Mechanical testing of thin-walled zirconia abutments

Luigi CANULLO, Paulo G. COELHO, Estevam A. BONFANTE

ABSTRACT

Although the use of zirconia abutments for implant-supported restorations has gained momentum with the increasing demand for esthetics, little informed design rationale has been developed to characterize their fatigue behavior under different clinical scenarios. However, to prevent the zirconia from fracturing, the use of a titanium connection in bi-component aesthetic abutments has been suggested. Objective: Mechanical testing of customized thin-walled titanium-zirconia abutments at the connection with the implant was performed in order to characterize the fatigue behavior and the failure modes for straight and angled abutments. Material and Methods: Twenty custom-made bi-component abutments were tested according to ISO 14801:2007 either at a straight or a 25° angle inclination (n=10 each group). Fatigue was conducted at 15 Hz for 5 million cycles in dry conditions at 20°C±5°C. Mean values and standard deviations were calculated for each group. All comparisons were performed by t-tests assuming unequal variances. The level of statistical significance was set at p≤0.05. Failed samples were inspected in a polarized-light and then in a scanning electron microscope. Results: Straight and angled abutments mean maximum load was 296.7 N and 1,145 N, the dynamic loading mean F_max was 237.4 N and 240.7 N, respectively. No significant differences resulted between the straight and angled bi-component abutments in both static (p=0.253) and dynamic testing (p=0.135). A significant difference in the bending moment required for fracture was detected between the groups (p=0.01). Fractures in the angled group occurred mainly at the point of load application, whereas in the straight abutments, fractures were located coronally and close to the thinly designed areas at the cervical region. Conclusion: Angled or straight thin-walled zirconia abutments presented similar F_max under fatigue testing despite the different bending moments required for fracture. The main implication is that although zirconia angled or straight abutments presented similar mechanical behavior, the failure mode tended to be more catastrophic in straight (fracture at the cervical region) compared to angled abutments.

Key words: Dental implants. Zirconium. Dental implant-abutment design. Fatigue
In essence, implant abutments can be made of ceramic (yttrium tetragonal zirconia polycrystals, i.e. Y-TZP) or titanium (commercially pure or alloyed) and can also be prefabricated or customized. The standardization of the prefabricated abutments may present a limitation to the establishment of an appropriate emergence profile, especially in cases where a discrepancy exists between the implant and the crown diameter. In such cases, the compensation will be made by the final contour of the crown, which could result in unfavorable core/porcelain thickness ratios. A way to overcome this issue is the use of a customized abutment that will allow for an individual emergence profile forthrightly by the abutment instead of the crown.

Customized-zirconia abutments have shown comparable survival rates relative to titanium abutments.

However, the internal connection between a zirconia customized abutment and the implant continues to be a mechanical challenge. Thus, to prevent the zirconia from fracturing at the connection, the use of a titanium connection in bi-component aesthetic abutments have been suggested.

Among the concerns regarding the use of CAD/CAM customized-zirconia abutments is their unknown mechanical performance in clinical situations where the implant positioning and occlusal restraints result in thin abutment walls that may negatively influence the long-term prosthetic functional outcome. Although the buccolingual positioning and angulation of the implant is crucial for the final prosthetic outcome, oftentimes there is a need to compensate non-ideal implant positioning with angled customized abutments. Whereas, the mechanical property of customized titanium abutments may be less affected by the resulting wall thinning, due to its ductile nature, the same assumption may not hold true for brittle ceramic abutments. Therefore, this study evaluated the mechanical performance of thinned zirconia abutments at the connection, in an attempt to simulate 2 implantation scenarios in terms of inclination. In fact, in the anterior aesthetic zone, according to the different available bone conditions, implant insertion may require straight (mostly in canine and bicuspid zones) or inclined (incisor zones) abutments.

The tested null hypothesis was that a straight bi-component abutment does not present a different fatigue life compared to an angled one.

**MATERIAL AND METHODS**

Twenty custom-made zirconia abutments (Sweden & Martina, Padua, Italy) were tested according to Norm UNI EN ISO 14801:2007 (Dynamic fatigue test of endosseous dental implants) either with a straight inclination (n=10) or a 25° angle relative to the implant long axis (n=10) (Figures 1A and B). In order to evaluate the abutments under a worst case scenario, an industrially imposed minimum thickness of 0.3 mm at the connection area with the implant was chosen.

The implant fixture was inserted in a prefabricated rigid Plexiglas® clamping device. Individualized zirconia abutments were cemented on a titanium connection and fixed to the implant using a titanium screw according to the manufacturer’s instructions: after cleaning with alcohol, the zirconia abutment was cemented onto the titanium connection (All Stone cement, Sweden & Martina, Padua, Italy). The mixed cement was applied onto the contact part of the titanium connection. The zirconia abutment was then fit onto the titanium connection. The remaining cement was removed immediately with steam and after polymerization, the excess cement was removed.

A PEEK (polyetherketone) ring was used for stress distribution at the zirconia/titanium interface interposed between the zirconia abutment and...
For mechanical testing, single load to fracture (SLF) was performed (6027, Instron, USA) (n=10 each), and the mean values were used to calculate the maximum load ($F_{\text{max}}$). The loading geometry was fixed by UNI EN ISO 14801:2007 both for the SLF and dynamic loading tests. The implant/abutment system was positioned with its long axis inclined at a 30°±1° angle relative to the loading direction. The dimensions of the indenter resulted in a distance of $l=11.0$ mm±0.1 mm from the center of the hemisphere to the clamping plane (Figure 3a).

A hemispherical indenter was used for the load application. Eighty percent of $F_{\text{max}}$ was used as a starting load value for the dynamic testing, which used an uni-axial testing equipment (FPF, Italsigma, Italy), with a 2.000 N load cell (TSTM, AeP, Italy) and an extensometer (2620-601, Instrom, USA) (Figure 3b). Fatigue was conducted at 15 Hz for 5 million cycles in dry conditions at 20°C±5°C. The bending moment was calculated as follows:

$$M = y \times F$$

where $y$ is the moment arm (defined by $l \times \sin 30^\circ$), and $F$ is the force expressed in newtons.

Failed samples were inspected in a polarized-light microscope (MZ-APO, Carl Zeiss Micro Imaging, Thornwood, NY, USA) and then in a scanning electron microscope at an acceleration voltage of 10 Kv (XVP®, Evo 50, Carls Zeiss AG, Oberkochen, Germany).

**Statistical analysis**

Mean values and standard deviations were calculated for each outcome variable (static and dynamic tests) as a function of the straight and inclined abutment groups.

All comparisons were performed by t-test assuming unequal variances [SigmaStat 3.0 (SPSS Inc., Chicago, IL, USA)]. The level of statistical significance was set at $p \leq 0.05$.

**RESULTS**

The mean $F_{\text{max}}$ value for SLF, dynamic loading are presented in Table 1, as well as the bending moments required for fracture.

No significant differences in load to failure were observed between the straight and angled bi-

**Figure 2** Components of the custom-made abutment composed by an individualized zirconia abutment cemented on a titanium connection linked to the implant using a titanium screw. A peek ring was used for stress distribution at the zirconia/titanium interface interposed between the zirconia abutment and retaining screw.

**Figure 3** (A) Single load to fracture (SLF) and (B) dynamic loading testing machines.
Table 1- Mean values for mechanical testing of the straight and 25° angled zirconia abutment groups

<table>
<thead>
<tr>
<th></th>
<th>STATIC Mean (N) (SD)</th>
<th>DYNAMIC F\textsubscript{max} (N)</th>
<th>BENDING MOMENT Mean (Nmm) (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRAIGHT</td>
<td>296.7 (34.42)</td>
<td>237.4</td>
<td>690.6 (60)</td>
</tr>
<tr>
<td>25° ANGLED</td>
<td>1145 (30.69)</td>
<td>240.7</td>
<td>410.5 (5.45)</td>
</tr>
</tbody>
</table>

SD: Standard Deviation

The present study simulated clinical scenarios where customized zirconia abutments presented the thinnest possible section at the connection area, resulting in significant implications in its mechanical response, according to our SLF testing. However, when evaluated under a more clinically realistic loading scenario, (fatigue) $F_{\text{max}}$ were not significantly different between the groups, but bending moments for fracture were higher for the straight relative to the angled abutments. Such a result was not expected considering the differences in the lever scenario created for both groups, but may be accounted by the difference in the moment of inertia between the two designs.

The resulting failure modes where the straight abutments showed fractures at the cervical region compared to fractures at the point of load application in the angled abutments likely reflected the resulting bending moments for both groups. From a clinical standpoint, although both scenarios may fail at similar time points, it can be speculated that in a restoration supported by a thinned angled zirconia abutment, the crown is more likely to shield the functional area receiving the load compared to a thinned straight abutment. Such an assumption warrants further investigation. The bending moments of both groups were significantly higher compared to values observed in the literature. This could be related to the double zirconia/titanium anchorage system.

As to the testing methods available for the evaluation of different implant-abutment system configurations, several have been described, such as the single load to fracture, the use of fatigue followed by the application of a static load until fracture, the staircase method, fatigue limit (ISO 14801:2007), step-stress accelerated life testing, and others. While the ISO 14801 was created in 2003 and revised in 2007, with the aim of standardizing the testing procedures and data presentation in the fatigue of dental implants, it has been shown that the results produced by such a method should be interpreted with caution. The wide range of testing parameters allowed in the ISO 14801:2007 regarding the testing frequency (2 to 15 Hz), environment (water or dry when testing above 15 Hz) and amount of cycles (2 or 5 million, depending on the chosen frequency) have shown that a very different failure probability distribution may result, as well as failure modes. Whereas, the present study utilized the highest end of the speed scale allowed by the norm, especially to optimize the machine testing time, potential differences in the fatigue limit and failure modes when testing in 2 Hz in water may exist and warrant future investigation. It may be suggested that, while attending industry requirements for implants quality assurance and control, the ISO 14801:2007 testing methodology may likely continue to be developed.
as observed from 2003 to the currently advocated version\textsuperscript{10,12}.

As generally reported and also in agreement with our testing results, the discrepancies in values arising from the static relative to the dynamic testing and the clinical relevance of each, should be acknowledged. If the selection of a system was based on the static test results, which do not simulate physiological loading scenarios where repetitive, lower load cycling is the chief mechanism leading to failure, most systems would be suitable irrespective of the area of application (molar or incisor). With static loading, materials will commonly fail at loads higher than those in fatigue. The mechanisms of subcritical crack growth that should be simulated in testing include those that operate in use-related failures which are stress corrosion and cyclic fatigue\textsuperscript{14}. In this study, static testing was only performed to provide load values for subsequent fatigue testing. Fatigue can provide more effective ways of simulating failures observed clinically\textsuperscript{1}.

Considering that the reported maximal bite force in the incisor area may vary from 108 N\textsuperscript{9} to 190 N\textsuperscript{7,9}, the $F_{\text{max}}$ fatigue loads observed for both thin-walled straight or angled zirconia abutments are above the physiologic range. Therefore, in esthetically demanding areas, zirconia abutments may be indicated especially when thin peri-implant soft tissues are present\textsuperscript{19}. Although no direct comparison was performed with titanium abutments, short-term clinical studies and systematic reviews point toward similar success rates for both materials and no influence in the failure behavior of the overlying restorative system\textsuperscript{9}. Future long-term clinical studies are warranted.

**CONCLUSION**

The postulated null hypothesis that a straight bi-component abutment would not present different $F_{\text{max}}$ than an angled abutment under fatigue was accepted. However, failure modes differed between the groups.

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