Fracture resistance and stress distribution of repairing endodontically treated maxillary first premolars with severe non-carious cervical lesions

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This study was to compare the influence of glass fiber post placement and crown restoration on endodontically treated maxillary first premolars with severe NCCLs using three-dimensional finite element analysis and fracture resistance testing. G1, intact teeth. G2, teeth with artificial defect. G3, composite resin (CR). G4, CR and fiber post in buccal canal (FPB). G5, CR and fiber post in palatal canal (FPP). G6, CR and fiber posts in buccal and palatal canals (FPBP). G7, CR and crown (C). G8, CR, FPB, C. G9, CR, FPP, C. G10, CR, FPP, C. Teeth in G2, G3, and G5 showed a similar stress concentration at the tip of the defect. The fracture resistance of G2 did not differ significantly from G3 and G5 (p>0.05) but differed significantly from that in other groups (p<0.05). The fractures in G4 were more favorable, and the difference of those in G1 from those in G7, G8, G9, and G10 was statistically significant (p<0.05). Restoration of root-filled maxillary premolars with severe NCCLs using fiber post in the buccal canal may be more efficacious than other restoration methods.

Keywords: Fracture resistance, Maxillary first premolar, Pulp perforation, Three-dimensional finite element analysis, Wedge-shaped defect

INTRODUCTION

Non-carious cervical lesions (NCCLs) involve the loss of cervical tooth structure in the absence of caries1). The anatomical shape of the maxillary premolar makes it easy for stress to become concentrated at the cervical area2-3). Many causes pulpitis and periapical periodontitis, necessitating root canal treatment (RCT). Endodontically treated teeth are considered to be more susceptible to fracture, due to the loss of dentin and anatomical structure, and a reduction in humidity4-6). To increase the success rate of root canal therapy, various restoration approaches have been used7). Teeth can be restored using composite resin, which has elastic properties similar to those of tooth structures8), making it useful for restoration of maxillary premolars with extensive loss of tooth structure. The use of posts has been suggested to promote retention of the final restoration and to help distribute occlusal stress over the residual tooth structure9). The elastic modulus of glass fiber posts and dentine is similar, which may reduce the risk of vertical root fractures10). However, some studies have indicated that the tooth was not strengthened by the use of posts11,12). Furthermore, a crown is usually used to protect the residual dentine structure, to prolong the clinical life of the restored tooth and improve esthetics; however, it remains possible that the restored teeth could fracture13).

The maxillary first premolar very often has a single root, which frequently has two canals14). Currently, there is no standard approach for deciding into which of these canals to place a fiber post for restoration. Moreover, it is not clear whether restorations using a fiber post and resin composite could attain the same strength as intact teeth, thereby negating the need for a crown restoration. Thus, we here investigated the influence of glass fiber post placement and crown restoration on endodontically treated maxillary first premolars with wedge-shaped defects perforating into the pulp.

MATERIALS AND METHODS

This study consisted of two parts, 3D finite element analysis (FEA) and fracture failure tests.

Three-dimensional FEA

One sound maxillary premolar, which had been extracted for orthodontic reasons, was used. The sample was scanned with an Inveon Micro-CT system (Siemens, Munich, Germany) and the dental structure reconstructed. The average thicknesses of the periodontal ligament and cortical bone were set to 0.175 and 0.15 mm, respectively, at the tooth root, 1 mm below the cement enamel junction (CEJ). Cancellous bone was constructed at the external root, following the edge of the periodontal ligament. Using Mimics software (V10.01, Materialise, Leuven, Belgium), Geomagic Studio 12.0, Pro/E software, and ANSYS16.0, a normal tooth 3D finite element (FE) model was generated, which served as a standard for simulating experimental models as shown in Fig. 1. The experimental models were generated using Solid Works. The width of the simulated wedge-shaped, triangular

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Three-dimensional FEA model generation.
A) FEA model of G1 (intact teeth), B) FEA model of G2 (teeth with defect), C) FEA model of G3 (restored with composite resin), D) FEA model of G4 (restored with fiber post in buccal canal and composite resin), E) FEA model of G5 (restored with fiber post in palatal canal and composite resin), F) FEA model of G6 (restored with fiber posts in buccal and palatal canals and composite resin), G) FEA model of G7 (restored with composite resin+crown), H) FEA model of G8 (restored with fiber post in buccal canal and composite resin+crown), I) FEA model of G9 (restored with fiber post in palatal canal and composite resin+crown), J) FEA model of G10 (restored with fiber posts in buccal and palatal canals and composite resin+crown).

Table 1  Characteristics of the groups

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1 (6)</td>
<td>Intact teeth</td>
</tr>
<tr>
<td>G2 (6)</td>
<td>Artificial NCCL (+), RCT (-), Restoration (-)</td>
</tr>
<tr>
<td>G3 (6)</td>
<td>Artificial NCCL (+), RCT (+), Fiber post (-), Composite resin restoration (+), Crown (-)</td>
</tr>
<tr>
<td>G4 (6)</td>
<td>Artificial NCCL (+), RCT (+), Fiber post in buccal root canal (+), Composite resin restoration (+), Crown (-)</td>
</tr>
<tr>
<td>G5 (6)</td>
<td>Artificial NCCL (+), RCT (+), Fiber post in palatal root canal (+), Composite resin restoration (+), Crown (-)</td>
</tr>
<tr>
<td>G6 (6)</td>
<td>Artificial NCCL (+), RCT (+), Fiber posts in both buccal and palatal root canals (+), Composite resin restoration (+), Crown (-)</td>
</tr>
<tr>
<td>G7 (3)</td>
<td>Artificial NCCL (+), RCT (+), Fiber post (-), Composite resin restoration (+), Crown (+)</td>
</tr>
<tr>
<td>G8 (3)</td>
<td>Artificial NCCL (+), RCT (+), Fiber post in buccal root canal (+), Composite resin restoration (+), Crown (+)</td>
</tr>
<tr>
<td>G9 (3)</td>
<td>Artificial NCCL (+), RCT (+), Fiber post in palatal root canal (+), Composite resin restoration (+), Crown (+)</td>
</tr>
<tr>
<td>G10 (3)</td>
<td>Artificial NCCL (+), RCT (+), Fiber posts in both buccal and palatal root canals (+), Composite resin restoration (+), Crown (+)</td>
</tr>
</tbody>
</table>

(+) the corresponding procedure was performed, (-) the corresponding procedure was not performed.

defect was 3.0 mm, and the occlusal wall was located at 2.0 mm above the CEJ, the gingival wall was located at the tooth root, 1.0 mm below the CEJ. The depth of the defect was 1/2 of the tooth neck diameter on the buccal and lingual side. The tip of the wedge-shaped defect was located 1 mm below the CEJ, and the periodontal tissues were cut 1.0 mm in the root direction (Fig. 1B). The RCT 3D FEA model was first established. Eight restored
Table 2  Mechanical properties of the glass fiber post

<table>
<thead>
<tr>
<th>Direction</th>
<th>Elastic modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>37,000</td>
<td>0.34</td>
<td>17)</td>
</tr>
<tr>
<td>Y</td>
<td>9,500</td>
<td>0.27</td>
<td>17)</td>
</tr>
<tr>
<td>Z</td>
<td>9,500</td>
<td>0.27</td>
<td>17)</td>
</tr>
</tbody>
</table>

Table 3  Material properties assigned to dental tissues and restorative material (MPa)

<table>
<thead>
<tr>
<th>Tissue or Material</th>
<th>Elastic modulus (Mpa)</th>
<th>Poisson’s ratio</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>84,100</td>
<td>0.30</td>
<td>18), 19)</td>
</tr>
<tr>
<td>Dentin</td>
<td>18,600</td>
<td>0.31</td>
<td>18), 19)</td>
</tr>
<tr>
<td>Pulp</td>
<td>2.0</td>
<td>0.45</td>
<td>18), 19)</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>68.9</td>
<td>0.45</td>
<td>18), 19)</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>13,700</td>
<td>0.30</td>
<td>18), 19)</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>1,370</td>
<td>0.30</td>
<td>18), 19)</td>
</tr>
<tr>
<td>Gutta-percha</td>
<td>0.69</td>
<td>0.45</td>
<td>18), 19)</td>
</tr>
<tr>
<td>Composite resin</td>
<td>10,000</td>
<td>0.24</td>
<td>18), 19)</td>
</tr>
<tr>
<td>All-ceramic crowns</td>
<td>78,000</td>
<td>0.28</td>
<td>20)</td>
</tr>
</tbody>
</table>

models were generated, which differed as described in Table 1. The cylindrical fiber post length was set at 20.0 mm, the tip diameter was 0.8 mm, the terminal diameter was 1.6 mm. The design aimed to preserve 4.0 mm of root filling at the apex and the fiber post was truncated 2.0 mm under the occlusal surface. The requirements for preparation of all-ceramic crown teeth were the removal of 2.0 mm from the occlusal surface, using a shaft wall aggregate of 6°, placing the buccal edge of the crown at the gingival wall of the wedge-shaped defect, and the palatal edge of the crown over the CEJ, on the coronal side, by 1.0 mm.

According to the basic assumption of elastic mechanics, tissues and materials other than the post, which was considered orthotropic, were considered isotropic, linear, and homogeneous\(^{15,16}\). The simulated mechanical properties of the tissues and the materials are shown in Tables 2 and 3\(^{17-20}\). The mesial, distal, and bottom surfaces of the model were completely fixed. The buccal and lingual alveolar bones were defined as freedom boundaries. The model was loaded with 135 and 270 N. The loading application, loading point, and direction were as follows. Vertical load: Central fossa, parallel to the longitudinal tooth axis. Oblique load: The midpoint of the lingual ridge, 45° to the longitudinal tooth axis.

**Fracture failure test**

Forty-eight human maxillary first premolars, with double canals, freshly extracted for orthodontic reasons (without caries, cervical abrasion, root canal resorption, and fracture) were collected and examined under a stereomicroscope (Carl Zeiss, Oberkochen, Germany). Dental plaque, calculus, and periodontal tissues were carefully removed using a hand scaler. Teeth were stored in a 0.1% thymol solution at room temperature within 3 months. The teeth were divided into 10 groups (G1–G6, n=6; G7–G10, n=3) and prepared as described in Table 1. The experimental groups were prepared so as to have an artificial severe wedge-shaped defect affecting 1/2 of the buccal-lingual distance, at the buccal cervix, by using a polishing silicon disc (thickness: 0.7 mm; diameter: 38 mm) under running water. For G3, G4, G5, G6, G7, G8, G9, and G10, the teeth were subjected to RCT. The pulp chamber of each tooth was opened using a standardized procedure, and the working length was set at 1 mm short of the apical foramen. The root canal patency of the selected teeth were ensured using K-files (Mani, Tochigi, Japan), and the root canal was prepared using a ProTaper system (Dentsply Mallefer, Ballaigues, Switzerland), following the manufacturer’s guidelines, from SX to F3, at the working length. The canals were obturated with gutta-percha (Dentsply Mallefer) and an AH Plus Sealer (Dentsply Mallefer), using the cold lateral condensation technique. Subsequently, the access cavities were filled with glass ionomer cement (GIC) (Fuji IX GP, GC, Tokyo, Japan). In G3, teeth were restored using only composite resin. After removing the GIC, the surfaces were treated with an adhesive bonding system (Single Bond, 3M ESPE, Maplewood, MN, USA), and light-cured for 10 s with a light-curing unit (VIP Junior, Bisco, Schaumburg, IL, USA) at a light intensity of 600
mW/cm². The cavity access and the defect were restored with composite resin (Filtek Z350, 3M ESPE) using the incremental technique, as shown in Fig. 2A. In G4, the teeth were restored with a glass fiber post in the buccal canal as well as with composite resin. The post space was prepared in the buccal canal by removing the filling material using a select universal drill, and preserving 4.0 mm of the filling at the root apex; then, the post system drill (RelyX Fiber Post drill 2#; 3M ESPE) was used to widen and shape the root canal. The canal was flushed with 2 mL of 5.25% NaOCl and 2 mL of saline solution. The root canal was then gently dried, and the resin cement (Rely X Unicem, 3M ESPE) delivered into the post space. The post (2#, 3M ESPE) was cleaned with 95% ethyl alcohol, air-dried, and additional resin cement was applied to the total surface. The cement was light-cured for 60 s from the occlusal direction via the post. The fiber post was truncated 2.0 mm below the cavity margin; then, the surfaces were treated with an adhesive bonding system (Single Bond, 3M ESPE), and the tooth anatomy restored as described for G3, as shown in Fig. 2B. In G5, the teeth were restored with a glass fiber post (2#, 3M ESPE) in the palatal canal as well as with composite resin. These teeth received posts in a similar manner as described for G4 and were filled as described for G3, as shown in Fig. 2C. In G6, the teeth were restored with glass fiber posts (2#, 3M ESPE) in both buccal and palatal canals; the method for placing the posts was similar to the placement described for G4, and they were filled with composite resin (Filtek Z350, 3M ESPE) in a similar manner as described for G3, as shown in Fig. 2D. In G7, G8, G9, and G10, the teeth were prepared under metal crown restoration standards.

All the specimens were subjected to thermocycling at 5±2°C to 55±2°C with 30 s dwell-time and 5 s for transfer, for 2,000 cycles. Subsequently, all specimens were vertically embedded in cold-cured acrylic resin to a level of 1.0 mm apical to the CEJ, to which 0.3 mm thick silicone paste was applied between the roots and acrylic resin to simulate the periodontal ligament. Fracture resistance was evaluated in a universal testing machine (Instron, Canton, MA, USA). Compressive force was applied to the long axes of the teeth, toward the central fossa of the crowns, by using a 4 mm diameter round tip load cell at a strain rate of 1.0 mm/min until fracture occurred. After fracture, all the specimens were evaluated for failure mode. Favorable failure was defined as fracture above the CEJ, or 1 mm or less apical to the CEJ; unfavorable failures were defined as fractures more than 1 mm apical to the CEJ, as shown in Fig. 3.

Data analysis
The values and distribution of Von Mises equivalent stress and maximum principle stress are presented for the residual dentine structures. Fracture resistance was recorded in Newton (N). One-way analysis of variance (ANOVA) followed by Tukey’s post-hoc test was carried out to compare the differences between the groups at a significance level of 0.05. The failure modes of the specimens were compared using Fisher’s exact test. All statistical analyses were carried out in SPSS18.0.

RESULTS

Stress distribution
The von Mises and maximum principal stress distribution are shown in Figs. 4 and 5, respectively. From these results, there is a similar stress distribution under 135 and 270 N. The von Mises stress distribution under vertical loading is shown in Figs. 4-i, iii. G2 showed a stress concentration at the loading zone and the tip of the defect. Stress distribution according to von Mises criteria showed that G3 had a stress distribution at the tip of the wedge-shaped defect (Fig. 4-iii-c) similar to that of G2. The von Mises stress distribution under oblique loading is shown in Figs. 4-ii, iv. The G2 model showed stress at the tip of the defect and at the palatal cervical surface. The intact teeth and the restored groups showed a similar stress distribution at the loading zone and the cervical area in the palatal surface. The stress distribution according to the maximum stress criteria under vertical loading are shown in Figs. 5-i, iii. G2 showed a high stress concentration on the root.
Fig. 4  The Von Mises stress distribution (MPa).
i) under vertical loading of 135 N, ii) under oblique loading of 135 N, iii) under vertical loading of 270 N, iv) under oblique loading 270 N. a) G1, b) G2, c) G3, d) G4, e) G5, f) G6, g) G7, h) G8, I) G9, J) G10.

Fig. 5  Stress distribution by maximum principal stress (MPa).
i) under vertical loading of 135 N, ii) under oblique loading of 135 N, iii) under vertical loading of 270 N, iv) under oblique loading 270 N. a) G1, b) G2, c) G3, d) G4, e) G5, f) G6, g) G7, h) G8, I) G9, J) G10.
dentine in the cervical third, and also exhibited a high concentration at the root surface. Teeth in G3 and G5 had a similar stress concentration at the tip of the defect as G2. The stress distribution based on maximum stress criteria under oblique loading are shown in Figs. 5-ii, iv. G2 demonstrated stress concentration at the tip of the defect. G1 and the restored groups had a stress distribution at the buccal root surface under the defect.

**Stress peak in residue dentin**
The von Mises stress peak and the maximum principle stress in dentin is shown in Figs. 6 and 7. G2 showed the highest stress peak. The stress was higher under 270 N loading than under the 135 N loading, and obliquely loaded teeth exhibited significantly higher stress in the cervical region of the restoration.

**Fracture resistance**
The means of the fracture resistance of all the groups are listed in Table 4. The results showed that there were statistically significant differences between the mean fracture resistance of the groups ($F=8.737$, $\alpha=0.05$, $p<0.05$). Additionally, fracture resistance of teeth in G2 was not significantly different from that of teeth in G3 and G5 ($p>0.05$) but was significantly different from those in other groups ($p<0.05$). Next, the fracture resistance in G1 was not significantly different from those in G3, G4, G5, and G6 ($p>0.05$), but was significantly different...
Table 4  Comparison of fracture strengths

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>Mean (SD)</th>
<th>Subgroups (α=0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1 (6)</td>
<td>1,266.83 (405.15)</td>
<td>b</td>
</tr>
<tr>
<td>G2 (6)</td>
<td>589.08 (92.62)</td>
<td>a</td>
</tr>
<tr>
<td>G3 (6)</td>
<td>841.07 (343.35)</td>
<td>a b</td>
</tr>
<tr>
<td>G4 (6)</td>
<td>1,068.30 (454.31)</td>
<td>b</td>
</tr>
<tr>
<td>G5 (6)</td>
<td>1,021.00 (625.12)</td>
<td>a b</td>
</tr>
<tr>
<td>G6 (6)</td>
<td>1,204.17 (586.87)</td>
<td>b</td>
</tr>
<tr>
<td>G7 (3)</td>
<td>2,477.67 (421.36)</td>
<td>c</td>
</tr>
<tr>
<td>G8 (3)</td>
<td>2,343.97 (534.68)</td>
<td>c</td>
</tr>
<tr>
<td>G9 (3)</td>
<td>2,356.57 (520.58)</td>
<td>c</td>
</tr>
<tr>
<td>G10 (3)</td>
<td>2,563.33 (552.25)</td>
<td>c</td>
</tr>
</tbody>
</table>

ANOVA test and post-hoc test

Fracture pattern

The percentages of teeth with favorable and unfavorable fractures are displayed in Fig. 8. The photographs of representative specimens displaying different fracture modes are showed in Fig. 9. The fracture modes in G4 were more favorable. The difference in fracture modes of G1 from those in G3, G4, G5, and G6 was not significantly different (p>0.05), while the difference of those in G1 from those in G7, G8, G9, and G10 was significantly different (p=0.028<0.05). There was no significant difference in fracture modes among G3, G4, G5, and G6 (p>0.05), or among the G7, G8, G9, and G10 (p>0.05).

Fig. 8  Fracture mode of each group.

Fig. 9  Photographs of representative specimens displaying different fracture modes. Favorable (A, B, C, D, I, J), Unfavorable (E, F, G, H, K, L). A) favorable mode, crown fracture in intact teeth; B) favorable mode, crown cross breaks; C) favorable mode, tooth tissue separated from the resin; D) favorable mode, both tooth tissue and resin breaks; E) unfavorable mode, fractures more than 1 mm apical to the cement enamel junction; F) unfavorable mode, coronal and lingual dehiscence; G) unfavorable mode, crown and root fracture; H) unfavorable mode, crown longitudinal fracture; I) favorable mode, crown cross breaks in teeth restored with crown; J) favorable mode, fiber post piled out; K) unfavorable mode, root fracture; L) unfavorable mode, both crown and root fracture.
DISCUSSION

Maxillary premolars were used in the resistance test, because they are highly likely to have NCCLs and are susceptible to cusp fracture in the oral cavity\(^{31}\). Bone support and the periodontal ligament may influence the fracture mode\(^{25,28}\). In this study, the periodontal ligament was simulated, using polyether impression material, and acrylic resin to simulate alveolar bone\(^{24,27}\).

In the fracture resistance test, the teeth were submitted to thermocycling in order to obtain more accurate results\(^{27}\).

In the present study, teeth in G2 demonstrated stress concentration in the cervical area, leading to more transverse fractures. G3 and G5 yielded a similar stress distribution, concentrated at the tip of the defect to teeth without restoration, which may thus not help to inhibit the progression of the defect. In contrast, G4 or G6 showed a similar stress distribution as in intact teeth. There were no significant differences in fracture resistance with or without fiber posts. The finding was consistent with a number of other studies\(^{12,25,29}\).

Additionally, the fracture resistances of teeth in G4 and in G6 were significantly different from those in G2. Moreover, the fracture resistance in G3 and G5 were not significantly different from those in G2. This may suggest that the location of the fiber post influences the fracture resistance of the restored teeth. Currently, the effect of fiber posts on enhancing the fracture resistance is still debated\(^{28}\). Salameh and Torres et al. showed that glass fiber posts restore the lost fracture resistance in endodontically treated maxillary premolars\(^{31,32}\). However, Bolay et al. revealed that fiber posts did not significantly improve the fracture resistance of the mandibular premolar after endodontic treatment, while reducing the incidence rate of root fractures, and improving the percentage of favorable fractures\(^{29}\). Keçeci et al. showed that insertion of a fiber post increased the fracture resistance; however, the effect was not statistically significant\(^{29}\). This may be because post preparation caused more loss of the dental structure, increased the square of the bonding interface, and may also have caused the formation of microfissures and microcracks, which in turn decreased the fracture resistance. Furthermore, a crown has an important effect on fracture resistance due to the protection of the crown, the good distribution of the stress, or the good ductility of the cobalt chromium metal full crown. Aquilino et al. revealed that the survival rate of endodontically restored teeth was significantly related to crown restoration in their retrospective study\(^{15}\). However, Mannocci et al. found that endodontically treated premolars, directly restored with composite resin and fiber posts, could acquire the same clinical therapeutic effect as achieved by crown restoration, in a 3-years’ follow-up study\(^{30}\).

The percentage of favorable fracture mode was as follows: G4 (83.3%)>G5, G6, G7 (66.7%)>G2, G3 (50%)>G8, G9 (33.3%)>G10. Teeth restored directly with composite resin only did not demonstrate an increase in the percentage of favorable fractures, and the placement of the fiber post increased the percentage of favorable fractures. The teeth restored with fiber posts in the buccal canal showed a higher percentage of favorable fractures than those treated with other repair methods.

In terms of failure modes, our results showed that application of fiber post produces more favorable patterns. This may be explained by the difference in stress distribution obtained when using a fiber post with a modulus of elasticity, similar to that of intraradicular dentin to restore the teeth; less stress is transferred from to the dentin\(^{35,36}\). In our study, we truncated the fiber post 2.0 mm under the occlusal surface, in this way, the fiber post is not directly stressed, which favors the stress distribution, and reduces the bonding interface between the post and the teeth, thereby reducing the occurrence of microleakage. Although the crown restoration may have improved the fracture resistance, it also increases the unfavorable fracture mode, and even the occurrence of root fracture. This may be because a full crown could protect the residual teeth crown tissue; under the activity in the oral activity, the stress could be easily transferred to the root, causing root fracture. In our study, the fracture resistance of crown restorations was markedly higher than the maximum bite force of the maxillary first premolar.

In our study, a loading force was applied at the central fossa in the axial direction of the compressive load of the tooth; the different loading conditions may lead to different results in various studies. Accordingly, the results should be interpreted with caution.

CONCLUSION

Based on the methodology and the results of this study, we concluded that root-filled maxillary premolars with wedge-shaped defects perforating into the pulp, restored with fiber post in the buccal canal, may have a better effect than other restoration methods, the use of this repair method is recommended, although further clinical effects should be observed.

ACKNOWLEDGMENTS

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