Bending moments of zirconia and titanium implant abutments supporting all-ceramic crowns after aging

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Abstract
To test the fracture load and fracture patterns of zirconia abutments restored with all-ceramic crowns after fatigue loading, exhibiting internal and external implant-abutment connections as compared to restored and internally fixed titanium abutments.


DOI: 10.1111/clr.12192
PMID: 23735182
Bending moments of zirconia and titanium implant abutments supporting all-ceramic crowns after aging

Key words: aging, all-ceramic restoration, bending moment, chewing simulation, implant abutments, implant-abutment connection, thermocycling, zirconia abutments

Abstract

Objectives: To test the fracture load and fracture patterns of zirconia abutments restored with all-ceramic crowns after fatigue loading, exhibiting internal and external implant-abutment connections as compared to restored and internally fixed titanium abutments.

Materials and methods: A master abutment was used for the customization of 5 groups of zirconia abutments to a similar shape (test). The groups differed according to their implant-abutment connections: one-piece internal connection (BL; Straumann Bonelevel), two-piece internal connection (RS; Nobel Biocare ReplaceSelect), external connection (B; Branemark MkII), two-piece internal connection (SP, Straumann StandardPlus) and one-piece internal connection (A; Astra Tech AB Oseospeed). Titanium abutments with internal implant-abutment connection (T; Straumann Bonelevel) served as control group. In each group, 12 abutments were fabricated, mounted to the respective implants and restored with glass-ceramic crowns. All samples were embedded in acrylic holders (ISO-Norm 14801). After aging by means of thermocycling in a chewing simulator, static load was applied until failure (ISO-Norm 14801). Fracture load was analyzed by calculating the bending moments. Values of all groups were compared with one-way ANOVA followed by Scheffé post hoc test (P-value<0.05). Failure mode was analyzed descriptively.

Results: The mean bending moments were 464.9 ± 106.6 N cm (BL), 581.8 ± 172.8 N cm (RS), 556.7 ± 128.4 N cm (B), 605.4 ± 54.7 N cm (SP), 216.4 ± 90.0 N cm (A) and 1042.0 ± 86.8 N cm (T). No difference of mean bending moments was found between groups BL, RS, B and SP. Test group A exhibited significantly lower mean bending moment than the other test groups. Control group T had significantly higher bending moments than all test groups. Failure due to fracture of the abutment and/or crown occurred in the test groups. In groups BL and A, fractures were located in the internal part of the connection, whereas in groups RS and SP, a partial deformation of the implant components occurred and cracks and fractures of the zirconia abutment were detected.

Conclusion: The differently connected zirconia abutments exhibited similar bending moments with the exception of one group. Hence, the type of connection only had a minor effect on the stability of restored zirconia abutments. In general, restored titanium abutments exhibited the highest bending moments.

Replacing single missing teeth in esthetically demanding anterior regions using osseointegrated implants has become a predictable treatment modality with high survival rates [Jung et al. 2008b; Jung et al. 2012]. Clinical success is not only dependent on successful osseointegration, but also on the performance of the respective suprastructure. Different materials and components were proposed for implant-supported single crowns.

As an abutment material, traditionally titanium is selected because of its mechanical properties [Andersson et al. 1995]. Yet, the color of underlying titanium abutments negatively affected the appearance of peri-implant mucosa [Park et al. 2007; Jung et al. 2008a; van Brakel et al. 2011]. To provide more predictable results regarding esthetic aspects, all-ceramic abutments made out of alumina and zirconia were introduced [Liu et al. 2012]. Among all-ceramic abutments, in vitro studies demonstrated superior fracture resistance of zirconia abutments ranging from 444 N to 738 N as compared to alumina
abutments [McGumph & et al. 1992, Yıldırım et al. 2003, Att et al. 2006b]. The maximal values of occlusal forces in the anterior region have been reported as ranging from 90 N to 370 N [Paphangkorakit & Osborn 1997]. Clinical studies evaluating zirconia abutments demonstrated sufficient stability to support the reconstruction [Glausser et al. 2004, Sailer et al. 2009c, Zembic et al. 2009]. Accordingly, a systematic review on the performance of ceramic and metal abutments showed similar 5-year survival rates estimated from annual failure rates [Sailer et al. 2009a].

Yet, the clinical information is limited to zirconia abutments exhibiting an external implant-abutment connection. Different mechanisms have been proposed to connect the zirconia abutment to the implant body. The connection can be external or internal, whereas the internal connection can be achieved by the abutment itself (one-piece) or by a secondary metallic component (two-piece). The design of the implant-abutment connection of titanium abutments influenced their mechanical properties. Greater stability was achieved with an internal implant-abutment connection [Möllersten et al. 1997, Norton & Norton 1997, Khraisat et al. 2002]. Similarly, the stability of zirconia abutments was analyzed, showing a potential mechanical advantage with an internal two-piece connection as compared to external or internal one-piece connections [Sailer et al. 2009b]. The stability of one-piece internally connected zirconia abutments was positively influenced by non-matching diameters to the implants [Leuteniger & et al. 2012]. Most of the studies applied static load on the abutments straight after fabrication.

Low-temperature degradation has to be considered an additional factor with zirconia [Chevalier 2006]. To simulate clinical conditions, the performance of differently connected abutments should be tested after subsequent aging [e.g. thermocycling, chewing simulation]. Accordingly, zirconia abutments were tested without a restoration and the results confirmed the beneficial influence of a secondary metallic component for internally fixed zirconia abutments [Truening et al. 2011].

Finally, the presence or absence of a reconstruction on a zirconia abutment may play a decisive role. In vitro studies showed that implant-bone reconstructions with all-ceramic crowns on zirconia abutments demonstrated sufficient stability to withstand physiological occlusal forces in the anterior region [Att et al. 2006a,b]. Furthermore, a systematic review on the survival of implant-supported single crowns confirmed that all-ceramic crowns on ceramic abutments performed similarly to metal-ceramic crowns [Jung et al. 2012]. Still the clinical data on implant-supported all-ceramic reconstructions are limited to zirconia abutments exhibiting an external implant-abutment connection. To date it is unknown whether restored zirconia abutments with an internal implant-abutment connection would perform similarly to externally connected zirconia abutments. It may be hypothesized that the different designs of the implant-abutment connection of zirconia abutments could have an influence on the stability of the entire implant-reconstruction complex.

The aim of this in vitro study was to test the fracture load and fracture patterns of zirconia abutments restored with all-ceramic crowns exhibiting internal and external implant-abutment connections after aging as compared to restored and internally fixed titanium abutments. The tested hypotheses were: a) The design of the implant-abutment connection of restored zirconia abutments influences the bending moments of the entire implant-reconstruction complex, and b) Restored titanium abutments exhibit higher bending moments as compared to any type of restored zirconia abutments.

Materials and methods

This study tested the bending moments of five types of customized zirconia abutments [groups BL, RS, B, SP, A] and one type of customized titanium abutments [group T]:

- Test group BL: zirconia abutments with 1-piece internal implant-abutment connection [CARES abutments on Bonelevel RC implants with implant diameter of 4.1 mm, Straumann Basel Switzerland].
- Test group RS: zirconia abutments with 2-piece internal implant-abutment connection [Procera abutments on Replace Select RP implants with implant diameter of 4.3 mm, Nobel Biocare, Gothenburg, Sweden].
- Test group B: zirconia abutments with external implant-abutment connection [Procera abutments on Bränemark MK III RP implants with implant diameter of 4.0 mm, Nobel Biocare].
- Test group SP: zirconia abutments with 2-piece internal implant-abutment connection [CARES abutments on Standard Plus RN implants with implant diameter of 4.1 mm, Straumann].
- Test group A: zirconia abutments with 1-piece internal implant-abutment connection [Atlantis abutments on OsseoSpeed implants with implant diameter of 4.5 mm, Astra Tech AB].

Control group T: titanium abutments with 1-piece internal implant-abutment connection [CARES abutments on Bonelevel RC implants with implant diameter of 4.1 mm, Straumann].

Fabrication of the abutments

The procedures for the fabrication of the master abutment have been published in detail and will therefore only be briefly summarized. In all groups, 12 identical abutments were fabricated matching the shape of a master abutment. The master abutment was designed in an anatomical shape to support a maxillary central incisor crown [Sailer et al. 2009b].

The master abutment was scanned in a CAD/CAM scanner [CARES, Straumann], and by means of these digital data, the test-abutments of groups T, BL and SP were fabricated. The test-abutments of groups B and RS were manufactured by mechanically scanning [Procera Forte 1.1 scanner, Nobel Biocare] the master abutment. In group B, the zirconia abutments were mounted directly, and in group RS, they were fixed internally with a secondary metallic component. For the manufacturing of the zirconia abutments of group A, the master abutment was sent to the manufacturer for the digitizing and reproduction.

Fabrication of the glass-ceramic crowns

For the fabrication of the 72 identical crowns, a CAD/CAM system was used [Cerec InEos scanner, Sirona, Bensheim, Germany]. By means of the corresponding software [Cerec 3D 3.6], one abutment per group was scanned and a central incisor crown was designed exhibiting the same outer shape at all abutments in the different groups. In a milling machine [Cerec InLab, Sirona], 72 identical glass-ceramic crowns were fabricated from glass-ceramic blanks [IPS Empress CAD, Ivoclar Vivadent, Schaan, Liechtenstein]. All crowns were glazed (c.max Ceram Glaze Powder, Ivoclar Vivadent) in a ceramic furnace [Austromat 4D, Dekema, Freilassing, Germany] according to the manufacturer’s instructions.

Preparation of specimens

The abutments were fixed on their respective implants with the torque according to
manufacturer’s instructions. The abutment-screw access holes were closed with a foam pellet (Pele Tim, Φ 5 mm, Voco, Cuxhaven, Germany) and a resin-based composite filling material on top (Tetric, Ivoclar Vivadent). The specimens were embedded in acrylic holders according to the ISO-Norm 14801 (“Dentistry-Implants-Dynamic fatigue test for endosseous dental implants,” International Organization for Standardization 2007, Geneva, Switzerland), using an acrylic resin (ScandiQuick, ScanDia, Hagen, Germany). From the implant shoulder to the top of the acrylic holder, a 3 mm vertical distance was left uncovered to simulate vertical bone loss (Fig. 1). All abutment surfaces were cleaned with ethanol (95%) and then conditioned: a) zirconia abutment using RelyX Ceramic Primer (3M ESPE, Seefeld, Germany) and b) titanium abutments with Alloy Primer (Kuray Dental Co Ltd., Osaka, Japan). Thereafter, the glass-ceramic crowns were cleaned with ethanol (95%), etched (VITA Zahnfabrik, Bad Säckingen, Germany) and silanized (RelyX Ceramic Primer, 3M ESPE). Finally, all crowns were adhesively cemented on the abutments using a self-adhesive resin cement (RelyX Unicem, 3M ESPE). All procedures were performed according to the manufacturer’s instructions.

**Chewing simulation and load testing**

The specimens were aged by means of thermocycling [5–50 °C, dwelling time 120 s] in a custom-made chewing simulator [1,200,000 cycles with chewing force 49 N and chewing frequency 1.67 Hz, University of Zurich, Switzerland]. As an antagonist a corrosion-free steel indenter (ST V4A) with a rounded tip (Φ 8 mm) was used. The specimens were loaded at a 30° angle of the indenter to the palatal surface of the crowns, 3 mm below the incisal edge. The vertical indenter movement for each chewing act was 2 mm.

The fracture load was measured using a Universal Testing Machine (Zwick/Reell Z2010, Zwick, Ulm, Germany, 1 mm/min). The palatal surface of the crowns was in a 30° angulation to the indenter [ISO-Norm 14801: 2007] with a 0.5-mm-thick thin foil (Dentaurum, Ispringen, Germany) in between to ensure even distribution of the force during load (Sailer et al. 2009b). The specimens were loaded until failure with static load, and the failure load was registered as soon as fracture load decreased by 20% of the maximum load (Fmax). The bending moment (M) was calculated in N cm with the formula M = 0.5 × F × l [DRAFT ISO-Norm 14801: 2006] with F being the load [N] and l being the vertical distance from the simulated bone level to the center of load [cm] (Fig. 1).

**Analysis of failure modes**

After aging and fracture load testing, each specimen was visually examined to locate and determine the mode of failure. In addition, mobility of the reconstruction and any plastic deformation of the implant were recorded. According to the observations, each specimen was categorized: [i] partial fracture or catastrophic failure of abutment and/or crown, [ii] visible crack of abutment and/or crown and [iii] plastic deformation of components (i.e. implant, abutment, screw).

After fracture load testing, four representative specimens of each test group were embedded and sectioned with a diamond saw through the center of the specimen in buccal-oral direction (Well Diamond Wire Saws, Inc., Norcross, GA, USA). The embedded cross sections were then observed with a microscope (Wild Heerbrugg, Heerbrugg, Switzerland) to further visualize the characteristics of failure modes.

**Statistical analysis**

The bending moments were analyzed using SPSS Version 20.0 (IBM SPSS Statistics, Chicago, IL, USA). Approximate normality of the data distribution was tested using Kolmogorov-Smirnov test. Descriptive statistics together with 95% confidence intervals for the mean were calculated. One-way ANOVA followed by Scheffe post hoc test was used to detect significant differences between the tested groups. 95% confidence interval for the true relative frequency was calculated by Wilson method (Altman et al. 2002). The level of statistical significance was set at 5% (α = 0.05).

**Results**

**Failures after aging and prior to fracture load test**

One crown of group T and two crowns of group B showed visible cracks [Fig. 2a] but could be included in the fracture load test. Five crowns of group SP fractured between 330,000 and 550,000 chewing cycles [Fig. 2b] and could subsequently not be tested for fracture load [42% with 95% CI [0.19, 0.68]]. All remaining specimens were stable, and no
mobility of the suprastructure was detected (Table 2). In these groups, the probability of failure during aging was only 0/12 – 0% with 95% CI [0; 0.24].

Fracture load test

The assumption of normality could not be rejected by Kolmogorov-Smirnov test ($P > 0.417$). The mean bending moments were $464.9 \pm 106.6$ N cm [BL], $518.1 \pm 172.8$ N cm [RS], $556.7 \pm 128.4$ N cm [B], $605.4 \pm 54.7$ N cm [SP], $216.4 \pm 90.0$ N cm (A) and $1042.0 \pm 86.8$ N cm (T) (Table 1). No difference of mean bending moment was found between groups BL, RS, B and SP. Test group A exhibited significantly lower mean bending moment than the other test groups ($P < 0.001$). Control group T had significantly higher bending moments than all test groups ($P < 0.001$) [Fig. 3].

Failures after fracture load test

The sequence of failure modes of specimens according to the categorization is described in detail in Table 2. In every test group, visible cracks of the crowns could be observed, whereas the crowns of control group T had no additional cracks after fracture load test. Complete fractures of crowns were observed in test groups RS, B and SP, whereas in test groups BL and A and in control group T, no crown fractures were observed. Abutments with cracks or complete fractures of the abutment were only found at test groups B and SP. All implants of test groups RS and SP showed plastic deformation. With the exception of test groups BL and A, all suprastructures showed mobility.

Cross-sectional analysis

One representative cross-section of every group is provided in Figs 4a-g. In all four selected abutments of group BL and group A, the fracture of the abutment was noted below the implant shoulder (Fig. 4a,e). All the fractures occurred in the internal part of the cone below the implant shoulder at the thinnest portion of the abutment and could not be detected by visual inspection after fracture load test. The origin of fracture in the abutments of group A was located in the transition to the engaging part of the abutment (Fig. 4f). Similar fracture patterns were observed in group BL in the transition to the thinner part of the internal portion of the abutment. In test groups B and SP, the fractures, which were observed in 3 and 2, respectively, of 4 abutments, were all located above the implant shoulder (Fig. 4c,d). In group RS, no cracks or fractures could be detected in any selected abutments (Fig. 4b). The abutment in control group T did not show any fractures (Fig. 4g).

Discussion

The differently connected zirconia abutments restored with glass-ceramic crowns exhibited similar bending moments with the exception of one group. Altogether, the type of implant-abutment connection had only a minor influence on the stability of the crown-abutment-complex. However, restored zirconia abutments of group A with one-piece internal implant-abutment connection exhibited significantly lower bending moments than all other groups. Therefore, the first hypothesis can only partially be accepted. Restored titanium abutments reached the highest mean bending moment; thus the second hypothesis is accepted. The presence of an all-ceramic crown positively influenced the stability of the

Table 1. Descriptive statistics of the bending moments (mean $\pm$ SD, 95% CI, min, median, max)

<table>
<thead>
<tr>
<th>Groups (n)</th>
<th>Mean (SD)</th>
<th>95% CI (Mean)</th>
<th>(Min; Median; Max)</th>
<th>95% CI (Median)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL (12)</td>
<td>464.9 (106.6)$^b$</td>
<td>(397.2; 532.6)</td>
<td>(300.6; 522.3; 585.7)</td>
<td>(311.1; 552.3)</td>
</tr>
<tr>
<td>RS (12)</td>
<td>581.8 (172.8)$^b$</td>
<td>(472.0; 691.6)</td>
<td>(131.1; 633.8; 755.9)</td>
<td>(405.4; 707.4)</td>
</tr>
<tr>
<td>B (12)</td>
<td>556.7 (128.4)$^b$</td>
<td>(475.1; 638.2)</td>
<td>(344.2; 573.3; 770.3)</td>
<td>(396.3; 700.9)</td>
</tr>
<tr>
<td>SP (7)</td>
<td>605.4 (54.7)$^b$</td>
<td>(559.7; 656.0)</td>
<td>(507.4; 602.1; 673.9)</td>
<td>(507.4; 673.9)</td>
</tr>
<tr>
<td>A (12)</td>
<td>216.4 (90.0)$^a$</td>
<td>(159.2; 273.5)</td>
<td>(110.1; 200.0; 415.3)</td>
<td>(122.4; 334.8)</td>
</tr>
<tr>
<td>T (12)</td>
<td>1042.0 (86.8)$^c$</td>
<td>(966.0; 1097.1)</td>
<td>(816.3; 1062.3; 1162.2)</td>
<td>(976.6; 1112.9)</td>
</tr>
</tbody>
</table>

$^a,b,c$: Different letters indicate significantly differing groups.
implant-supported reconstructions. With the exception of group A, the stability of the crown-abutment-complex of all test groups was similar. Compared with a similar study, the values of the mean bending moment were higher and the differences between the test groups were diminished (Trünger et al. 2011).

On the other hand, during aging, the presence of a crown influenced the survival of specimens in group SP negatively. The initial shape of the abutments in group SP differed from all other abutments, although the abutment was designed from the same data set as for group T and group BL. To follow standardized test conditions, the shape of the abutments in group SP was left unchanged.

The greater dimension of the abutment-screw access hole created by the dimension of the screw of the secondary metallic component (synOcta, Straumann) resulted in sharp cusps of the zirconia abutments (Fig. 2b). Most likely they acted as stress factor and provoked tensile forces in the glass-ceramic crowns (Fig. 2b). As ceramics are brittle and therefore prone to fatigue (Belser et al. 2004), a crack may have been initiated and finally caused fractures of the crowns during aging. Being aware of this limitation, a dental technician would not leave the incisal edges this sharp and would round the edges. Thus, the performance of the specimens in group SP would probably be improved.

Former studies indicated a possible influence of the design of the implant-abutment connection of zirconia abutments on the stability of implant-borne reconstructions. Internally connected two-piece abutments with a secondary metallic component showed significant better performance compared with one-piece internally or externally connected abutments in a laboratory study (Sailer et al. 2009b). However, the specimens were not aged before applying static load.

The possible detrimental effect of aging on the mechanical properties of zirconia has to be considered (Jung et al. 2000, Studart et al. 2007, Kohorst et al. 2008). The anatomical conditions of the peri-implant mucosa expose the abutment to a moist environment and different temperatures. In addition, the abutment has to withstand a variation of loads over long time. Thus, low-temperature degradation can be initiated and damage may be accumulated (Rekow et al. 2011). An in vitro study assessed the stability of abutments after aging by chewing simulation and thermostimulation and confirmed a favorable effect of a secondary metallic component on the stability of internally connected zirconia abutments (Trünger et al. 2011).

In the present study, all zirconia abutments restored with glass-ceramic crowns showed similar mean bending moments with the exception of zirconia abutments of group A exhibiting a one-piece internal connection. Group BL with the same type of abutment connection showed a similar performance to two-piece internally or externally connected zirconia abutments. As reason for the difference between the two groups, the design of the internal connections may be assumed. In both groups, the origin of fracture was located in the transition zone to the thinner part (group BL) or to the engaging part (group A) of the internal connection, representing a locus minoris resistentiae. Interestingly in both groups, the location of the fracture was located in the zone, which did not have an

![Fig. 3. ScatterPlot representation of bending moments of tested abutments after chewing simulation (N cm).](image)

<p>| Table 2: Visual inspection of failure modes after chewing simulation and fracture load test (in % with 95% CI) |</p>
<table>
<thead>
<tr>
<th>Groups</th>
<th>Fractured crowns</th>
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<th>Fractured crowns</th>
<th>Fractured crowns</th>
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<th>Fractured crowns</th>
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<tr>
<td>BL</td>
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<td>RS</td>
<td>100</td>
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<td>B</td>
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<td>SP</td>
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<td>A</td>
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Fig. 4. (a) Cross-section group BL [b] Cross-section group BS [c] Cross-section group BS [d] Cross-section group SP [e] Cross-section group A [f] Cross-section group A internal part [g] Cross-section group T.
intimate contact to the inner part of the implant. In addition, the type of zirconia may have an influence on the stability and may be responsible for the difference between the two groups with the same type of implant-abutment connection (Guzzato et al. 2004). Interestingly, zirconia abutments similar to the ones in group A exhibited very good outcomes when externally connected to regular platform implants [Kerstein & Radke 2008]. This observation supports the assumption that the type of implant-abutment connection influences the performance of ceramic abutments.

In the present study, different types of implants were included, which due to manufacturer's specific design exhibited slight variation of the implant diameters. Consequently, the types and dimensions of the connecting parts were different. Although all included abutments were manufactured using one master data set, slight differences with respect to their dimensions were observed.

The influence of design and dimension of zirconia abutments was already reported in previous studies [Tripodakis et al. 1995; Manicone et al. 2007; Wang et al. 2008; Nguyen et al. 2009]. The design and the dimensions of the internal part of zirconia abutments seem to affect the stability of the abutment-crown entity. To reach sufficient fracture resistance, minimal thickness of abutment walls must be considered. Interestingly, the fractures were not localized in the customized part, but in the prefabricated standardized part of the abutments.

The restored titanium abutments exhibited the highest values of bending moment. This is in agreement with other studies showing that titanium abutments restored with metal crowns exhibited significantly higher fracture load as compared to restored zirconia abutments (Mitsias et al. 2010).

Interestingly, the specimens of group BL and A did not show any mobility after static loading. The clinical significance of the internally fractured abutments is questionable due to the fact the specimens were not mobile. It may be assumed that because of the existing fracture, the abutment-crown complex would become loose in function over time. The required clinical intervention of removing the fractured zirconia components in the implant may be complicated by the deep submucosal localization of the implant.

Plastic deformation of the secondary metallic component of the implant-abutment connection occurred in test groups RS and SP. Considering the similar mean bending moments of all test groups except group A, at the same bending moment, the loads in groups RS and SP are transferred from the superstructure to the implant by the implant-abutment connection. Thus, plastic deformation of the implants occurred, while in the remaining test groups, the implants were left intact. These results confirm the observations of a previous study [Truninger et al. 2011].

Considering the results of the present study, it may be assumed that irrespective of the type of implant-abutment connection, zirconia abutments are a valuable treatment option to support single crowns especially in the esthetic anterior region. Clinical studies with externally connected zirconia abutments already confirmed the high reliability of zirconia abutments [Glauser et al. 2004; Sailler et al. 2009b; Zembic et al. 2009]. According to the in vitro performance of internally connected one-piece or two-piece zirconia abutments, similar results may be expected. Prospective clinical studies are necessary to validate the clinical performance of zirconia abutments exhibiting internal and external implant-abutment connections.

Acknowledgements: The authors like to express their gratefulness to the dental technician Albert Trotmann for the preparation of the cross-sections.

Conflict of interest and Source of funding

The authors declare no conflict of interest. The implant companies Straumann, Nobel Biocare and Astra Tech supported the study with implants and abutments.

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