The effect of thermal change on various dowel-and-core restorative materials

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Statement of problem. Severe thermal stresses caused by food-induced temperature changes may result in dowel-and-core failure.

Purpose. This study investigated the influence of thermal stresses on various combinations of dowel-and-core materials of a restored endodontically treated incisor.

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 thermal stress distribution. Four combinations of dowel-and-core materials were used: (1) gold/gold, (2) stainless steel/resin composite, (3) stainless steel/amalgam, and (4) carbon fiber-reinforced composite/resin composite. For thermal analysis, a cold irritant (0°C) was applied on the outer surface of a metal-ceramic crown for 7 seconds.

Results. The metal dowel and core generated lower thermal stresses in the restorations and dentin than the nonmetallic dowel and cores.

Conclusion. Stress level is closely related to the degree of thermal gradient. The nonmetallic dowel and cores generated greater thermal stresses than metal dowel and cores. (J Prosthet Dent 2001;86:74-80.)

CLINICAL IMPLICATIONS
Nonmetallic dowel-and-core materials produced greater stress than metallic dowel materials. The former generated greater stress in the cement layer, which may lead to cohesive failures of these systems within the cement or at its interface with dentin. It appears preferable to use a metal dowel and core in the oral environment.

Since the time Pierre Fauchard used wooden dowels to retain crowns, various dowel-and-core systems have been introduced to dentistry.1 Although the custom dowel and core is more conservative of remaining tooth structure, the prefabricated dowel and core requires fewer appointments and is a less complex procedure. According to Shillingburg et al,2 the prefabricated dowel-and-core system is the most widely used system. It consists of 3 components: the dowel, a core material, and luting cement.

Metallic materials such as gold alloy, stainless steel, and titanium are widely used as conventional dowel materials because of their high strength. Recently, non-metallic dowels were introduced as theoretically acceptable alternative dowel materials.3,4 McDonald et al5 compared the fracture resistance of teeth restored with a steel dowel or a carbon fiber dowel with intact root-filled teeth. No significant difference was found among the groups. Silver amalgam and resin composite are widely used as core materials for prefabricated dowel-and-core systems. Although a vast number of dowel-and-core components are commercially available, useful biomechanical criteria for evaluating prefabricated dowel-and-core components do not exist.6

Cohen et al7 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.8

The oral cavity is subjected to thermal irritation from hot and cold foods and beverages. Palmer et al9...
measured the maximum and minimum temperatures that could be reached at the natural tooth surface on 13 human subjects as they ingested hot and cold beverages. They reported temperature extremes that ranged from 0°C to 67°C.

Thermal conductivity and thermal expansion of nonmetallic restorative materials, metal, and dentin are significantly different. Thermal conductivity is the heat, in calories per second, passing through a body 1 mm thick with a cross-section of 1 mm.² Metals tend to be better heat conductors than nonmetals. Heat flow is defined as the thermal conductivity divided by the product of specific heat times density. The specific heat of a substance is the quantity of heat needed to raise the temperature of a unit mass of substance by 1°C.¹⁰ A difference in heat flow may cause temperature differences in the oral structures and restorations when hot or cold foods are in the oral cavity.

The linear coefficient of thermal expansion is defined as the change in length per unit length of a material for 1°C change in temperature. Tooth structure and restorative materials in the mouth expand when warmed by hot foods or beverages and contract when exposed to cold substances. If there are differences in volumetric thermal expansion by different temperature changes and/or different coefficients of thermal expansion, the induced stress may cause fracture of the dental structure or leakage of the restoration.¹⁰ These thermal changes might lead to dowel-and-core failure. Although internal stress caused by different thermal expansions and contractions is clinically important, there is no thermal analysis on the dowel-and-core restoration in the literature. This may be due, in part, to the difficulty of examining temperature at the interfaces between different biomaterials. Finite element analysis does, however, allow examination of the temperature at these interfaces.

Several studies¹¹-¹³ have evaluated dowel-and-core restorations by the finite element method (FEM) in elastic analyses; however, none of these evaluated thermal stress. The purposes of this study were to investigate the following: (1) the influence of the dowel-and-core material on restoration-tooth heat flow and (2) the influence of temperature gradient on the stresses in the dentin, dowel, core material, cement, and a metal-ceramic crown. The null hypothesis of this study was that restorative material used to fabricate the dowel-and-core would have no effect on the thermal 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 labiolingual cross-sectional anatomy of a maxillary central incisor, dowel-and-core metal-ceramic crown, and supporting structures. The standard model included a metal-ceramic crown and a parallel dowel 12 mm in length and 1.5 mm in diameter. The average thickness of the zinc phosphate cement (ZPC) layer and cortical bone were 60 µm and 0.4 mm, respectively (Fig. 1).

Either plane-strain analysis or plane-stress analysis could be used to evaluate the structure. In this study, a linear plane stress analysis program (Supersap, Algor Inc, Pittsburgh, Pa.) was used to solve two 2-dimensional stress analysis problems. Plane stress elements simulate a special 3-dimensional stress state. The assumption of the 2-dimensional FEM in this study was that the stress along a mesiodistal direction was negligible and that stress components in any direction were independent of the mesiodistal dimension. Because it plays a more significant role in occlusion due to the direction of occlusal force, faciolingual width was evaluated.

The choice of a 2- or 3-dimensional model is dependent on the objective of the analysis. The aim of this
study was to investigate the influence of the dowel-and-core material on the restoration-tooth heat flow and the influence of temperature gradient on stresses. Because the heat flow starts from the outer surface of the crown and moves toward the center, the pattern of heat flow and stress generation by temperature gradient will be similar in 2- and 3-dimensional models.

The model used in this study was 13 mm wide and 30 mm in height. It consisted of 778 elements and 430 nodes. In modeling the cement layer, the interface between the cement layer and the other structures had no gap or slip. The model was constrained at the bottom boundaries.

The elements were triangular-shaped and demonstrated a uniformity of fit in the geometrically complex structure of the model. The finite element program (Algor Inc) includes software for automatic meshing. The software will not run when the aspect ratio of the element is too large. Although the elements of the cement layer were long because of the layer thinness, the aspect ratio did not exceed 10 (the elements were within the allowable level to maintain uniformity of the element design). Convergence testing on the model to determine the appropriate element mesh density was completed before the final analysis.

The 4 material combinations of the dowel and cores studied are listed in Table I. The properties were assumed to be linear and isotropic for both the prosthesis and supporting tissues. Table II contains data on the mechanical and thermal properties obtained from the biomaterial properties database provided by the University of Michigan–NIDR Materials Science Research Center and from the literature.

At present, there is very limited thermal property data on dental restorative materials and vital vascularized tissues. Because of the lack of property data on stainless steel, assumptions were made about the thermal properties of this material based on the information available regarding thermal conductivity and specific heat of known metallic restorative materials.

For thermal analysis, ice water was introduced and then removed as the thermal stimulant. On the basis of studies by Palmer et al., it was postulated that the surrounding temperature dropped from the initial body temperature (36°C) to 0°C 2 seconds after introduction of the external irritant (ice water). In a pilot study of thermal analysis, the length of time of external stimulus was varied from 0.5 to 10 seconds to evaluate the appropriate length of stimulant contact. On the basis of the initial results, 7 seconds was determined to be an appropriate length of time to create a temperature difference between tooth and restoration. Therefore, in this investigation, the temperature remained constant at 0°C for 7 seconds, after which time it returned to normal. The cold irritant was applied to all nodes on the superficial surface of the crown. Once a thermal stimulus is removed, it is normal oral physiology for the temperature of the oral cavity and restorative materials in the oral cavity to return to body temperature. The analysis was repeated at 0.1-second intervals from 0.1 to 7.0 seconds.

The analyses were based solely on thermal expansion and thermal conductivity of the biomaterials. The heat transfer analysis program Supersap (Algor Inc) was used for the calculations. The following analyses were performed on each model of the dowel and cores: (1) evaluation of thermal conductivity and temperature of restorative components and tooth, and (2) thermal stress analysis of stresses produced by the temperature gradient. The results obtained were compared.

RESULTS

The temperature at the outer section of the metal-ceramic crown varied more than that inside the root and supporting tissues. The temperature gradient was more pronounced in the resin-core models (resin...
core/carbon fiber–reinforced dowel [RC] and resin core/stainless steel dowel [RS]) than in the metal-core models (gold dowel and core [GG] and amalgam core/stainless steel dowel [AS]) 7 seconds after the introduction of the 0°C thermal irritant. In model GG, the gold dowel and core distributed the temperature changes to produce the smallest temperature differences within the structures (Fig. 2). Temperature differences

![Temperature gradient](image)

**Fig. 2.** Thermal changes of metal-ceramic crown, core, dowel, dentin, and supporting bone 7 seconds after introduction of cold external irritant. Temperature difference between dowel and outer section of crown in GG and AS was less than that in RS and RC.

![Temperature distribution](image)

**Fig. 3.** Time-dependent temperature distribution from coronal tip of core to dowel apex with application of cold external irritant. Temperature gradient of metal dowel and core was less than that of resin core. Temperature gradients of resin-core models (RC and RS) were much greater at coronal section of core than at middle or apical sections of dowel.
between the apical and coronal tips of the dowel and cores were 5.7°C, 9.7°C, 15.5°C, and 20.2°C in models GG, AS, RS, and RC, respectively (Fig. 3).

Figures 4 and 5 show the results of thermal stress in the different combinations of dowel-and-core materials. The gold dowel and core showed the smallest von Mises stresses in the dentin, cement, and restorations. The magnitude of thermal stress in both the restora-
tions and dentin was greater in the resin composite core groups than in the metal core groups. The combination of a resin core with a carbon fiber dowel generated the highest stress in the cement layer, core, and metal-ceramic crown. The peak dentinal stress by thermal irritant for model RC was 2 times greater than that for model GG (Table III). Thermal changes generated stresses that were located primarily in the restoration. No stress changes were evident in the supporting bone.

**DISCUSSION**

Of the various dowel-and-core designs available, the most widely used can be classified into 2 basic types: metal dowel and cores that are custom cast as a single piece, and 2-piece designs comprised of a commercially prefabricated dowel to which silver amalgam, glass silver cement, or resin composite core material is subsequently adapted. Various dowel materials and core materials are commonly used for prefabricated dowel-and-core components. The challenge for the restorative dentist is to select the most appropriate combination of materials to meet the overall system objective. The clinician must be able to make an informed choice from among the components and to structure readily available components to create alternative systems.

Teeth restored with various dowel-and-core materials are subjected to cyclic thermal changes in the oral cavity. Thermal conductivity and thermal expansion of nonmetallic restorative materials, metal, and dentin are significantly different. In this investigation, dowel-and-core materials with a low thermal conductivity increased the thermal gradient in both the restorations and dentin (Fig. 2). The temperature gradient of the metal dowel and core was smaller than that of the resin core because of differences in thermal conductivity. Temperature changes in the cement layer of resin-core models (RC and RS) were much greater at the coronal section of the core than at the middle or apical sections of the dowel (Fig. 3).

The thermal conductivity of metal is reported as ranging from 66.944 J/(mm·s·°C) to 125.52 J/(mm·s·°C), whereas the conductivity of resin composite and dentin is reported as 1.0878 J/(mm·s·°C) and 0.6276 J/(mm·s·°C), respectively. High thermal conductivity of metal dowel-and-core materials clearly reduced the temperature gradient in the dowel and core, cement layer, and tooth. As a result, thermal stress in the restorative materials and tooth was reduced (Fig. 4).

Nonmetal restorations reduce the heat flow into dentin because of their low thermal conductivity. However, thermal stresses generated from the thermal gradients of the nonmetallic dowel-and-core materials generated additional stresses in the cement and its interface. With increasing thermal expansion, the von Mises stresses in the restorations and coronal portion of the dentin increased more markedly than did stress levels in the supporting bone (Fig. 5).

The thermal expansion coefficients of dentin, gold alloy, and resin composite are $8.3 \times 10^{-6}/°C$, $14.1 \times 10^{-6}/°C$, and $39.4 \times 10^{-6}/°C$, respectively. With increasing thermal expansion, the magnitude of von Mises stresses in the restorations and coronal portion of the dentin increased because of the change in volume. As a result, thermal stress from the thermal gradient in the nonmetallic dowel-and-core materials generated an additional stress in the cement layer. This would support the finding that failures of these systems occur cohesively within the cement or at its interface with dentin rather than in the dentin. The peak dentinal stresses of the gold dowel and cores were significantly lower. In this study, thermal analysis showed that stress level is closely related to the degree of thermal gradient. The thermal stress of RC was 2 times greater than that of GG. On the basis of the thermal stress analysis, it can be concluded that it is preferable to use a metal dowel and core in the oral environment (Table III). The results of this study suggest that nonmetallic dowel-and-core materials such as resin composite, carbon fiber, and ceramic dowels produce greater stress than metallic dowel materials of stainless steel, titanium, and gold alloy.

It should be noted that this investigation dealt with only 1 aspect of a very complex question and that the

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

<table>
<thead>
<tr>
<th>Model</th>
<th>Bone</th>
<th>Dentin</th>
<th>ZPC</th>
<th>Dowel</th>
<th>Core</th>
<th>PFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>GG</td>
<td>0.01</td>
<td>0.21</td>
<td>0.52</td>
<td>0.47</td>
<td>0.21</td>
<td>0.42</td>
</tr>
<tr>
<td>AS</td>
<td>0.00</td>
<td>0.25</td>
<td>0.69</td>
<td>1.10</td>
<td>1.07</td>
<td>1.05</td>
</tr>
<tr>
<td>RS</td>
<td>0.00</td>
<td>0.52</td>
<td>0.94</td>
<td>1.15</td>
<td>0.86</td>
<td>1.61</td>
</tr>
<tr>
<td>RC</td>
<td>0.00</td>
<td>0.48</td>
<td>1.14</td>
<td>0.84</td>
<td>1.08</td>
<td>2.02</td>
</tr>
</tbody>
</table>

Thermal stresses were generated by 36°C temperature change without occlusal load. See Table I for model abbreviations. ZPC = Zinc phosphate cement; PFM = metal-ceramic crown.
evaluation was based on a 2-dimensional finite element analysis. Other compounding variables such as occlusion should be investigated, and more complex numerical analyses supported by validation experiments are needed to confirm the findings and evaluate the combined effects of thermal changes and occlusion.

CONCLUSIONS

Within the limitations of this 2-dimensional finite element analysis study, the following conclusions were drawn:

1. The temperature gradient of the metal dowel and cores was smaller than that of the resin cores because of the high thermal conductivity of the former materials.
2. The gold dowel and core showed the smallest thermal stress.
3. The magnitude of stress in both the restorations and dentin was greater in the resin composite core groups than in the metal core groups.
4. The combination of a resin core with a carbon fiber dowel generated the highest stress in the cement layer, core, and metal-ceramic crown.
5. Thermal changes generated stresses in the restorations but had no effect on the supporting bone.

REFERENCES


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