The Influence of Ferrule on the Marginal Gap and Fracture Resistance of Zirconia Endocrowns

Arwa Bamajboor, BDS, AEGD, DClinDent (Pros)
Adelaide Dental School, Adelaide Health & Medical Sciences, The University of Adelaide, Adelaide, Australia.

James Dudley, BDS, MHSM, DClinDent(Pros)
Adelaide Dental School, The University of Adelaide, Adelaide, Australia.

Purpose: To investigate the precementation mean marginal gap, fracture resistance, and mode of failure of monolithic zirconia endocrowns cemented to endodontically treated molar teeth with butt joint porcelain margins and added ferrule preparation designs. Materials and Methods: A total of 20 mandibular molars were endodontically treated and prepared to receive endocrown restorations. The teeth were randomly divided into two groups: Group B had a butt joint porcelain margin, while Group F received additional axial reduction with a shoulder finish line that added ferrule. Monolithic zirconia endocrowns were milled, and the marginal gaps were measured at four locations prior to cementation with resin cement. All samples were subjected to thermocycling, followed by compressive static loading. The maximum load causing fracture and mode of failure were recorded. Results: The mean load to failure for Group B (5,616 ± 1,503 N) was not significantly different compared to Group F (5,762 ± 1,618 N) (P = .84). Both groups recorded high rates of irreparable fractures (P = .2699, df = 2). The mean marginal gap in Group B (48.20 ± 12.37 µm) was not statistically significantly different compared to Group F (45.14 ± 8.45 µm) (P = .527). Conclusion: The addition of ferrule to the preparation design had no significant effect on the precementation mean marginal gap, fracture resistance, or mode of failure of monolithic zirconia endocrowns cemented to endodontically treated molar teeth. Monolithic zirconia endocrowns failed predominantly in an irreparable manner, but these failures were at high failure loads. The precementation mean marginal gap for both groups was small in comparison to other materials. Int J Prosthodont 2022;35:494–501. doi: 10.11607/ijp.8060

A n endocrown is an indirect monobloc restoration used to restore endodontically treated teeth. There have been a limited number of papers published since the introduction of the endocrown concept by Pissis in 1995, but interest has increased more recently, as evidenced by 80% of all papers being published in the last 5 years. Endocrowns offer potential benefits, including a simplified crown preparation design, short clinical preparation time, use of a monobloc material (thus eliminating material interfaces), the ability to use CAD/CAM technology, a simplified restoration design, and the ability to use robust materials.

A recent systematic review established endocrowns as a reliable treatment for restoring endodontically treated molars. However, a common complication reported in clinical studies is fracture of the endocrown. The effect of modifying the butt joint porcelain margin to a shoulder finish line to facilitate a bracing effect has been found to increase the fracture resistance of endocrowns constructed with a range of nonzirconia materials. The role of ferrule in increasing the fracture resistance of endodontically treated teeth is well documented in the literature, with more favorable failure modes and increased fracture resistance reported.
Monolithic zirconia is a popular material with favorable properties of low thermal and electrical conductivity, chemical inertia, biocompatibility, corrosion resistance, high flexural strength, fracture toughness, and high wear resistance. However, zirconia has a high modulus of elasticity that is not compatible with dentin. To the authors’ knowledge, no published papers have investigated the effect of a shoulder finish line that adds ferrule on the fracture resistance and mode of failure in zirconia endocrowns.

The aim of this in vitro study was to investigate the precentementation mean marginal gap, fracture resistance, and mode of failure of monolithic zirconia endocrowns cemented to endodontically treated teeth with butt joint porcelain margins and added ferrule preparation designs. The null hypothesis was that there is no difference in precentementation mean marginal gap, fracture resistance, or mode of failure of monolithic zirconia endocrowns cemented to endodontically treated teeth with butt joint porcelain margins vs added ferrule preparation designs.

MATERIALS AND METHODS

This research was approved by the Human Research Ethics Committee at the University of Adelaide (H-2019-226). The G*Power tool was used to calculate the sample size. The smallest effect size of interest was based on a comparable study conducted by Taha et al. and estimated to be 2.18. The G*Power tool suggested that a total of six samples were needed in each group in a paired-samples t test to detect an effect size of Cohen’s d = 2.18 with 95% power (alpha = .05, two-tailed). Due to the differences between the comparable study and the present study, the sample size was increased to 10 per group to allow a reasonable margin of error and to fit within the limitations of sourcing suitable natural teeth.

A total of 20 intact mandibular molar teeth with standardized dimensions were collected, cleaned, and stored in water. The tooth dimensions were measured and confirmed for normal distribution using Shapiro-Wilks tests. Each tooth received endodontic treatment using the crown-down canal preparation technique and lateral obturation condensation. Periapical radiographs were taken to confirm the accuracy of endodontic treatment (Fig 1).

Each tooth was mounted in autopolymerizing acrylic resin (Vertex self-curing, Vertex Dental) 2 mm below the cementoenamel junction to simulate the bone. A dental surveyor (Ney Surveyor, JM Ney) facilitated positioning of the tooth along its long axis. Each sample was assigned a number from 1 to 20. All teeth were prepared using ×3.5 magnification under water spray using a flat-end tapered diamond bur with internal taper ranging from 8 to 10 degrees. All internal angles were smoothed and rounded using a round-end, fine diamond bur. All teeth received horizontal reduction (butt joint porcelain margin) perpendicular to the long axis of the tooth. For standardization, the depth of the pulp chamber preparation was 5 mm regardless of the cementoenamel junction location as measured using a periodontal probe (Williams, Hu-Friedy) from the center of the pulpal floor to the margin of each surface of the pulp chamber. The samples were randomly divided into two groups using online software that generated random numbers for research purposes.

The first 10 samples were assigned to the control group that received a butt joint porcelain margin (group B), and the remaining 10 samples were assigned to the test group that received an axial shoulder finish line that added ferrule (group F). Following the allocation of each sample to a group, the samples in the control group (group B) received no further reduction. The test group samples received axial reduction of 1 mm in depth and 2 mm in height with a shoulder finish line using a flat-end diamond bur (Fig 2). Each tooth was dried and then scanned with an intraoral scanner (Trios 3, 3Shape), and endocrowns were designed with a minimum occlusal thickness of 2 mm. One endocrown was designed for each sample and then milled (inLab MC X5, Dentsply Sirona) from zirconium oxide blocks (IPS e.max ZirCAD Prime, Ivoclar Vivadent). Milled endocrowns were sintered (inFire HTC Speed, Dentsply Sirona) at 1,540°C and allowed to cool, then checked for accuracy of fit under ×10 magnification using a laboratory microscope (SZ61, Olympus).

Endocrowns were seated onto their tooth preparations, and the marginal gap was measured using a stereomicroscope (SMZ25, Nikon Instruments) at a magnification range of ×2.0 to ×32.0 and a zoom range of ×1.0 to ×9.0. Three readings were taken at each of four locations, resulting in a total of 12 readings for each
crown (Fig 3). Each measurement was taken vertically from the crown margin to the preparation finish line and recorded in micrometers (Fig 4).

The endocrowns were cleaned with aluminum oxide (50 μm, Argibond) at a maximum pressure of 1 bar. Self-adhesive universal resin cement (RelyX Universal, 3M) was applied to the intaglio surface, and each restoration was seated onto its prepared tooth using firm finger pressure. A 10-kg vertical load was placed on the restoration, and the cement was allowed to set at room temperature for 12 minutes. Excess cement was removed using an explorer. To simulate aging, the samples were stored in 100% humidity at 37°C for 24 hours, then subjected to thermocycling according to ISO/TS 11405:2015 standard, involving 500 cycles in 5°C and 55°C deionized water with a dwell time of 20 seconds.

Each sample was rigidly fixed to the lower plate in a biaxial servohydraulic testing unit (8874 testing machine) (Fig 5) and subjected to compressive static loading until failure using a stainless steel indenter of 3-mm diameter at a crosshead speed of 0.5 mm/minute. The load was applied vertically at the center of the occlusal surface along the long axis of the tooth. The testing machine recorded the force in Newtons and the position of the tip until failure. The maximum load was used for analysis, and the fractured components were collected for further examination.

All samples were visually examined under a stereomicroscope (Nikon SMZ25, Nikon Instruments) to determine the mode of failure and classified according to the categorization proposed by El Ghoul et al11 (Table 1). The classification was performed twice by the same examiner (A.B.) at two different times, with 1 week between examinations.

Statistical Analysis
The analysis was performed using the statistical package RStudio (version 1.4.1717). Descriptive statistics for each sample were recorded. Shapiro-Wilk test for assessing normality was used, and the data were assumed to be normally distributed. Two-way analysis of
The mean load to failure and precementation mean marginal gap for the two different preparation designs are presented in Table 2. Although the mean load to failure for group F was slightly greater than group B, the difference was statistically insignificant ($P = .84$). Similarly, although the mean marginal gap for group F was slightly less than group B, the difference was statistically insignificant.
Analysis of the mean marginal gap for each tooth surface for both groups showed a statistically insignificant difference (Table 3). Both groups recorded the largest mean marginal gap on the buccal surface, while group B recorded the smallest mean marginal gap on the mesial surface compared to the distal surface for group F. Shapiro-Wilk test to assess normality with 95% CI showed a normal distribution of the data ($P > .05$).

The modes of failure for groups B and F are presented in Table 4 and illustrated in Fig 6. A total of 60% of all samples failed in an irreparable manner. Although there was a greater number of samples that demonstrated irreparable fractures (class 5) in group F than group B, Fisher exact test showed no statistically significant difference ($P = .2699, \ df = 2$) between the different modes of failure.

A two-way ANOVA test to assess the interaction of finish line design on the load to failure and failure mode revealed insignificant interaction among the variables tested ($P = .9, \ F \ value = 0.016$).

**DISCUSSION**

This study found no significant difference in the pre-cementation mean marginal gap, fracture resistance, or mode of failure of monolithic zirconia endocrowns cemented to endodontically treated molar teeth with butt joint porcelain margins and added ferrule preparation designs. As such, the null hypothesis was accepted.

The high mean failure loads reported in this study can be attributed predominantly to the material properties and long axis direction of loading. Zirconia restorations have high flexural strength and fracture toughness, which is reflected in the high loads required to cause fracture. The increased strength resulting from the increased thickness of the material from the occlusal surface to the pulpal floor of up to 7 mm results in a higher fracture resistance of endocrowns compared to conventional crowns. Furthermore, the loads required to cause fracture in both zirconia endocrown groups were considerably greater than the recorded maximum bite forces in natural dentitions of up to 800 N. The use of a monobloc material adds to the material resilience, as there are no interfaces that typically exist with conventional post-and-core crowns. Such interfaces between dissimilar materials with dissimilar moduli of elasticity can affect the load distribution, which in turn creates weak points and facilitates fractures.
There are a limited number of studies that compare the fracture resistance of different materials used for the fabrication of endocrowns and an even smaller number of studies that include monolithic zirconia endocrowns. Kanat-Ertürk et al\textsuperscript{12} compared different types of CAD/CAM materials and found that monolithic zirconia recorded the highest failure values (610.54 ± 214.04 N for the 6-mm preparation depths and 533.61 ± 189.05 N for the 3-mm preparation depths), followed by lithium disilicate, polymer-infiltrated ceramic, resin ceramic, and feldspathic ceramic. Monolithic zirconia showed a significantly greater fracture resistance than the other materials tested despite variable preparation depths but also exhibited catastrophic failures.\textsuperscript{12} A direct comparison of these results to the present study is not possible, as incisor teeth were used and the direction of load was at 45 degrees.

A recent study by Dartora et al\textsuperscript{13} compared the fracture strengths of different CAD/CAM materials used in the fabrication of endocrowns on mandibular molars, where the samples were subjected to thermomechanical loading before undergoing static loading. Of all materials tested, the monolithic zirconia endocrowns recorded the highest fracture resistance (6,333 ± 2,391 N) compared to leucite-based glass-ceramic (1,178 ± 273 N), lithium disilicate (1,935 ± 530 N), and glass-ceramic based on zirconia-reinforced lithium silicate (1,859 ± 588 N).\textsuperscript{13} However, the load cell of the universal testing machine used (Biopdi) had a maximum capacity of 4.9 kN, which is inconsistent with the reported failure loads of monolithic zirconia, which exceed 5,000 N.\textsuperscript{13} Despite some heterogeneities in methodology, the mean failure loads of monolithic zirconia are comparable to the present study. In both studies, the high reported fracture loads were much greater than those exhibited in human mastication (reported to be 150 to 200 N) and parafunctional activity (500 to 700 N), suggesting the materials could have a reliable clinical application.\textsuperscript{12,13} The relatively large SDs observed in the present study were consistent with other studies of this nature,\textsuperscript{4,5,12,13,19} possibly due to the variations in using extracted human teeth that were standardized but have natural variations. Natural teeth have the advantage of closely resembling the clinical situation regarding the presence of enamel and dentin and endodontic architecture.\textsuperscript{4}

The role of ferrule in reducing fractures in endodontically treated teeth has been well documented in the literature.\textsuperscript{6-8} Einhorn et al\textsuperscript{5} found that adding ferrule heights of 1 and 2 mm to lithium disilicate endocrowns significantly increased the fracture resistance and the surface area for bonding compared to the absence of ferrule. Similarly, Taha et al\textsuperscript{20} found that a shoulder margin improved the fracture resistance of polymer-infiltrated ceramic endocrowns regardless of the material thickness. In addition to the bracing effects of the ferrule, it was proposed that the shoulder margin improved the load distribution and neutralized the shear forces directed toward the axial walls. In contrast, the incorporation of 2 mm of ferrule height in the present study did not demonstrate the same results with monolithic zirconia.

### Table 3
Mean Marginal Gap (µm) and Statistical Analysis at Each Tooth Surface for Groups B and F

<table>
<thead>
<tr>
<th>Surface</th>
<th>Group</th>
<th>Mean (µm)</th>
<th>Maximum (µm)</th>
<th>Minimum (µm)</th>
<th>F</th>
<th>P</th>
<th>df</th>
</tr>
</thead>
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<tr>
<td>Buccal</td>
<td>B</td>
<td>61.825</td>
<td>118.49</td>
<td>25.10</td>
<td>1.1022</td>
<td>.2882</td>
<td>14.637</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>50.412</td>
<td>82.62</td>
<td>31.27</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mesial</td>
<td>B</td>
<td>41.879</td>
<td>72.41</td>
<td>13.54</td>
<td>–1.0208</td>
<td>.3229</td>
<td>15.619</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>49.229</td>
<td>68.58</td>
<td>31.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lingual</td>
<td>B</td>
<td>44.0350</td>
<td>85.25</td>
<td>17.66</td>
<td>0.1856</td>
<td>.8548</td>
<td>17.945</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>42.2763</td>
<td>76.28</td>
<td>4.037</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Distal</td>
<td>B</td>
<td>45.0410</td>
<td>84.82</td>
<td>22.65</td>
<td>0.76637</td>
<td>.4537</td>
<td>17.455</td>
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<tr>
<td></td>
<td>F</td>
<td>38.6293</td>
<td>82.44</td>
<td>21.93</td>
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### Table 4
Modes of Failure of Group B and F Samples (n)

<table>
<thead>
<tr>
<th>Class</th>
<th>Group B</th>
<th>Group F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Class I</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Class II</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Class III</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Class IV</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Class V</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
endocrowns. The addition of the shoulder finish line that added ferrule may be postulated as a relatively micromechanical addition to the structural durability of the restoration in the context of the high fracture loads found in the present study.

In addition to the material properties and fracture resistance, another factor to consider when selecting an endocrown material is the predicted mode of failure and subsequent potential to restore the tooth. The present investigation demonstrated that 60% of all samples failed in an irreparable (catastrophic) manner, which generates at least some consideration of the statement by El Ghoul et al. who proposed that endocrowns should be avoided due to the perceived high number of irreparable fractures. In this study, a variety of nonzirconia materials were tested, with 33% of all samples failing in an irreparable manner, of which 12% were in traditional glass fiber post/composite resin–core retained crowns, and 88% were in endocrowns constructed from different materials. The mode of failure can be affected by the compatibility of the material’s modulus of elasticity with that of dentin (18 GPa). A greater number of catastrophic failures are typically seen in restorations with a high modulus of elasticity and correspondingly in studies involving zirconia endocrowns.5,12,13

The addition of ferrule did not significantly affect the failure modes in the present study, which is in agreement with the results of comparable studies that used nonzirconia ceramic materials.5,19 In the study by Einhorn et al.,5 the failure modes of lithium disilicate endocrowns were identified using microcomputed tomography, which allowed the detection of more irreparable fractures that could not be detected visually or with a stereomicroscope, while the failure modes of polymer-infiltrated ceramics in the study by Taha et al.19 were identified using a stereomicroscope. The percentage of reparable fractures recorded with endocrowns manufactured from polymer-infiltrated ceramics was higher than those reported by other studies that used lithium disilicate ceramics, which was credited to the plastic properties of the polymer phase in the polymer-infiltrated ceramic that improved the resistance to cracking. However, the limitations of using a stereomicroscope to detect root fractures may have contributed to the observations. Although a high proportion of catastrophic failures were reported, the loads were greater than normal masticatory function.5

The mean marginal gap of the monolithic zirconia endocrowns recorded at each of the four locations in this study were significantly less than those of other studies performed at the same institution using exactly the same scanning unit, milling unit, and methodology using lithium disilicate, but were similar to comparable studies using monolithic zirconia while noting the variations reported in the literature. The differences may be attributed to the different milling burs used for the different materials; the easier milling procedure of zirconia in its softer partially sintered state; the capability to mill zirconia in more detail because of its larger presintered state volume compared to lithium disilicate; and the requirement to sinter zirconia postmilling with resulting material shrinkage. Specifically for endocrowns, the preparation design and its complexity and the depth of the pulpal extension have been associated with increased marginal gaps when using a hybrid ceramic material.5,24 Although conducted in vitro and limited to the vertical dimension, these measurements were well within clinically acceptable limits.25,26

The current study used freshly extracted human molars tested under in vitro conditions that aimed to simulate the in vivo environment using the available resources but did not equate to in vivo conditions. During testing, it was inevitable that the samples underwent some degree of dehydration that could have affected the mechanical properties of the tooth structure, load-absorbing capacity, and fracture resistance.27,28 The samples were not subjected to cyclic loading or fatigue testing, which may have affected the fracture resistance.29 The load to failure was directed longitudinally and not laterally, which can be more damaging, as the stresses are concentrated at the cervical areas. The present analysis of the fracture mode was performed using direct visualization with a stereomicroscope. Using more advanced assessments, such as scanning electron microscopy or microcomputed tomography analysis, could improve the detection of root fractures.

CONCLUSIONS

Within the limitations of this in vitro study, the addition of ferrule to the preparation design had no significant effect on the precementation mean marginal gap, fracture resistance, or mode of failure of monolithic zirconia endocrowns cemented to endodontically treated molar teeth. Monolithic zirconia endocrowns failed predominantly in an irreparable manner, but these failures were at high failure loads. The precementation mean marginal gap for both groups was small in comparison to other materials.

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