Wear at the Titanium-Zirconia Implant-Abutment Interface: A Pilot Study

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**Purpose:** The purpose of this study was to use a clinical simulation to determine whether wear of the internal surface of a titanium implant was greater following connection and loading of a one-piece zirconia implant abutment or a titanium implant abutment. **Materials and Methods:** Two implants received zirconia abutments and two received titanium abutments. The implants were secured into four fiber-reinforced epoxy resin disks that had been prepared to receive the internal-connection implants. The assemblies were cyclically loaded off-axis for a total of 1,000,000 cycles. At various intervals, the abutments were removed, photographed, examined using scanning electron microscopy (SEM), and returned to the implants for further testing. The area of titanium transfer from the implants to the abutments observed in the SEM images was quantified using image analysis software. **Results:** The method was able to quantify the area of material transferred to the abutments. There was considerably more wear associated with the zirconia abutments, but the rate of wear slowed after about 250,000 cycles. Parabolic curves were fit to the data. The projected mean ± standard deviation maximum area (wear) values associated with the titanium and zirconia abutments were $15.8 \pm 3.3 \times 10^3 \mu m^2$ and $131.8 \pm 14.5 \times 10^3 \mu m^2$, respectively, and this difference was statistically significant ($P = .0081$). **Conclusions:** The implants with the zirconia abutments showed a greater initial rate of wear and more total wear than the implants with the titanium abutments following cyclic loading. The amount of titanium transfer seen on the zirconia abutment increased with the number of loading cycles but appeared to be self-limiting. The clinical ramifications of this finding are unknown at this time; however, the potential for component loosening and subsequent fracture and/or the release of particulate titanium debris may be of concern. Int J Oral Maxillofac Implants 2011;26:970–975

**Key words:** cyclic loading, fatigue testing, fretting wear, implant abutment, implant-abutment interface, titanium, zirconia

Titanium dental implants are an effective means of replacing teeth in the oral cavity.\textsuperscript{1} Restoring implants in the anterior region of the mouth presents many esthetic challenges, including the discoloring effect of the titanium implant abutment beneath translucent gingival tissue. A recent study demonstrated that discoloration occurs when the soft tissue thickness is 2.0 mm or less.\textsuperscript{2} Some clinicians have attempted to overcome this problem by applying porcelain to cast gold alloy abutments.\textsuperscript{3} Implant manufacturers have addressed this problem with ceramic implant abutments, which do not result in gray discoloration of the gingival tissues.\textsuperscript{4} Ceramic abutments are primarily used in the anterior region of the mouth, but they have also been used in the premolar region with success.\textsuperscript{5} Clinical survival studies of ceramic abutments have shown clinically satisfactory performance at 2 to 5 years.\textsuperscript{6}

One popular material for fabrication of ceramic implant abutments is 3-yttrium–stabilized tetragonal zirconia polycrystals, also referred to as zirconia. This white ceramic has a flexural strength above 1,000 MPa and an elastic modulus greater than 200 GPa.\textsuperscript{7} Currently, there is limited information in the dental literature on the mechanical characteristics of zirconia abutments and their interface with titanium implants. One study described a median fracture resistance of 443.6 N,\textsuperscript{8} with the main mode of failure being abutment and abutment-crown fracture. This level of fracture resistance is only slightly higher than the anterior bite force,
which has been reported to range between 90 and 370 N.\textsuperscript{9} Another study examined the implant-abutment interface of titanium and ceramic abutments after dynamic loading.\textsuperscript{10} Scanning electron microscopy (SEM) was used to measure the implant-abutment microgap after 47,250 cycles, and there was no significant difference in the width of the microgap between the two types of abutments. Another study examined the wear effects of dynamically loaded external-connection titanium implants with loosened ceramic abutments. This paper was descriptive and showed that wear does occur between the components. No attempt was made to quantify the amount or pattern of wear.\textsuperscript{11} Intuitively, wear at a zirconia-titanium interface would be expected because of the significant difference in the mechanical properties of each material. Zirconia is about 10 times harder than titanium, based on the Knoop hardness scale,\textsuperscript{11} and has about twice the strength.

Designs of zirconia abutments vary greatly and would also be expected to affect any wear at the interface with the implant. Some zirconia abutments use a titanium core that attaches the implant and abutment through a titanium-to-titanium connection. Other zirconia abutments are one-piece designs that create a zirconia-to-titanium interface.

Because these differences in mechanical properties and designs could lead to wear, it is important to characterize wear at the interface between titanium implants and zirconia abutments. One approach could be to study the abrasion of flat surfaces and focus on the mechanisms of wear. Alternatively, a clinical simulation would allow for examination of materials and designs with actual components. The current authors found no quantitative investigations of the effects of cyclic loading on wear at the titanium-zirconia interface in the literature. Accordingly, the purposes of this study were to develop a clinical simulation method to quantitatively evaluate abrasion at the titanium-zirconia implant-abutment interface and to evaluate this behavior as a function of the number of loading cycles.

**MATERIALS AND METHODS**

Four internal-connection titanium implants (grade IV, 4.5 × 9 mm, Astra Tech) were embedded in separate 25-mm reinforced epoxy resin disks (NEMA G10 Rod, Piedmont Plastics). The resin has an elastic modulus of about 20 GPa, similar to that of bone, and has been used in previous clinical simulations of implant loading.\textsuperscript{12} Two types of abutments were secured to the implants: grade IV titanium abutments (3-mm TiDesign, Ref 24236, Lot 57854, Astra Tech) and zirconia abutments (3-mm ZirDesign, Ref 24708, Lot 56737, Astra Tech). Two samples of each abutment type were tested. The abutments were torqued to 25 Ncm, as recommended by the manufacturer. After tightening, the disks were marked so that the abutments could be returned to the same position after each stage of testing. The abutments were examined at 200 × magnification with a tabletop SEM (TM-1000, Hitachi Technologies).

**Mechanical Testing**

The specimens were attached to the loading platform of a fatigue testing instrument (Model 3300, EduraTEC ELF) at 30 degrees off-axis (Fig 2). The instrument has a load precision of ± 0.5%. The specimens were loaded with a sinusoidal force of 20 to 200 N at a frequency of 2 Hz. The angle of loading and applied force were representative of a Class I anterior occlusion. The specimens were loaded in six stages—25,000, 25,000 (a second time), 50,000, 150,000, 250,000, and 500,000 cycles—for a cumulative total of 1,000,000 cycles. After each stage, the abutments were carefully disconnected, photographed,

![Representative photographs of the evaluated abutments.](image1)

![Cyclic loading instrumentation showing a zirconia abutment specimen.](image2)
and examined in the SEM. The implant-abutment pairs were then reconnected using the same screws and again tightened to 25 Ncm torque for subsequent testing.

During a normal rebooting of the equipment software, one titanium and one zirconia specimen unintentionally received an excessive load and fractured during the third stage of testing (between 50,000 and 100,000 cycles). Two new implant-abutment specimens were assembled to replace those that were lost. The new implants and abutments came from the same manufacturer’s lot and were identical to the previous components. These replacement specimens were loaded from 0 to 250,000 cycles (through stage four), examined, and then returned to the original loading protocol.

Image Analysis
After each stage of testing, SEM micrographs were taken of an area approximately 0.75 × 1.00 mm in size, adjacent to the reference marks. Image analysis software (Image J, National Institutes of Health) was used to quantify the amount of darkened area in the SEM micrographs. The method requires establishing a threshold between “darkened” and “not darkened.” This was accomplished by examining the particles at higher magnification and setting the threshold to match the known shape. Similar image analysis procedures have been used to establish thresholds in the measurement of cell area.13 The threshold value was maintained within a narrow range for all specimens. Trial runs over this range resulted in only small differences in calculated area. The total “darkened” area was measured on all SEM micrographs. It was assumed that the darkened area was caused by wear of the titanium and referred to as “titanium transfer.”

Statistical Analysis
The means and standard deviations of area of wear were plotted against the number of cycles for both types of abutments. Because of the apparent shape of the data and the potential for soft metals,14 including titanium,15 to exhibit decreasing rates of wear against harder surfaces, parabolic curves were fit to the data using nonlinear regression (Prism 5, Graphpad Software). The goodness-of-fit parameter ($r^2$) was calculated for each abutment type. The maximum wear asymptotically approached by the curves was calculated for each abutment type, and the difference between these two values was evaluated with a t test.

RESULTS

Digital Photographs
Patterns of wear were visible in the digital images. Dark striations were clearly visible on both the zirconia and the titanium abutments after each stage of testing. Images taken after 250,000 cycles are representative (Fig 3). It appeared that the titanium transfer was uniform around the entire perimeter of both the zirconia and the titanium abutments. The grey rings around the zirconia abutments appeared to be consistent in area and darkness. The pattern of titanium deposition appeared heavier closer to the point at which the abutment emerged from the implant shoulder. The increased deposition of titanium with an increasing number of cycles was visually evident, as seen by comparing Figs 1 and 3.

Area of Wear Measured from SEM Images
The SEM micrographs of the zirconia and titanium abutments obtained at baseline showed no dark patterns (Fig 4). After each stage of cyclic loading, the patterns of titanium transfer (wear) were apparent. Micrographs of the abutments after 250,000 cycles clearly show the striations caused by wear (Fig 5).

After the threshold values were established, the area of titanium transfer was readily calculated for all specimens with the Image J software. The means and standard deviations (SDs) for area of wear for both types of abutments at the end of each testing phase and the fitted parabolic curves were plotted in Fig 6. The goodness of fit ($r^2$) of the curves to the data was 0.4772 for titanium and 0.9290 for zirconia. The initial rate of wear was greater with the zirconia than the titanium abutments. There was a distinct slowing of wear with the zirconia abutments after 250,000 cycles. The mean ± SD maximum
values asymptotically approached by the parabolic curves were $15.8 \pm 3.3 \times 10^3 \mu m^2$ and $131.8 \pm 14.5 \times 10^3 \mu m^2$ for the titanium and zirconia abutments, respectively. The difference between these values was statistically significant ($P = .0081$). While the mechanism of wear for each material cannot be confirmed, clearly there was significantly more transfer of titanium onto the zirconia abutments.

**DISCUSSION**

The methodology employed in the present study was able to quantify the wear at the implant-abutment interface. It is not known whether more titanium transfer occurred in the compressive, tensile, or shear areas of the implant-abutment interface. It appeared that the titanium transfer was uniform around the entire surface of the zirconia abutment. The grey rings around the zirconia abutments appeared to be consistent in area and darkness. Although the samples were loaded off-axis, this result was not unexpected because of the tight tolerances of fit and the preload placed on the abutment screw. In future studies, the wear at various locations could be measured and compared.

After each stage of loading, the specimens were removed and examined with SEM. The tabletop SEM was advantageous for this purpose because it did not require sputter coating of the specimens; this would have required separate samples for each stage of testing.
and likely would have decreased the precision of the measurements. The quantitative measurements were made using the SEM images; however, much was learned from the digital images. The titanium deposition on the zirconia abutments was evident in the digital photographs and clearly increased with the number of loading cycles. The pattern of titanium deposition appeared to become denser nearer to the point at which the abutment exited the implant (Fig 3). This may have been a result of the geometry of the internal connection as well as levering action within the system. It was assumed that the darker areas were areas of higher pressure or greater relative motion at the implant-abutment interface.

The results demonstrated increased wear of the titanium implant with the one-piece zirconia abutment. The wear of the titanium implant was evident both macroscopically and microscopically as titanium transfer onto the zirconia abutment. Under higher-magnification SEM examination, it appeared that some of the titanium particles were embedded into the abutments in certain regions, whereas some particles appeared to be superficially resting on the zirconia surface (data not shown). Between stages of testing, the components were carefully disconnected; any touching of the contacting surface was avoided, and there was no apparent loss of any loose wear debris. It is possible that some wear particles were created by torquing of the abutment on and off the implant. However, the small amounts of measured wear during the first three stages of testing and the reasonable ratios of SDs to means (coefficients of variation) of about 10% suggest that any contribution from placement and removal of the abutments was small.

The long-term consequences of wear at the implant-abutment interface are not known. The rate of wear between the zirconia abutment and the implant continually slowed after about 250,000 cycles. Nevertheless, the total wear for the zirconia abutments after $10^6$ cycles was about six times greater than the wear for the titanium abutments. This wear might put the implant/abutment interface at risk for undesirable mechanical changes in the wall of the implant and could eventually lead to abutment loosening or fracture. However, at the present time, because of the relatively young age of these abutments, there is no evidence of a pattern of such clinical problems. The design of the implant-abutment connection in the present study limits mobility. Future studies of various designs would be of interest, particularly those that may have resulted in increased mobility between the implant and the abutment. It should be noted that there was no evidence of screw loosening on any of the abutments throughout the testing period.

This preliminary study demonstrated that the test method produced quantitative data capable of distinguishing the in vitro behavior of the implant-abutment interfaces. Further studies could address questions raised by the present results. In the image analysis, the sensitivity of the area measurement to variations in threshold values could be specifically established. Measuring the roughness of each surface and the coefficients of friction between the mating surfaces would contribute to understanding the mechanism of wear and the observed pattern of decreasing wear with number of cycles. High-magnification examination with the SEM showed that all particles had a similar appearance, which was assumed to be titanium. Had zirconia particles also been present, particles with a different appearance would have been expected. In future studies, surface analysis methods could be used to confirm the chemical composition of the wear debris. Additionally, it would be helpful to establish that all worn material is transferred to the opposing surface and that the area measurement reflects the amount of wear. Finally, having demonstrated the utility of this method, additional studies with larger sample sizes and the elimination of replacement samples would be justified.

The effect of moisture in the oral environment also needs to be examined because it might affect interfacial wear characteristics. An aqueous environment may increase or reduce the amount of wear compared to dry testing. An additional concern is whether particulate titanium abraded from the implant walls could migrate from the connection into the adjacent soft tissues and create a shadow or tattoo of titanium particles in this area. If this were to occur to a significant degree, it could pose a risk of tissue discoloration in the area of the connection, which could become an esthetic complication.

This study examined the effects of wear on implant abutments after up to 1,000,000 cycles. A definite increase in the amount of titanium transfer was observed, and it increased with the number of cycles for both the titanium and the zirconia specimens. The initial rate of wear (up to 100,000 cycles) was 4.5 times greater with the zirconia than with the titanium abutment specimens, and the projected maximum wear was 8.3 times greater ($P = .0081$). It is interesting to note that the hardness of zirconia (1,600 to 2,000 Vickers hardness) is approximately 10 times higher than that of grade 4 commercially pure titanium (258 Vickers hardness).

There should have been no titanium transfer observable on the abutment surface prior to insertion into the implant; however, the SEM image of the baseline zirconia abutment (Fig 4a) showed small dark spots in an evenly distributed pattern throughout the entire surface of the abutment. At high magnification, these particles had a different appearance from those in the wear bands. The authors speculate that these areas were either impurities in the stock zirconia material or they represented debris left from the machining process of the abutment. The intensity and size of these areas were...
within the selected threshold (detection) limits. Values were comparable for all samples and were included in the results for each stage of testing.

The present test method was intended as a clinical simulation to quantify material transfer between implants and abutments of disparate properties. Although the procedure used here did not focus on the mechanism of this wear, the results may provide some insight. There was a good fit of the wear-versus-cycles data of the zirconia abutments to a parabolic curve ($r^2 = 0.9290$). This pattern of a decrease in wear rate is consistent with the well-known industrial practice of using a soft metal as a bearing surface against an opposing harder surface. A similar approach has been suggested for titanium artificial orthopedic joints. In the present study, the titanium implant may have acted as a soft bearing surface. As metal is transferred to the zirconia abutment, a titanium-to-titanium couple may be created with a lower rate of wear. Although wear would be a clinical concern for the reasons stated earlier, a self-limiting mechanism may explain the lack of clinical problems to date.

A titanium abutment connected to a titanium implant served as the control in this experiment. It was hypothesized that the titanium control abutment would not show as much wear as the zirconia abutment, because the interfacing materials had similar physical properties. The results of this experiment show that some wear occurs with a titanium-to-titanium interface; however, it is not comparable to the amount of wear seen with a zirconia abutment. In summary, the wear between a zirconia abutment and a titanium implant was 8.3 times greater than that occurring with a titanium abutment ($P = .0081$). Wear increased initially with the number of loading cycles; however, the rate decreased after about 250,000 cycles. It is uncertain what long-term clinical effect this may have on implant-supported restorations utilizing zirconia abutments. Further investigations of this phenomenon are necessary to provide a better understanding of the interaction of dissimilar interfacing materials in dental implant systems.

CONCLUSIONS

1. A clinical simulation and image analysis methodology was developed to quantitatively measure material transfer at the implant-abutment interface, although the accuracy of this wear method will need to be confirmed independently.
2. The zirconia abutment caused more implant wear than the titanium abutment under cyclic loading conditions. This was apparent through photographic and microscopic evidence of titanium transfer from the implant to the zirconia abutment.
3. The amount of titanium transfer seen on the zirconia abutment initially increased with the number of loading cycles, but then the rate of wear decreased.

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REFERENCES