

RESEARCH AND EDUCATION

# Fatigue survival and failure resistance of titanium versus zirconia implant abutments with various connection designs



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Replacing missing teeth with osseointegrated implants has proven to be a successful treatment with high success rates in long-term clinical studies.<sup>1-5</sup> However, the success of implant treatment is related to the careful balance of different parameters, including biological, mechanical, and esthetic considerations.<sup>3,6-8</sup>

Titanium dental implants in combination with titanium abutments have been widely used and are considered the gold standard in implant dentistry because their biological and mechanical excellence results in high survival rates.<sup>2-4,8-10</sup> However, the greyish gingival discoloration caused by titanium is an issue, especially in patients with thin gingival biotype or a high smile line.<sup>3,6,11,12</sup> To fulfill the increasing demand for optimal esthetics, alternative abutment materials and techniques have been adopted to overcome such disadvantages.<sup>7,8,11</sup> Zirconia abutments have been introduced to provide better esthetics than titanium abutments.<sup>7,9,11,12</sup> However, zirconia has different mechanical properties than titanium; its strong, hard, and more abrasive material characteristics may affect the

## ABSTRACT

**Statement of problem.** Data regarding the effect of connection design and abutment material on the fatigue survival and failure resistance of implant abutments are scarce.

**Purpose.** The purpose of this in vitro study was to investigate the effect of connection design and abutment material on the fatigue survival and failure resistance of implant abutment assemblies.

**Material and methods.** Three types of implants (n=18, N=54) and 6 groups of abutments (n=9, N=54) with different connection designs—internal conical (IC), internal tri-channel (IT), and external hexagonal (EH)—and abutment materials—titanium (T) and zirconia (Z)—were investigated. All the abutments were restored with identical central incisor crowns. Fatigue testing, including thermal and mechanical aging, was performed in a mastication simulator (Esetron Smart Robotechnologies) for up to  $1.2 \times 10^6$  cycles with a load of 50 N at an angle of 45 degrees. Then, the surviving specimens were subjected to failure resistance testing in a universal testing machine (Shimadzu AG-IS; Shimadzu Corp) at a crosshead speed of 1.0 mm/min. The maximum loads to failure (N) were recorded. Survival performance of the specimens throughout the fatigue testing was examined by the Kaplan-Meier survival analysis. The failure loads were analyzed by using the Kruskal-Wallis test followed by the Mann-Whitney U tests with Bonferroni-Holm correction ( $\alpha=.05$ ).

**Results.** All the specimens of groups ICT, ITT, ITZ, and EHT survived fatigue testing, whereas 2 specimens from group ICZ and 3 specimens from EHZ failed. Statistically significant differences were found among the groups, based on the results of maximum failure loads ( $P<.05$ ). The highest mean failure load was obtained in the ICT group ( $1069 \pm 182$  N), followed by the ITT ( $926 \pm 197$  N), EHT ( $873 \pm 126$  N), ITZ ( $568 \pm 81$  N), EHZ ( $311 \pm 45$  N), and ICZ ( $287 \pm 63$  N) groups.

**Conclusions.** Abutment material and connection design affected the fatigue survival of implant abutment assemblies. Implant abutment assemblies with a titanium-titanium interface revealed higher failure resistance than the implant abutment assemblies with a titanium-zirconia interface. (J Prosthet Dent 2019;122:315.e1-e7)

mechanical reliability of implant abutment connections and thus influence long-term clinical success.<sup>10,11,13,14</sup> Furthermore, zirconia abutments have been reported to be sensitive to functional loading and prone to fracture, especially at the connection of the abutment to the implant body.<sup>13,15</sup> Different zirconia abutment designs are available, some with a titanium insert. The metal

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## Clinical Implications

The fatigue survival and failure resistance of implant abutments are affected by the type of connection design and abutment material. Zirconia abutments with a titanium insert may be a more reliable option with higher failure resistance than one-piece zirconia abutments.

insert attaches to the implant body and creates a titanium-to-titanium interface rather than a zirconia-to-titanium interface.<sup>4,15-17</sup>

Implant-to-abutment connections can be classified as external or internal.<sup>13,18</sup> Both types can be subclassified according to the antirotational geometry of the implant abutment interface,<sup>10,12</sup> including hexagonal, octagonal, conical, tri-channel, spline, and Morse taper.<sup>8-10,14</sup> The mechanical properties and failure modes of implant abutments have been reported to be affected by the type of connection design.<sup>9,10,13,15-19</sup> However, a uniform testing approach is lacking in these *in vitro* studies, which limits their clinical relevance.<sup>9</sup> Limitations of these studies include different loading methods, different superstructure designs, and the use of implant analogs instead of implants.<sup>20-23</sup> Fatigue survival and failure resistance of the tested abutments could be adversely affected by the limitations of the testing conditions.<sup>24-26</sup> A standardized and more clinically relevant testing of fatigue survival and failure resistance of zirconia and titanium implant abutments with various connection designs might better validate their clinical use.

Data regarding the effects of connection design and abutment material on the fatigue survival and failure resistance of implant abutment assemblies are scarce. The null hypothesis of the present *in vitro* study was that the connection design and abutment material would not affect the fatigue survival and failure resistance of implant abutments.

## MATERIAL AND METHODS

Three types of implants ( $n=18$ ,  $N=54$ ) and 6 groups of abutments ( $n=9$ ,  $N=54$ ) with different connection designs—internal conical (IC), internal tri-channel (IT), and external hexagonal (EH)—and abutment materials—titanium (T) and zirconia (Z)—were investigated (Table 1) (Fig. 1). Six different groups of implant abutment assemblies were subjected to fatigue testing with standard load and cycle time. Then, the failure resistance of the implant abutment assemblies was tested and compared.

Custom-made, 2-piece specimen holders were prepared to hold the specimens identically during the fatigue and failure resistance testing (Fig. 2). Implants were centrally embedded in autopolymerizing acrylic resin

(Technovit 4000; Kulzer GmbH) with a Young modulus of 12 GPa to simulate the elastic reaction of cortical bone during the loading process as specified in International Organization for Standardization (ISO) 14801:2016.<sup>27</sup> Following the ISO standard, 3 mm of vertical distance from the acrylic resin top layer to the implant platform was left uncovered to simulate alveolar bone resorption. The abutments were connected to their corresponding implants and tightened to the 35-Ncm torque recommended by the manufacturer (calibrated torque wrench; Nobel Biocare). The abutment screws were retightened after 10 minutes to compensate for the preload loss.<sup>24</sup> The screw-access channels were closed with gutta percha and composite resin.

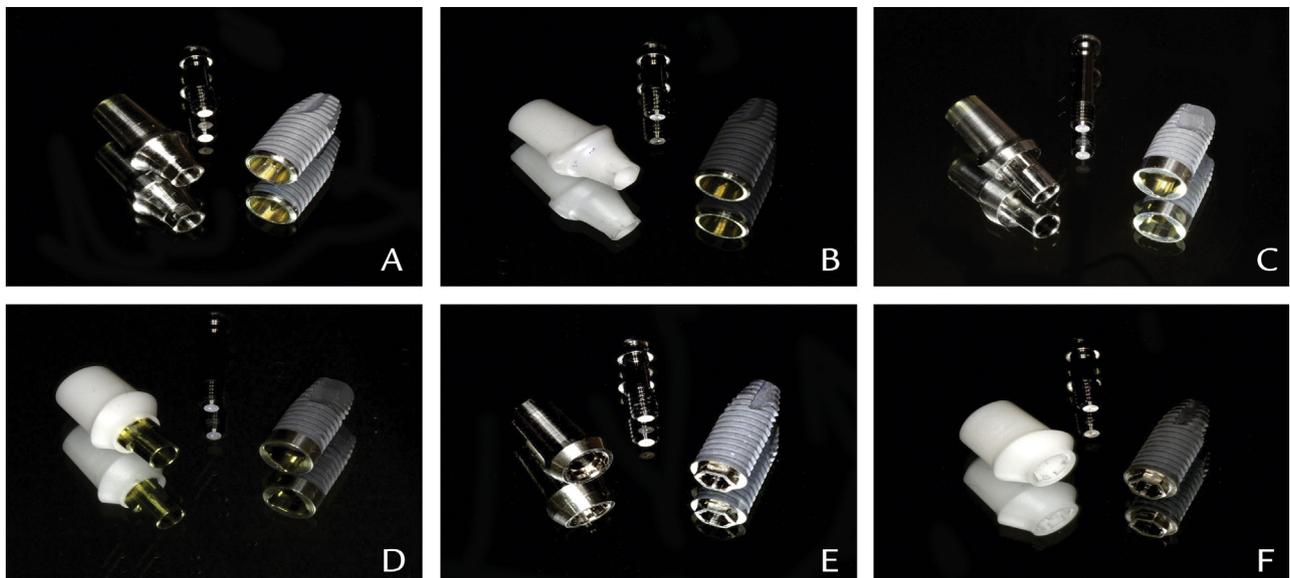
The abutments were restored with identical central incisor crowns fabricated from monolithic zirconia (VITA YZ ST, Lot: 59220; VITA Zahnfabrik) by means of computer-aided design and computer-aided manufacturing (CAD-CAM) technology (inLab MC X5; Dentsply Sirona). Three typodont models (KaVo Dental, Biberach) representing a clinical situation with a missing maxillary left central incisor were used to fabricate the crowns. One abutment from each group with different connection designs was connected to the implant replica on the master model and scanned (CEREC inEos X5; Dentsply Sirona). The crowns were virtually designed to present identical external shapes requiring minimal or no preparation of the abutments. The intaglio surfaces of the crowns were airborne-particle abraded with 50- $\mu$ m alumina particles (Korox; Bego) for 10 seconds at a pressure of 2.5 MPa and at 10 mm (EasyBlast; Bego). The crowns were cemented on the abutments by using self-adhesive resin cement (RelyX Unicem, Lot: 651113; 3M ESPE) under a load of 50 N for 10 minutes, and the excess cement was removed.

A mastication simulator (occlusal loading-chewing simulator; Esetron Smart Robototechnologies) that included thermal and mechanical aging to simulate the anterior loading conditions was used for fatigue testing. Custom-designed specimen holders were fixed to the test chambers of the simulator. A loading force of 50 N was applied 3 mm below the incisal edge with a 6-mm stainless steel ball on the palatal aspect of each crown at an angle of 45 degrees to the implant long axis. Test specimens were both mechanically treated at a frequency of 2.0 Hz for  $1.2 \times 10^6$  cycles and thermally aged for 5000 cycles (5 °C to 55 °C; 1 minute each cycle). During the fatigue test, all the specimens were optically monitored to detect failures. Specimens exhibiting screw loosening, fractures, or cracks were defined as failed and excluded from further testing.

The failure resistance of surviving specimens was tested in a universal testing machine (Shimadzu AG-IS; Shimadzu Corp) at a crosshead speed of 1.0 mm/min until the implant abutment connection failed. The load

**Table 1.** Overview of implants and abutments tested

Group	Abutment (Lot no.)	Implant Diameter×Length (mm) (Lot no.)	Material	Connection Design	Implant/Abutment Interface	Manufacturer
ICT (n=9)	Procera Esthetic Abutment CC RP 1.5 mm #5 (13060524)	Nobel Parallel CC RP 4.3×10.0 (12103619)	Titanium	Internal conical connection (titanium screw-retained)	Titanium/Titanium	Nobel Biocare
ICZ (n=9)	Esthetic Abutment CC RP 1.5 mm (12098745)	Nobel Parallel CC RP 4.3×10.0 (12103619)	Zirconia	Internal conical connection (titanium screw-retained)	Titanium/Zirconia	Nobel Biocare
ITT (n=9)	Procera Esthetic Abutment NobRpl RP 1 mm #10 (13061407)	Replace Select Straight TiU RP 4.3×10.0 (12101424)	Titanium	Internal tri-channel connection (titanium screw-retained)	Titanium/Titanium	Nobel Biocare
ITZ (n=9)	Esthetic Abutment NobRpl RP 1 mm (12098515)	Replace Select Straight TiU RP 4.3×10.0 (12101424)	Zirconia plus Ti insert	Internal tri-channel connection (titanium screw-retained)	Titanium/Titanium	Nobel Biocare
EHT (n=9)	Procera Esthetic Abutment BmkSyst RP 1 mm #10 (12106471)	NobelSpeedy Groovy RP 4.0×10.0 (12107497)	Titanium	External hexagon (titanium screw-retained)	Titanium/Titanium	Nobel Biocare
EHZ (n=9)	Esthetic Abutment BmkSyst RP 1 mm (12096030)	NobelSpeedy Groovy RP 4.0×10.0 (12107497)	Zirconia	External hexagon (titanium screw-retained)	Titanium/Zirconia	Nobel Biocare



**Figure 1.** Overview of tested abutments and their corresponding implants. A, ICT, Internal conical connection titanium. B, ICZ, Internal conical connection zirconia. C, ITT, Internal tri-channel connection titanium. D, ITZ, Internal tri-channel connection zirconia. E, EHT, External hexagon titanium. F, EHZ, External hexagon zirconia.

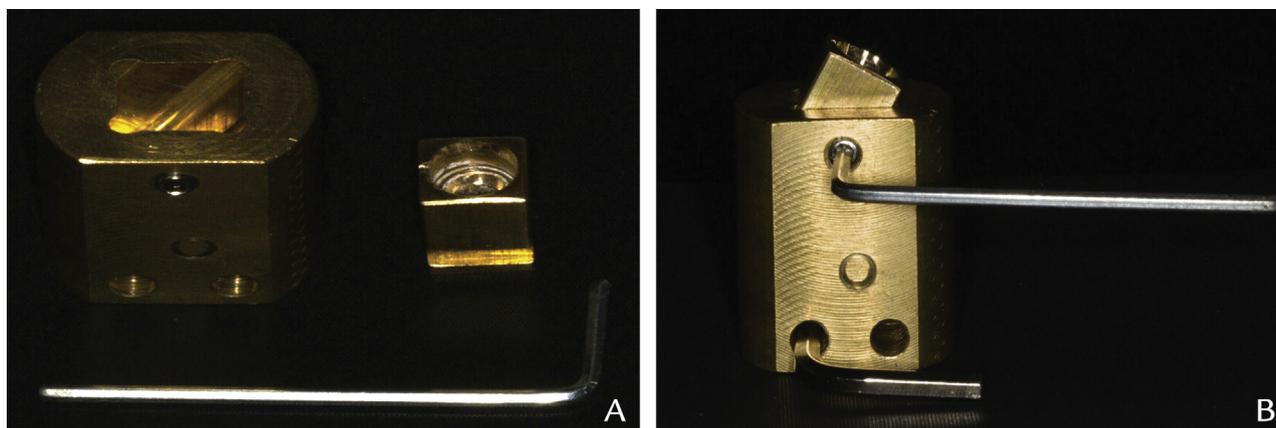
was applied similarly to the fatigue test at the same angle of 45 degrees to the implant long axis and 3 mm below the incisal edge. The maximum load to failure, identified as fracture or plastic deformation, was recorded. All the failed specimens were visually examined by using a stereomicroscope (Stereomicroscope; Leica Microsystems) to determine the failure modes and categorized as fracture (abutment or abutment screw) or deformation (abutment, abutment screw, or implant).

The data were analyzed by using a statistical software program (IBM SPSS Statistics, v20; IBM Corp). The normality of data distribution was tested with the Shapiro-Wilk test. Survival performance of the specimens throughout the fatigue testing was examined with the Kaplan-Meier survival analysis. The failure resistance

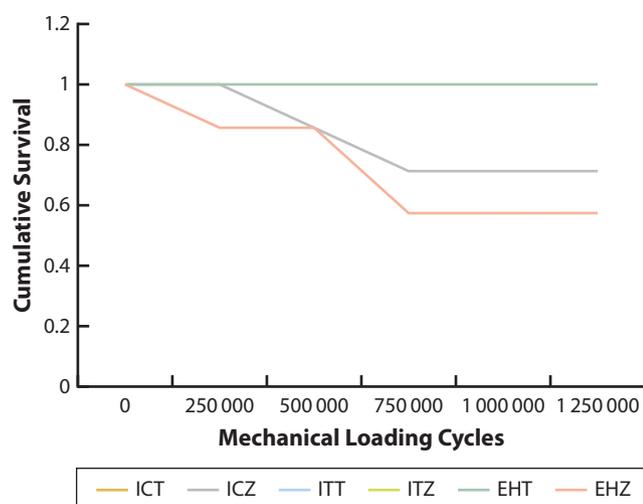
data were analyzed by using the Kruskal-Wallis test, followed by the Mann-Whitney U tests with the Bonferroni-Holm correction ( $\alpha=.05$ ).

## RESULTS

Implant abutment assemblies of groups ICT, ITT, ITZ, and EHT survived  $1.2 \times 10^6$  mechanical loading and 5000 thermocycles in the mastication simulator. Two assemblies in the ICZ group and 3 assemblies in the EHZ group failed, abutment fracture in groups ICZ and EHZ and screw loosening in group EHZ. The cumulative survival curves of the specimens after fatigue testing are presented in Figure 3. The surviving specimens of fatigue testing were subjected to a failure resistance test.



**Figure 2.** Custom-made, 2-piece specimen holder. A, system components. B, connection of system components.



**Figure 3.** Kaplan-Meier survival analysis of implant abutment assemblies tested. ICT, internal conical connection titanium; ICZ, internal conical connection zirconia; ITT, internal tri-channel connection titanium; ITZ, internal tri-channel connection zirconia; EHT, external hexagon titanium; EHZ, external hexagon zirconia.

The results of the failure resistance of implant abutment assemblies are presented in [Table 2](#). Statistically significant differences were found among the groups, based on the results of maximum failure loads ( $P < .05$ ) ([Table 3](#)). The highest mean failure load was observed in the ICT group ( $1069 \pm 182$  N), while the lowest mean failure load was obtained in the ICZ group ( $287 \pm 63$  N). No significant difference was found among groups ICT, ITT, and EHT, which were characterized by different connection designs and 1-piece titanium abutments ( $P > .05$ ). ICZ and EHZ, with different connection designs and 1-piece zirconia abutment, had similar failure resistance results ( $P > .05$ ) that were significantly lower than those in groups ITZ, ITT, EHT, and ICT ( $P < .05$ ).

The failure modes observed after the failure resistance test are shown in [Table 3](#). Plastic deformation of abutment and screw was the predominant failure mode for

**Table 2.** Maximum failure loads (N) after fatigue testing

Group	n	Mean $\pm$ SD	Minimum	Median	Maximum
ICT	9	1069 $\pm$ 182 <sup>c</sup>	843.3	1107.5	1192.1
ICZ	7	287 $\pm$ 63 <sup>a</sup>	161.2	301.7	361.9
ITT	9	926 $\pm$ 197 <sup>c</sup>	701.8	1014.0	1216.3
ITZ	9	568 $\pm$ 81 <sup>b</sup>	475.4	575.3	641.9
EHT	9	873 $\pm$ 126 <sup>c</sup>	794.5	891.7	1103.1
EHZ	6	311 $\pm$ 45 <sup>a</sup>	254.3	306.4	374.6

Same superscript letters represent groups with no statistically significant ( $P > .05$ ) difference.

groups ICT, ITT, and EHT ([Fig. 4](#)). The predominant failure mode of groups ICZ and EHZ was abutment fracture at the screw head level without damage to the screw or implant. The fractures were observed below the implant shoulder for ICZ and above the implant shoulder for EHZ. In group ITZ, multiple failure modes were observed as abutment fracture or plastic deformation of the abutment and screw ([Fig. 5](#)).

## DISCUSSION

The null hypothesis was rejected as significant differences were found among the groups based on the results of fatigue survival and failure resistance. Long-term clinical success is dependent on the mechanical properties of implant abutment assemblies, which should be investigated in reliable in vitro studies.<sup>21,23</sup> The results of these studies simulating intraoral variables may help clinicians decide on the suitability of the implant components for the desired clinical application.<sup>9,12,21,22</sup> In the present study, a common clinical situation representing a missing maxillary central incisor restored with a monolithic zirconia crown supported by regular diameter implants was evaluated.

Factors including mechanical loading and thermal aging can affect the success and longevity of implant-supported restorations.<sup>1-4</sup> Fatigue testing has been considered a reliable method of generating data on the

**Table 3.** Failure modes after fatigue and failure resistance testing

Group	ICT	ICZ	ITT	ITZ	EHT	EHZ
Failure modes after fatigue testing (n=5)	Not failed	(2) Abutment fracture (at 550 000 and 983 000 cycles)	Not failed	Not failed	Not failed	(2) Abutment fracture (at 334 000 and 942 000 cycles) (1) Screw loosening (at 785 000 cycle)
Failure modes after failure resistance test (n=49)	(7) Plastic deformation of abutment and screw (2) Plastic deformation of abutment and screw fracture.	(7) Abutment fracture	(7) Plastic deformation of abutment and screw (2) Plastic deformation of implant, abutment and screw,	(2) Plastic deformation of metal insert and screw (3) Abutment fracture (4) Abutment fracture and plastic deformation of metal insert and screw.	(6) Plastic deformation of abutment and screw (3) Plastic deformation of abutment and screw fracture.	(6) Abutment fracture.

efficiency, longevity, and reliability of implant abutments by simulating clinically relevant conditions,<sup>11,13,21</sup> and parameters for fatigue testing were standardized in ISO 14801:2016.<sup>27</sup> However, this standard has been modified in some studies, including the present study.<sup>21,24-26</sup> Testing conditions such as the number of fatigue cycles, applied force, simulated bone level, superstructure design, specifications of the loading indenter, hydrothermal aging conditions, and loading angle may influence the results.<sup>8-13,15-17,21-26</sup>

In the present study, a loading angle of 45 degrees to replicate the interincisal relationship was used,<sup>28</sup> differing from the loading angle of 30 degrees described in ISO 14801.<sup>27</sup> All the implant abutment assemblies of groups ICT, ITT, ITZ, and EHT survived fatigue testing, whereas 2 assemblies from group ICZ and 3 assemblies from group EHZ failed. The mode of failure for ICZ was abutment fracture at the screw head level without any damage to the screw or implant. Two abutment fractures at the apical portion and 1 screw loosening were observed in the EHZ group. Abutments in groups ICZ and EHZ were characterized by a 1-piece zirconia abutment, which is reported to be more susceptible to thermal aging and fatigue loading than titanium abutments.<sup>8,20,21</sup> Zirconia is a chemically stable polycrystalline ceramic<sup>6,7</sup> with excellent physical properties because of its transformation toughening ability that helps to prevent crack propagation by increasing localized fracture toughness.<sup>7</sup> However, mechanical, physical, thermal, and chemical stimuli could decrease the fracture toughness of zirconia from increased phase transformation.<sup>6,7,24,26</sup> The transformation from the tetragonal to monoclinic phase leads to a volume increase of 3% to 5% that can deleteriously affect the mechanical properties.<sup>6</sup>

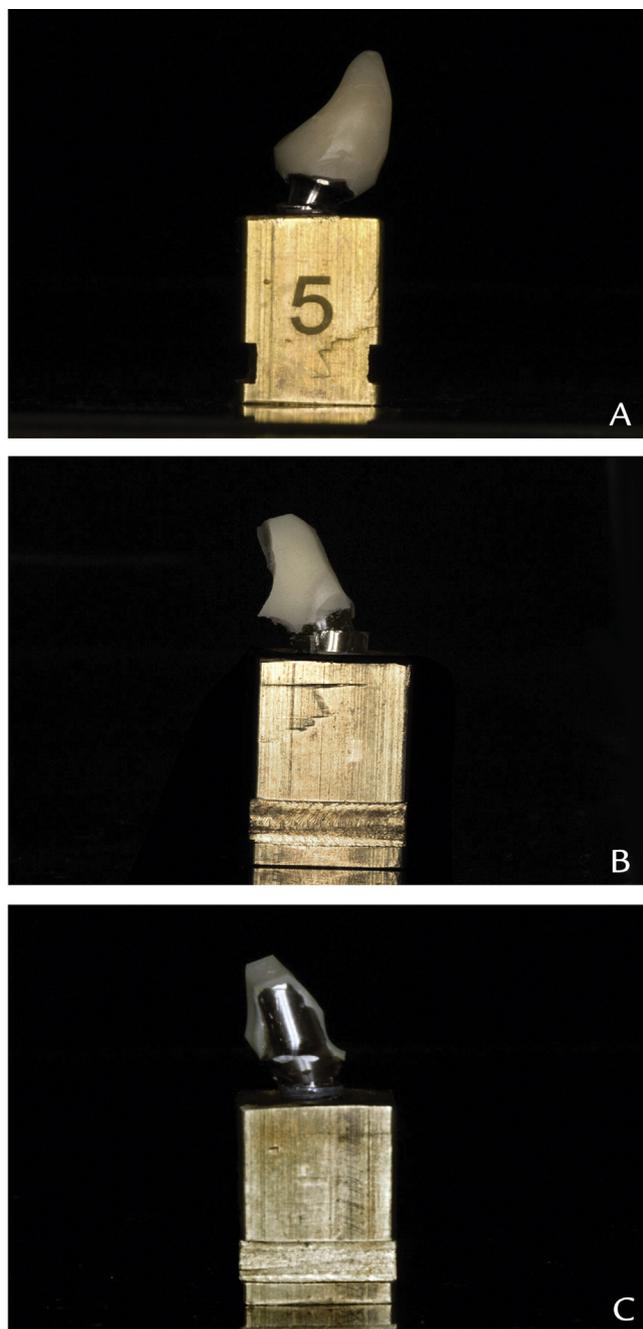
Abutments with an external connection design have increased rotational misfit after mechanical loading when compared with other connection designs.<sup>18,29,30</sup> Complications such as fractures or screw loosening have been reported with zirconia abutments with an external connection design in *in vitro* and *in vivo* studies.<sup>10,18,23,29,31</sup> In the present study, zirconia abutments with a titanium insert (ITZ group) showed no

failures in the fatigue testing. The presence of a metal insert seems to be advantageous for the fatigue survival of zirconia abutments.<sup>11,15,24</sup>

Fatigue-induced aging or deterioration of the materials or system components may not be obvious or show any evidence of failure.<sup>21</sup> Static failure resistance testing on the surviving specimens of fatigue testing could help further analyze the mechanical reliability of the system components.<sup>10,11,20</sup> In the present study, the failure resistance of the implant abutment assemblies was tested by applying the load at the same angle of 45 degrees as in the fatigue testing. Significant differences were found among the groups. The failure resistance obtained in the titanium abutment groups (ICT, ITT, and EHT) was significantly higher than that in the zirconia abutment groups (ICZ, ITZ, and EHZ). These results are consistent with those of previous studies.<sup>10,24,31</sup> The highest mean failure load was obtained in the ICT group (1069 ±182 N), followed by the ITT (926 ±197 N), EHT (873 ±126 N), ITZ (568 ±81 N), EHZ (311 ±45 N), and ICZ (287 ±63 N) groups. Maximal occlusal forces in the anterior region are reported to range between 150 N and 235 N.<sup>32,33</sup> The mean failure loads of all the implant abutment assemblies tested in the present study range above those previously reported average occlusal forces.<sup>32</sup> However, the average forces will be higher in patients with bruxism and could change depending on the hardness of the food.<sup>33</sup>

Significant differences were not found among the titanium abutments with design variations. Contrary to the present results, bending moments or fracture modes have been reported to be affected by the implant abutment connection design.<sup>10,21</sup> These differences could be explained by the differences in experimental conditions such as the loading angle or presence of fatigue testing before the failure resistance test.<sup>34</sup> All the titanium abutments showed plastic deformation with or without screw fracture. This was consistent with studies that reported plastic deformation as the main mode of failure for titanium abutments.<sup>16,24-26,31</sup>

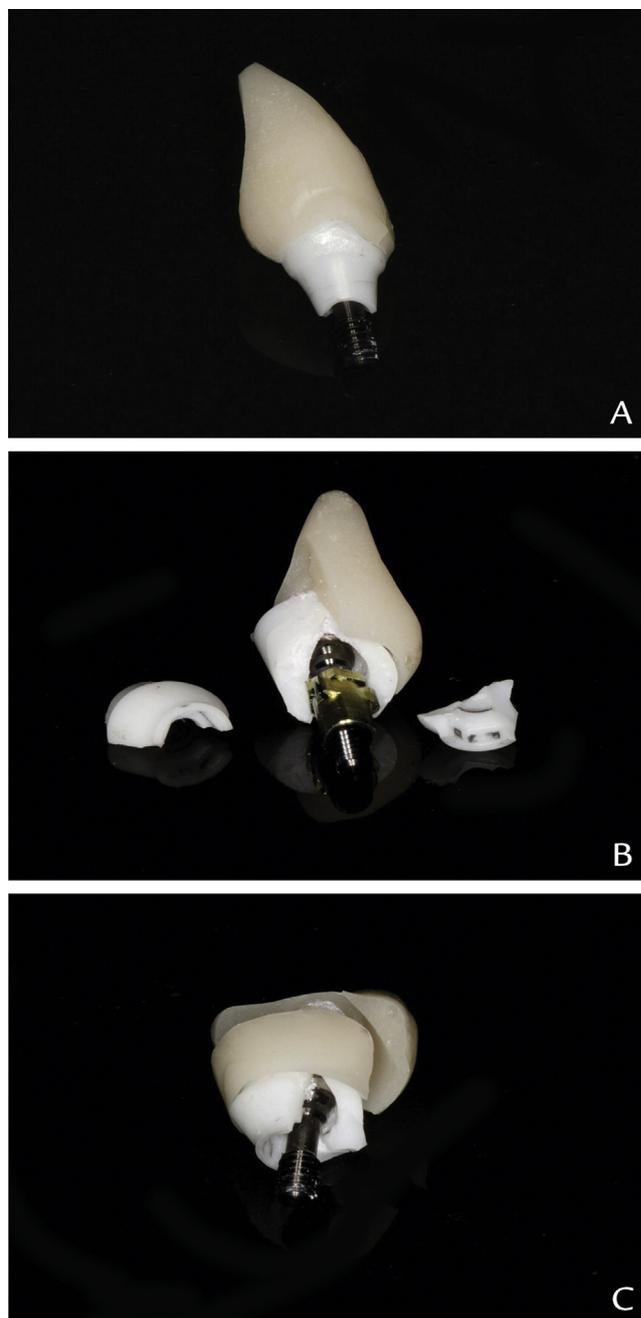
Significant differences were found among the zirconia abutment groups with design variations. Those with a metal insert and internal tri-channel connection design presented higher failure resistance than groups ICZ and



**Figure 4.** Failure modes of titanium abutments after failure resistance test. A, ICT, Internal conical connection. B, ITT, Internal tri-channel connection. C, EHT, External hexagon.

EHZ. The main mode of failure was abutment fracture for ICZ and EHZ. Plastic deformation of the metal insert and screw was observed in the ITZ group in addition to abutment fracture. Similar findings that reported higher resistance to failure for the zirconia abutment with a metal insert have been reported.<sup>10,16,19,24-26</sup>

Further studies with a higher sample size are needed to compare different loading scenarios. Clinical



**Figure 5.** Failure modes of zirconia abutments observed after failure resistance test. A, ICZ, Internal conical connection. B, ITZ, Internal tri-channel connection. C, EHZ, External hexagon.

investigations assessing the failures and survival rates of implant abutments with different connection designs and materials are also essential to make clinical recommendations.

## CONCLUSIONS

Within the limitation of this in vitro study, the following conclusions were drawn:

1. Abutment material and connection design affected the fatigue survival of the implant abutment assemblies.
2. Zirconia abutments had lower failure resistance than titanium abutments.
3. The failure resistance of titanium abutments was not affected by the type of connection design.
4. The fatigue survival and failure resistance of zirconia abutments increased with the presence of a metal insert.

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