In restoring endodontically treated teeth when insufficient coronal tooth structure remains to retain a crown, the use of the root canal space may be required for retention of the core and subsequent restoration. A cast gold dowel and core has long been advocated for the rehabilitation of endodontically treated teeth. The custom cast dowel and core is usually more conservative of remaining tooth structure. Morgano has recommended its use whenever a dowel-and-core system is indicated. However, complications such as loosening of the dowel and core or fracture of the remaining root may sometimes occur.

Clinical longevity of the dowel-and-core restoration can be influenced by many factors, including the magnitude and direction of the occlusal load, design of the dowel, thickness of the remaining dentin, and quality of the cement layer. Goodacre and Spolnik found loosening of the dowel and core to be influenced by many factors, including the amount of remaining dentin, direction of the occlusal load, and design of the dowel. Most stress analyses of dowel and cores were conducted without including all aspects of the restorations and supporting structures.

Clinical implications

Ideal occlusion to avoid nonaxial forces appears to be the most important factor that influences stress production in both restorative materials and supporting tissues. However, it appears that a parallel-sided dowel and core with a dowel length of 12 mm will result in the smallest peak stresses in the dentin and restoration of an anterior tooth.

The effects of dowel design and load direction on dowel-and-core restorations

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Statement of problem. Complications such as loosening of the dowel and core or fracture of the remaining tooth root can be influenced by many factors, including the amount of remaining dentin, direction of the occlusal load, and design of the dowel. Most stress analyses of dowel and cores were conducted without including all aspects of the restorations and supporting structures.

Purpose. The purpose of this study was to investigate the influence of occlusal stresses on various dowel designs in a restored, endodontically treated maxillary incisor by using a 2-dimensional finite element analysis model.

Material and methods. A 2-dimensional finite element model was constructed in a labiolingual cross-sectional view of a maxillary central incisor, a dowel, a core, and the supporting tissues to investigate stresses in various dowel designs. As a control, a metal-ceramic crown on an endodontically treated tooth without a dowel and core was modeled. A 10-kg force was applied as follows: (1) in a vertical load on the incisal edge, (2) in a horizontal load on the labial surface, and (3) in a 20-degree diagonal load on the lingual surface.

Results. The use of a dowel reduced the peak dentinal stress to 75% of the magnitude of the control. When a vertical force was applied, the magnitudes of stress of the various dowel designs were similar; however, when loaded horizontally, the short dowel produced the greatest dentinal stress concentration, and the tapered dowel showed the greatest stress concentration within the cement layer. Greater deflections and higher stresses were generated with horizontal loading.

Conclusion. The dowel and core provided little reinforcement to the remaining tooth. The direction of the functional load had a greater effect than dowel design on maximum stress and displacement. Parallel-sided dowel and cores with a length of 12 mm distributed the stress widely in the restoration and dentin, resulting in the smallest stresses. (J Prosthet Dent 2001;85:558-67.)
tooth fractures to be the 2 most common causes of dowel-and-core failures.

Sapone and Lorencki suggested that one function of the dowel is to provide reinforcement of the tooth. Dentin, however, must be removed during preparation of the dowel space, and this may reduce the fracture resistance of the remaining dentin. The most current literature disputes the reinforcement potential of dowels. Because many authors have stated that dowels do not strengthen teeth and may actually weaken the remaining tooth structure, it appears logical that dowel-retained restorations should be avoided when possible.

Functional loading of a crown with a cemented dowel and core creates stresses in the prosthesis and the root. If the stresses exceed the yield strength of the materials, fracture of the restorative materials or the tooth may occur. Frequent loading may cause strains and stresses in the cement layer that could result in damage of the cement film and consequent release of the restoration. Cohen et al reported that micromovement of a cemented dowel results in disintegration of the cement and the concentration of stress at the apical end of the dowel over time. The fracture strength of dental cements is less than that of dentin or dowel material. Thus, failure of the system usually occurs cohesively within the cement or at its interface with dentin. Cooney et al found that dowels with tapered ends were less retentive than parallel-sided dowels. They also noted that the tapered end produced wedging stresses near the apex.

Despite the importance of stresses in the cement layer, metal-ceramic crown, periodontal ligament, and supporting bone, most recent stress analyses of dowel and cores were conducted without including all components of the restoration and supporting structures. The specific clinical problems considered in this study involve the potential of the dowel to strengthen pulpless teeth with a metal-ceramic crown and the comparative evaluation of parameters among various loading directions and dowel designs. The null hypothesis of this study was that the dowel design would have no effect on the stress distribution of an endodontically treated maxillary central incisor restored with a metal-ceramic crown.

**MATERIAL AND METHODS**

A 2-dimensional finite element model was constructed according to the labiobuccal cross-sectional anatomy of a maxillary central incisor, a cast dowel and core, a metal-ceramic crown, and supporting structures. The standard model (STAN) included a
metal-ceramic crown, a parallel-sided gold dowel and core (12 mm in length, 1.5 mm in diameter), and a 3.5-mm gutta-percha apical seal. The average thickness of the zinc phosphate cement (ZPC) layer, periodontal ligament, and cortical bone were 60 µm, 0.3 mm, and 0.4 mm, respectively.

A linear plane stress analysis program (Supersap; Algor Inc, Pittsburgh, Pa.) was used to solve the 2-dimensional stress analysis problems. Plane stress elements simulate a special 3-dimensional stress state. The assumption of the 2-dimensional finite element method in our study was that the stress along a mesiodistal direction was negligible and that stress components in any direction were independent of the mesiodistal dimension. The choice of a 2- or 3-dimensional model is dependent on the objective of the analysis. Three-dimensional models of dental anatomy require digitizing many cross-sections of the model and the connection of each layer. This process is not only time-consuming, but also may be prone to critical geometric inaccuracies in the thin cement layer.

In this research model, the elements were triangular shaped and fit well into the geometrically complex structure. The model was 13 mm wide and 30 mm in height. It consisted of 780 elements and 431 nodes. In modeling the cement layer, the interface between the cement layer and the other structures had no gap or slip. Although the shape of the elements of the cement layer was attributable to the layer thinness, the elements were within the allowable level of the finite element analysis (FEA) software (Supersap). The model was constrained at the bottom boundaries.

The 4 dowel designs were created by changes in the diameter, length, and shape of the dowel (Table I). An endodontically treated tooth with a metal-ceramic crown (NOPC) and another without a metal-ceramic crown (NCPC) served as the positive and negative controls, respectively. The experimental model (STAN) and the control models are shown in Figure 1. The force of 10 kg was applied to the modeled crown as follows: vertical load on the incisal edge (L1), horizontal load on the labial surface (L2), and 20-degree diagonal load on the lingual surface (L3) (Fig. 1).

The elastic modulus and Poisson’s ratio of the materials were obtained from the published literature\textsuperscript{13,14} and recorded (Table II). The calculated numeric data of stress and displacement on the dowel-and-core restorations were visualized in color graphics, and peak von Mises stresses in each area were tabulated (Figs. 2 through 9).
RESULTS

Similar stress patterns were revealed when the positive and negative controls were compared (Figs. 3 and 4). However, the metal-ceramic crown markedly reduced dentinal stress in the coronal portion of the dentin. The evaluation of the endodontically treated tooth without a crown was included only for purposes of completeness. It will not be discussed further because the aim of the study was to evaluate the dowel-and-core design.

Load directions

Greater deflection and higher stresses were generated with horizontal loading than with vertical loading. In model STAN, the deflections of incisal edge with L1, L2, and L3 were 53.4 \( \mu \text{m} \), 549.5 \( \mu \text{m} \), and 150.8 \( \mu \text{m} \), respectively. The alveolar bone crest was deflected 13.3 \( \mu \text{m} \) with vertical force (L1) and 127.3 \( \mu \text{m} \) with horizontal force (L2). The amount of deflection at the incisal edge with horizontal loading was 10 times greater than that with vertical loading. When lateral forces were applied, the center of rotation in the teeth of all models was approximately 3 mm coronal to the root apex (Fig. 2). The dowel design had no significant influence on the amount or the pattern of deflection.

Over all dowel designs, the magnitudes of peak stress values in the dentin, dowel, cement layer, and metal-ceramic crown were approximately 2 to 3 times greater with L2 (horizontal loading) than with L1 (vertical loading). In horizontal loading, stress concentrations were observed at the middle of the root and around the dowel apex, whereas during vertical loading, the stress was well distributed in the metal-ceramic crown and the dowel and core.

The lateral force produced a long band of high stress concentration along the cortical bone. The vertical force generated stress in the cortical bone around

**Fig. 3.** Graphic presentation of stress in endodontically treated natural tooth (NCPC). Magnitudes of von Mises stress are indicated with color code (unit: kg/mm\(^2\)). With horizontal loading, widest and greatest stress concentrations were generated; greatest dentinal stress was observed at midroot. Ten kilograms vertical force produced smallest stress concentration in tooth and supporting structures.

**Table II.** Mechanical properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (kg/mm(^2))</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone(^{13})</td>
<td>1,500</td>
<td>0.30</td>
</tr>
<tr>
<td>Cancellous bone(^{13})</td>
<td>50</td>
<td>0.30</td>
</tr>
<tr>
<td>PDL(^{14})</td>
<td>0.7</td>
<td>0.45</td>
</tr>
<tr>
<td>Dentin(^{13})</td>
<td>1,500</td>
<td>0.31</td>
</tr>
<tr>
<td>Enamel(^{13})</td>
<td>13,270</td>
<td>0.33</td>
</tr>
<tr>
<td>Composite resin(^{13})</td>
<td>1,480</td>
<td>0.24</td>
</tr>
<tr>
<td>Gutta-percha(^{13})</td>
<td>19</td>
<td>0.45</td>
</tr>
<tr>
<td>Type III gold(^{13})</td>
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<td>0.33</td>
</tr>
<tr>
<td>PFM gold(^{13})</td>
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<td>0.33</td>
</tr>
<tr>
<td>ZPC(^{13})</td>
<td>1,400</td>
<td>0.35</td>
</tr>
<tr>
<td>Porcelain(^{13})</td>
<td>6,120</td>
<td>0.19</td>
</tr>
</tbody>
</table>

PDL = Periodontal ligament; PFM = metal-ceramic crown; ZPC = zinc phosphate cement.
the root apex. However, the peak stress values were as small as 16.5% of the stress magnitude of the lateral load. Stresses generated in the bone and periodontal ligament (PDL) were influenced more by the loading direction than the design of the dowels (Table III) (Figs. 3 through 8).

**Table III.** Peak stresses in materials of each design (unit: kg/mm²)

<table>
<thead>
<tr>
<th>Design</th>
<th>Force direction</th>
<th>Bone</th>
<th>PDL</th>
<th>Dentin</th>
<th>ZPC</th>
<th>Dowel</th>
<th>PFM</th>
</tr>
</thead>
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<tr>
<td>NCPC</td>
<td>Vertical</td>
<td>0.75</td>
<td>0.09</td>
<td>0.32</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td></td>
<td>Horizontal</td>
<td>4.72</td>
<td>0.27</td>
<td>1.49</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Oblique</td>
<td>1.65</td>
<td>0.10</td>
<td>0.58</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NOPC</td>
<td>Vertical</td>
<td>0.75</td>
<td>0.09</td>
<td>0.34</td>
<td>0.31</td>
<td>—</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>4.72</td>
<td>0.27</td>
<td>1.49</td>
<td>0.79</td>
<td>—</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>Oblique</td>
<td>1.65</td>
<td>0.10</td>
<td>0.65</td>
<td>0.41</td>
<td>—</td>
<td>2.15</td>
</tr>
<tr>
<td>STAN</td>
<td>Vertical</td>
<td>0.75</td>
<td>0.09</td>
<td>0.29</td>
<td>0.36</td>
<td>0.45</td>
<td>1.77</td>
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<tr>
<td></td>
<td>Horizontal</td>
<td>4.80</td>
<td>0.26</td>
<td>1.06</td>
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<td>1.66</td>
<td>0.92</td>
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<td></td>
<td>Oblique</td>
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<td>0.10</td>
<td>0.44</td>
<td>0.51</td>
<td>0.63</td>
<td>1.17</td>
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<tr>
<td>NARR</td>
<td>Vertical</td>
<td>0.75</td>
<td>0.09</td>
<td>0.31</td>
<td>0.63</td>
<td>0.54</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>4.79</td>
<td>0.26</td>
<td>1.13</td>
<td>0.95</td>
<td>1.70</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Oblique</td>
<td>1.65</td>
<td>0.10</td>
<td>0.48</td>
<td>0.51</td>
<td>0.73</td>
<td>1.17</td>
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<tr>
<td>SHORT</td>
<td>Vertical</td>
<td>0.75</td>
<td>0.09</td>
<td>0.29</td>
<td>0.36</td>
<td>0.41</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>4.70</td>
<td>0.27</td>
<td>1.40</td>
<td>0.61</td>
<td>0.87</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Oblique</td>
<td>1.65</td>
<td>0.10</td>
<td>0.38</td>
<td>0.51</td>
<td>0.59</td>
<td>1.17</td>
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<tr>
<td>TAPER</td>
<td>Vertical</td>
<td>0.75</td>
<td>0.09</td>
<td>0.20</td>
<td>0.36</td>
<td>0.50</td>
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<tr>
<td></td>
<td>Horizontal</td>
<td>4.81</td>
<td>0.26</td>
<td>0.87</td>
<td>1.27</td>
<td>2.17</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Oblique</td>
<td>1.65</td>
<td>0.10</td>
<td>0.25</td>
<td>0.51</td>
<td>0.70</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Vertical force = 10 kg applied on the incisal edge; horizontal force = 10 kg applied on the labial surface; oblique force = 10 kg applied at 20 degrees to the tooth axis on the lingual surface.

PDL = Periodontal ligament; ZPC = zinc phosphate cement; PFM = metal-ceramic crown.
Dowel designs

A comparison of the designs NOPC and STAN showed that the effect of dowel design was most apparent in the metal-ceramic crown and the middle of the root. When lateral forces were applied, peak dentinal stresses in STAN were attained near the apices of the dowel, whereas NOPC generated peak dentinal stresses in the middle of the root surface. The dowel reduced the dentinal peak stress in STAN to three fourths of the magnitude of the control (NOPC). The metal dowel absorbed more occlusal stresses, resulting in lower dentinal stresses around the dowel and core (Figs. 4 and 5). The peak stress values in the metal-ceramic crown without a dowel were 2 times greater than the stress values of designs with a dowel when lateral forces were applied (Table III). When a vertical force was applied, the magnitudes of peak stresses in restorative materials and the supporting tissues of various dowel designs were nearly equivalent.

Minor changes in the overall stress pattern resulted from variations in the diameter of the dowel. STAN and the narrow dowel model (NARR) produced a similar magnitude and pattern of stress distribution. No qualitative differences were seen in the peak stress regions of either the periodontium or the dentin (Figs. 5 and 6). The greatest peak dentinal stresses were produced in the short dowel (SHORT) and NOPC when a horizontal force was applied. SHORT generated a stress pattern similar to NOPC, which showed wide stress concentration around the outer area of the dentin in the middle of the root (Figs. 4 and 7). Conversely, the other dowel designs generated peak dentinal stresses around the dowel apex. The tapered model (TAPER) produced 2.17 kg/mm² peak stress in the dowel compared with 1.66 kg/mm² in design STAN during horizontal loading. TAPER showed the greatest stress in the dowel with a horizontal load. TAPER, when compared with the nontapered design (STAN), resulted in an increase of approximately 38% in the peak stresses in the cement layer near the apex of the dowel (Fig. 8). A typical plot of stresses in the cement layer showed the stress concentrations in the vicinity of the dowel apex (Fig. 9).

The effect of dowel design on maximum stress and displacement was much less than the effect of load direction. The quantitative differences of stress values in the supporting structures of all 5 prosthesis designs considered were less than 50%, whereas the loading direction produced more than a 200% difference in calculated stress values (Table III) (Figs. 3 through 9).

DISCUSSION

A dowel and core is commonly placed to provide retention for a subsequent crown when coronal tooth structure is lacking. It has been believed that one func-
tion of the dowel is to provide reinforcement of the tooth. The most current literature, however, seems to dispute that reinforcement potential. Sorensen and Martinoff evaluated 1273 endodontically treated teeth retrospectively and found no significant increase in resistance to fracture with intracoronal reinforcement. Assif et al compared the fracture resistance of teeth restored with cast dowel and cores with various dowel designs and did not detect any significant differences. Crowned endodontically treated teeth with a composite core and no dowel did not show a significant difference from intact teeth with respect to fracture resistance.

In this experiment, the dentinal stresses observed in the NOPC model were 17% to 48% higher than those in the STAN design (Table III). In comparing any of the designs with a dowel to NOPC, it was observed that the peak stresses in the dentin were greater in the root without a dowel. The presence of the relatively high modulus dowel substantially reduced the stress levels in the surrounding dentin.

In this study, the TAPER model showed the greatest stress concentration in the dowel subjected to a horizontal load. The tapered design resulted in an increase in peak stresses in the cement layer near the apex of the dowel. When comparing the peak stresses in the cement and at the dentin-dowel interface of the various dowel designs, the tapered dowel was the worst design among those examined (Fig. 9).

In an evaluation of the retention of dowel-and-core designs, Cooney et al found that the tapered end produced wedging stresses near the apex and that dowels with tapered ends were less retentive than parallel-sided dowels. The findings of the present investigation suggest that normal occlusal forces might create stresses in the dowel-cement-dentin interface, resulting in disintegration of the cement and a concentration of stress at the apical end of the root.

The results of the design comparison for the varying dowel diameters showed only 7% differences in calculated stresses in the most highly stressed regions. This suggests that a small dowel diameter should be used, providing that the dowel material composition has adequate strength to resist fracture. The small-diameter dowel preserves the remaining dentin of the root, which is significant in preventing fracture of the tooth. The purpose of varying the dowel length was to alter the location of stress concentrations that occur at the dowel apex. As dowel length increased beyond two thirds of the root, the stresses in the apical region of the root increased. Stresses induced by extending the dowel length may damage the apical seal of the pulpless tooth. Therefore, the decision on dowel length should be made based on the need for retention.
It must be noted that presently available mathematical tools for stress analysis are considerably more advanced than the knowledge of mechanical properties of dental tissues. The uncertainties in mechanical property data for the biologic materials give rise to corresponding uncertainties about the actual numerical stress values obtained.

Theoretically, the best FEA model would be a
A 3-dimensional model, which would accurately describe the 3-dimensional geometry of the tooth and prosthesis. The size of the numerical problem to be solved grows tremendously in converting to an adequate 3-dimensional model. If the modeling of the thin layer of cement and periodontal ligament is omitted, or the mesh is made coarser to reduce the time required for modeling and calculation of the structure, the actual stress values can be affected considerably. A 2-dimensional model allows for division into finer meshes so that fine representation of the thin cement layer and periodontal ligament is practically possible and less time is required for modeling and calculation.

The results of finite element analyses of all 5 prosthesis designs demonstrated that the dowels had little reinforcement effect in the dentin of a reconstructed maxillary central incisor under a lateral load. The dowel design, over the range considered in this experiment, was not a significant parameter in altering peak stresses. The quantitative differences among the dowel designs did not produce significant difference, whereas the loading direction produced more than a 200% difference in stress magnitude at critical points in the models.

CONCLUSIONS

To study the mechanical behaviors of dowel-and-core–retained crowns and supporting structures, 5 types of 2-dimensional finite element models were constructed. On the basis of STAN, variations were made by changing the dowel design (tapered vs parallel shape, length, and diameter). As a control, a metal-ceramic crown on an endodontically treated tooth without a dowel and core (NOPC) was used. Force was applied vertically on the incisal edge, horizontally on the labial surface, and 20 degrees laterally on the lingual surface, respectively. Within the limitations of the design of this FEA study, the following conclusions were drawn:

1. The magnitude of deflection and peak stress generated in a reconstructed tooth with horizontal loading was more than 2 times greater than that with vertical loading.
2. The magnitude of peak dentinal stresses observed in NOPC was 17% to 48% higher than the design of STAN according the direction of load.
3. Dowel designs of STAN and NARR produced a similar magnitude and distribution pattern of stress.
4. With horizontal loading, SHORT produced the greatest dentinal stress; TAPER showed the greatest stress in the cement layer.

5. Load direction had a much greater effect than dowel design on maximum stress and displacement.

REFERENCES


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