The wear volumes of CpTi and TiAlV abraders against TZP substrates were significantly smaller than those against CpTi and TiAlV substrates.
3.3 EPMA analysis

Characteristic X-ray images of the worn surface of the TZP abrader specimen against CpTi substrate are shown in Figure 8. Optical image of TZP abrader specimen with black-colored staining after wear test is also given in the Figure 8. Ti element was identified as abraded particles that had adhered to abrader specimens from the CpTi substrate (arrows). Figure 9 shows characteristic X-ray images of the worn surface of the CpTi abrader specimen against TiAlV substrate. Elements of Al and V as well as Ti originating in the TiAlV substrate were detected adhering to the CpTi abrader specimen (arrows).

4. Discussion

The aim of this study was to estimate the wear behavior when the TZP and titanium (Ti and Ti alloy) were used for the antagonist on fixed dental prostheses (FDPs) using a two-body wear test.

In this study, the wear behavior was evaluated by estimating the wear volume of the abrader specimen as the antagonist according to the previous reports [2-5]. Silva et al. evaluated the volumetric loss of lithium disilicate glass-ceramic and TZP restorations in *in vivo* study [18]. Kim et al. also evaluated the wear volume of the abrader specimens using feldspathic porcelain cusp as well as the cusp of the premolar teeth in *in vitro* study [2]. Accordingly, the use of abrader specimen with hemisphere is considered to be beneficial for evaluating the wear behavior between antagonists.

TZP abrader specimen showed quite a small wear volume against all substrate specimens in this study. In contrast, the wear volume of CpTi and TiAlV abrader specimen showed approximately twenty times larger than those of TZP abrader specimen against all substrate specimens. This is considered mainly due to the differences in hardness between the TZP and
CpTi (TiAlV) that have the hardness (Hv) of 1356, 177 and 256 on TZP, CpTi and TiAlV, respectively [16]. This indicates that the operating mechanism of wear between the CpTi (TiAlV) and the TZP was abrasive wear due to the ultra-hardness of the TZP.

In the present study, the wear volume of CpTi and TiAlV abrader specimen against TZP substrate was significantly smaller than CpTi and TiAlV substrates despite the hardness of TZP was much larger than those of CpTi and TiAlV. These phenomena can be explained by the adhesive wear mechanism [19]. Adhesive wear appears when two bodies slide over each other, or are pressed into one another, which enhances material transfer between the two surfaces. In the contact, fragments of one surface are pulled off and adhere to the other, due to the strong adhesive interaction between two surfaces with similar physicochemical properties such as metal to metal [20, 21]. This supposition is supported by the differences in the coefficient of friction between the materials used in this study. The previous study revealed that the coefficient of friction between CpTi and CpTi showed a higher value than the CpTi/TZP combination, showing that a strong adhesive interaction had occurred on the CpTi/CpTi combination [16]. This is also supported by SEM observation of the worn surfaces on CpTi/CpTi combination (Figure 4, lower left, arrow), in which irregular shapes at peripheral morphology had resulted from eroded particles from the substrate specimens adhering to the abrader specimens.

Another underlying mechanism can be linked to the microstructure of TZP. The grain size of the TZP is less than 0.5µm with a homogenous distribution of crystal sizes and orientations. The grain size is an important parameter, which determines the surface topography and the tribological behavior of the materials. The fine grain size of TZP may lead to very smooth surfaces after polishing, leading to its lower susceptibility to the antagonist wear behavior.

In the present study, the comparative large wear volume on TiAlV abrader specimen
was shown compared to CpTi abrader specimen against TZP substrates. Though the reason for these results is still unclear, the existence of β phase in the TiAlV is possibly responsible for the abrasion behavior in contrast to homogeneous structure of CpTi.

In the EPMA analysis, Ti element was detected on TZP abrader specimen when CpTi was used as the substrate. In addition, elements of Al and V originating in the TiAlV substrate were detected adhering to the CpTi abrader specimen, showing that the worn particles of CpTi and TiAlV had attached to the opposite specimens, which would represent a hazard to health from the presence of metal particles. On the other hand, the TZP was less susceptible to wear by either TZP or titanium. Thus, it would be better to carry out metal-free restoration using TZP in FDPs in order to successfully avoid metal allergy originating in worn particles.

In the present study, we used opaque (non-translucent) monolithic TZP that has been increased for using as the FDPs without veneering ceramics due to the less enamel wear characteristics compared to porcelain antagonist. However, using a translucent TZP is more appropriate in the interest of aesthetic dental treatments. Further study is necessary to clarify the wear behavior using a translucent TZP instead of conventional opaque TZP that is used in this study.

In this study, the wear behavior of the hemisphere abrader specimens was evaluated assuming the cusp abrasion on the FDPs. However, in order to elucidate of the wear phenomena, both contacting surfaces should be analyzed. The wear behavior of the substrate specimens was evaluated previously under the assumption of wear between TZP implant abutments and titanium retaining screws on the dental implant treatment [16]. The results of the present study showed the same tendency as those of the previous study except the comparative large wear volume on TiAlV abrader compared to CpTi abrader against TZP substrates in the present study. Accordingly, it is confirmed by both previous and present study that the operating mechanism of the wear CpTi/TZP combination was abrasive wear,
whereas that of CpTi/ CpTi combination was adhesive wear.

The two-body wear test was used to evaluate the wear behavior in this study. However, this test method does not truly simulate the clinical chewing situation. The wear behavior using the chewing simulator with thermo-mechanical loading and simultaneous thermal stress should be addressed [5].

In conclusion, the results in the present study showed that titanium FDPs (CpTi and TiAlV) are susceptible to wear against not only TZP but also CpTi and TiAlV in contrast to TZP fixed dental prostheses. It should be noted that the wear volume of 0.53 mm$^3$ on CpTi abrader against CpTi substrate is equivalent to 190 µm of cusp height reduction on the FDPs, which may influence a vertical dimension on the occlusion. Therefore, the results of this study may provide useful information to clinical application of zirconia and titanium fixed dental prostheses from the point of view of the cusp abrasion.

**Acknowledgments**

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**References**


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Figure Legends

Figure 1 (a) Experimental wear simulator.  
(b) Higher magnification of areas shown in rectangle in (a).

Figure 2 (a) Schematic illustrations of the wear test.  
(b) Wear area (S) of the worn surface of abrader specimen observed with SEM  
(c) Wear volume (V) of abrader specimen.

Figure 3 Representative SEM images of worn surfaces of abrader specimens (TZP) against various substrates.

Figure 4 Representative SEM images of worn surfaces of abrader specimens (CpTi) against various substrates.

Figure 5 Representative SEM images of worn surfaces of abrader specimens (TiAlV) against various substrates.

Figure 6 Mean wear volume of TZP abrader specimen against various substrate specimens.  
Standard deviations are shown by error bars.  
Identical letters indicate no significant difference (p>0.05).

Figure 7 Mean wear volume of CpTi and TiAlV abrader specimens against various substrate specimens.  
Standard deviations are shown by error bars.  
Different letters indicate significant difference (p<0.05).

Figure 8 Characteristic X-ray images of the worn surface of the TZP abrader specimen against CpTi substrate. Optical image of TZP abrader specimen with black-colored staining after wear test is also given in the Figure.

Figure 9 Characteristic X-ray images of the worn surface of the CpTi abrader specimen against TiAlV substrate.
Table 1 Materials used in this study

<table>
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<th>Material</th>
<th>Manufacturer</th>
<th>Composition (mass%)</th>
<th>Code</th>
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<td>Ti-6Al-4V alloy</td>
<td>Tokyo Titanium</td>
<td>Ti: balanced, Al: 6.2, V: 4.2</td>
<td>TiAlV</td>
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Table 2  Multiple comparisons between groups on the wear volume of abrader specimens

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Abrader/Substrate,  -: NS, *: P<0.05, **: P<0.01
Figure 1  (a) Experimental wear simulator
(b) Higher magnification of areas shown in rectangle in (a)
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