Zirconia Cantilever Fixed Dental Prostheses Supported by One or Two Implants: An In Vitro Study on Mechanical Stability and Technical Outcomes

Duygu Karasan, DDS, PhD1/Senay Canay, DDS, PhD2/Irena Sailer, DDS, Dr Med Dent3/Wael Att, DDS, Dr Med Dent, PhD4

Purpose: To evaluate the mechanical stability of highly translucent zirconia (Zr) cantilevered fixed dental prostheses (cFDPs) and to investigate the influence of the number of implants (one versus two) supporting cFDPs with different restorative materials on their mechanical stability and load-bearing capacity. Materials and Methods: Thirty-two specimens consisting of implant-supported prostheses embedded in resin blocks were fabricated. Sixteen specimens received one implant (bone-level implant, 4.1-mm diameter, 13-mm length; Straumann) to support two-unit cement-retained cFDPs with one extension unit and the other 16 received two implants (bone-level implant, 4.1-mm diameter, 13-mm length; Straumann) positioned corresponding to the missing maxillary central incisors to support three-unit cement-retained cFDPs with one extension unit. Two different prosthetic materials, chromium-cobalt (Cr-Co; Wirobond C1, Bego) and highly translucent Zr (Lava Plus, 3M ESPE) were selected to fabricate the two- and three-unit cFDPs. Standardized two- and three-unit Cr-Co frameworks (CC-I, n = 8; CC-II, n = 8) and highly translucent Zr frameworks (Zr-I, n = 8; Zr-II, n = 8) with a 6-mm cantilever extension were fabricated using CAD/CAM (EOS M 290). Following thermomechanical fatigue loading, the specimens were tested for fracture resistance under static loading. The influence of restoration material and number of supporting implants on fracture resistance were tested using two-way analysis of variance (ANOVA). The level of statistical significance was set below 5% (α < .05). Results: All specimens survived aging. The mean (± standard deviation) fracture resistance values were 416.25 (± 42.71) N for Zr-I, 548.75 (± 75.41) N for Zr-II, 601.0 (± 41.51) N for CC-I, and 644.5 (± 37.59) N for CC-II. CC and Zr group specimens showed significantly different fracture resistance results (P < .001). The number of implants significantly influenced the fracture resistance of Zr groups (P = .001), whereas the influence was not significant for CC groups (P = .089). Conclusion: Within the limitations of this in vitro study, highly translucent zirconia cFDP frameworks demonstrated the potential to withstand reported physiologic occlusal forces applied in the anterior region. The increase in the number of implants supporting zirconia cFDPs significantly contributed to achieving higher fracture resistance values. Int J Oral Maxillofac Implants 2022;37:748–755. doi: 10.11607/jomi.8953

Key words: dental implants, fixed dental prosthesis, cantilever, zirconia, highly translucent zirconia

The use of dental implants has become a routine procedure for the replacement of missing teeth in both posterior and anterior regions,1–3 and clinicians have a wide spectrum of material alternatives for implant-supported prostheses.4,5 Even though mid- or long-term prosthesis survival is not influenced by the prosthesis material selection,6 the capabilities expected from the material for implant-supported restorations may differ depending on the restoration type and the edentulous region.

The use of CAD/CAM technology has deeply impacted the treatment approaches and materials in use for prostodontic treatments. While metal-ceramic restorations are still considered as the standard of care in connection with their long track record in the literature,4 the use of zirconia for implant-supported restorations has increased with the digitalization of the treatment processes.7 Moreover, their excellent biocompatibility8–11 and reported superiority in terms of esthetics12 created higher interest in zirconia over metal-ceramics for implant-supported restorations, particularly in the

1Assistant, Division of Fixed Prosthodontics and Biomaterials, University Clinics for Dental Medicine, University of Geneva, Geneva, Switzerland.
2Professor, Department of Prosthodontics, Faculty of Dentistry, Hacettepe University, Ankara, Turkey.
3Professor and Chair, Division of Fixed Prosthodontics and Biomaterials, University Clinics for Dental Medicine, University of Geneva, Geneva, Switzerland.
4Professor and Chair, Department of Prosthodontics, Tufts University School of Dental Medicine, Boston, Massachusetts, USA.

Correspondence to: Duygu Karasan, Division of Fixed Prosthodontics and Biomaterials, University Clinics for Dental Medicine, University of Geneva, Michel Servet 1, CH-1211 Geneva, Switzerland. Email: Duygu.Karasan@unige.ch

Submitted August 31, 2020; accepted March 16, 2022. ©2022 by Quintessence Publishing Co Inc.
esthetics. However, their brittle nature is still raising questions when it comes to their use in biomechanically compromised restoration designs, such as prostheses with cantilevers.

In the case of multiple tooth loss in the anterior maxilla, vertical and horizontal dimensional changes of the alveolar bone flatten the crest and form a limited mesiodistal gap. This change makes it difficult to place adjacent implants with ideal interimplant distance (3 mm), which is considered essential for pink esthetics. Moreover, the dimensional changes influencing both hard and soft tissues often create the need for complex surgical procedures that involve longer treatment times, higher morbidity, and higher complication rates as well as an increase in cost. Techniques such as implant-supported cantilevered fixed dental prostheses (cFDPs) that allow optimized time- and cost-benefit ratios as well as reduced esthetic risk can be considered as a valid treatment option for anterior partial edentulism.

The clinical outcomes of metal-ceramic cFDPs supported by two or more implants were reported in a few clinical studies, and existing evidence suggests that the presence of a cantilever does not increase the total complication rate. Therefore cFDPs (metal-ceramic, supported by two or more implants) can be considered as a reliable treatment option to avoid multiple adjacent implant placement in the esthetic zone. However, the clinical evidence regarding single-implant-supported cFDPs with one extension unit remains limited. A recently published retrospective case series evaluating single-implant-supported cemented metal-ceramic cFDPs suggested that two-unit metal-ceramic cFDPs showed similar prosthetic outcomes compared to single crowns supported by adjacent implants.

Zirconia (Zr) cFDPs were investigated in a number of in vitro studies focusing on framework design, cantilever length–occlusocervical thickness, and retention type, either using finite element or biomechanical testing methods. However, clinically relevant, well-designed in vitro investigations on the performance of zirconia as a restorative material for cFDPs when used in framework designs with different numbers of restorative units and supporting implants remain scarce.

Therefore, this study aimed to evaluate the mechanical behavior of zirconia cFDPs compared to metal-ceramic cFDP frameworks supported by one or two implants and after artificial aging in a chewing simulator. The tested null hypotheses were the following: (1) The fracture resistance of cFDPs would not be influenced by the number of supporting implants and (2) chromium-cobalt (Cr-Co) cFDPs would have similar fracture resistance values compared to Zr cFDPs.

**MATERIALS AND METHODS**

A maxillary Typodont model (Frasaco) was modified by removing the two central incisors and the right lateral incisor in order to simulate a partial edentulous clinical situation. A master model was fabricated by duplicating this model out of resin (Pattern Resin, GC).

Two bone-level implants (4.1-mm diameter, 13-mm length; Straumann) were placed in the master model using a surveyor in the position of the central incisors and fixed with resin. Two one-piece internal-connection titanium abutments (RC Anatomic Abutment, GH 2 mm, Straumann) were screwed on the implants and torqued to 35 Ncm. The model was scanned in order to obtain abutment-level impressions with a laboratory scanner (Lava, 3M ESPE). The scan data were then used to for computer-aided design (CAD) of the cFDP frameworks with a 6-mm cantilever length, a 0.5-mm wall thickness, and a 9-mm² connector area. The highly translucent Zr cFDP frameworks (Lava Plus, 3M ESPE) were milled (CNC 240, Lava, 3M ESPE) and Cr-Co (Iwirobond C+, Bego) cFDP frameworks were fabricated using a laser sintering technique (3D printer EOS M 290). Thirty-two specimens were fabricated, half with one implant replica to support two-unit FDPs with a cantilever extension (CC-I and Zr-I; n = 16; Figs 1a and 2a), and the other half with two implant replicas to support three-unit FDPs with a cantilever extension to the lateral incisor site (CC-II and Zr-II; n = 16; Figs 1b and 2b). Groups Zr-I and Zr-II received highly translucent Zr (Lava Plus) cFDPs, and groups CC-I and CC-II received Cr-Co (Iwirobond C+) cFDPs. The specimens were fabricated by embedding the implant replicas (RC Implant Analog, Ti, 12-mm length, Straumann) in polyurethane molds suitable for a chewing simulator (CS 4.8, Willytech) with autopolymerizing acrylic resin (Technovit 4000, Kulzer) at an angle of 30 degrees to the horizontal plane (Fig 3). The resin's elasticity modulus was 12 GPa, which approximates natural conditions (human bone = 18 GPa).

Internal-connection titanium abutments (RC Anatomic Abutment, straight, GH 2 mm) were fixed onto the implant replicas that were embedded in the study molds using titanium screws and torqued to 35 Ncm according to the manufacturer’s recommendations. The abutment screws were retightened to 35 Ncm 1 minute later. The inner surfaces of the Zr and Cr-Co frameworks were sandblasted uniformly with 30-mm and 50-mm aluminum oxide (Al₂O₃), respectively, and cleaned in 70% isopropanol alcohol using an ultrasonic bath for 4 minutes. Following the sandblasting (30-mm Al₂O₃, 2 bar/10 s), the Ti abutments were rinsed and dried. A universal primer (Monobond Plus, Ivoclar Vivadent) was applied to the abutment and restoration. The restorations were then cemented using a resin luting cement (Multilink Automix, Ivoclar Vivadent).
A previously published thermomechanical fatigue test protocol was adopted. Briefly, specimens were tested with a computer-controlled dual-axis chewing simulator for 1,200,000 cycles. The force was applied 3 mm below the incisal edge at the midpalatal point of the cantilever area at a frequency of 1.6 Hz using a ceramic (steatite) ball (Hoechst CeramTec) with a 6-mm diameter and a Vickers hardness similar to enamel. A 49-N load was applied to simulate a load within the clinical range. 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 thermostatically controlled liquid circulator (Haake, Thermo Scientific).

The specimens were examined with a stereomicroscope (Carl Zeiss) to identify any possible complications following the thermomechanical loading, such as cracks in framework or framework fracture. Mobility of the superstructure and components were evaluated manually in order to detect any possible screw loosening or decementation. Specimens that survived the aging were tested for fracture resistance using a universal testing machine (Z010, ZwickRoell). A 0.5-mm-thick tin foil (Dentaurum) was placed, and a static force was applied, ensuring the same angulation and point as fatigue loading (1-mm/min head speed). The fracture resistance (Fmax) was registered when the load decreased by 20%. Specimens were then examined under the stereomicroscope to identify the mode of failure. Any plastic deformation or fracture of the implant components.
was recorded. The specimens that had fractures were further analyzed to understand the fracture behavior.

The fracture resistance values were analyzed using SPSS version 20.0 (IBM). Descriptive statistics together with 95% confidence intervals for the true mean were calculated. Following normality analysis using Shapiro-Wilk test, a two-way ANOVA was used to test the main effect of material, the number of implants, and their interaction. Tukey post-hoc test was used to detect significant differences among the tested groups. The level of statistical significance was set at 5% (α = .05).

RESULTS

All specimens survived 1,200,000 cycles of thermomechanical fatigue. None of the abutments or restorations showed visible cracks. No mobility of the framework or screw loosening was detected.

Two-way ANOVA revealed significant main effects for restoration material (P < .001) and number of supporting implants (P < .001). The mean fracture resistance values are presented in Table 1. Post hoc analysis showed that the values of CC-II were significantly higher when compared to Zr-I (P < .001) and Zr-II (P = .001), but similar to CC-I (P = .89). No significant differences were found between Zr-II and CC-I (P = .203). Zr-I group obtained the significantly lowest fracture resistance values when compared to other groups (Zr-II [P = .001], CC-I [P = .001], CC-II [P = .001]; see Table 1). Accordingly, Zr cFDPs with two implants had significantly higher fracture resistance values than those with one implant (P = .001).

The failure mode for every group is shown in Table 2. In groups CC-I and CC-II, the failure was represented by either implant replica neck distortion or acrylic resin fracture. In the CC-I group, the failure was represented by implant neck distortion (Fig 4a) in all specimens; in two specimens this was combined with acrylic resin fracture. In CC-II group, except two specimens that also demonstrated plastic deformation of the implant replica and/or abutment (Fig 4b), the failure was caused by acrylic resin fracture (Fig 4c). In CC group specimens, no screw, abutment, or framework complications were detected.

In groups Zr-I and Zr-II, the failure was represented by catastrophic fracture of the FDP. Most of the specimens in the Zr-I group depicted failure of the restoration from the distal restoration wall in immediate proximity to the cantilever site (Figs 5a and 5b), whereas Zr-II specimens demonstrated fractures that were located at the restoration wall of the first (Fig 5c) or second abutments (Fig 5d) or multiple fracture lines at both the first and second abutment restoration walls (see Table 2).

The cFDPs were identified as the weakest components for the Zr-I and Zr-II groups, whereas the implant replicas and the embedding resin were identified as the weakest components in the CC-I and CC-II groups.

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Table 1  Mean Fracture Resistance Values ± SD, Range

| Material | Number of implants | P  
|----------|--------------------|----|
|          | One                | Two | P  
| CC       | 601 ± 41.5, 546 to 601 | 664.5 ± 376, 613 to 721 | .89 |
| Zr       | 416.2 ± 42.7, 361 to 469 | 548.7 ± 75.4, 429 to 667 | < .001 |
| P  | < .001 | .001 |

SD = standard deviation.
*Two-way ANOVA and Tukey test results (α = .05).

Table 2  Location and Mode of Failure After Fracture Resistance Tests

<table>
<thead>
<tr>
<th>Groups</th>
<th>Plastic deformation of the implant replicas and/or abutment</th>
<th>Abutment failure</th>
<th>Acrylic resin failure</th>
<th>Failure of the FDPs</th>
<th>Location of the fracture line</th>
<th>Screw failure or screw loosening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr-I</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>At the restoration wall with immediate proximity to the cantilever site (n = 8)</td>
<td>0</td>
</tr>
<tr>
<td>Zr-II</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>Restoration wall of the first abutment (n = 5)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Restoration wall of the second abutment (n = 1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Multiple fracture lines on the restoration wall of the first and second abutments (n = 2)</td>
<td></td>
</tr>
<tr>
<td>CC-I</td>
<td>8</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>CC-II</td>
<td>2</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>–</td>
<td>0</td>
</tr>
</tbody>
</table>

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DISCUSSION

Based on the results of the present study, both CC and Zr two-implant-supported cFDPs demonstrated higher fracture resistance values than one-implant–supported cFDPs of the same material; however, the difference was only statistically significant for the Zr cFDP groups. Thus, the first null hypothesis was rejected. Zr cFDPs exhibited lower fracture resistance values compared to metal frameworks independent from the number of supporting implants; therefore, the second null hypothesis was also rejected.

The present study suggests that both one- and two-implant–supported Zr cFDPs demonstrated favorable fracture resistance results in relation to the reported physiologic biting forces for the anterior maxilla. The physiologic limits are considered to range between 50 and 400 N in the anterior zone.33–37 Even though the number of supporting implants played a significant role in the fracture resistance of Zr cFDPs (Zr-I = 416.2 N, Zr-II = 548.7 N; \( P = .001 \)), the Zr-I group, the weakest among the four groups, still demonstrated fracture resistance values greater than 400 N (see Table 1).

Fig 4  Stereomicroscope images of specimens from the CC groups after fracture resistance testing. (a) In the CC-I group, the failure was represented by implant replica neck distortion. (b and c) CC-II group specimens showed failure caused mainly by acrylic resin fracture or the combination of both acrylic resin fracture and implant replica neck distortion.

Fig 5  Stereomicroscope images of the Zr group specimens after fracture resistance testing. (a and b) Zr-I specimens depicting failure of the cFDP restoration wall next to the cantilever site. (c and d) In the Zr-II group specimens, the fracture line was located at the restoration wall of either the first or second abutment.
So far, implant-supported metal-ceramic cFDPs were used successfully for reconstruction of multiple missing adjacent teeth in the anterior maxilla.\textsuperscript{21,22,38} A systematic review\textsuperscript{25} reported a 98.9% 5-year cumulative survival rate for implant-supported cFDPs. Cementation failure was estimated as 5.9%, and screw loosening was estimated as 7.9% at 5 years. Accordingly, screw loosening was reported as one of the most common technical complications.\textsuperscript{25} Because all specimens tested in this study survived and showed no signs of technical complications after artificial aging of 1,200,000 cycles, one- and two-implant-supported Zr cFDPs seem to be promising.

A laboratory study comparing different clinically relevant framework designs for three-unit cantilevered, two-implant-supported FDPs reported fracture resistance values ranging from 346 to 548 N.\textsuperscript{28} Even though the fatigue loading in the mentioned study is limited to 60,000 cycles, the fracture resistance values were reported to be lower than the results of the two-unit, one-implant-supported cFDPs of the present study (416.25 N). This can be explained by the cantilever length, which was set to 7 mm in the previous study.\textsuperscript{28} Different methodology, load application, specimen design, thickness, brands, involvement of implant components, and aging period might explain the differences observed between the studies. A recent in vitro study on monolithic zirconia blocks testing the effect of different cantilever lengths and occlusocervical thicknesses reported high fracture resistance values ranging from 2,427 to 6,075 N.\textsuperscript{30} However, axial loading conditions were reported to result in two times higher fracture resistance values (1,115 N) for the two-unit cemented anterior cFDPs when compared to oblique loading (657 N).\textsuperscript{31} Therefore, the authors recommended the use of oblique loading for the in vitro testing of cFDPs in order to avoid the possible overestimation of their mechanical capacity.\textsuperscript{31}

For the present study, cement-retained cFDPs were selected to be tested for the rehabilitation of multiple missing teeth in the anterior region. Based on the clinical data,\textsuperscript{39} screw-retained cFDPs can be a more favorable alternative in terms of biologic outcomes for the same clinical scenario. However, occasionally clinicians are obliged to choose cement retention over screw retention. Different retention types may yield to different technical failure or complication modes. Rues et al concluded that the retention type (screw versus cement retention) has no influence on the fracture resistance of two-unit cFDPs; however, the screw was the predominant reason for failure of screw retained cFDPs (94% of specimens), whereas failure of the restoration was the reason for failure of cement-retained FDPs, as supported by the present study.\textsuperscript{31}

According to finite element analyses on implant-supported cFDPs, the stress concentration is located in the connector area between the extension and terminal abutment.\textsuperscript{29} In the current study a different fracture behavior was observed. Although the connectors were designed at the minimum limit recommended by the manufacturer (9 mm$^2$), the fracture line of the Zr-I specimens was located in the distal wall of the restoration next to the pontic area (see Figs 5a and 5b). This can be explained, as the rotation center of the assembly was located around the terminal wall of the restoration; therefore, the highest loads were concentrated at that area. The predominant fracture area for Zr-II specimens was also the crown walls, with none at the connector (see Figs 5c and 5d). Accordingly, while a 9-mm$^2$ connector area can be considered clinically acceptable for Zr restorations, during the design of the restoration, thicker framework walls might be more essential. This finding can be considered promising in terms of the use of monolithic Zr cFDPs for the rehabilitation of multiple missing anterior maxillary teeth, as the monolithic design will allow higher material thickness at the retainer area.

The aging by means of dynamic loading and simultaneous thermocycling with distilled water have been demonstrated to induce the low-temperature degradation of Zr, which then initiates the spontaneous phase transformation of Zr crystals from tetragonal to monoclinic phase.\textsuperscript{40,41} Therefore, a careful design of an in vitro study to simulate clinical conditions as closely as possible is important. The load applied was 49 N because the mean forces generated during mastication were reported to be 2 to 50 N in the anterior zone.\textsuperscript{42–44} The three-dimensional load curve was programmed by the combination of horizontal (0.5 mm) and vertical (6 mm) motion, resulting in precisely defined vertical impact and horizontal sliding under contact. The loading was restricted to 3 mm below the incisal edge.

In this study, cFDP frameworks were not veneered. This situation does not completely simulate clinical applications in the esthetic zone. The rationale behind the absence of veneering was to avoid any complications such as chipping or fracture of the veneering porcelain that might jeopardize the continuity of both dynamic and static loading tests of cFDPs frameworks. Moreover, the use of implant replicas instead of original implants can be regarded as a limitation of the current study. However, implant replicas were made from the same alloy that is used to fabricate the implants from the same system (Straumann). It should be kept in mind that abutment/implant replica connection might be different than the abutment/original implant connection; therefore, the mode of failures, especially for the CC groups, may differ when the original implants are used. In the CC groups, the failure was presented by either implant replica and/or abutment plastic distortion or acrylic resin fracture (see Fig 4).

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Within the limitations of this in vitro study, one- or two-implant-supported Zr cFDPs can be a promising alternative to metal-ceramic cFDPs. However, clinical interpretations of the results must be made carefully. Accordingly, future well-designed clinical studies are needed to obtain information on the clinical performance of Zr cFDPs.

CONCLUSIONS

Cr-Co and Zr cFDPs survived the cyclic loading without any mechanical complications. Cr-Co cFDPs required higher loads to fail compared to Zr cFDPs when supported by same number of implants. Number of supporting implants had a positive influence on fracture resistance of Zr cFDPs. Both one- and two-implant–supported Zr cFDPs withstood the reported physiologic occlusal forces applied in the anterior region.

ACKNOWLEDGMENTS

The authors declare no conflict of interest. No benefit of any kind was reported Zr cFDPs withstood the reported physiologic occlusal forces applied in the anterior region.

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