Different Cavity Designs with Additional Wings Increase the Fracture Resistance of Inlay-Retained Monolithic Zirconia Fixed Dental Prostheses

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Purpose: To evaluate the effect of different cavity designs and cement types on the fracture resistance of monolithic zirconia inlay-retained fixed dental prostheses (IRFDPs). Materials and Methods: Four study models consisting of a second premolar, a missing first molar, and a second molar were used for the different cavity designs. Four different inlay cavity designs were prepared: DO-MO (dista-occlusal–mesio-occlusal cavity), MOD-MOD (mesio-occlusodistal-mesio-occlusodistal cavity), WDO-WMO (DO-MO with additional wings), and WMOD-WMOD (MOD-MOD with additional wings). A total of 64 epoxy resin models were produced and scanned individually. IRFDPs were then fabricated from monolithic zirconia using CAD/CAM software. The bonding surface of the IRFDPs was airborne particle abraded (50-μm alumina/2 MPa), then cemented onto the epoxy resin models using two cementation protocols (n = 8 per group): (1) P = cemented with Panavia SA Cement Plus Automix; and (2) Z/C = cemented with MDP-containing primer (Z-Prime Plus) combined with Calibra Universal resin cement. All IRFDPs were fatigue-aged through thermal aging (6,000 cycles/5°C to 55°C) and chewing simulations (600,000 cycles × 50-N load, 2.1 Hz). All IRFDPs were then subjected to a fracture resistance test using a universal testing machine with a crosshead speed of 0.2 mm/minute. Data were statistically analyzed using one- and two-way ANOVA and Bonferroni multiple comparisons test (P = .001). Results: The mean fracture load (N) of the designs were as follows: WMOD-WMOD = 1,111.1; WDO-WMO = 1,057.4; MOD-MOD = 725.6; DO-MO = 682.7. According to two-way ANOVA, the differences among the cavity designs were statistically significant (P < .05). Conclusion: The cavity design of IRFDPs affected the fracture resistance. However, the fracture resistance of monolithic zirconia IRFDPs with any cavity design was enough to withstand expected posterior chewing forces. Int J Prosthodont 2022;35:487–493. doi: 10.11607/ijp.8010

Treatment of a single-tooth deficiency can be done with conventional metal-ceramic, all-ceramic, or implant-supported fixed dental restorations. REGARDLESS OF THE TYPE OF RESTORATIVE MATERIAL, THE PREPARATION OF A CONVENTIONAL CROWN ALWAYS POSES A RISK FOR Pulp vitality and may cause pulpal reactions in the long term. Therefore, missing teeth can be replaced by implant-supported single crowns without compromising the healthy tooth structure; however, patients may refuse a time-consuming, expensive implant treatment that may require bone and soft tissue surgery. In cases where implant treatment is not an option and teeth adjacent to the tooth cavity are decayed or filled, inlay-retained fixed dental prostheses (IRFDPs) are recommended.

The ideal cavity design has been defined as having a cavity depth of 1.5 to 2 mm, a maximum isthmus width of one-third the total intercuspal width, and a total occlusal convergence angle of 20 degrees, with all internal line angles rounded and flattened to reduce stresses. It has been suggested that both the tooth preparation and the frame design need to be modified to adapt the specific qualities of the ceramic materials.
used in the manufacture of inlay-supported restorations. Chaar and Kern used a new zirconia ceramic IRFDP design with additional short retainer wings on the buccal and palatal sides to improve stress distribution. IRFDPs are usually produced from metal-ceramic, full-ceramic, and fiber-reinforced composite materials. The new high-strength ceramics with high mechanical properties and hardness are considered the right choice for IRFDPs. Monolithic zirconia restorations became popular with the development of CAD/CAM technologies and zirconia materials. It appears that monolithic translucent restorations result in improved survival via the elimination of porcelain veneers with lower fracture strength. Full-contour restorations are favored over bilayer restorations due to the simplified procedure. In addition, the mechanical properties of the monolithic zirconia materials are superior to those of all-ceramic restorative materials. The risk of chipping in ceramic veneers is eliminated with monolithic restorations.

In vitro studies, monolithic zirconia single crowns showed greater fracture resistance than layered zirconia crowns. The stress that occurs in the molar region during chewing varies between 441 and 981 N. As a result of their high fracture resistance, monolithic zirconia crowns are resistant to chewing forces in the molar region even at 0.5-mm occlusal thickness. Different types of mechanical and chemical surface treatment methods have been suggested for zirconia. Airborne particle abrasion with aluminum oxide particles is the most widely used mechanical procedure. Recently, however, bonding agents containing 10-methacryloyloxydecyl dihydrogen phosphate (MDP) monomers have been used for chemical surface treatment. MDP-containing primer has a strong chemical affinity for the hydroxyl groups on the zirconia surface, which is easily covered with a passive oxide layer with application of the MDP primer. This increases the bond strength between the zirconia and the resin cement. For this reason, new universal adhesives containing MDP and single-stage self-adhesive cements containing MDP have started to be preferred for the cementation of zirconia restorations. Studies have also found that using primer or resin cement containing MDP monomer after airborne particle abrasion increases the bond strength.

Survival of IRFDPs is thought to be affected by factors such as tooth preparation design, adhesive system, and retainer design. Additional retainer wings are known to improve the stress distribution of the IRFDPs and increase the adhesive bonding area. This study aims to evaluate the effect of different designs and cement types on the fatigue survival and fracture resistance of IRFDPs made of monolithic zirconia. The null hypothesis of this study was that different designs and bonding cements would not affect the fracture resistance of monolithic zirconia IRFDPs.

**MATERIALS AND METHODS**

Four different designs were determined for IRFDPs. The mandibular left first molar was removed from the student model jaws (Klas Dental Phantom Jaw, Barış Dental). The toothless crest was formed by filling the cavity with wax. Teeth adjacent to the toothless area were prepared to form four different design groups. A parallel measuring device (Amann) was used to ensure a standardized preparation procedure. The amount of preparation for the designs is shown in Table 1.

In this study, the connector width for all samples was determined as $3 \times 3 \times 1.5$ mm, according to the manufacturer’s instructions. Each epoxy resin model was scanned (Dental Wings) individually, and IRFDPs

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**Table 1** Preparation of Retainer Abutments

<table>
<thead>
<tr>
<th>Design</th>
<th>Preparation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO-MO</td>
<td>DO-MO inlay</td>
<td>DO-MO standard preparation: Distal and mesial boxes: 3 mm wide, 3 mm high, and 1.5 mm deep Occlusal preparation: 1.8 mm wide, 2 mm long, and 1.5 mm deep</td>
</tr>
<tr>
<td>WDO-WMO</td>
<td>DO-MO inlay with additional wings</td>
<td>As in DO-MO, but with additional wings (buccal and lingual): 3 mm long, 0.7 mm deep</td>
</tr>
<tr>
<td>MOD-MOD</td>
<td>MOD-MOD inlay</td>
<td>MOD-MOD standard preparation: Proximal boxes: 3 mm wide, 3 mm high, and 1.5 mm deep Occlusal preparation: 1.8 mm wide, 2 mm long, and 1.5 mm deep</td>
</tr>
<tr>
<td>WMOD-WMOD</td>
<td>MOD-MOD inlay with additional wings</td>
<td>As in MOD-MOD, but with additional wings (buccal and lingual)</td>
</tr>
</tbody>
</table>
were designed (Fig 2). The designs that were used were transferred to SOLIDWORK 2021 software to calculate the cementation surface areas (CSAs), and the values were recorded (Fig 3).

A total of 64 IRFDPs were produced with DWOS (Dental Wings) software using CAD/CAM (Yenamak d50, Yenadent) for four different cavity designs from monolithic zirconia blocks (Vita YZ T, Vita Zahnfabrik).

The bonding surfaces of the IRFDPs were airborne particle abraded with 50-μm alumina particles (P-G 400; Harnisch+Rieth) at 0.1 MPa pressure for 15 seconds. Before cementation, the samples were cleaned with an ultrasonic cleaning device in 99% ethanol solution for 5 minutes (Sonnex Super RK 510 H, Bandelin).

Each of the four design groups was randomly divided into two subgroups of eight samples each, and the specimens in the subgroups were bonded to the epoxy models with two different dual-cure self-adhesive resin cements: (1) A resin cement containing MDP (Panavia SA Cement Plus Automix, Kuraray Noritake Dental; P group); and (2) a resin cement (Calibra Universal, Dentsply Sirona) applied in combination with MDP-containing adhesive primer (Z-Prime Plus, Bisco) were used (Z/C group). During the cementation process, finger pressure was applied from the occlusal surface of the pontic, as is done in clinical practices.

All samples were kept in deionized water at 37ºC for 24 hours. To prepare the samples for chewing simulation, a supporting material (cold autopolymerizing acrylic resin, Me- liodont, Bayer Limited) was poured around the master die, which was fixed in a standardized position in the chewing simulator’s specimen cup. All of the IRFDPs were subjected to an aging process by means of a chewing simulator (600,000 cycles x 50-N load, 2.1-Hz frequency) with thermocycling at 5ºC to 55ºC (Multifunctional chewing simulator, Analitik Medikal) (Fig 4).
fatigue testing, each IRFDP was loaded in a universal testing machine (Besmak). The steel ball (6-mm diameter) was placed perpendicular to the occlusal surface, in the central fossa of the pontic, and the measurement was conducted at a crosshead speed of 2 mm/minute. The failure load was defined as the load at maximal load as reported by the universal testing machine, and force at failure was recorded in Newtons (N) for each specimen.

**Statistical Analysis**

All statistical tests were performed using SPSS version 23.0 (IBM). Normal distribution of data was tested using one-sample Kolmogorov-Smirnov test. The data were then analyzed using one- and two-way analysis of variance (ANOVA). Bonferroni and independent sample t test were used for multiple comparisons of groups and subgroups, respectively (P < .05).

**RESULTS**

According to the one-way ANOVA test results, there was a statistically significant difference between groups in terms of fracture load values (F = 86.069, P = .001). While the DO-MO group showed the lowest fracture resistance at 682.73 N, the WMOD-WMOD group showed the highest fracture resistance at 1,111.12 N.

There was a statistically significant difference between the fracture resistance values of the groups with additional wings (WDO-WMO, WMOD-WMOD) and the groups without additional wings (DO-MO, MOD-MOD) (P < .05). The differences in fracture resistance of the groups without additional wings (DO-MO, MOD-MOD) were not statistically significant among themselves (P > .05). The differences in fracture resistance of the groups with additional wings were also not statistically significant among themselves. Fracture resistance and SD values of each group are given in Table 2.

According to the results of two-way ANOVA, there was a statistically significant difference between the fracture resistance values of the four groups (P < .05). When the two subgroups were examined, there was also a statistically significant difference in terms of fracture resistance (P < .05). However, the group*subgroup interaction, when examined in terms of fracture resistance, was not statistically significant (P > .05).

The comparison between the groups revealed that, of the fracture resistance values, the P*DO-MO (647.3 N) interaction had the lowest value, and the Z/C*WMOD-WMOD (1,124.02 N) interaction was the highest.

A statistically significant difference was found in terms of fracture resistance values in the P and Z/C subgroups of the four groups (P < .05) (Table 3). While WMOD-WMOD had the most resistance against fracturing in both subgroup Z/C (1,124.02 N) and P (1,098.2 N), the lowest fracture resistance value belonged to subgroup Z/C (718.07 N) and P (647.3 N) of the DO-MO group.

Table 2 Fracture Resistance (N) of Tested Groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO-MO</td>
<td>682.73</td>
<td>90.03</td>
<td>486.57</td>
<td>858.23</td>
</tr>
<tr>
<td>MOD-MOD</td>
<td>725.60</td>
<td>59.80</td>
<td>612.31</td>
<td>825.03</td>
</tr>
<tr>
<td>WDO-WMO</td>
<td>1,057.49</td>
<td>84.91</td>
<td>902.69</td>
<td>1,211.13</td>
</tr>
<tr>
<td>WMOD-WMOD</td>
<td>1,111.12</td>
<td>132.33</td>
<td>953.59</td>
<td>1,399.97</td>
</tr>
</tbody>
</table>

One-way ANOVA was used for statistical analyses. The same superscript letters indicate no statistically significant difference (P > .05) between groups, while different superscript letters indicate a statistically significant difference (P < .05).
234.18 mm², respectively.

Consequent variability in stress distribution may result in different fracture patterns. In the present study, a standardized three-member IRFDP was modeled, and prefabricated teeth were prepared to obtain homogenous results by minimizing variable factors.

Table 3: Comparison of Fracture Resistance (N) Between Subgroups

<table>
<thead>
<tr>
<th>Groups</th>
<th>MO-DO</th>
<th>MOD-MOD</th>
<th>WMO-WDO</th>
<th>WMOD-WMOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subgroups</td>
<td>P</td>
<td>Z/C</td>
<td>P</td>
<td>Z/C</td>
</tr>
<tr>
<td></td>
<td>647.39 ± 83.80 A a</td>
<td>692.40 ± 53.67 A a</td>
<td>1,021.25 ± 77.12 A b</td>
<td>1,098.22 ± 111.70 A b</td>
</tr>
<tr>
<td></td>
<td>718.07 ± 86.56 A a</td>
<td>758.80 ± 47.56 A a</td>
<td>1,093.73 ± 80.62 A b</td>
<td>1,124.02 ± 157.05 A b</td>
</tr>
</tbody>
</table>

Data are reported as mean ± SD. The same lowercase superscript letters indicate no statistically significant difference (P > .05) between subgroups, while different lowercase superscript letters indicate a statistically significant difference (P ≤ .05). The same uppercase superscript letters indicate no statistically significant difference (P > .05) between groups, while different uppercase superscript letters indicate a statistically significant difference (P ≤ .05).

It was concluded that there was a statistically significant difference between the subgroups of the MOD-MOD group in terms of fracture resistance—the Z/C subgroup (758.8 N) had the higher fracture load value than the P group (692.4 N) (P ≤ .05).

The CSAs were measured using SOLIDWORKS 2021 software. According to this program, the surface area of DO-MO, MOD-MOD, WDO-WMO, and WMOD-WMOD groups was 38.89 mm², 70.78 mm², 203.07 mm², and 234.18 mm², respectively.

After the fracture test in the DO-MO and MOD-MOD groups, the fracture line was observed in the pontic in only one sample and in the connector area between the inlay and the pontic in the other samples. In groups with additional wings design, the fracture line was observed only on one wing, on both wings, or in the connector area. In these groups, the fracture line was in the connector area in 13 samples and on the wings in others.

**DISCUSSION**

The results of this study showed that different cavity designs and cement types affected the fracture resistance of monolithic zirconia IRFPDs. Therefore, the null hypothesis that the different designs and bonding cements would not affect the fracture resistance of monolithic zirconia IRFPDs was rejected.

When replacing missing teeth, it is desirable that little to no tooth preparation be made on the abutment teeth. For this reason, IRFPDs are a conservative option for the restoration of damaged teeth. Researchers have proposed various inlay designs, such as troughs, tubs, box-shaped proximal preparations, and occlusoproximal preparations. IRFPDs do not have a uniform shape, which can affect stress concentrations, and the consequent variability in stress distribution may result in different fracture patterns. In the present study, a standardized three-member IRFDP was modeled, and prefabricated teeth were prepared to obtain homogenous results by minimizing variable factors.

In in vitro studies, the study models can be produced from different materials. Increasing the modulus of elasticity of these supporting materials is known to cause an overestimation of the fracture resistance. In a finite study by Yucel et al, the stress distribution on the restoration was examined based on the abutment materials, and the restoration showed a similar stress distribution when bonded to dentin and to an epoxy resin die, but a different stress distribution when bonded to a metal die. Sagsoz et al reported that CAD/CAM crowns on epoxy resin dies had fracture resistance values similar to CAD/CAM crowns on dentin dies. To achieve a standardized configuration of the experimental specimens, epoxy resin replicas were used as abutments instead of prepared natural teeth. Epoxy resin was chosen because its elastic modulus is close to that of natural dentin and because it has been used as a representation of natural teeth in previous studies.

In the present study, one of the resin cements used was Calibra Universal, with the use of Z-Prime Plus containing 10-MDP. 10-MDP, which is used in the cementation of zirconia, is thought to be a monomer that increases adhesion. Butler et al reported that application of Z-Prime Plus in combination with airborne particle abrasion showed higher bond strength than zirconia with an untreated surface. According to the present results, IRFPDs bonded with resin cement combined with primer containing 10-MDP showed higher fracture resistance than those bonded with cement containing 10-MDP. The findings of this study are in accordance with a previous study examining the effects of different surface treatments on zirconia cementation, which found that primer application increased the bond regardless of the resin cement content.

Some previous studies revealed that the mechanical retention of MOD inlays was better than MO inlays and that the number of retainer wings improved adhesion, thus ensuring high failure load resistance. According to the findings of a systematic review on the...
clinical effectiveness of zirconia bonding methods, the clinical survival rate increases with the use of properly designed buccal and lingual partial coverage retainers.52 Bishri et al50 reported that, regardless of inlay design, inlay-supported cantilever FDPs with two additional retainers had the highest failure loads under static and dynamic loading. The results of this study revealed that the fracture resistance of the WMOD-WMOD group was higher than the fracture resistance of the WMOD group. The mean fracture resistance of the groups with additional wings was statistically higher than the fracture resistance of the groups without wings (P < .05). When the fracture resistance values of the groups in this study were examined, it was found that the CSA was found to be directly proportional to the fracture resistance. When the CSAs of the groups were calculated and proportioned to each other, the CSAs of the additional wings caused a great difference between the groups. This explains the statistical difference in fracture resistance values between groups with additional wings and groups without additional wings. When the group*subgroup interaction was examined, the Z/C subgroup of MOD-MOD group showed statistically higher fracture resistance than all groups without additional wings. This is thought to be due to the CSA ratio among the groups without wing design.

In order for full-ceramic IRFDPs to be an alternative to metal-ceramic IRFDPs in the posterior region, the material must withstand posterior chewing forces of approximately 500 N.5,53 In a previous study, it was concluded that IRFDPs produced from zirconia showed similar fracture resistance (1,247 N) to conventional metal-ceramic IRFDPs (1,318 N).31 In the present study, the fracture resistance of IRFDPs produced from monolithic zirconia showed average values ranging from 486 to 1,399 N in all of the groups that were tested. The fracture resistance values within this study are within the critical range of the results of another study investigating the post-aging fracture resistance of inlay-retained fixed prostheses designed on two abutments.54 The use of epoxy resin as an abutment material may be considered a limitation because it may not accurately reflect the mechanical behavior of natural teeth under loading. However, as previously stated, the inability of natural teeth to produce highly standardized abutments encourages simulation with a material with a close modulus of elasticity.39,55 Also, the unknown nature of the bond between the luting agent and the die material is another limitation of the present study. Using natural teeth may affect the results because of resin cement diffusion into the prepared dentin surfaces. The presence of a hybrid layer at the dentin-cement interface is likely to influence the biomechanical behavior of the monolithic zirconia and epoxy resin models. However, in the present study, this factor had an equal impact on all IRFDPs.

CONCLUSIONS

Within the limitations of this in vitro study, it can be concluded that additional wings increase the fracture resistance of IRFDPs. According to the findings, resin cement with the use of primer containing 10-MDP provides better fracture resistance than resin cement containing 10-MDP for the cementation of monolithic zirconia IRFDPs. The fracture resistance of all monolithic zirconia IRFDPs tested in the study was enough to withstand expected posterior chewing forces.

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