**Mechanical Stability of Zirconia Implant Abutments Supporting Cantilevered Fixed Dental Prostheses After Fatigue Loading**

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**Purpose:** To evaluate the mechanical stability and complication rates of titanium (Ti) and zirconia (Zr) abutments restored with cantilevered fixed dental prostheses (cFDPs) when supported by one or two implants.  
**Materials and Methods:** A total of 32 specimens were fabricated. Half of the specimens received one implant, and the other half received two implants to simulate the clinical situation of two or three missing maxillary incisors, respectively. Each group was divided into two subgroups (n = 8). The Ti-1 and Ti-2 groups received Ti abutments (Anatomic Abutment, Straumann) supporting two- or three-unit metal cFDPs, respectively, while Zr-1 and Zr-2 groups received Zr abutments (IPS e.max Anatomic Abutment, Straumann). Following the cementation of cFDPs using resin cement (Multilink Automix, Ivoclar Vivadent), the specimens were subjected to thermomechanical fatigue load and then subsequently loaded until fracture in a universal testing machine. Following the static loading test, stereomicroscopic analyses (Carl Zeiss) were done to identify the weakest component of the cFDP, abutment, and implant assembly. Mann-Whitney U test was used to evaluate the effect of the number of supporting implants and abutment material on fracture strength values, and the level of statistical significance was set at 5% (α = .05).  
**Results:** All specimens survived aging, and no screw loosening or fracture was recorded. The mean fracture strength values were 226 N (± 26.45), 551.12 N (± 82.19), 601 N (± 41.51), and 664.5 N (± 37.59) for Zr-1, Zr-2, Ti-1, and Ti-2, respectively. The difference between fracture strength values of the Ti and Zr groups was significant in favor of Ti abutments (P < .001). The number of supporting implants showed a significantly positive effect on the fracture strength of Zr abutments.  
**Conclusion:** Zr abutments demonstrated lower fracture strength values than Ti abutments independent from the number of supporting implants when used under cFDPs. Two implant–supported cFDPs with zirconia abutments have the potential to withstand physiologic forces applied in the anterior region. Int J Prosthodont 2021;34:615–625. doi: 10.11607/ijp.6700

Clinical evidence indicates that the replacement of a single missing tooth with dental implants in the esthetic zone can be successful in both esthetic and functional aspects. On the other hand, restoration of an extended edentulous area in the anterior maxillary zone by placing implants is not considered a predictable procedure regarding esthetic outcomes. Related to the decrease in both vertical and horizontal dimensions of bone and soft tissue volumes following loss of multiple teeth, the alveolar ridge becomes flattened, which may lead to difficulties placing adjacent implants with adequate inter-implant distance without complex soft and hard tissue management. To avoid the possible esthetic complications of placing adjacent implants in the esthetic zone, reducing the number of implants and restoring the edentulous space with implant-supported cantilevered FDPs (cFDP) may be considered.
Implant-supported cFDPs allow for a simpler and less costly rehabilitation.⁵ The clinical outcome of implant-supported cFDPs has been evaluated in a number of studies. While one study reported higher technical and biologic complication rates,⁶ other studies showed similar outcomes to those of non-cantilevered implant-supported FDPs.⁷⁻⁹ In a systematic review by Romeo and Storelli, implant-supported cFDPs were considered a reliable treatment option that do not increase the complication rate.¹⁰ Unfortunately, despite the promising current evidence, there is still a lack of information comparing the effect of number of supporting implants on the mechanical behavior of zirconia (Zr) abutments under implant-supported cFDPs in the anterior region.

In the maxillary anterior region, success depends not only on successful osseointegration, but also on the harmonious integration of the restoration with neighboring teeth regarding both pink and white esthetic aspects. Implant abutments are usually fabricated from titanium (Ti) because of its well-documented biocompatibility and mechanical properties.¹¹ One major disadvantage of metal abutments is their gray gingival discoloration, which has been reported in several studies.¹²,¹³ Ceramic abutments were developed as an alternative to metal abutments to overcome esthetic problems originating from gray gingival discoloration and to offer several clinical advantages, including well-documented esthetic benefits, less bacterial adhesion and plaque accumulation compared to Ti abutments,¹⁴ and a biocompatibility similar to Ti abutments.¹⁵,¹⁶ Even though the 5-year survival rate of implant abutments under fixed restorations was reported to be similar for ceramic and metal abutments,¹⁶ ceramic abutments have a major shortcoming, which is their brittleness and less resistance to tensile forces. Implant-supported restorations with cantilever extensions reportedly create higher nonaxial forces on the implant and implant components near the cantilever extension.¹⁷ Accordingly, an in vitro study with a clinically relevant design would provide essential information about the use of zirconia abutments under implant-supported cFDPs. Hence, the aim of this in vitro study was to compare the fracture strength of Zr and Ti abutments.
abutments supporting cFDPs using a device simulating the oral environment and cyclic loading. A further aim was to evaluate the effect of the number of supporting implants on the failure of both the restorations and implant components and to obtain data about the weakest component of the entire system following maximum fracture resistance test. The tested hypotheses were: (1) Fracture strength values of implant abutments under cFDPs would be influenced by the number of supporting implants; and (2) Ti implant abutments would have higher fracture strength values compared to Zr abutments when supporting the cFDPs.

MATERIALS AND METHODS

A total of 32 specimens simulating two clinical situations (two or three missing maxillary incisors) were fabricated. Half of the specimens received one implant in the position of the right central incisor to support two-unit FDP frameworks with a cantilever extension to the lateral incisor area (Figs 1a and 1b), and the other half received two implants in the two central incisor positions to support three-unit FDP frameworks with a cantilever extension to the lateral incisor site (Bone Level Implant, ø = 4.1, 13 mm, Straumann; Figs 1c and 1d). Each group was divided into two subgroups based on the number of supporting implants (Ti-1 and Ti-2; Zr-1 and Zr-2), with eight specimens in each subgroup. Groups Ti-1 and Ti-2 received one-piece internal connection Ti abutments (Anatomic Abutment, Straumann) supporting cantilevered two- and three-unit FDPs, respectively, whereas Zr-1 and Zr-2 groups received one-piece internal connection zirconia abutments (IPS e.max Anatomic Abutment, Straumann).

A maxillary typodont (Frasaco) model was used to fabricate the specimens in order to obtain a clinically relevant master model with standard inter-implant space and favorable angulation of the implants. The typodont model was modified by removing the central incisors and the right lateral incisor. The lateral incisor site was reshaped with wax to create an edentulous crest form. A pattern resin (Pattern Resin, GC) duplication model was fabricated to be used as a master model. Implants
were placed using a surveyor in the center of the alveolar sockets and fixed with the same pattern resin. The Ti and Zr abutments were placed on the implants, and abutment-level digital impressions were taken using a laboratory scanner (Lava, 3M ESPE) for every study group. Based on the digital impressions, the two- and three-unit cFDPs were designed with a 6-mm cantilever length, a 0.5-mm restoration wall thickness, and a 9-mm² connector area. One implant–supported (n = 16) and two implant–supported (n = 16) cobalt-chromium (Co-Cr) cFDP frameworks (Wirobond C+, BEGO) were fabricated using a laser sintering technique (M 290, EOS). The abutments were removed, and transfer copings were placed on the master model. Impressions were taken with custom-made trays and polyether impression material (Impregum Polyether, 3M ESPE) and used as an index while fabricating 32 standardized specimens. Implant replicas were embedded in polyurethane molds suitable for a chewing simulator with autopolymerizing acrylic resin (Technovit 4000, Kulzer) at an angle of 30 degrees to the horizontal plane to simulate clinical conditions (Fig 2).18–22 The resin that was used had a modulus of elasticity of approximately 12 GPa, which approximates that of human bone (18 GPa).

The Zr and Ti abutments were fixed on the implant replicas using Ti screws and torqued to 35 Ncm according to the manufacturer’s recommendations. After 1 minute, the occlusal screws were retightened. The inner surfaces of the frameworks were airborne particle–abraded uniformly with 50-mm aluminum oxide and were cleaned in an ultrasonic unit for 1 minute. The Zr and Ti abutment outer surfaces were airborne particle–abraded with 30 mm aluminum oxide under 2-bar pressure for 10 seconds. The abutments were then rinsed thoroughly and dried with oil-free air. A universal primer (Monobond Plus, Ivoclar Vivadent) was applied to both the abutment and restoration inner surfaces. Then, all crowns were definitively cemented using a resin luting cement (Multilink Automix, Ivoclar Vivadent).

The detailed protocol for the thermomechanical fatigue test has been published elsewhere.23 Briefly, all of the specimens were exposed to 1,200,000 cycles of thermomechanical fatigue in a computer-controlled dual-axis chewing simulator (CS 4.8, Willytech) to simulate clinical function. The force was applied 3 mm below the incisal edge on the palatal aspect of the cantilever area at a frequency of 1.6 Hz using a ceramic ball with a 6-mm diameter (steatite ball, Hoechst CeramTec). Given its spherical shape, the contact of the ceramic ball and the restoration surface was restricted to one point. It was assured that there was no interference with the ceramic ball from other parts of the restoration surfaces (ie, connector, neighboring tooth surface). The ceramic ball has a Vickers hardness that is similar to that of enamel. A force of 49 N was chosen to simulate a load within clinical range. During testing, all specimens were subjected to simultaneous thermal cycling between 5°C and 55°C for 60 seconds each, with an intermediate pause of 12 seconds, maintained by a thermostatically controlled liquid circulator (Haake).

The specimens were examined under digital microscopy (Stemi 305, Carl Zeiss) to identify any possible complications following the chewing simulation, such as cracks on both abutments and frameworks, screw loosening, and decementation. Finally, all survived specimens were loaded compressively in a universal testing machine (Zwick/Roell Z010, Zwick) with force application positioned in the same position, with fatigue loading at an angle of 30 degrees to the implant axis and a crosshead speed of 1 mm/minute (Figs 3a and 3b). A 0.5-mm–thick thin foil (Dentaurum) was placed to ensure homogenous stress distribution. The applied force was graphically recorded (testXpert 7.1, Zwick/Roell). The specimens were loaded until failure with static load, and the failure load was registered as soon as the fracture load decreased by 20% of the maximum load (Fmax). Following the static loading, each specimen was examined with a stereomicroscope (Stemi 305) once again to
locate and determine the mode of failure. First, the specimens were examined to determine whether there was plastic deformation or fracture in any component of the implant-abutment-framework-acrylic resin assembly. The fractured specimens were further analyzed to determine the location of the fracture. In the specimens with abutment fracture, the levels of the fracture were divided into fracture above or below the implant shoulder. Furthermore, for the two implant–supported samples, the fracture localization was differentiated as the first or second abutment according to the proximity to the cantilever area.

The fracture strength values were analyzed using SPSS version 20.0 (IBM) and R programming language. Normality assessment of numeric variables was conducted using a graphical approach and Shapiro-Wilk normality test. Mean fracture resistance values were compared between the number of supporting implants (one vs two) for each material subgroup. A similar comparison was conducted between materials (Ti vs Zr) for each number of supporting implant subgroups. Although mean fracture resistance values were found to be normally distributed for each subgroup, non-parametric tests were preferred due to the very small sample sizes (n = 8 per group). The rationale behind this selection was that normality tests and graphical evaluations might poorly perform on small samples, and such samples most often pass normality tests due to little power of detecting non-normally distributed data. Between-group comparisons were evaluated using Mann-Whitney U test due to small sample sizes, and the level of statistical significance was set at 5% (α = .05).

RESULTS

All specimens survived 1,200,000 cycles of thermomechanical fatigue loading, simulating 5 years of clinical function. No abutment, implant replica,
or restoration showed visible cracks or deformation. No mobility of the superstructure or screw loosening was detected.

The mean fracture strength values were 601.0 ± 41.51 N (Ti-1), 664.5 ± 37.59 N (Ti-2), 226.0 ± 26.45 N (Zr-1), and 551.2 ± 82.19 N (Zr-2), as shown in Table 1. The mean fracture strength values were significantly higher for Ti abutments when compared to Zr abutments for both subgroups of number of supporting implants (P = .006 and P < .001). Ti abutments had approximately 2.7-times higher resistance than Zr abutments when one implant was used. Ti abutments with two implants showed significantly higher fracture strength values than Zr abutments; however, the difference between materials was not as high as in the one implant–supported specimens. An overall comparison between each clinical scenario is graphically shown in Fig 4.

The specimens from Ti abutment groups showed similar load displacement curves for both one- and two-implant–supported samples with an elastic deformation region and a plastic deformation region (Fig 5a). On the other hand, the specimens from the Zr groups showed load displacement curves with elastic deformation until the elastic limit and a sudden decrease at the failure point (Fig 5b).

The failure mode for every group is described in detail in Table 2. In groups Ti-1 and Ti-2, the failure was presented by plastic deformation of the implant–abutment assembly and acrylic resin fracture (Fig 6a). In all specimens of the Ti-2 group, the plastic deformation was accompanied by the acrylic resin fracture, whereas all but two failures in the Ti-1 group were represented by plastic deformation of the implant–abutment assembly (Fig 6a). All frameworks remained intact in all groups after the fracture strength test.

In groups Zr-1 and Zr-2, the predominant reason for failure was catastrophic fracture of the abutment, except for one specimen in the Zr-1 group, which demonstrated a perpendicular crack line above the implant shoulder and no catastrophic failure. In all specimens with catastrophic fracture, the fracture line was located above the implant shoulder. Furthermore, seven specimens from

### Table 1  Mean (SD) Fracture Resistance Values

<table>
<thead>
<tr>
<th>Material</th>
<th>No. of implants</th>
<th>P*</th>
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<tbody>
<tr>
<td>Ti</td>
<td>One: 601 (41.51) 664.5 (37.59)</td>
<td>.006</td>
</tr>
<tr>
<td>Ti</td>
<td>Two: 226 (26.45) 551.2 (82.19)</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Zr</td>
<td>One: 601 (41.51) 664.5 (37.59)</td>
<td>.006</td>
</tr>
<tr>
<td>Zr</td>
<td>Two: 226 (26.45) 551.2 (82.19)</td>
<td>&lt; .001</td>
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* Mann-Whitney U test. There are 8 specimens in each cell.

**Fig 4**  Box plot of results following the load-to-fracture test after fatigue loading (n = 8 each). Pairwise comparisons yielded statistical differences between and within groups, before and after artificial aging (P < .005). Fmax = maximum load to fracture.

**Fig 5**  Representative graphics of load displacement curves in the (a) Ti-1 and (b) Zr-2 groups.
the Zr-2 samples showed failure of the abutment in immediate proximity to the cantilever site (Fig 6b), while the second abutment showed no visible fracture above the implant level. In one specimen, cementation failure of the second abutment was observed. The fracture line was located at the abutment neck close to the screw level (Fig 6c). No screw fracture or loosening was detected in these groups (Fig 6d).

The implant abutment was identified as the weakest component for one- and two-implant-supported zirconia abutment groups, whereas the implant-abutment assembly and the embedding resin were identified as the weakest components in the Ti-1 and Ti-2 groups.

DISCUSSION

In the present study, two-implant-supported cFDPs based on Zr abutments exhibited significantly higher fracture strength values than one-implant-supported cFDPs. A similar trend was observed in Ti abutment groups, but the difference was negligible. Thus, the first null hypothesis was partially accepted. In general, the Zr abutment groups exhibited lower fracture strength than the Ti abutment groups, independent of the number of supporting implants; thus, the second null hypothesis was accepted.

 Clinically, the extent of the edentulous area dictates the number of implants that will be placed. Accordingly, two clinical scenarios with one or two implants should not be considered as a direct treatment alternative to each other. Even though the titanium abutments have been proven to be reliable supporting two- or three-unit anterior cFDPs, the use of zirconia abutments supporting cFDPs has not been investigated yet, neither clinically nor mechanically. The current study suggests that the use of zirconia abutments in combination with anterior implant–supported cFDPs may be a promising alternative; however, only when supported by a minimum of two implants.

In this study, specimens exhibited 100% survival from a mechanical aspect following artificial aging. No visible cracks, deformations of the restorations, or implant components were detected. These findings are in agreement with clinical studies and systematic reviews that reported 5-year outcomes of metal-ceramic cFDPs supported by titanium abutments. Moreover, surprisingly, no screw loosening was detected, which was reported to be one of the most frequent complications for implant-supported cFDPs for a 5-year follow-up (7.9%).

Despite limited evidence concerning the mechanical stability of zirconia abutments supporting cFDPs, the outcomes after artificial aging for all of the groups were interestingly similar, even for the group representing a more questionable clinical situation (one implant–supported Zr abutment).

Concerning the fracture strength of the zirconia abutments under implant-supported cFDPs, the outcomes of the current study have demonstrated similar values to the reported values of Zr abutments under single-crown implant restorations. Those studies had similar testing methods in terms of artificial aging and loading, with 30-degree angulation to the implant axis. On the other hand, there is a set of studies that reported fracture strength capacities of Zr abutments ranging between 429 and 793 N without artificial aging. It is known that artificial aging has a significant effect on fracture resistance of zirconia abutments. The findings of the in vitro studies testing mechanical behavior of the zirconia abutments without artificial aging can be expected to report higher values.

The fracture mode of the ceramic abutments in this study is similar to the findings of another in vitro study. It appears that the cervical aspect of the abutments represents the area of the highest torque and stress concentrations caused by levering effects. In comparison to Ti abutments, the weakest component of the system for the Zr group was the abutment itself. Failures in the Zr abutment groups were limited to the abutments, while screws or implant replicas remained intact. Also, the load displacement curves demonstrated no plastic deformation, which can be explained by the characteristics of the brittle materials (Fig 5b), which is in agreement with clinical studies and systematic reviews that reported 5-year outcomes of metal-ceramic cFDPs supported by titanium abutments.
with a previous study. Interestingly, in the present study, regardless of the number of supporting implants in both Zr abutment groups, the fractures were located above the implant shoulder, leaving the implant intact. This fracture pattern is favorable because it is easy to determine the complication and the possibility of better clinical access. The results of the present study differ from findings of former studies that reported that all of the zirconia one-piece abutments under 30 degrees of static load demonstrated fracture below the implant shoulder. However, it is possible that there were undetected fractures below the implant shoulder in the present study, even though there was no detectable decrease in the load displacement graphics (Figs 5a and 5b). Moreover, investigations on the fracture strength of Zr abutments have an important dissimilarity compared to the present study, which is restoration type. Accordingly, substantial differences between the bending forces generated by a cFDP and a single crown need to be considered when interpreting the results.

Previous observations on the effect of aging on the mechanical properties of Zr showed that the aging by means of cyclic loading and exposure to moisture under changing temperatures induces low-temperature degradation of the material, which leads to spontaneous phase transformation of the Zr crystals from the
tetragonal phase to the weaker monolithic phase.\textsuperscript{31,33}
Therefore, this in vitro study was designed carefully to simulate clinical conditions, and all specimens were exposed to an artificial oral environment. The decision for the applied force orientation and direction (30 degrees to the implant axis) was done based on previous studies in which maxillary anterior implant restorations were tested.\textsuperscript{18–22} The parameters used for cyclic loading were limited to 49 N so as to have a clinically relevant approach.\textsuperscript{34–36} There are several studies reporting that mastication forces usually range between 2 and 50 N during function.\textsuperscript{35,36} The 3D load curve is programmed by the combination of the horizontal (0.5 mm) and vertical (6 mm) motions, resulting in precisely defined vertical impact and horizontal sliding under contact. In order to minimize the bending forces, the occlusal arrangement for cantilevered FDPs requires the avoidance of possible occlusal contact. However, in the present study, the loading point was at the cantilever area. The rationale behind this selection was to create the worst clinical condition. Thermocycling was an important part of fatigue testing and was applied continuously and simultaneously during the dynamic loading.

As a possible limitation in this study, cantilever FDP frameworks were fabricated from a Co-Cr alloy, and no veneering was done. Obviously, this selection does not
comply with clinical application in the esthetic zone. Nevertheless, the rationale behind this selection was to avoid any framework failure or complication during the aging or fracture strength test of the abutments. Implant replicas instead of original implants were used in the current study. Even though the alloy used to fabricate these replicas is the same alloy used for implants from the same system, the connection between the abutment and replicas is not identical to the abutment and original implant connection. Therefore, it should be kept in mind that the failure modes may differ when the original abutments are used.

The physiologic limits can be considered to range between 50 and 400 N in the anterior zone and up to 1,000 N in the posterior zone, especially for individuals with parafunctional behaviors. In relation to the reported physiologic biting forces, except for the Zr-1 group, all groups showed fracture strength values greater than 400 N. This clearly demonstrates that they are applicable in the anterior zone. Within the limitations of this study, the authors emphasize that there is still uncertainty in predicting the performance of Zr abutments supporting two-unit cantilevered FDPs. Therefore, further investigations are needed to verify the resistance of the Zr abutments under cantilevered restorations before they can be recommended for clinical application.

CONCLUSIONS

Zr abutments under cFDPs when supported by a minimum of two implants can be considered reliable for withstanding physiologic occlusal forces applied in the anterior region. The fracture strength values of Zr abutments are lower than Ti abutments regardless of the number of implants; hence, in situations with high load, Ti abutments should be preferred.

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Literature Abstract

Retrospective Long-Term Analysis of Tooth Loss Over 20 Years in a Specialist Practice Setting: Periodontally Healthy/Gingivitis and Compromised Patients

The objective of this study was to assess tooth loss (TL) in initially periodontally healthy/gingivitis (PHG) and periodontally compromised (PC) individuals during a 15- to 25-year follow-up in a specialist practice and to identify the factors influencing TL. Patients were re-examined 240 ± 60 months after active periodontal therapy (PC) or initial examination (PHG). PHG patients were periodontally healthy or had gingivitis, and PC patients exhibited at least stage II periodontitis. TL, patient-related outcomes, and risk factors for TL were assessed at the patient level (group relation, gender, age, smoking, bleeding on probing, educational status, mean number of visits/year). A total of 56 PC patients receiving regular supportive periodontal care (12 women, mean age 49.1 ± 10.9 years, stage II: 10, stage III/IV: 46) lost 38 teeth (0.03 ± 0.05 teeth/year). Fifty-one PHG patients (23 women, mean age 34.5 ± 12.4 years) following regular oral prevention lost 39 teeth (0.04 ± 0.05 teeth/year; P = .631). Neither the PC nor PHG groups showed any significant differences regarding visual analog scale (VAS) measurements (esthetics, P = .309; chewing function, P = .362; hygiene, P = .989) or overall Oral Health Impact Profile (P = .484). Age at the start of follow-up was identified as a risk factor for TL (P < .0001). PC and PHG patients exhibited similarly small TL rates over 240 ± 60 months, which should, however, be interpreted with caution in view of the group heterogeneity.


Literature Abstract

At Which Bone Level are Implants Explanted?

Clear guidelines on when to remove an implant are missing. The aim of this study was to evaluate the amount of peri-implant bone loss at explantation by specialists. Implantology specialists were asked to provide implants explanted due to peri-implantitis with related clinical information. Early failures (survival time < 12 months) were analyzed separately. Questionnaires inquired as to age, sex, smoking, implant location, usage of bone substitutes, and implant brand. Explants were measured and bone loss was assessed using radiographs. Covariate-adjusted mixed-effects models were evaluated for bone loss and survival time. Twelve dental offices provided 192 explants from 161 patients with 99 related radiographs. Thirty-three (17.2%) explants were early failures. Excluding early failures, the average survival time was 9.5 ± 5.8 years with absolute and relative bone loss of 7.0 ± 2.7 mm and 66.2 ± 23.7%, respectively. Late failures were removed at mean bone loss of 57.7% in the maxilla and 73.7% in the mandible, irrespective of survival time. In fully adjusted mixed-effects models, only age at implantation (B = −0.19; 95% CI: −0.27, −0.10) remained a significant factor for survival time. Implants exhibited significantly more relative bone loss if they were positioned in the mandible (B = 17.3; 95% CI: 3.91, 30.72) or if they were shorter (B = −2.79; 95% CI: −5.50, −0.08). Conclusions: Though the mean bone loss (66.2%) at which implants were explanted was in accordance with the literature, its wide variation and differentiation between arches showed that the profession has no universally accepted threshold beyond which an implant cannot be preserved.


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