Load-Bearing Capacity of Monolithic Zirconia Fixed Dental Prostheses Fabricated with Different Connector Designs and Embrasure Shaping Methods

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Keywords
All-ceramic restorations; connector design; translucent zirconia; zirconia; Y-TZP.

Abstract

Purpose: To investigate the load-bearing capacity and failure mode of monolithic zirconia fixed dental prostheses (FDPs) fabricated with different connector designs and embrasure shaping methods.

Materials and Methods: Seventy four-unit zirconia FDPs (with two premolar pontics) were fabricated and divided into seven groups (n = 10) according to the different connector designs gained by using different embrasure shaping methods. The groups were as follows: monolithic FDPs fabricated with sharp embrasures, monolithic FDPs fabricated with blunt embrasures, monolithic FDPs fabricated with blunt embrasures and no occlusal embrasures, two groups of monolithic FDPs fabricated with blunt embrasures and interproximal separations made with diamond discs at the soft stage and at the fully sintered stage, and monolithic FDPs fabricated with blunt embrasures and interproximal separation accentuated by localized porcelain build-up. A final group was used as a control group, where fully veneered traditional zirconia FDPs were fabricated with default milling settings. The FDPs were artificially aged and loaded to fracture. Load to fracture and failure modes were analyzed by one-way ANOVA, Tukey's post hoc test, and Fisher exact test (α = 0.05).

Results: The FDPs fabricated with interproximal porcelain separation showed significantly the highest load to fracture (1038 N ± 82) of all groups (p < 0.001), with no significant difference compared to the FDPs with no occlusal embrasures (934 N ± 175; p > 0.29). The FDPs fabricated with blunt embrasures showed significantly higher load to fracture (873 N ± 115) compared to the FDPs in the control group (689 N ± 75) and the FDPs with sharp embrasures (417 N ± 87; p < 0.001). There were no significant differences between the FDPs with sharp embrasures (417 N ± 87) and the FDPs with interproximal disc separations (467 N ± 94; p > 0.23). Failure mode of the FDPs fabricated with sharp embrasures and interproximal disc separations differed significantly compared to the FDPs in the other groups (p < 0.001).

Conclusions: Sharp embrasures and interproximal separations made with diamond discs significantly decrease the load-bearing capacity of monolithic zirconia FDPs compared to FDPs made with blunt embrasures. Blunt embrasures in combination with localized porcelain build-up produce FDPs with high load-bearing capacity in relation to loads that might be expected under clinical use.

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) has been used for all-ceramic fixed dental prostheses (FDPs) since the mid-1990s, and is today accepted as a high-strength material with unique transformation toughening properties.1,2 The conventional way of using Y-TZP for dental purposes is as a framework combined with veneering porcelain. Since Y-TZP has high light-scattering properties,1 it appears almost opaque if not covered with a veneering material, such as specially developed porcelain, a material combination that has now been used for several years.3,4

An inherent weakness in such veneered Y-TZP restorations is the veneering material.5,6 Chip-off fractures of the veneer...
porcelain have been commonly and more frequently reported than with metal-ceramic restorations.\textsuperscript{7,8} This problem might have diminished today, since slow cooling protocols have been introduced at dental labs to avoid subsurface stress formation during sintering of the veneer.\textsuperscript{9,10} Still, the veneer and the interface of the two different materials constitute the weak link of veneered Y-TZP restorations.

Monolithic translucent zirconium dioxide (zirconia) restorations, designed without veneering material, were recently developed and have become a popular choice for replacing missing teeth.\textsuperscript{11-13} One advantage of monolithic zirconia FDPs is that such restorations can be prepared without the need for space for the veneering material. With that in mind, it is easy to believe that the extra space gained, allowing for the strength of the zirconia material, will give the restoration a much higher load-bearing capacity compared to the veneered restorations with less space left for the strong framework. Previous studies, however, have pointed out that the design of the connector area is the most influential factor in the clinical failures of Y-TZP FDPs, being second only to chip-off fracture.\textsuperscript{7,8,14-16}

Esthetic considerations play an important role in designing the connector area of an FDP. This applies to monolithic FDPs as well, although the framework shape differs, and when using veneering material, the connector should preferably be designed with U-shaped gingival embrasures. The radius of the embrasure is important because a larger radius increases the load-bearing capacity of the restoration, whereas a smaller radius acts as a stress concentrator for crack propagation. Thus, connector design plays an important role in the overall strength of all-ceramic FDPs.\textsuperscript{17,20}

Monolithic zirconia FDPs are prepared in such a way to allow pontics to appear as individual teeth. One way of doing this is to use a thin diamond disc to accentuate the separations. Interproximal porcelain build-up is another way of enhancing the perception of separations after milling. Both are common methods used in dental laboratories to shape interproximal embrasures of monolithic FDPs so that they appear natural, thus improving the esthetic appearance; however, there is always a risk that the connector design will become sharp and V-shaped rather than U-shaped and thus structurally weaken the restoration. Additionally, esthetic separation procedures carried out on a fully sintered restoration may cause damage to the zirconia surface that initiates phase transformations in the monoclinic microstructure of the material.\textsuperscript{12,21}

The aim of this study was to investigate the load-bearing capacity and failure mode of monolithic zirconia FDPs with different connector designs gained by using different embrasure shaping methods. The null hypothesis was that there would be no difference in the load-bearing capacity and failure modes among the groups under study.

**Materials and methods**

Seventy four-unit zirconia FDPs (with two premolar pontics and two retainers) were fabricated. The FDPs were divided into seven groups (n = 10; Table 1) according to the different connector designs gained by using different embrasure shaping methods performed at the intermediate connector of the FDPs (Fig 1).

A plastic model of a maxillary jaw was used (KaVo YZ; KaVo Dental GmbH, Biberach, Germany), and two abutment preparations were made on the canine and the first molar. The two premolars were removed to provide space for pontics in a four-unit FDP. The abutment preparations were designed to provide the space allowance for an all-ceramic restoration, with a 120° chamfer and 15° convergence angle. A full-arch impression (President; Coltene AG, Altstätten, Switzerland) was made and poured with die stone (Vel-Mix; Kerr Corp, Orange, CA) to produce a master cast. Using a double-scan technique, the master cast was scanned first by using a laboratory scanner (D900L; 3Shape, Copenhagen, Denmark). Subsequently, two different wax-ups were scanned: full anatomy for monolithic groups and reduced anatomy (cut-back) for the veneered group.

After the master cast and the wax-ups were scanned, the data were transferred to a computer loaded with computer-aided design (CAD) software. The connector dimensions of all the FDPs were set identically to 3 mm × 3 mm, except for the FDPs designed without occlusal embrasure, to which 1 mm extra was added occlusally. In all groups, the minimum thickness of the occlusal core was set to 1 mm, and the minimum thickness of the axial walls was set to 0.8 mm. The FDPs in the control group were designed to be fully veneered with 1 mm porcelain according to the manufacturer’s recommendations (IPS e.max Ceram; Ivoclar Vivadent, Schaan, Liechtenstein).

In all groups, the gingival and occlusal radii of the embrasures in the connector areas were set according to the default settings of the CAD program, except for monolithic FDPs with interproximal porcelain separation where a large radius cut-back was used to accommodate the buccal veneering material. The CAD data were sent to a certified production center (Cosmodent AB, Malmö, Sweden) where they were used to produce the FDPs: 60 monolithic, translucent zirconia (BruxZir HT; Glidewell Dental Laboratories, Newport Beach, CA) and 10 traditional zirconia frameworks (BruxZir Solid Zirconia; Glidewell Dental Laboratories). The FDPs with sharp embrasures were fabricated using a sharp milling tool (0.30 mm diameter, Zenotec; Wieland Dental/Technik GmbH, Pforzheim, Germany). The FDPs in the other groups were fabricated with a blunt milling tool with a 1 mm diameter followed by different post-milling embrasure shaping procedures on the same intermediate connector. No such shaping procedures were carried out in two groups (the FDPs with blunt embrasures and the FDPs designed with no occlusal embrasures). In two FDP groups, the intermediate connector was separated manually using a separation disc (S-H 394F 220; Sunshine Diamonds GmbH, Langenhagen, Germany). The FDPs in the other groups were fabricated with a blunt milling tool with a 1 mm diameter followed by different post-milling embrasure shaping procedures on the same intermediate connector. No such shaping procedures were carried out in two groups (the FDPs with blunt embrasures and the FDPs designed with no occlusal embrasures). In two FDP groups, the intermediate connector was separated manually using a separation disc (S-H 394F 220; Sunshine Diamonds GmbH, Langenhagen, Germany) at both the soft stage and the fully sintered stage.

Disc separation was standardized and performed using the same type of disc, with a rotational speed of 17 rpm for 15 seconds. New discs were used for each FDP in these two groups. One operator, using the same hand pressure as far as possible in a manual process, did the disc separation. The connector area was examined by using a light microscope (Leica DFC 420; Leica Microsystems CMS GmbH, Wetzlar, Germany) to confirm the standardization of both the location and the depth of the notch area created during the disc separation step. Monolithic FDPs with interproximal porcelain separation and the FDPs in the control group were not veneered but instead underwent
Table 1  Description of study groups

<table>
<thead>
<tr>
<th>Connector design and embrasure shaping method</th>
<th>FDP design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp embrasures</td>
<td>Monolithic four-unit FDPs</td>
</tr>
<tr>
<td>Blunt embrasures</td>
<td>Monolithic four-unit FDPs</td>
</tr>
<tr>
<td>Blunt embrasures with no occlusal embrasures</td>
<td>Monolithic four-unit FDPs</td>
</tr>
<tr>
<td>Blunt embrasures and interproximal separations made with diamond discs at soft stage</td>
<td>Monolithic four-unit FDPs</td>
</tr>
<tr>
<td>Blunt embrasures and interproximal separations made with diamond discs at fully sintered stage</td>
<td>Monolithic four-unit FDPs</td>
</tr>
<tr>
<td>Blunt embrasures and interproximal separations accentuated by localized porcelain build-up</td>
<td>Monolithic four-unit FDPs</td>
</tr>
<tr>
<td>Control group with default milling settings</td>
<td>Veneered four-unit FDPs</td>
</tr>
</tbody>
</table>

Figure 1  The FDPs with different connector designs gained by different embrasure shaping methods. *Two different groups of monolithic FDPs were fabricated with interproximal separations made with diamond discs at the soft stage and at the fully sintered stage.

a veneer-simulating process in which the frameworks were subjected to heat treatment according to the manufacturer’s recommendations to simulate the firing cycles of the veneering porcelain (IPS e.max Ceram). Seventy abutment models were produced from a polymer material (POM-C GF25; Simrishamns Mekaniska AB, Simrishamns, Sweden) with a modulus of elasticity comparably close to dentin (9 GPa).

All FDPs underwent 10,000 thermal cycles in two water baths at temperatures of 5°C and 55°C (THE-1100; SD Mecharonik GmbH, Feldkirchen-Westerham, Germany). The FDPs were cemented onto the abutment models using dual-polymerized resin (Panavia V5; Kuraray Medical Inc., Okayama, Japan) following the manufacturer’s instructions. Before cementation, an air abrasion device (Basic Quattro IS; Renfert GmbH, Hilzingen, Germany) was used to air-abrade the abutment models with 110 um aluminum oxide at a pressure of 2 bars, from a distance of 10 mm and at an angle of 90° to the abutment surface. The abutment models were also treated with two primers (Tooth Primer, Clearfil Ceramic Primer; Kuraray Medical Inc.) according to manufacturer’s instructions. After cementation, the specimens were subjected to 10,000 cycles of preload at 30 to 300 N at a frequency of 1 Hz in the preloading machine (MTI Engineering AB; Lund, Sweden/Pamaco AB, Malmö, Sweden). The specimens were mounted submerged in water, at 10° of inclination relative to the vertical plane. The loads were applied centrally on the buccal cusp of the second premolar pontic in the control group using a special indenter designed to prevent sliding movements during loading. The other groups were loaded with a ball indenter (4 mm diameter) on the mesial marginal fossa of the second premolar pontic (Fig 2). All specimens were stored in a humid environment at 37°C for 60 days before they were loaded to fracture.

After aging, all specimens were mounted in a testing jig at 10° of inclination and loaded to fracture by using a universal
testing machine (Instron 4465; Instron Corp, Norwood, MA). All specimens were submerged in water during loading with 1 mm thick plastic foil placed between the indenter and the FDPs to distribute the loading forces evenly (Fig 2). The crosshead speed was set to 0.255 mm/min, and the loads were registered. The fracture was defined as either an apparent crack, a load drop in the graph, or an acoustic event, whichever came first. The acoustic event was determined by a crack sound accompanied by changes in the stress and strain graph on the computer connected to the testing machine.

Power analysis was based on previous studies where differences regarding the level of significance and standard deviation were detected among the zirconia-based specimens. The differences in load to fracture of the groups were analyzed using one-way ANOVA, followed by Tukey’s post hoc test (IBM SPSS Statistics v24; IBM Corp, Chicago, IL). Failure mode data were analyzed using Fisher exact test. Results were considered statistically significant if \( p \leq 0.05 \).

**Results**

Load to fracture and levels of significance of the groups are detailed in Table 2. There were significant differences in load to fracture among the groups based on the connector designs gained by different embrasure shaping methods used in the study, \( F (6, 63) = 69.623, p < 0.001 \). The FDPs fabricated with interproximal porcelain separation showed significantly the highest load to fracture (1038 N ± 82) of all groups \( (p < 0.001) \), with no significant difference compared to the FDPs fabricated with no occlusal embrasures (934 N ± 175; \( p > 0.29 \)). The FDPs fabricated with blunt embrasures showed significantly higher load to fracture (873 N ± 115) compared to the FDPs in the control group (689 N ± 75) and the FDPs with sharp embrasures (417 N ± 87; \( p < 0.001 \)). The FDPs fabricated with interproximal disc separation at soft stage had the lowest load values numerically (357 N ± 45), but with no significant differences compared to the FDPs fabricated with interproximal disc separation at fully sintered stage (467 N ± 94; \( p > 0.23 \)).

All FDPs fractured in the intermediate connector of the two pontics, and no abutment fracture was observed. There were significant differences among the groups with regard to failure modes \( (p < 0.001) \). Table 3 presents the distribution of failure modes of the FDPs among the tested groups. Failure mode of the FDPs with sharp embrasures and the FDPs with interproximal disc separations showed that all fractures (100%) started from the gingival side of the intermediate connector in the notch area created by either the disc or the sharp milling tool, propagating toward the loaded pontic (Fig 3). By contrast, all fractures (100%) in the FDPs of the other groups occurred at the distal corner of the intermediate connector on the gingival side, propagating toward the loading site (Fig 4).

**Table 2 Load to fracture (N)**

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Sharp embrasure</th>
<th>Blunt embrasure</th>
<th>No occlusal embrasure</th>
<th>Separation with disc (soft)</th>
<th>Separation with disc (fully sintered)</th>
<th>Separation with porcelain</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>367</td>
<td>820</td>
<td>743</td>
<td>360</td>
<td>449</td>
<td>1014</td>
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<tr>
<td>2</td>
<td>394</td>
<td>745</td>
<td>855</td>
<td>422</td>
<td>380</td>
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<tr>
<td>3</td>
<td>463</td>
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<td>1076</td>
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<td>516</td>
<td>1011</td>
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<td>464</td>
<td>774</td>
<td>988</td>
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<td>332</td>
<td>947</td>
<td>691</td>
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<td>5</td>
<td>374</td>
<td>1033</td>
<td>1220</td>
<td>330</td>
<td>442</td>
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<td>6</td>
<td>376</td>
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<td>744</td>
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<td>7</td>
<td>477</td>
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<td>1107</td>
<td>340</td>
<td>503</td>
<td>990</td>
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<td>8</td>
<td>608</td>
<td>1099</td>
<td>736</td>
<td>300**</td>
<td>370</td>
<td>1177</td>
<td>688</td>
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<tr>
<td>9</td>
<td>347</td>
<td>858</td>
<td>1048</td>
<td>377</td>
<td>460</td>
<td>1185</td>
<td>561</td>
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<tr>
<td>10</td>
<td>300**</td>
<td>831</td>
<td>827</td>
<td>300**</td>
<td>578</td>
<td>1022</td>
<td>823</td>
</tr>
<tr>
<td>Mean*</td>
<td>417a</td>
<td>873b</td>
<td>934bc</td>
<td>357c</td>
<td>467a</td>
<td>1038b</td>
<td>689</td>
</tr>
<tr>
<td>SD</td>
<td>87</td>
<td>115</td>
<td>175</td>
<td>45</td>
<td>94</td>
<td>82</td>
<td>75</td>
</tr>
</tbody>
</table>

*Means with the same letters in superscript (denoted a, b, and c) did not show any significant difference in load to fracture \( (p > 0.05) \).
**FDPs fractured at 30 to 300 N preload.
Discussion

There were substantial differences in load-bearing capacity and failure modes among the groups, and consequently the null hypothesis was rejected. The FDPs in the study were divided into seven groups depending on the connector designs gained by different embrasure shaping methods used. The embrasure shaping methods used in this study were at the CAD/CAM (computer-aided manufacturing) milling step (using sharp and blunt milling tools) and after the milling step (using discs and porcelain separations). The results show that different connector designs gained by varying embrasure shaping methods play a significant role in the load-bearing capacity and failure mode, and this is an essential factor to be considered when designing and fabricating the monolithic FDP.

The FDPs with sharp embrasure design were the only ones prepared with a sharp milling tool. All the FDPs in the other groups were prepared with a blunt milling tool. This group, together with interproximal disc separation groups, where the bluntly milled separations were sharpened manually with a diamond disc, failed at significantly lower loads compared to the other groups. The small embrasure radii of the FDPs in those groups formed starting points for crack formation, acting as stress concentrators, which most probably played a significant role in the low load-bearing capacity of the FDPs.

The loads in the study were applied at $10\degree$ inclination relative to the vertical plane to create a stress distribution mimicking clinical conditions. This test set-up results in major stress concentrations, with compressive stress occurring in the occlusal area and tensile stress occurring in the gingival embrasure of the connector, which is the thinnest part of the framework. The latter contributes to the propagation of the existing flaws created by the sharp milling or post-milling disc separation, leading to fracture at relatively moderate loads. These findings are in agreement with previous studies, which concluded that three-unit FDPs fail at lower load to fracture if they are shaped with a sharp connector design compared to round symmetrical connector designs.\textsuperscript{19,24}

The results also revealed that monolithic FDPs fabricated with blunt embrasures with post-milling separations made by porcelain build-ups to create the desired interproximal embrasure shape withstood the highest load to fracture of all the other FDPs including the ones with a larger connector dimension. This might be because the FDPs in this group were designed with a large radius of curvature to allow space for the added porcelain. Previous studies have shown that large radii of curvature are favorable for the durability of all-ceramic FDPs.\textsuperscript{18-20}

The connector dimension of all groups was identical and was selected based on the manufacturer’s instructions and the recommendations from previous studies.\textsuperscript{16-20} Only the FDPs

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Table 3  Distribution of failure modes for each group

<table>
<thead>
<tr>
<th>Groups</th>
<th>Notch area in intermediate connector</th>
<th>Distal corner of intermediate connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp embrasure</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Blunt embrasure</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>No occlusal embrasure</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Separations with disc (soft)</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Separations with disc (fully sintered)</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Separation with porcelain build-up</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Control</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>
with no occlusal embrasures were designed with a larger connector dimension to observe the effect of changing the connector dimension. As expected, apart from the interproximal porcelain separation group, the FDPs of this group demonstrated a higher load to fracture than those with a smaller connector.

Previous studies have reported an average maximum bite force ranging from 90 to 200 N in the anterior region and 300 to 800 N in the posterior region.25,26 Hence, all milling and postmilling separation procedures investigated in this study could be used for anterior monolithic zirconia prostheses, but with a low margin of safety when using the sharp milling and post-milling disc separation strategies; however, in the posterior area, both the sharp milling and post-milling disc separation strategies should be avoided, given the loads expected in this area under clinical use.

With regard to failure mode results, all the fractures occurred in the connector area of the FDPs, which is in line with previous reports.2,3 The fracture origin of the FDPs with sharp embrasure design and the FDPs with interproximal disc separations was located in the notch area created either during machining with the sharp milling tool or post-milling by using a separation disc. These processes form a pattern of cracks and scratch-like flaws in the interproximal area and subsequently result in detrimental crack growth during function. The fracture origin in the groups with blunt milling, on the other hand, was located close to the corner of the gingival embrasure of the intermediate connector of the loaded pontic. This fracture pattern has been demonstrated in previous in vitro studies and may be related to the tensile stress created by the strain in the gingival embrasure of the connector and the compressive stresses in the loaded area.16-20 Further fractographic analysis, using a scanning electron microscope might provide more information on failure behavior with specific fracture features.

The frameworks of the FDPs were not veneered with an actual porcelain material due to the difficulty of standardizing the veneering process; however, all the FDPs in the control group and all the FDPs with interproximal porcelain separation were subjected to a simulated heat treatment process, following the recommended porcelain firing cycles. This was done in line with previous studies to ensure realistic results, since potential changes in the mechanical properties of the Y-TZP might result from the porcelain firing cycles.27

In this study, during mechanical tests (cyclic loads and load to fracture), the external loads were transferred to the FDPs using indenters made of steel. The hardness and stiffness properties of the (steel) contact counterpart may have played a role in the magnitude of stress in the material. High internal forces within zirconia are expected to develop as a result of external loads with stiff indenters. Therefore, it is not possible to translate the resulting load to fracture directly to the clinical situation, where different contact counterparts (teeth, crown materials, fillings, food) with different mechanical properties are present. However, the loading conditions were similar for all the groups included, which justifies comparisons among the different groups. In reality, only clinical studies can confirm the results and real-life differences among monolithic zirconia FDPs fabricated with different connector designs and embrasure shaping methods.

Conclusions

1. Sharp embrasures and interproximal separations made with diamond discs significantly decreased the load-bearing capacity of monolithic zirconia FDPs compared to FDPs made with blunt embrasures.
2. Blunt embrasures in combination with localized porcelain build-up produced FDPs with high load-bearing capacity in relation to loads that might be expected under clinical use.
3. Great care should be taken when performing interproximal disc separations to avoid decreasing the overall strength of monolithic zirconia FDPs.

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References