Abutment Forms and Restorative Materials in Adhesive Prosthesis: A Finite Element Analysis

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This study evaluated experimental abutment forms utilizing adhesion for clinical treatment by the three-dimensional finite element method. Three experimental abutment forms with no axial wall were evaluated: Form 1 was the occlusal surface reduced by 1.5 mm, Forms 2 and 3 were the crown cut perpendicular to the tooth axis 2 mm or 4 mm from the central groove. The restorations were made of 3 types of materials: composite resin, porcelain, and a gold-based alloy. Restorations were bonded to the abutments with an adhesive resin. A vertical load of 300 N was applied to the center of the inner incline of the buccal cusp. The stresses in the adhesives were largest in Form 1 with composite resin and in Form 3. It was indicated that the stresses were greatly affected by the form of the abutment and the restorative materials.

Key words: Abutment form, Adhesion, FEM

INTRODUCTION

The retentive form of cavities for composite resin fillings is not always necessary because of developments in adhesive resins, and the use of adhesive resins offers great advantages in the ability to preserve sound tooth structure. However, early adhesive resins had good adherence to human enamel but not to human dentin. When preparing abutment teeth for crowns, almost all of the surface of the abutment teeth consists of dentin and it is difficult to ensure an adequate retentive force by adhesion alone. Therefore, the sound tooth structure must be removed to enable sufficient retention by the interlocking forces.

Recently, dentin bonding with new dental adhesives with stronger adhesion to dentin has been studied. We have reported a dental adhesive cement (Panavia, Kuraray Co., Kurashiki, Japan) that has strong adhesion to dentin pretreated with H3PO4 and NaClO3.3 The adhesive strength and durability to dentin is equal to that with enamel in this adhesion system.

Using extracted human teeth, the study has continued on the possibility of experimental abutment forms being used with this adhesion system when there are no retentive forms to support the interlocking forces. An experimental abutment design without an axial wall, with half the adhesive surface consisting of dentin, and where occlusal surfaces were reduced to 1.5 mm was shown to have sufficient retentive force, larger than with conventional full coverage cast crowns luted with zinc phosphate cement. In addition, it had good marginal sealing ability when intermittent extreme functional loads were applied. A similar onlay abutment form for molar teeth was reported by Crispin5 and a porcelain laminate veneer abutment form for anterior teeth was reported by Magen6. These abutment forms have numerous advantages in the preservation of sound tooth structure and simplification of tooth preparation. They also made the taking of impressions easier and are effective to prevent secondary caries to the end of the gingival margin on the enamel above the level of the gingiva7. Applications of this abutment form have shown good clinical results.

This study examined an experimental abutment form that dealt with a larger defect in the tooth structure for the purpose of clinical application. The study was performed by the three-dimensional finite element method (FEM).

MATERIALS AND METHODS

3D FEM models

This study examined a maxillary premolar. The shapes of the enamel, dentin, and pulp chamber were traced from the micro CT photographs of an extracted maxillary first premolar. Then the outlines were digitized to create a simplified three-dimensional FEM model. From this model, three types of experimental abutment forms were created as follows:

a) With a small defect in the tooth, the occlusal surface was reduced evenly by 1.5 mm (Fig. 1 left, Form 1).

b) With a medium defect in the tooth, the crown was cut perpendicular to the tooth axis, 2 mm from the central groove (Fig. 1 center, Form 2).
c) With a large defect in the tooth, the crown was cut perpendicular to the tooth axis, 4 mm from the central groove (Fig.1 right, Form 3).

In Forms 2 and 3, the exposed pulp chamber was filled with composite resin, the dowel core was not considered in this study. All cases had the root only partially modeled 1.5 mm from the center of the buccal enamel-cement junction as it was assumed that the overall stress distribution was restricted to the coronal restoration.

Restorations were created by simulating the reduced tooth structure. The restorations were assumed to be made of 3 types of material: composite resin (C), porcelain (P), and a type 4 gold-based alloy (G), and it was assumed that they were bonded to the abutments with adhesive resin cement. The thickness of the adhesive resin cement layer was maintained at 100 micrometers. The 3D FEM models consisted of 23,832 (Form 1), 20,226 (Form 2), and 12,599 (Form 3) elements (3-D 10-Node tetrahedral structural solid) and there were 4,789 (Form 1), 4,036 (Form 2), and 2,639 (Form 3) nodes (Fig.2).

Experimental conditions

The material properties assigned to the dental structures, the materials of the restorations, and the resin cement are presented in Table 1, based on the University of Michigan Biomaterial properties database.

Fixed zero-displacement in both the horizontal and vertical directions was defined at the cut plane of the root, approximately 1.5 mm below the cement-enamel junction (Fig.2).

A load of 500 N was applied from the axial (vertical) direction at the center of the inner inclined of the buccal cusp to simulate bruxism where the strongest stress is loaded to the molar teeth (Fig.2).

The stress distribution was solved by means of a finite element program (ANSYS/Structural 5.6, ANSYS, Inc., USA) using a personal computer, and the maximum principal stress distribution at the surface of the resin cement next to the abutment tooth was examined.

<table>
<thead>
<tr>
<th>Form</th>
<th>Stress Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Form 1</td>
</tr>
<tr>
<td>2</td>
<td>Form 2</td>
</tr>
<tr>
<td>3</td>
<td>Form 3</td>
</tr>
</tbody>
</table>

Table 1 Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus (GPa)</th>
<th>Poison's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>84</td>
<td>0.33</td>
</tr>
<tr>
<td>Dentin</td>
<td>15</td>
<td>0.31</td>
</tr>
<tr>
<td>Composite Resin</td>
<td>20</td>
<td>0.24</td>
</tr>
<tr>
<td>Porcelain</td>
<td>78</td>
<td>0.19</td>
</tr>
<tr>
<td>Gold-based alloy</td>
<td>95</td>
<td>0.33</td>
</tr>
<tr>
<td>Resin cement</td>
<td>20</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Table 2 Maximum principal stress magnitudes of the experimental models (MPa)

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Composite Resin</th>
<th>Porcelain</th>
<th>Gold-based alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form 1</td>
<td>72.5</td>
<td>21.1</td>
<td>13.5</td>
</tr>
<tr>
<td>Form 2</td>
<td>5.90</td>
<td>6.44</td>
<td>6.71</td>
</tr>
<tr>
<td>Form 3</td>
<td>8.13</td>
<td>9.27</td>
<td>9.53</td>
</tr>
</tbody>
</table>

RESULTS

The maximum principal stress distributions on the adhesive resin cement surface bonded to the abutment teeth at various conditions are shown in Figs. 3 (a)-3 (i). Figures for the stress distributions on the adhesive resin cement surface bonded to the restorations are not shown as they are very similar to the stress distributions on the surfaces bonded to abutment teeth. The red areas indicate higher stress values, grading to blue areas with lower stresses. The correspondence of color and stress value in each figure is not the same. The peak values of the maximum stress of the experimental models are presented in Table 2.

The results for the different experimental abutment forms are as follows:

Form 1 (Figs. 3 (a)-3 (c))

In the composite resin and porcelain restorations, the peak of the maximum principal stress was in the center of the buccal margin, and in the gold-based alloy restoration it was just under the load point. The value of the peak maximum stress with the composite resin was 72.6 MPa, the largest of all
Fig. 2 Three-dimensional FEM model of maxillary pre-molar. 3-D 10-Node tetrahedral structural solid was used. Fixed zero-displacement in both the horizontal and vertical directions was defined at the cut plane of the root, and a vertical load was applied to the center of the inner incline of the buccal cusp.

Fig. 3 The distribution of stress values on the adhesive resin cement.

Fig. (a) Form 1-Composite resin.  
Fig. (b) Form 1-Porcelain.  
Fig. (c) Form 1-Gold-based alloy.

Fig. (d) Form 2-Composite resin.  
Fig. (e) Form 2-Porcelain.  
Fig. (f) Form 2-Gold-based alloy.

Fig. (g) Form 3-Composite resin.  
Fig. (h) Form 3-Porcelain.  
Fig. (i) Form 3-Gold-based alloy.

Fig. 4 Vector representation in side view of the adhesive cement layer in the composite resin.
conditions. In the porcelain and gold-based alloy restorations, the values of the peak maximum stresses were larger than those in Forms 2 and 3. On the lingual margin there was no tensile stress in any of the cases.

Form 2 (Figs. 3 (d)-3 (f))
The peak of the maximum principal stress was in the center of the lingual margin in the porcelain and gold-based alloy restorations and in the area under the load point in the composite resin restoration. The peak value of the maximum principal stress in the lingual margin of the composite resin was about 3.0 MPa.

Form 3 (Figs. 3 (g)-3 (i))
In all restorations, the peak of the maximum principal stress was in the center of the lingual margin. The peak values were all larger than in Form 2: 170% larger with the composite resin, 44% larger with the porcelain, and 42% larger with the gold-based alloy. There were no cases with tensile stress in the buccal margin.

DISCUSSION

3D FEM models
Many studies analyzing the stress distribution of crown prostheses consider 2 types of 3D models: one with root and periodontal tissue and one without periodontal tissue with a partially modeled root. In fixed partial dentures, a model with root and periodontal tissue is needed because displacement of the abutment tooth caused by the viscoelastic mobility of periodontal tissue when loads are applied influences the displacement and stress distribution of other abutment teeth. With post cores, a stress analysis of the tooth and periodontal tissue is necessary as the periodontal tissue influences the stress distribution in the root. However, in most studies of stress in crown prostheses without a post core the periodontal tissue is not modeled as it is thought that the overall stress distribution is restricted to the coronal restoration. This study did not model the periodontal tissue for the same reason.

Load
The largest force loading on restorations in the oral cavity is bite forces, and the forces pulling a restoration in the axial direction caused by sticky food are very small. It was assumed that the force disengaging a restoration from an abutment tooth was tensile stress caused by the bite force when it destroyed the luting cement. When examining retentive forces of restorations in vitro, we have observed dye penetration at the interface between adhesive resin cement and abutment teeth using extracted human lower premolar teeth after 10,000 loadings by simulated bite forces. In a previous study, dye penetration did not take place with an abutment form similar to Form 3 in this study when a vertical load was applied at the top of the buccal cusp. There was, however, dye penetration when the vertical load was applied at the point of the outer incline of the buccal cusp. It was thought that the vertical load at the top of the cusp is almost entirely due to the compressive stress, but the vertical load at the incline of the cusp produces tensile or shear stress that breaks the adhesion and allows dye to penetrate. This study applied a vertical 500 N load at the center of the inner incline of the buccal cusp, simulating an unusual force like bruxism. Studies have reported a wide range of values in bite forces using different measuring devices under varying test conditions. It was reported that the maximum bite force of healthy humans at the posterior teeth was 430 N. Other findings reported 522 N (males) - 441 N (females). From this it was thought that the load used in this study was appropriate considering that a premolar tooth was used.

Observation of the adhesive cement layer
It was predicted that failure of the experimental abutment occurred in the adhesive cement layer because the adhesive strength was lower than the physical strength of the restorative materials and tooth structures. To verify this the stress distribution on the adhesive resin cement layer was observed in this study.

The stress distribution for the three forms was as follows:

For Form 1, the areas where the peak of the maximum principal stress was observed in the composite resin and porcelain were different from the area in the gold-based alloy. A peak in the maximum principal stress was observed in the buccal margin with only composite resin and porcelain in this study. Further, the value of the stress was the largest among the three types of abutment forms in each of the restorative materials. In the composite resin, the peak stress value was 54.6 MPa, the largest value in this study. A vector representation in a side view of the adhesive cement layer in the composite resin is shown in Fig.4. The black vector indicates tensile stress and the blue vector is the compressive stress. The largest compressive stresses were observed in the area around the load point and relatively large compressive stresses were observed everywhere on the inclined portion of the buccal cusp. Large tensile stresses were observed in only the buccal margin. Because the composite resin was more elastic and more easily transformed, and as the thickness of the restoration in this abutment form was relatively small, it was speculated that the load deformed the composite resin around the load point and that large tensile stresses were generated at the buccal margin.
The gold-based alloy was comparatively stiff and less easily transformed than the composite resin and porcelain, so the restoration deformed with difficulty and the stress in the restoration dispersed widely. Consequently it was speculated that the peak of the maximum principal stress value was the smallest and was not in the buccal margin. This leads to the conclusion that the gold-based alloy was adequate in Form 1 restorations. In Form 1 restorations, no tensile stress was observed in the lingual margin of any of the materials. It was thought that because of the inclined adhesive surface of Form 1, no moment of rotation of the restoration by the load was generated.

For Form 2, the Form 2 abutment design was different from that of Form 1 in the shape of the adhesive surface and the thickness of the restoration. The adhesive surface of Form 1 was inclined and that of Form 2 was horizontal. The thickness of the restoration in the central groove was 1.0 mm in Form 1 and 2.0 mm in Form 2, and the thickness at the load point was 1.5 mm in Form 1 and 3.0 mm in Form 2. In the porcelain and gold-based alloy restorations the maximum principal stress value was observed at the center of the lingual margin. The elastic modulus of both the materials is larger than that of the composite resin and Form 2 is thicker than Form 1. Therefore the restorations deform with difficulty and moments of rotation around the buccal margin were produced by loads applied at the inner incline of the buccal cusp. Consequently tensile stresses were produced at the lingual area of the adhesive resin cement and compressive stresses were produced in the buccal area. It was thought that the composite resin deformed by the load resulting in a smaller peak of maximum principal stress than that of the porcelain and the gold-based alloy.

The bond strength of adhesive resin cement to enamel or dentin is affected by factors such as differences in individual teeth\(^{20-22}\), the quality of the bond surface\(^{23,24}\), the aptitude of the operator\(^{25}\), and the adhesive resin bond strength decreasing with time\(^{26}\). The 3D finite element analysis in this study did not examine the influence of the orientation of enamel prisms or dentinal tubules and other factors on the stress distribution. The results of this study have been of help in screening and evaluating the application of experimental abutment forms. The experimental abutment forms (Forms 1 and 2) have been applied clinically for several years and it will be necessary to examine failures of restorations and perform long-term observations of outcomes. Further, it is necessary to improve the FEM analysis to predict the clinical outcomes better.

CONCLUSIONS

This study evaluated 3 experimental abutment forms utilizing adhesion for clinical treatment by the three-dimensional finite element method, and the results may be summarized as follows:

1. The stresses on the adhesive surfaces of experimental abutments are greatly affected by the form of the abutment and the restorative materials.
2. With the Form 1 abutment, the gold-based alloy was adequate.
3. With the Form 2 abutment, composite resin was the most suitable material.
4. With the Form 3 abutments, the tensile stresses in the lingual margin were considerably larger than with Form 2.

ACKNOWLEDGMENT

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