Zirconium implant abutments: Fracture strength and influence of cyclic loading on retaining-screw loosening

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Objective: The purpose of this study was to determine the fracture strength of zirconium implant abutments and the torque required to unfasten the retaining screw before and after applying cyclic loading to the implant-abutment assembly. The dynamic behavior and stress distribution pattern of zirconium abutments were also evaluated. **Methods and Materials:** Static and cyclic loading of seven XiVE implants with straight Cercon zirconium abutments were simulated under worst-case conditions. Cyclic loading tests were performed via a servohydraulic dynamic testing machine at loads between 100 and 450 N, for up to 5 million loading cycles, at 15 Hz. The dynamic behavior of the zirconium abutments was analyzed by finite element modeling and Pro/Mechanica software, comparing van-der-Mises and maximum stress levels. **Results:** Cercon zirconium-ceramic abutments exhibited a maximum fracture strength of 672 N during static loading, and 269 N at 800,000 to 5 million cycles runout point, and 403 N at 10,000 cycles runout point during cyclic loading.[Au: Please clarify what is meant by "runout point" (in text also).] The mean torque value required to unfasten the abutment retaining screws was 20.86 Ncm ± 1.07 before cyclic loading and 19.71 Ncm ± 1.11 after loading with up to 5 million cycles. Although the torque values decreased minimally, the difference was statistically significant. However, screw loosening did not occur. FEM analysis displayed higher stress peaks up to 1,000 N at the cervical aspect of the zirconium abutment and at the apical third of its retaining screw at an external load of 250 N. **Conclusion:** Within the limitations of this study, zirconium implant abutments exceeded the established values for maximum incisal bite forces reported in the literature, and tightly fit into the titanium implant after several millions of loading cycles. *(Quintessence Int 2006;37:XX–XX)*

Key words: cyclic loading, finite element analysis, fracture strength, screw loosening, zirconium implant abutments

Smile design, restoration durability, and color conformity of natural and replaced teeth are prerequisites for a highly esthetic restoration.

Although metal implant abutments have inherent esthetic disadvantages, they are most widely considered a standard treatment option for implant-supported restorations. Improved material characteristics, complying with clinicians' and patients' increased demands for highly esthetic results, have contributed significantly to the development of a new generation of ceramic abutments.

Yttrium-stabilized zirconium dioxide (Y-TZP) abutments have been noted for their toothlike color, high load strength, tissue tolerability, and intrasulcular design enhancement.[1–5] The phenomenon of transformation toughening of zirconium oxide results in

[Au please provide, affiliation information for each author, including professional title, and address for reprint request (corresponding author), including a fax and/or e-mail address.]

Fig 1 Cercon abutment with hexagonal implant-abutment connection.

extremely high component strength, extraordinary bending and tensile strength, and fracture and chemical resistance.[6,7] To be considered a true alternative, the mechanical and biologic qualities of ceramic implant abutments must be equal to or better than those of widely used titanium abutments. These requirements can be met only by high-performance and biocompatible oxide ceramics.[8–10] Oxide ceramics are equal to metals from a mechanical standpoint, but are biologically stronger.[11–14] However, one exception is the high brittleness of ceramics and their potential to crack. So far, the use of full-ceramic implant abutments for implant restorations has been limited because of this feature.

Abutment and prosthetic loosening of single- and multiple-screw-retained, implant-supported fixed partial dentures is a concern in general. The abutment screw in which the bending starts is assumed to be the weakest link in all-ceramic single-implant restorations.[15] The purpose of this study was to determine the fracture strength of zirconium implant abutments and the torque required to unfasten the retaining screw before and after applying cyclic loading to the implant abutment assembly. In addition, the dynamic behavior and stress distribution pattern of zirconium abutments, using the transient dynamic analysis of finite element modeling (FEM), was evaluated.

METHODS AND MATERIALS

A laboratory study according to the international standards (DIN ISO/WD 14801 Rev (F), International Organization for Standardization) was carried out, simulating the functional loading of an endosseous dental implant body and its abutment components under worst-case conditions.

Straight Cercon zirconium implant abutments (Dentsply/Friadent) were assembled onto seven internally hexed XiVE implants, 4.5 mm in diameter and 18 mm in length (Dentsply/Friadent) (Fig 1).[Au: Original Fig 6 was inserted here. ok?] All implants were embedded into an elastic material (EpoFix, Stuers) with a Young's modulus of 210 GPa.[Au: Has change retained the meaning? ie, Young's modulus of the EpoFix, not zirconium oxide, is 210 GPa?] The top of the implant extended 3 mm above the level of the surrounding material to create a worst-case situation of crestal bone resorption. Spherical caps were fabricated and cemented (TempBond, Kerr) on each zirconium abutment and adjusted to the same 8-mm length. During testing, the spherical cap rested on a flat plate.

The load was applied via a stainless steel rod (pin-loaded using a small center drill point) to withstand external forces and to prevent the rod and the attached holding fixture to deflect too far laterally. Cyclic loading tests were carried out by means of a servohydraulic dynamic testing machine (Instron 8872, Instron) at loads between 100 and 450 N for up to 5 million loading cycles, at 15 Hz. The tests were performed by applying a compression load 30 degrees off the axis of the implant (Fig 2). This resulted in a combination of compression, bending, and shear loads in the device. The tests were performed both statically, for single overload conditions, and in repeated loading, to provide fatigue curves of load versus cycles required to cause failure. The same implant type (XiVE) was used for both the static load tests (0.05 in/min crosshead speed) and the fatigue tests (15 Hz). The torque values required to unfasten the retaining screws were determined with a Tohnichi torque gauge (Tohnichi America).

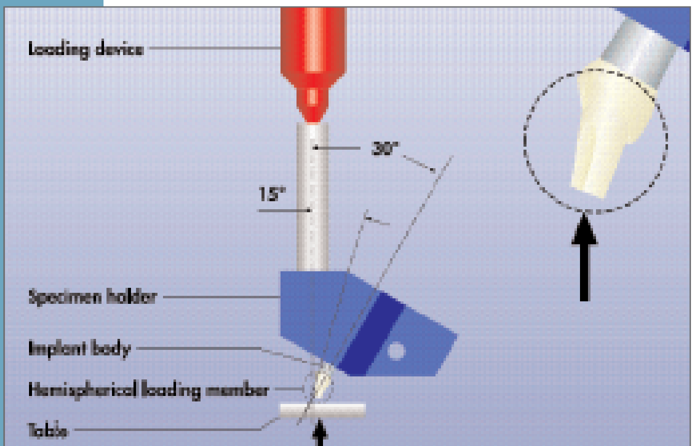

Fig 2 Test setup for cyclic loading by means of servohydraulic dynamic testing. Compression load was applied 30 degrees off the axis of the implant.

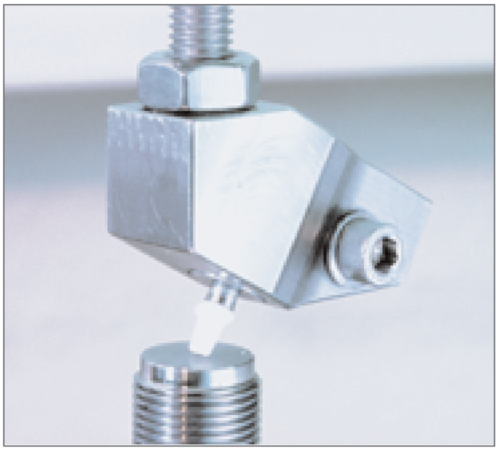

Fig 3 Closeup of dynamic strength testing of the implant–zirconium abutment assembly.

Table 1 **Fatigue testing of zirconium abutments and mean torque value required to unfasten the abutment retaining screw**

Specimen	Cercon abutment Statistical mean (N)	Maximum force (N)	Fracture cycle (n)	Removal torque (Ncm) Before cyclic loading	After cyclic loading
		672			
1	40%	268.8	811,930	23	21
2	40%	268.8	811,023	20	18
3	40%	268.8	905,645	21	20
4	40%	268.8	5,000,000	20	19
5	60%	403.2	10,000	21	19
6	60%	403.2	10,000	20	20
7	60%	403.2	10,000	20	20

[Au: Would you like to show removal torque measurements to the tenth place, as in the text, to be more precise? Also, what do the percentages represent in the abutment column? Is "Statistical mean" referring to 672 N? This relationship is unclear.]

In addition, the dynamic behavior of the zirconium implant abutments was analyzed by transient dynamic analysis of finite element modeling (Fig 3), a software optimization method based on a computer-aided design drawing of the implant-abutment assembly. A mathematic mesh was superimposed onto the drawings of the implant-abutment assembly. Subsequently, a virtual load was chosen according to clinical conditions in the oral cavity. An identical setup was selected for the computer analysis with straight abutments. External loads of 100 and 250 N were applied to the assembly at a 30-degree inclination toward the axis of the implant. FEM was carried out by Pro/Mechanica software (Parametric Technology) comparing van-der-Mises and maximum stress levels obtained from the calculation.

RESULTS

The Cercon zirconium-ceramic abutments investigated in the present study exhibited a maximum fracture strength of 672 N during static loading, and 269 N at 800,000 to 5 million cycles runout point and 403 N at 10,000 cycles runout point during cyclic loading (Table 1).[Au: What is meant by "runout point"? Please revise sentence to clarify.]

The mean torque value required to unfasten the abutment retaining screws was 20.86 Ncm ± 1.07 after initial tightening (before loading) and 19.71 Ncm ± 1.11 after loading with up to 5 million cycles (Fig 4). Although the torque values decreased minimally, the difference was statistically significant (P = .015). However, screw loosening did not occur. The FEM analysis revealed a pattern

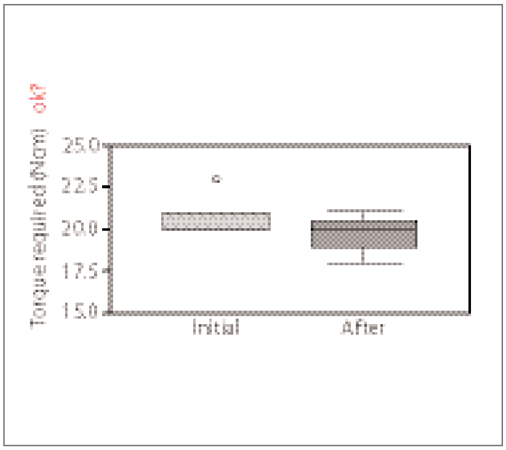

Fig 4 Box-plot values of torque required to unfasten an abutment retaining screw before (initial) and after applying cyclic loading to the implant-abutment assembly. Although the torque values decreased minimally, the difference was statistically significant ($P = .015$).

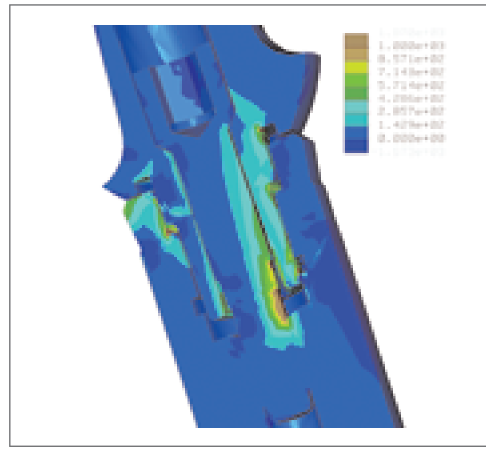

Fig 5 Finite element model of implant–zirconium abutment assembly at an external load of 100 N.

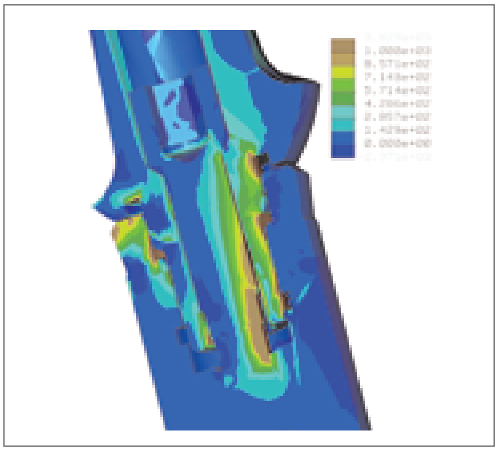

Fig 6 Finite element model of implant–zirconium abutment assembly at an external load of 250 N.

of low, well-distributed stresses along the entire implant-abutment assembly at an external load of 100 N (Fig 5). However, higher stress peaks up to 1,000 N have been shown at the cervical aspect of the zirconium abutment and at the apical third of its retaining screw at an external load of 250 N (Fig 6).

DISCUSSION

The use of zirconium dioxide in implant abutments has been introduced recently because of its high fracture resistance compared to aluminum and other dental ceramics.[16–18] So far, little data is available on the survival rate and average lifetime of zirconium implant restorations.[4,5,19] On investigating the fracture strength of zirconium implant abutments and the effect of cyclic loading on screw loosening, maximal bite forces have to be considered. Research has extensively focused on the bite forces occurring during mastication.[21–24] Apart from individual anatomic and physiologic characteristics, it has been shown that maximal bite forces vary according to the region in the oral cavity. While the greatest bite force was found in the first-molar region, incisors bear only about one-third to one-fourth of that force in the posterior region. Mean values varying from 216 to 847 N for the maximum force level could be shown, whereas smaller values ranging from 108 to 299 N have been reported for the incisal region.[21,22] After intensive investigation, Körber and Ludwig[25] presumed that posterior fixed partial dentures should be strong enough to withstand a mean load of 500 N. It appears feasible to expect a similar minimum permissible value for posterior implant abutments and their restorations.

In addition, a cyclic fatigue pattern and stress corrosion fatigue caused by the oral environment must be considered.[2] In the oral environment, the inherent flaws of ceramic materials have been considered to induce propagation of crack to a critical size. A failure ultimately results from a final loading cycle that exceeds the mechanical capacity of the ceramics. As a rule of thumb, the endurance limit for fatigue cycling that can be applied to dental ceramics is approximately 50% of the maximum fracture strength.[26] Consequently, it is reasonable to demand an initial fracture resistance within a safety range of 650 N for the anterior region and 1,000 N for the posterior region of the maxilla and mandible, to ensure a favorable clinical prognosis of zirconium implant abutments and their all-ceramic restorations. Further in vitro and in vivo studies are necessary to prove that this claim can be transferred to clinical situations.

The zirconium-ceramic abutments investigated in the present study exhibited a maximum fracture strength of 672 N during static loading and 269 N and 403 N during cyclic loading. This provides evidence that Cercon abutments can safely be used in the incisor region of the maxilla and mandible, while caution is recommended in the molar regions. The results comply with the manufacturer's instructions for using the zirconium abutments only in the anterior region of the maxilla and mandible. Cyclic loading simulates the mastication forces under clinical conditions in the most appropriate manner. However, caution must be exercised when extrapolating laboratory data to clinical situations, since multiple in vivo variables are usually excluded from a controlled laboratory study.

It has been assumed that the phenomenon of transformation toughening contributes to this high fracture strength and the "self-repairing" properties of zirconium that prevent crack propagation.[6,7] Zirconium dioxide exists in three crystal conditions, even if the chemical composition is identical.[16] This material characteristic is called *polymorphism*. At temperatures exceeding 2,300°C, zirconium oxide is found as a cubic crystal phase that changes into a tetragonal crystal phase when it cools. Zirconium oxide transforms into a monoclinic phase at temperatures below 1,200°C. The transformation from tetragonal to monoclinic is completed by a volume increase of approximately 3% to 5%. These volume changes will lead to very high inner structure tensions and component fracture. For this reason, oxide additives (eg, magnesium oxide, calcium oxide, or yttrium oxide) are necessary to completely or partially stabilize the high temperature phases (cubic or tetragonal) down to room temperature. This reduces the compression stress within the structure to a controlled level and prevents component destruction while cooling off.

The phenomenon of preventing microcrack propagation, which results from high material tension, is called *transformation toughening*. New zirconium oxide ceramics were developed for different applications. The most significant dental application is the polycrystalline stabilization of zirconium dioxide with yttrium oxide (Y-TZP).[27] Compared to other stabilizing oxides, this is the finest-grained, most densely packed and mechanically highest-grade structure. Transformation toughening and the resulting pseudoelastic reaction is at its maximum if 5 vol% yttrium oxide is added.[28]

Restorations in the esthetically demanding anterior region present significant challenges in both the surgical and prosthetic stages of implant dentistry. Titanium has been established as the material of choice for endosseous implants, resulting in a high degree of predictability. Zirconium ceramic appears to be a suitable material for manufacturing implant abutments with a low bacterial colonization potential.[13,29,30] Ceramic abutments also minimize the gray color associated with metal components showing through the peri-implant tissues. Their durability and color conformity are prerequisites for highly esthetic implant restorations (Figs 7a to 7f).[4,5,31–33] [Au: This seems to be the best place to site these figs. However, since the article is research (not clinically) oriented, please insert a sentence or two about the case in the most appropriate location.]

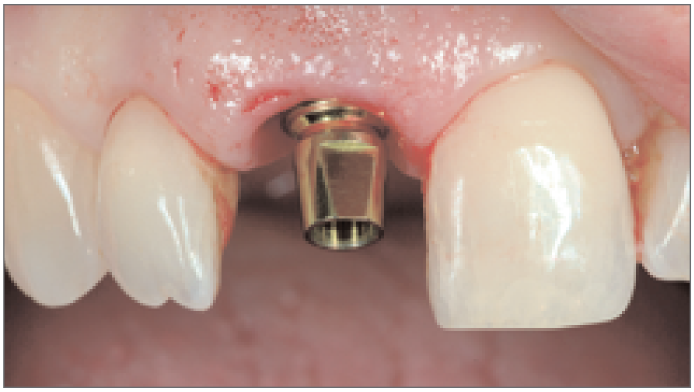

Fig 7a Situation after flapless implant placement. Premounted XiVE TempBase abutment is used as a provisional abutment.

Fig 7b Nonfunctional provisional acrylic resin restoration immediately after implant placement.

Fig 7c Postoperative labial view after 4 months with Cercon abutment in situ.

Fig 7d Postoperative labial view at the time of full-ceramic crown delivery.

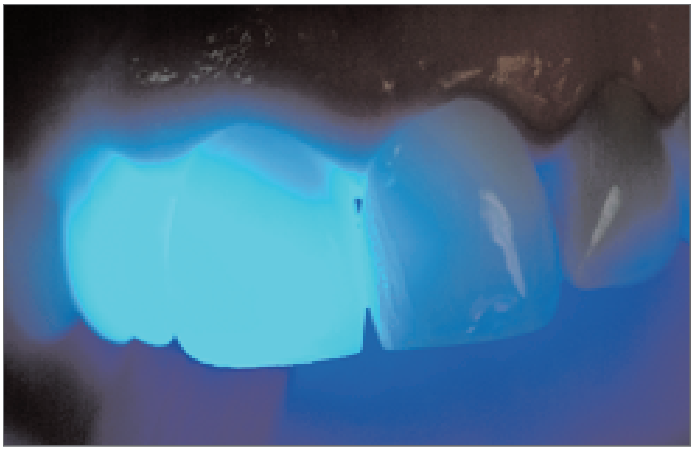

Fig 7e Labial view of full-ceramic restoration in situ with polymerization light. Note the identical translucency of the ceramic restoration and the adjacent natural dentition.

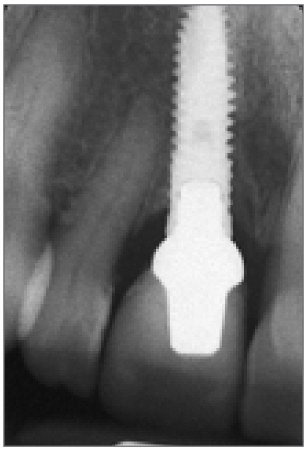

Fig 7f Postoperative radiograph with final restoration.

CONCLUSION

Within the limitations of this study, zirconium implant abutments exceeded the established values of up to 300 N for maximum incisal bite forces reported in the literature, and tightly fit into the titanium implant after several millions of loading cycles. The high fracture resistance determined for ceramic abutments made of yttrium-stabilized zirconium dioxide underscores remarkable mechanical properties under high load conditions.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the statistical assistance provided by Dr Jörg Neugebauer. We thank Andre Spanel for his advice in FEM analysis and Lolita Reder for her invaluable linguistic assistance.

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