Endodontically treated teeth with extensive loss of tooth structure have a reduced capacity to resist forces during function. Accordingly, the residual coronal dentin must be carefully assessed before tooth restorability can be determined. In several studies, the ferrule was assessed without focus on the thickness of remaining coronal tooth structure. A ferrule does not improve tooth fracture resistance when only thin walls of remaining dentin are present, and the required thickness and strategic preservation of dentin to optimize clinical survival is not entirely clear.

In vivo studies have evaluated the clinical longevity of endodontically treated teeth, but little information has been included regarding the amount of remaining dentin. Accordingly, few prospective data are available on which to base guidelines for the restoration of these teeth.

In a previous study, the thickness of remaining dentin after various endodontic access preparations on a maxillary second premolar was reported. After it had been prepared for a crown, the thinnest sections of remaining tooth structure were 0.8 and 0.3 mm. Nissan et al found that remaining coronal structure most influenced the fracture resistance of crowned endodontically treated maxillary first premolars.

Bandlish et al developed a method for measuring remaining coronal dentin in endodontically treated teeth by using a series of interlocking custom trays and impressions to produce a cast of the remaining dentin structure.
coronal to the finish line after crown preparation. This cast was scanned with a laser profilometer, and the volume of remaining dentin was calculated. A tooth restorability index (TRI) was developed. The TRI assigned scores of 0 to 3 in each sextant, with a maximum score of 18 per tooth. The volume of residual coronal tooth structure derived in these studies is informative. However, it does not indicate the strategic value of the remaining tooth structure because the volume might be distributed in areas not important to the resistance of occlusal forces or in areas with undermined or thin walls, thereby compromising load resistance. A good correlation was found between the volume of remaining coronal tooth structure and the TRI, but only a weaker correlation when the height-width ratio of tooth structure was unfavorable.

Naumann et al classified defect size using 3 parameters: remaining tooth substance in the vertical dimension, remaining tooth substance in the horizontal dimension as assessed from the occlusal view, and size of the access cavity orifice (mm). On the basis of interobserver and intraobserver reliability, they concluded that their classification could be applied as an appropriate and reproducible method to define defect extension in endodontically treated teeth. Most recently, Davis et al have developed a method using x-ray microtomography scans for measuring dentin thickness after tooth preparation for metal ceramic crowns. This method can be useful in dental research for visualizing and quantifying the remaining dentin thickness and allowing preparation techniques and instrumentation to be evaluated in vitro, leading to improvements in clinical procedures.

The purposes of this study were to measure the cross-sectional area of the remaining coronal tooth structure of endodontically treated maxillary premolar teeth at the level of the finish line after the removal of different patterns of remaining coronal structure, to assess the resistance to fracture of these teeth after restoration under simulated occlusal load, and to assess the relationship between the cross-sectional area, the location of remaining coronal tooth structure, and fracture resistance. The null hypothesis was that the surface area and location of remaining coronal dentin have no effect on the fracture resistance of restored endodontically treated maxillary premolars.

Clinical Implications
The location of remaining coronal dentin has a significant influence on the fracture resistance of endodontically treated maxillary premolars.

MATERIAL AND METHODS
The Human Research Ethics Committee of the University of Adelaide granted ethical approval for this study (H-110-2010). Fifty-five freshly extracted, intact, unrestored, maxillary premolars were collected from the Oral and Maxillofacial Surgery Department in the Adelaide Dental Hospital. Initial preparation of the teeth involved the removal of any superficial staining, calculus, and adhering soft tissue with an ultrasonic scaler (EMS) and subsequent polishing with a rotary polishing brush (Guangzhou Bytech) and pumice/water mixture (Zircate; Dentsply Intl). The teeth were examined with optical loupes at ×2.5 magnification to ensure they were free from caries, craze lines, or fractures. The buccolingual and mesiodistal dimensions were recorded to ensure that teeth of similar sizes were included in each of the study groups to allow meaningful comparisons. The teeth were kept hydrated at room temperature in distilled water at all times during the study other than during the operative procedures and testing. An access cavity was prepared in the center of the occlusal surface with a high-speed handpiece with a tungsten carbide round bur (Komet) until the root canal orifices were identified. A hand file (Dentsply Maillefer), size 10 K, was inserted until the tip of the file was visible at the apical foramen, and this length was measured. The working length was established by deducting 0.5 mm, and the teeth were then prepared with hand K-files (Dentsply Maillefer) using the step-back technique. The canals were irrigated with 5% NaOCl between each file change and dried with paper points (Zipper; Dentsply Intl).

The canals were obturated with gutta percha master cones (Zipper; Dentsply Intl), fine accessory cones, and root canal sealer (AH26; Dentsply Intl) using the lateral condensation technique. The excess gutta percha was removed from pulp chamber with a heated instrument, and the access cavities were wiped with alcohol.

Two polyvinyl siloxane (Honigum; DMG) reduction guides were fabricated for each tooth. The same operator (A.I.) prepared all teeth using ×2.5 optical loupes. A 1 mm deep chamfer finish line was made 1 mm above and following the cement-enamel junction with a round-end diamond rotary cutting instrument (No. 856; Komet) under constant water cooling.

After crown preparation, the teeth were assigned to 11 groups of 5 teeth each. Power calculations based on the data published by Ng et al showed that a sample size of 5 was adequate to demonstrate a difference in fracture strength of 150 N. Each group of teeth received different tooth preparations according to the pattern of missing walls and the surfaces were named occlusal (O), buccal (B), palatal (P), and proximal (Px) (Table 1, Fig. 1).

In order to measure the remaining amount of coronal dentin, an impression of the prepared teeth was made.
with light and medium viscosities polyvinyl siloxane impression material (Honigum; DMG) and small plastic trays. Dies for each tooth were poured with epoxy resin (Megapoxy; Vivacity Engineering Pty Ltd).

The epoxy dies were sectioned 1 mm above the most occlusal point of the finish line with a slow-speed sectioning machine (Isomet; Buehler) (Fig. 2) and photographed from an occlusal view at 90 degrees to the long axis of the die with an SLR camera (EOS 450; Canon) and a macrolens (Macrolite 100mm; Canon). The images were analyzed with ImageJ software (Image Processing and Analysis in Java; US National Institutes of Health; http://rsb.info.nih.gov/) to calculate the surface area. Data for comparison were recorded. The reproducibility and validity of the method were tested in a previous unpublished study (Ha, personal communication).

Each tooth was etched with 37% phosphoric acid solution (Adper Scotchbond Etchant; 3M ESPE) for 30 seconds, then washed with water for 20 seconds and dried with air. Primer and bonding adhesive (Scotchbond Multi-Purpose System; 3M ESPE) were applied according to the manufacturer’s instructions and light-polymerized for 20 seconds. Composite resin (Filtek Supreme XT; 3M ESPE) was placed into the cavity incrementally, with each increment light-polymerized for 40 seconds with a visible-light polymerization unit (XL2500; 3M; light intensity; 580 mW/cm²).

The same laboratory technician fabricated all the wax patterns for the cast metal crowns. A small groove was placed across a flap facet on the midpalatal surface of the buccal cusp of each crown at 45 degrees to the long axis of the tooth to ensure a consistent loading direction and to prevent the loading rod from slipping. This groove was carved into the wax patterns using the loading device for the universal testing machine. The wax patterns were invested in high expansion phosphate-bonded investment material (Speed Vest; Argibond) and cast using a Type III gold alloy (Argeloy Sunray; Argen Corp).

The cast crowns were cemented with self-adhesive, dual-polymerizing resin cement (RelyX Unicem; 3M ESPE) under static firm finger pressure. The excess cement was removed, and the margins were light polymerized from all directions. All specimens were subjected to 500 cycles between 5°C and 55°C for 20 seconds each with an intermediate pause of 3 seconds’ transfer time between hot- and cold-water baths. 31-33

The experimental teeth were then mounted with autopolymerizing acrylic resin (ProBase Cold; Ivoclar Vivadent AG) within a brass cylinder (2 cm in diameter, 2.5 cm high) to a level 1 mm below the cementoenamel junction. A dental surveyor (J. M. Ney Co) was used to ensure that the teeth were mounted parallel to the long axis of the holding device. 35

A universal testing machine (H50K; Hounfield Test Equipment Ltd) was used to fracture test the specimens with a maximum load cell of 2000 N and a crosshead speed set at 1 mm/min. 37,38 A compressive load was applied to tooth specimens at a 45-degree angle until failure occurred. 9,39-42 This was achieved by securing the specimen in the testing machine using a custom-made jig to support the brass cylinder (Fig. 2). A force (N) versus extension (mm) curve was dynamically plotted for each tooth, and from this, the maximum force at failure was recorded. Statistical analysis was performed to detect any significant difference in mean failure loads and mean surface areas between groups. One-way ANOVA was carried out to compare the mean values of the 11 groups using statistical software (SAS v9.3; SAS Institute Inc). Post hoc comparisons were made, adjusting for multiple comparisons with a Sidak adjustment (α=.05). A linear regression analysis was performed to determine the correlation between the surface area and the mean failure load for each group.

### Table 1. Specimen grouping according to missing wall

<table>
<thead>
<tr>
<th>No. of Surfaces</th>
<th>Group No.</th>
<th>Missing Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>OPx</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>OP</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>OB</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>MOD</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>BOP</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>BOPx</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>POPx</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>MODP</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>MODB</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>BOPPx</td>
</tr>
</tbody>
</table>

O, occlusal access; Px, proximal; P, palatal; B, buccal; M, mesial; D, distal.

### Figure 1. Specimen grouping.

### Figure 2. Tooth mounted in universal testing machine with chisel-end rod applying load to palatal incline of buccal cusp at 45-degree angle.
model was fitted to assess the relationship between the remaining dentin surface area and the fracture strength (Excel 2010; Microsoft Corp), and the significance of the derived correlation coefficient was determined by a t test where \( t = r \left( \frac{n-2}{1-r^2} \right) \) with \( n-2 \) degrees of freedom.

**RESULTS**

The means and SDs of the calculated surface areas and the failure loads for each group are presented in Table 2. The surface area values varied from 9.54 ±1.61 mm² to 31.38 ±3.50 mm². As the number of missing walls increased, the surface area of the remaining dentin decreased.

A total of 52 load values were available for statistical analysis for fracture resistance. Two specimens failed at loads more than 2 standard deviations below the mean for their group and were excluded. One was from group O and the other from group MODP, with values of 544 and 262 N, respectively. A third specimen from group B fractured during adjustment of the load in the testing machine before the computer recorded a load application. As a result, no data were available for this specimen.

The group with only the occlusal access prepared (group O) had the highest fracture resistance, which was significantly different from all other groups, except groups OPx and OB. Compared with these 3 groups, OP had a significantly lower fracture resistance. When comparing groups with 3 surfaces missing with each other, there were no significant differences between MOD, BOP, and POPx. No significant differences in fracture resistance were found between the groups with 4 missing surfaces, MODP, MODB, and BOPPx. The correlation between the remaining dentin surface area and the fracture strength (\( r=0.72 \)) indicated a strong, positive relationship between the 2 variables (\( P<.001 \)) (Fig. 3).

**DISCUSSION**

The present study investigated the influence of remaining coronal dentin surface area on the fracture resistance of endodontically treated maxillary premolars. The results showed a strong correlation (\( r=0.72 \)) between the remaining dentin surface area and the fracture resistance. This finding supports previous studies\(^2,4,22\) that have found that maximal thickness of axial tooth structure at the crown margin is necessary to resist fracture. However, it differs from the study by Sorensen and Engelman\(^29\) in which there was no correlation between the thickness of tooth structure and the failure threshold. This difference could be attributed to the fact that they investigated maxillary central incisors with post-retained crowns.

In the present study, the surface area values decreased as expected with the increase of the number of missing walls. Interestingly, the group with only the palatal wall remaining (MODB) showed the lowest mean surface area of all groups but not the lowest mean fracture strength. This indicates that the strategic location of remaining tooth structure may be more important than the absolute volume of the remaining tooth. This is reinforced by the observation that the group with only a remaining buccal wall (MODP) showed the lowest mean fracture resistance among all specimens, rendering it the least favorable situation, even though this group did not have the lowest remaining dentin surface area. This can be explained by the findings of Nam et al.,\(^9\) where high levels of stress were produced in the remaining internal tooth structure along the canal space. However, as the number of walls reached zero, higher stress was noted at the lingual side of crown and cementoenamel junction area. In contrast, in a study by Samran et al.,\(^34\) the location of the remaining tooth structure did not affect the fracture resistance of endodontically treated mandibular premolars.

The direction of loading can be a critical factor. In the present study, a static load from the palatal direction.

### Table 2. Summary of results

<table>
<thead>
<tr>
<th>No. of Missing Walls</th>
<th>Missing Surface</th>
<th>Remaining Dentin Surface Area (mm²), Mean ± SD</th>
<th>Failure Loads (N), Mean ±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>O</td>
<td>31.3 ±3.50</td>
<td>1380.5 ±393.93</td>
</tr>
<tr>
<td>2</td>
<td>OPx</td>
<td>26.7 ±2.22</td>
<td>1142.8 ±307.96</td>
</tr>
<tr>
<td>3</td>
<td>OP</td>
<td>18.6 ±2.60</td>
<td>500.4 ±90.21</td>
</tr>
<tr>
<td>4</td>
<td>OB</td>
<td>21.7 ±4.67</td>
<td>1043.7 ±247.52</td>
</tr>
<tr>
<td>5</td>
<td>MOD</td>
<td>15.8 ±2.60</td>
<td>800.8 ±208.82</td>
</tr>
<tr>
<td>6</td>
<td>BOP</td>
<td>19.3 ±4.48</td>
<td>631.8 ±124.73</td>
</tr>
<tr>
<td>7</td>
<td>BOPx</td>
<td>15.3 ±2.55</td>
<td>748.4 ±249.49</td>
</tr>
<tr>
<td>8</td>
<td>POPx</td>
<td>13.5 ±1.73</td>
<td>398.4 ±149.59</td>
</tr>
<tr>
<td>9</td>
<td>MODP</td>
<td>11.0 ±2.94</td>
<td>344.7 ±91.25</td>
</tr>
<tr>
<td>10</td>
<td>MODB</td>
<td>9.5 ±1.61</td>
<td>682.8 ±172.29</td>
</tr>
<tr>
<td>11</td>
<td>BOPPx</td>
<td>15.1 ±3.67</td>
<td>540 ±121.33</td>
</tr>
</tbody>
</table>

O, occlusal access; Px, proximal; P, palatal; B, buccal; M, mesial; D, distal.

![Figure 3. Correlation between surface area and fracture strength.](image)
applied to the buccal cusp was used. The teeth tended to flex buccally with a fulcrum situated on the buccal surface. A palatal coronal wall may be critical in resisting the displacement of the crown.

In this study, the groups with missing palatal walls showed the lowest fracture resistance in comparison with other groups in the same category. Among the groups with 2 missing walls, an intact palatal wall (OPx and OB) was as effective as an intact circumferential axial wall (O) in providing fracture resistance to the force applied.

The forces placed on the dentition during normal masticatory function are generally small compared with the maximal biting force. For women, maximum occlusal forces in the first and second premolar areas of 178.54 ±77.20 N and 206.01 ±86.52 N have been reported, while for men, corresponding forces of 254.08 ±72.20 N and 291.36 ±57.29 N have been described. In a study by Lepley et al., higher occlusal forces were recorded on premolars (373.8 ±102.6 N in men and 314.7 ±96.5 N in women). Taking this into account, together with the fact that processing may have weakened the teeth in vitro, the actual forces required to create failure may be much higher in vivo. Therefore, 400 N might be considered as a threshold below which a premolar tooth is too weak to withstand normal occlusal force.

For the control group with only an occlusal access preparation, the mean fracture load (1380 ±393.9 N) was more than 4 times greater than this threshold. The groups OPx, OB, MOD, BOP, BOPx, and MODB displayed fracture resistance values which were greater than the maximum reported in vivo loads. In comparison, the OP, POPx, MODP, and BOPPx groups, all of which had a missing palatal cusp, showed fracture resistance values in the range of maximal occlusal loads but greater than physiological masticatory forces. However, experimental conditions in this study did not identically simulate the intraoral environment because maxillary premolars are subjected to a mixture of shear and compressive forces. The group with 4 remaining coronal dentin walls (O) had a significantly higher fracture resistance than the groups with only 1, 2, or 3 walls of remaining coronal dentin. These findings are supported by Nissan et al., who found that teeth with remaining coronal structure showed higher fracture loads (828.17 ±226.63 N) compared with teeth with no remaining coronal structure (616.15 ±222.6 N).

Higher values were reported in a previous study of first maxillary premolars with missing palatal walls (782.57 ±182.20 N). In this study, these values tended to be greater than the comparison group with missing buccal walls (730 ±214.17 N), but the differences were not statistically significant. The study differed substantially, though, in that threaded, tapered posts were placed into the root next to the missing wall, which most likely influenced the reaction of the tooth to stress, making comparison difficult.

In another study, lower fracture strength values (489.66 ±149.45 N) were recorded for endodontically treated maxillary premolars with DO cavities compared with the strength values of 1142 ±307.9 N in the present study. This difference is likely due to the restorative technique used. In the groups with 2 remaining dentin walls, the mean fracture resistance value for group MOD was significantly lower than that of the control group (group O). These values were similar to a previously reported study where the mean fracture resistance value for teeth with MOD cavities was 723.93 ±147.18 N compared with 800.8 ±208.8 N in the present study. This agrees with Linn and Messer, who also demonstrated that endodontically treated teeth with MOD cavities were severely weakened because of the loss of reinforcing structures such as the marginal ridges and pulp chamber roof. A study by Caplan et al. showed that endodontically treated teeth with no or only 1 proximal contact at the time of endodontic access was lost at more than 3 times the rate of endodontically treated teeth with 2 proximal contacts. Therefore, the preservation of the marginal ridge (if possible) appears to be of importance.

The group with only the buccal cusp remaining (group MODP) had the lowest mean load value of all groups (344.7 ±91.25 N), suggesting that the restorability of teeth with this condition is questionable. This value is lower than values reported by Kivanc et al., who found a mean failure load value of 920.33 ±162.24 N for maxillary premolars restored with different post systems and composite cores without a crown. An in vivo study by Eakle et al. reported that the lingual cusps of maxillary premolars fractured more often than the buccal cusps, suggesting that maxillary premolars with only 1 remaining buccal cavity wall may be a common clinical situation.

The limitations of the present study are associated with the mechanical testing of extracted human teeth. They include the difficulty of collecting sound teeth, free of any developmental anomalies or damage from extraction procedures; tooth preparation without creating thermal or mechanical damage; and limitations of individual variations such as age, pulp size, time elapsed after extraction, and the unknown effects of the storage conditions. Furthermore, in vitro research is limited in its ability to simulate the elasticity of the periodontal ligament, bone, tooth structure, and the reproduction of the clinical environment, including functional forces. Prospective clinical trials are necessary to validate the results.

CONCLUSIONS

Within the limitations of this in vitro study, the following can be concluded for restored endodontically treated maxillary premolars:
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12. There is a positive correlation between the remaining dentin surface area decreases with the increase in the number of missing walls. J Endod 2011;37:21-5.

13. The remaining dentin surface area decreases with the increase in the number of missing walls. J Endod 2011;37:21-5.


22. The remaining dentin surface area decreases with the increase in the number of missing walls. J Endod 2011;37:21-5.


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