Bending Moments and Types of Failure of Zirconia and Titanium Abutments with Internal Implant-Abutment Connections: A Laboratory Study

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Purpose: *The aim of this study was to examine the bending moments and fracture patterns of different zirconia abutments with internal implant-abutment connections after static loading and to compare their bending moments to those of internally connected titanium abutments.* **Materials and Methods:** *Three types of customized zirconia abutments (Straumann CARES abutments/Straumann BL implants [T1], Astra ZirDesign abutments/Astra Micro Thread OsseoSpeed implants [T2], Zirabut prototype abutments/Straumann SP implants [T3]) and one type of customized titanium abutment (control group, Straumann CARES abutments/ Straumann BL implants [C]) were included. All abutments were one-piece abutments with an internal implant-abutment connection and were customized to the same shape but featured different implant-abutment connection designs. For each group, 20 identical copies of a master abutment were fabricated and fixed on their corresponding implants. Half of the abutments in each group were left unrestored, and the other 10 received glass-ceramic crowns. Static loading was applied at a 30-degree angle to the palatal surface until failure, and bending moments were calculated. The type of failure was characterized visually by dismounting the abutments and by examination of cross-sections of the embedded specimens. The results were analyzed statistically.* **Results:** *The mean range of bending moments was higher for the unrestored groups (158.2 to 678.2 Ncm) than for the restored groups (117.9 to 419.4 Ncm). The highest mean bending moments were seen in the control group, both restored and unrestored (419.4/678.2 Ncm). Unrestored, T1 and T2 exhibited significantly higher bending moments than T3. This was also observed in the restored groups.* **Conclusion:** *Both the abutment material and the implant-abutment connection design affected the bending moments of abutments after static loading. Internally connected zirconia abutments with horizontal mismatch to the implant exhibited significantly higher bending moments compared to those without horizontal mismatch.* Int J Oral Maxillofac Implants 2012;27:505–512.

Key words: *bending moments, horizontal mismatch, implant-abutment connection, implant abutments, titanium abutments, zirconia abutments*

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In recent years, all-ceramic implant abutments have been used increasingly frequently in implant dentistry because of their esthetic and biologic advantages versus traditional metal abutments.[1,2] A recent trial showed that the dark grey color of metal abutments may lead to discoloration of the peri-implant mucosa.[3] All-ceramic abutments help to preserve the natural soft tissue color much better than conventional metal abutments.[3] For this reason, many different ceramic abutments made of zirconia, alumina, or other ceramic materials are now available.

A limitation of all-ceramic abutments is their mechanical behavior, as ceramics are brittle and therefore less resistant to tensile forces compared to metal abutments.[4] In brittle materials, fractures begin at a

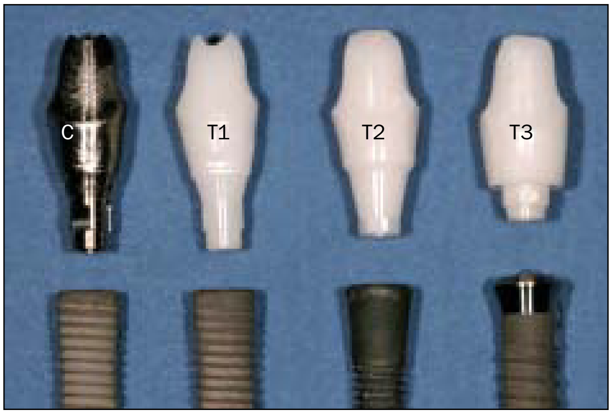


Fig 1 Test and control abutments with corresponding implants. *Left to right*: Control group (C, CARES titanium abutment/Straumann Bone Level implant), test group 1 (T1, CARES zirconia abutment/Straumann Bone Level implant), test group 2 (T2, Astra zirconia abutment/Astra Micro Thread OsseoSpeed implant), test group 3 (T3, Zirabut zirconia abutment/Straumann Standard Plus implant). The diameter of the implant platform in the control group (C) and in test groups 1 and 2 (T1/T2) is wider than the abutment diameter (horizontal mismatch). In test group 3 (T3), the diameters of the implant platform and the abutment matched.

single location (eg, microporosity, crack) and propagate through the material under loading, leading to catastrophic failure when the flaw penetrates the substance to the point of fracture.[5] Hence, microscopic defects or insufficient material dimensions may cause a severe decrease in stability.

With the development of high-strength ceramics, especially zirconia, the mechanical disadvantages of ceramic material have been minimized. Mechanically, zirconia features twice the flexural strength and fracture toughness of another high-strength ceramic, alumina.[4,6,7] An in vitro study showed that the resistance to fracture of zirconia abutments was significantly higher than that of alumina abutments.[8] This finding is supported by different clinical studies of alumina and zirconia abutments tested in similar indications; no fractures of zirconia abutments supporting single crowns were observed after 4 years, whereas in a prospective 1- to 3-year multicenter study, alumina abutments had a cumulative survival rate of only 93%.[9,10] Furthermore, zirconia is highly biocompatible and causes fewer inflammatory changes in the peri-implant soft tissue compared to other restorative materials.[1,2] As a result of these advantages, zirconia abutments are the most applicable ceramic alternative for conventional titanium abutments and are available for many different implant systems. The implant-abutment connection designs vary among these systems.

The design of the implant-abutment connection in titanium reconstructions has shown great influence on their performance.[11,12] Several studies have shown that internal implant-abutment connections are superior to external connections with respect to the long-term stability of the implant-abutment complex.[11,12] A frequent technical complication of the external implant-abutment connection is the loosening of the abutment screw.[13] Furthermore, the internal conical connection has been demonstrated to exhibit significantly higher strength in vitro than the external-hexagonal connection because of its higher resistance to bending. The occurrence of abutment screw fracture is lower with the internal connection.[11,12,14] However, little is known about the influence of the implant-abutment connection design on stability with ceramic abutments. Different types of implant/abutment/crown combinations seem to be suitable for clinical use,[15,16] and the all-ceramic crown may play a decisive role in the overall stability of the implant/abutment/crown complex.[15,16]

The aim of the present study, therefore, was to analyze the bending moments and fracture patterns of zirconia abutments with different internal implant-abutment connections and to compare them to those of internally fixed titanium abutments.

MATERIALS AND METHODS

Three types of customized zirconia abutments (test groups T1 to T3) and one type of customized titanium abutment (control group C) were included in the present investigation (Fig 1). All abutments were one-piece abutments with an internal implant-abutment connection. Detailed information on the included abutments, the respective implants, and the torque used for the fixation of both are reported in Table 1.

Fabrication of Abutments and Crowns

In accordance with a previous study,[17] all abutments were customized to the same shape, which was based on an actual patient. A master abutment was produced, and for each group 20 copies of this master abutment were fabricated. The shape of the master abutment was transferred to the groups as follows (Fig 1).

- **Test group 1 (T1):** CARES zirconia abutments on Straumann Bone Level implants (Institut Straumann). The master abutment was scanned with a computer-aided design/computer-assisted manufacture (CAD/CAM) scanner (Etkon, Straumann). The data were transferred electronically to a centralized production facility and 20 identical abutments were fabricated industrially.

Table 1 Materials Used and Their Connection Configurations and Fixation Torques

Group	Abutment material	Abutment	Implant	Configuration of connection	Fixation torque
T1	Zirconia	CARES RC	Straumann Bone Level RC, 4.1 × 12 mm	Cone and square	35 Ncm
T2	Zirconia	ZirDesign	Astra Micro Thread OsseoSpeed, 4.5 × 13 mm	Cone and hexagon	25 Ncm
T3	Zirconia	Zirabut	Straumann Standard Plus RN, 4.1 × 12 mm	Cone and octagon	35 Ncm
C	Titanium	CARES RC	Straumann Bone Level RC, 4.1 × 12 mm	Cone and square	35 Ncm

RC = regular connection; RN = regular neck.

- **Test group 2 (T2):** Astra zirconia abutments on Astra Micro Thread OsseoSpeed implants. The abutments in this group were fabricated by means of a CAD/CAM procedure (ZirDesign, Astra Tech). These abutments were fabricated of sintered zirconia with a computer numeric controlled milling machine.
- **Test group 3 (T3):** Zirabut zirconia abutments for Straumann Standard Plus implants. The abutments were produced by copy milling (Copy-Milling Machine, Wohlwend AG), which transferred the shape of the master abutment to densely sintered zirconia blanks (Metoxit). These one-piece prototype zirconia abutments were designed with a cone and an octagonal fitting to the internal part of the implants.
- **Control (C):** CARES titanium abutments on Straumann Bone Level implants. The abutments were fabricated analogous to the procedures described for T1.

All abutments were fixed on their corresponding implants using a torque controller with the torque values recommended by the manufacturers (Table 1). In each group, half the abutments (n = 10) were left unrestored (T1, T2, T3, C) and the other 10 received glass-ceramic crowns (T1crown, T2crown, T3crown, Ccrown; CEREC, Sirona Dental).

For the fabrication of the crowns, the master abutment was fixed to the implant replica of the master cast and scanned with a CAD/CAM system (Cerec InEos scanner, Sirona Dental). By means of computer software for three-dimensional simulation and construction of dental reconstructions (Cerec 3D software 3.60), the missing central incisor crown was designed virtually. Lucite-reinforced glass-ceramic ingots (IPS Empress CAD, Ivoclar Vivadent) were used to produce 40 identical crowns in a milling machine (Cerec InLab, Sirona Dental). After the milling, the crowns were glazed (IPS Empress Glaze, Ivoclar Vivadent) according to the manufacturer's instructions. Prior to the cementation of the crowns, all abutments were cleaned with ethanol (95%).

The zirconia abutments (T1crown, T2crown, T3crown) were then silanized (Clearfil Porcelain Bond Activator and Clearfil SE Bond Primer, Kuraray). The titanium abutments (Ccrown) were pretreated with a specific metal primer (Alloy Primer, Kuraray). All crowns were cemented to the abutments (Panavia 21 TC, Kuraray) in accordance with the manufacturer's instructions.

Testing Protocol

For the loading test, both the restored and the unrestored specimens (T1–C and T1crown–Ccrown) were embedded according to the draft ISO Norm 1480118 in an acrylic resin holder at 3 mm vertically from the most coronal bone-to-implant border to the top of the holder. The required cylindric acrylic glass holders (diameter 16.4 mm), with a modulus of elasticity of more than 3 GPa, were custom-made for each implant system. After the implants were placed in the corresponding drill hole in the center of the specific holders, self-curing acrylic resin (Technovit 4071, Heraeus Kulzer) was used to fix them in this position. The modulus of elasticity of this acrylic resin was within the specifications of the ISO norm.[18,19] By the use of a lateral drill hole, the flowable acrylic resin was injected between the implant and the corresponding hole using a syringe. Any excess acrylic resin was carefully removed. The cement was left to indurate for 24 hours before testing. The screw access holes in all groups were filled with light-curing composite (Tetric Classic, Ivoclar Vivadent).

A universal testing machine (Z 010, Zwick/Roell) was used to measure the fracture load of each embedded specimen. The specimens were mounted in a 30-degree angled steel holder, and a static load was applied on the palatal side of the specimens until fracture or deformation occurred. The palatal position of the indenter was 2 mm below the incisal edge of the abutments on the unrestored specimens and of the crowns on the restored specimens. The fracture load was determined by calculating the bending moments ($M = 0.5 \times l \times F$).

Table 2 Comparison of Bending Moments Among the Unrestored and Restored Groups

	Bending moment (Ncm)				Unrestored vs Restored	
Group	Mean (SD)	95% CI	Min	Max	P*	Mean difference (95% CI)
Unrestored						
T1	344.8 (61.0)[b]	(301.0, 388.4)	218.9	426.1	< .001	119.9 (76.8, 163.0)
T2	324.8 (150.9)[b]	(216.7, 432.7)	224.1	733.5	.52	32.0 (–76.5, 140.5)
T3	158.2 (34.7)[a]	(133.3, 183.1)	121.4	246.3	.006	40.3 (13.5, 66.7)
C	678.2 (77.9)[c]	(622.4, 733.9)	475.1	753.0	.001	258.8 (125.3, 392.3)
Restored						
$T1_{crown}$	224.8 (22.0)[a,b]	(209.0, 240.6)	196.1	262.0		
$T2_{crown}$	292.8 (24.8)[b]	(275.0, 310.5)	239.1	318.6		
$T3_{crown}$	117.9 (16.9)[a]	(105.8, 130.0)	95.4	146.1		
C_{crown}	419.4 (185.2)[c]	(286.9, 551.9)	216.0	648.2		

[a,b,c]Superscripts reflect results of one-way analysis of variance followed by post hoc Scheffé test. Different superscripts represent significant differences within the respective groups (unrestored/restored).
*Two-sample *t* test.

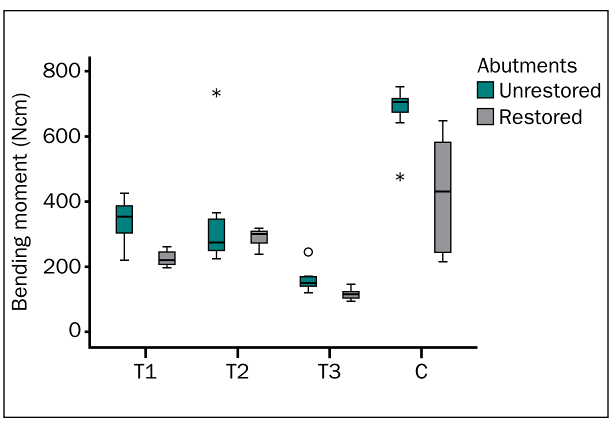


Fig 2 Bending moments of tested unrestored and restored abutments after static loading.

A detailed description of the preparation/embedding of the specimens, the test method, and the calculation of bending moments is available elsewhere.[17] Following testing in the universal testing machine, each specimen was examined visually by dismounting the abutments or by inspecting cross sections of the embedded specimens. The type of failure was defined and categorized by two investigators.

Statistical Analysis

The data were analyzed descriptively (means, maximums, minimums, and standard deviations [SDs]) with SPSS software (version 15, SPSS Inc). Furthermore, in all groups, the mean bending moments were determined with a 95% confidence interval (95% CI). One-way analysis of variance followed by the post hoc Scheffé test was applied for comparisons within groups (T1–C and T1crown–Ccrown). The influence of the crowns on the bending moments of the abutments was analyzed by means of a two-sample Student *t* test (T1–C versus T1crown–Ccrown). Types of failure were classified and the relative frequencies of each failure type in each test group were computed together with the corresponding 95% CI.[20] The level of statistical significance was set at $P < .05$.

RESULTS

Bending Moments

The mean range of bending moments for the unrestored groups (158.2 to 678.2 Ncm) was generally higher than the one in the restored groups (117.9 to 419.4 Ncm). All measured values are displayed in Table 2 and Fig 2.

Unrestored Groups. The lowest mean bending moments ($P < .05$) were detected in group T3. Groups T1 and T2 exhibited similar bending moments, which were higher than those observed for T3 ($P < .05$). Group C showed the highest bending moments ($P < .05$) among all groups.

Restored Groups. Groups T3crown and T1crown exhibited significantly lower values than the other groups ($P < .05$). T3crown showed significantly lower values than T2crown and Ccrown. T2crown showed similar bending moment values as T1crown, but T2crown values were significantly lower versus Ccrown. Within the tested groups, the highest bending moments (419.4 Ncm; statistically significant difference; $P < .05$) were seen in Ccrown.

Table 3 Damage/Fracture Patterns of Unrestored and Restored Specimens After Static Loading (n = 10 per Group) with Confidence Intervals (CI)

Group	Plastic deformation of implant (%)	% of fractures (95% CI)				Mobility of abutments (%)	No visible defect (%)
		Abutment*	Abutment†	Crown (%)	Implant and/or abutment screw		
Unrestored							
T1	–	90 (55.5, 99.8)	10 (0.2, 44.5)	–	–	–	–
T2	60 (26.2, 87.9)	80 (44.3, 97.5)	20 (2.5, 55.7)	–	–	–	–
T3	–	–	100 (69.1, 100.0)	–	–	–	–
C	90 (55.5, 99.8)	–	–	–	90 (55.5, 99.8)	10 (0.2, 44.5)	–
Restored							
$T1_{crown}$	–	–	10 (0.2, 44.5)	70 (34.7, 93.3)	–	–	30 (6.7, 65.2)
$T2_{crown}$	–	–	–	30 (6.7, 65.2)	–	–	70 (34.7, 93.3)
$T3_{crown}$	–	–	100 (69.1, 100.0)	70 (34.7, 93.3)	–	–	–
C_{crown}	70 (34.7, 93.3)	–	–	60 (26.2, 87.9)	30 (6.7, 65.2)	20 (2.5, 55.7)	–

*Below implant shoulder; †Above implant shoulder.

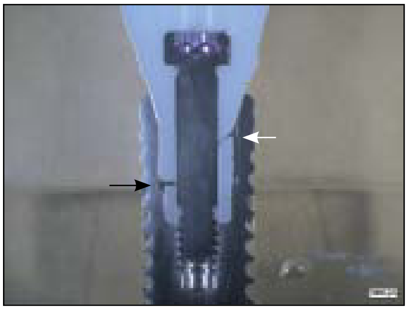


Fig 3 *(Left)* Cross section of embedded T1 specimen. Fracture of the internal cone of the abutment (below implant shoulder) occurred (*arrows*).

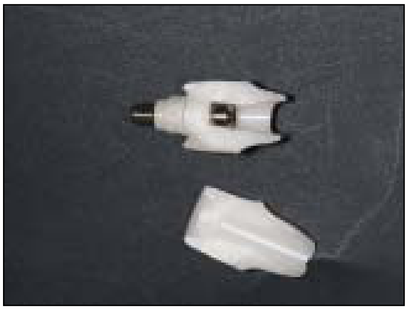
Fig 4 *(Right)* Abutment fracture, T2, below the implant shoulder. Situation after unscrewing the abutment.

***Restored Versus Unrestored Groups*.** T1, T3, and C exhibited significantly lower bending moments than T1crown, T3crown, and Ccrown, respectively. Similar values were detected for T2 versus T2crown.

Types of Failure

The fracture patterns of the unrestored groups after static loading are displayed in Table 3. Ninety percent of the titanium abutments fractured within the internal connection (Fig 3) without visible plastic deformation of the implant-abutment complex. Similar failure modes were observed for T2, 80% of which fractured below the implant shoulder (Fig 4). In addition, 60% of the tested specimens in this group showed plastic deformation of the implant-abutment complex. In T3, all fractures were located above the implant shoulder (Fig 5). Static loading of the control group (C) led first to plastic deformation of the implant-abutment complex in 90% of the specimens and ended in fracture of the implant or abutment screw or both (Fig 6). In one case, a loosening of the implant-abutment complex was observed after plastic deformation.

The fracture patterns of the restored groups after static loading are displayed in Table 3, and typical specimens are shown in Fig 7. The majority of specimens tested in T1crown showed a fracture of the crown (70%), whereas no visible defect was observed in three specimens. Cross sections of the specimens



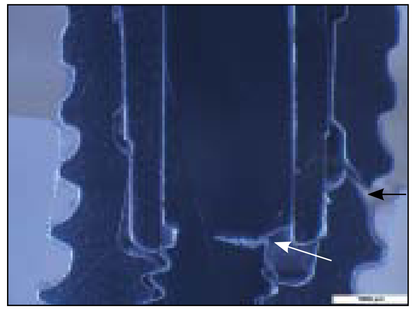
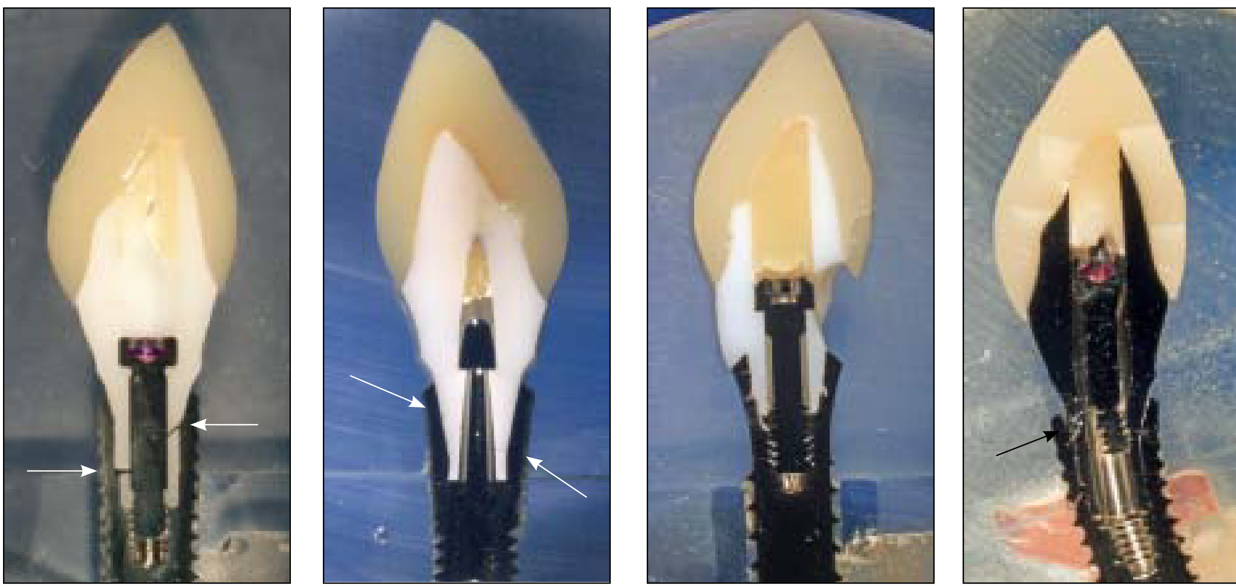


Fig 5 *(Left)* Fracture mode in T3. The fracture line on the abutment is above the implant shoulder.

Fig 6 *(Right)* Cross section of embedded control specimen. Both the implant (*black arrow*) and the abutment screw (*white arrow*) have fractured.

Fig 7 *Cross sections of restored test and control group specimens.*



Figs 7a and 7b Abutment fracture (*arrows*) of the internal cone (ie, below the implant shoulder) in (*left*) T1 and (*right*) T2.

Fig 7c Abutment fracture above the implant shoulder in T3.

Fig 7d Plastic deformation of a control implant-abutment complex with fracture of the implant (*arrow*).

with no visible defect revealed a fracture of the zirconia abutment in the area of the internal cone (Fig 7a). In T2crown, a fracture of the crown was observed in only 30% of the specimens, and 70% showed no visible defects after static loading. Again, however, cross sections of these specimens showed a fracture of the internal cone of the abutments (Fig 7b). A fracture of either the abutment (above the implant shoulder), the cemented crown, or both was observed in all T3crown specimens (Fig 7c).

Generally, no plastic deformation of any abutment-implant complex was detected in the restored zirconia groups. In contrast, plastic deformation of the abutment-implant complex was observed in 70% of specimens in the restored control group (Fig 7d). In addition, 60% of the tested specimens within the control group showed a fracture/crack of the crown (Fig 8), 30% showed a fracture of the abutment screw or the implant, and 20% showed mobility of the abutments.

DISCUSSION

This laboratory study showed a significant influence of the abutment material and the design of the implant-abutment connection on bending moments of internally connected abutments after static loading. Titanium abutments showed the highest bending moments. Zirconia abutments with a horizontal mismatch ("platform switching") exhibited significantly higher bending moments compared to zirconia abutments without a horizontal mismatch.

The stability of the implant-abutment complex with titanium abutments is decisively influenced by the type of connection.[11,12] Internal implant-abutment connections have shown significantly greater stability compared to external implant-abutment connections.[11,12] The type of implant-abutment connection seems to be relevant for the stability of zirconia abutments as well. In a recent in vitro study, internally connected two-piece

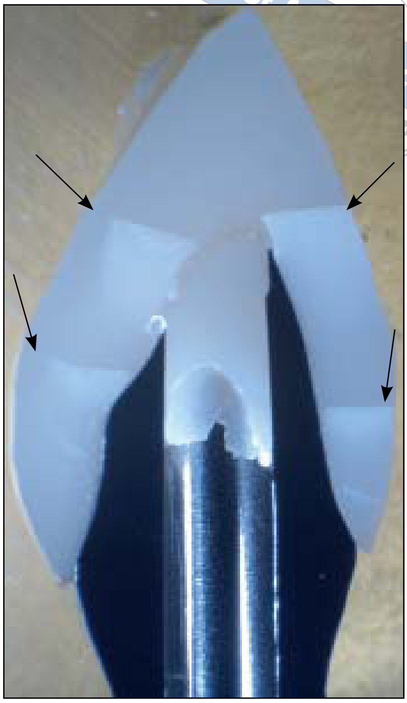


Fig 8 Cross section of a control group specimen. Cracks within the restoration are indicated by arrows.

zirconia abutments (which used a secondary metallic component) exhibited significantly higher bending moments than one-piece internally or externally connected abutments.[17] However, the tested abutments in that study were heterogenous (two-piece, one-piece, with/without secondary component, prototypes).[17] In the present study, only internally connected one-piece zirconia abutments were used and compared with an internally connected one-piece titanium abutment. The results demonstrated enhanced stability of internally connected zirconia abutments with a horizontal mismatch with the implant diameter (no zirconia overlaying the implant shoulder) compared to internally connected zirconia abutments without horizontal mismatch (zirconia laying on implant shoulder). These findings were observed for both restored and unrestored abutments. Every specimen tested in test group 3 (T3/T3crown, no horizontal mismatch) fractured in the area of the implant shoulder at relatively low bending moments (158.2 Ncm for the unrestored group, 117.9 Ncm for the restored group). On the other hand, T1 and T2 (with horizontal mismatch) showed much greater stability on bending. Almost all tested specimens in these groups (90% for T1, 80% for T2) exhibited fractures within the internal cone of the abutment (in the unrestored group). Interestingly, despite the fractures, the implant-abutment complex of these groups did not display any mobility. It may therefore be assumed that a fracture of the internal cone might not be diagnosed in the clinical situation. However, under the prevailing circumstances, the specimens were not tested after aging (eg, thermocycling, chewing simulation), which would eventually modify the results. With bending moments of 324.8 Ncm and 344.8 Ncm, respectively, these abutments should be stable enough for clinical use. Plastic deformation of the implant-abutment connection, observed in more than half of the T2 specimens, is another indicator of the great stability of these connections. However, these two groups were not restored, which lessens the clinical relevance.

Within the restored test groups, a striking number of failures were traced to fractures of the glass-ceramic crown (30% to 70%). Thus, the weakest link is often not the zirconia abutment but the reconstruction. This finding may be the reason for the differences in bending moments between the restored and the unrestored groups. In any event, many restored T1 and T2 specimens did not exhibit any visible defect. The cross sections of these samples revealed fractures of the internal cones of the abutment (similar to the unrestored specimens of these groups) or cracks in the cemented crowns.

The control group, with titanium abutments, showed the highest stability. Based on the elastic properties of the metal, plastic deformation of the titanium implant-abutment connection was observed most often. Fractures of the abutment screw and/or mobility of the implant-abutment complex were also detected.

Physiologic chewing in the anterior region on a single tooth has been reported to exert between 150 and 200 Ncm of force.[21,22] A recent randomized controlled clinical trial, which compared zirconia and titanium implant abutments on single-tooth implants in the canine and posterior regions, reported the same survival and technical, biologic, and esthetic outcomes at 3 years.[23] The zirconia abutments used in the aforementioned study were tested in vitro by means of the identical test method applied in the present study.[17] The measured bending moments in that study were comparable to the bending moments observed in T1crown and T2crown (196.1 to 318.6 Ncm). Therefore, within the limitations of the present investigation, good clinical performance of these abutments, in combination with glass-ceramic crowns, can be expected. With regard to the reduced stability of glass-ceramic crowns in comparison to zirconia-based crowns and porcelain-fused-to-metal crowns, it is assumed that the clinical performance of such combinations should be even better. In contrast, the majority of specimens in test group 3 fractured with bending moments below the suggested 150-Ncm threshold.

CONCLUSION

Titanium abutments exhibited the highest bending moments, both restored and unrestored. The stability of internally connected zirconia abutments with horizontal mismatch was greater than that of internally connected zirconia abutments without horizontal mismatch. The fracture pattern of zirconia abutments without horizontal mismatch was predominantly characterized by fractures located at the abutment shoulder. These findings demonstrate an important effect of the abutment design and type of connection on the stability of the implant-abutment complex.

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