Finite element stress analysis of restored primary teeth: A comparative evaluation between stainless steel crowns and preformed zirconia crowns

Atiguppe Ramasetty Prabhakar, Amrita Chakraborty1, Basappa Nadig, Chandrashekar Yavagal

Department of Pedodontics and Preventive Dentistry, Bapuji Dental College and Hospital, Davangere, Karnataka, India, 1Herman Ostrow School of Dentistry, University of Southern California, Los Angeles, California, USA

Original Article

INTRODUCTION

It is extremely important to preserve the natural teeth in the mouth especially so in the case of primary dentition. The primary teeth are the best possible space maintainers and help to preserve the integrity of the arch length. Due to the increasing prevalence of dental caries in today’s world, it has become imperative to perform various restorative treatments to maintain the functional integrity of the primary dentition. However, restorative procedures all involve the loss of a certain amount of tooth structure and in the case of endodontic therapy, the loss of the entire pulp.

Abstract

Background: Stainless steel crowns (SSCs) till now accepted as the best restorative modality for primary teeth, are being frowned on due to their poor esthetic appeal. The recently introduced preformed zirconia crowns are a more esthetic alternative, but the ability of these crowns to withstand stresses in the intraoral environment has not been tested. This study is a continuation of an earlier study done by the same authors to understand the stresses an SSC is subjected to under occlusal forces.

Aims: The aim of this study is to compare the effectiveness of preformed zirconia crowns with the gold standard SSC for the restoration of primary teeth through a finite element analysis.

Settings and Design: In vitro.

Materials and Methods: The study design employed two finite element models, with the same amount of tooth structure, one restored with SSC and the other with preformed zirconia crown. The finite element models were exported to ANSYS software and subjected to an average simulated bite force of 245N.

Statistical Analysis Used: The finite element models were exported to ANSYS software subjected to an average simulated bite force of 245N.

Results: Preformed zirconia crowns suffered lesser Von maximal stresses along with its underlying dentine.

Conclusions: Even at maximal physiologic masticatory force levels, a grossly destructed tooth restored with preformed zirconia crown can withstand stress better than a tooth restored with SSC.

Keywords: Deciduous maxillary second molar, finite element analysis, fracture resistance, preformed zirconia crown, stainless steel crowns

Address for correspondence: Dr. Amrita Chakraborty, 1169 W 24th St, LA, CA - 90007, USA.
E-mail: amritach@usc.edu

Access this article online

Quick Response Code:
Website: www.ijohsjournal.org
DOI: 10.4103/ijohs.ijohs_18_17

This weakens the structural integrity of the tooth.\textsuperscript{[3]} The weakened tooth is then reinforced to be better capable of withstanding the masticatory forces with restorative materials such as amalgam, resin-modified glass ionomer cement, resin filled composites or stainless steel crowns (SSCs). Although SSCs are considered as the best treatment modality for teeth with extensive caries lesions or postendodontic therapy, its use is still limited in the clinical practice due to the poor esthetics offered.\textsuperscript{[4]} Endowed with properties of adequate mechanical strength and toughness along with good chemical and dimensional stability, the evolution of zirconia as a ceramic biomaterial was natural. Due to their excellent properties, white color, and superior biocompatibility; preformed zirconia crowns are being evaluated as an alternative to preformed SCCs.\textsuperscript{[5]} However, there are very few studies in literature demonstrating the ability of these crowns to withstand masticatory forces.\textsuperscript{[6]} Most of the existing studies are also in vitro as it is difficult to judge the reaction to stress in an in vivo setting. The analysis of stress through the finite element study is useful for indicating the physical response of the system, such as the most likely place for the fracture to occur.\textsuperscript{[7]} An earlier study was performed along similar principles to establish the efficacy of SSCs as restorative agents for grossly destructed primary teeth.\textsuperscript{[8]} This study has been undertaken to compare the efficacy of SSCs with that of preformed zirconia crowns as full coverage pediatric restorations through the results of a finite element analysis.

**MATERIALS AND METHODS**

This in vitro study utilizes two models of primary maxillary second molar both with the same amount of tooth structure. Maxillary second primary molars were selected as they are integral in maintaining the arch length by preventing the mesial migration of the permanent first molar.\textsuperscript{[9]} The control for the study was a model with the same amount of tooth structure but unrestored and subjected to similar forces as the experimental models.

**Model preparation**

169L Crown preparation bur was used by a single operator to eliminate interoperator bias. The crowns were prepared according to the guidelines of 3M ESPE and EZ·Pedo, respectively. A gradual, sequential circumferential tooth reduction was performed, such that all the enamel with most of the dentine was reduced. Only 30\% of the dentine was left behind to replicate a grossly destructed tooth [Table 1]. After crown preparation, SSC (3M ESPE) and preformed zirconia crown (EZ·Pedo) were luted using glass ionomer cement (GC Fuji Type 1) [Table 2].

**Finite element model generation**

Three-dimensional images of the prepared primary second molars were obtained through spiral computed tomography scans. The ANSYS (ANSYS v. 12; ANSYS Inc; Canonsburg, PA, USA) software converted 0.5 mm sections of each model into cloud data points, which were connected to form the surface models of each primary tooth. The SSC was considered to be of a uniform width of 0.13 mm and the preformed zirconia crown of width 0.73 mm.\textsuperscript{[10]}

**Load application**

Perpendicular and angulated forces of 245N\textsuperscript{[12]} were applied to the crowns of the teeth to simulate physiologic masticatory forces. Axial forces on the inner inclines of the buccal cusps, inner inclines of the palatal cusps, and the outer inclines of the palatal forces simulated maximum bite forces in patients of pediatric age group.\textsuperscript{[9]} Lateral masticatory forces were simulated through angulated forces on the palatal inclines of the buccal cusps at 0°, 45°, and 90°.

The stress values and patterns due to load application were calculated based on the von Mises dimensional criterion, which always yields positive results. The equation used is:

\[
\sigma_e = \frac{1}{2} \left( \sigma_1 - \sigma_2 \right)^2 + \sigma_2 - \sigma_3 + \sigma_3 - \sigma_1 \right)^{1/2}
\]

Where, \(\sigma_1, \sigma_2, \sigma_3\) represent the principal stresses within the material.\textsuperscript{[10]}

**RESULTS**

The stresses were visualized in color coding ranging from dark blue (minimum stress) to red (maximum stress) [Figure 1].

Stress areas are the cuspal inclines in contact with the adjacent tooth, and maximal stresses are restricted to the crown with very little penetrating to the underlying tooth. There is an overall increase in stress with decreasing tooth structure though it remains well below the ultimate tensile strength of each material [Figure 2 and Table 3].

The stresses dissipate gradually from the point of loading to the rest of the crown. However, the maximal stresses on lateral loading are greater than that on axial loading [Figure 3 and Table 3].
The maximum stress on SSC and dentine is greater than at axial loading or 0° lateral loading with stresses concentrated on a small surface area [Figure 4 and Table 3]. Stresses observed are the greatest as compared to the previous simulated conditions.

DISCUSSION

Clinical trials, retrospective studies, prospective studies, reviews, and meta-analysis conducted over time[1,4,6,13,16] have established the efficacy of SSCs as a semi-permanent restorative therapy for primary teeth affected with rampant caries, hypoplasia, following pulp therapy and for those being used as an anchorage for interceptive orthodontic appliances.[17] However, of late, increasing emphasis is being placed on esthetics in pediatric dentistry. Patient's parents often have unrealistic demands on the final appearance of the restored dentition of their children.[18] The esthetic restoration of grossly destructed primary anterior and posterior teeth poses a great challenge to the pediatric dentist and literature speaks of the use of either prefabricated partial veneer SSCs or direct or indirect composite restorations.[19] A recent entry into the market of esthetic pediatric dentistry is the preformed zirconia crowns available from EZ-Pedo, NuSmile, Kinder Krows to name a few. The mechanical properties of zirconia (zirconium dioxide), which include low thermal conductivity, low corrosion, good radiographic contrast, and good biological compatibility have made it a favorable choice for metal free posterior restorations.[20] Although a few clinical studies have been published about the use of preformed zirconia crowns, there are no long-term clinical trials. Moreover, there is no literature comparing the suitability of preformed zirconia crowns with that of SSCs as long-term restorative therapy for grossly destructed posterior primary teeth. An extrapolation of the results of stress behavior conducted in an in vitro setting to an in vivo setting is obviously impractical. Hence, this study was undertaken to demonstrate the mechanical behavior of the SSC and compare it to that of a preformed zirconia crown (under masticatory stress) when used to restore a grossly destructed tooth through a finite element analysis. When a structure is subjected to a load, stress is induced in the structure which may lead to deformation of the latter. A finite element analysis can be used to study a single variable in a complex structure such as the stress concentration on a tooth model. The ability of finite element analysis to accurately approximate a dental prosthesis is closely coupled with the manner in which the finite element model is constructed. This includes caution with the type of finite element models used (2D plane-stress, 2D plane-strain or axisymmetric, and 3D brick elements), the particular way in which the mesh is constructed, and the way in which the system is modeled in terms of constraints and loads. In areas of high tensile stress, the probability of fracture
is greatest. Therefore, it is vital to analyze those areas of high tensile stresses and investigate the influences on these peak tensile stresses. The previous study has shown that the biting forces in primary dentition fall in the range of 161–330 N and hence, in the present study, an average force of 245 N was considered for application on the cuspal planes. The analysis showed that on the application of force, maximum stress is taken up by the SSC and zirconia crown with minimal stress reaching the underlying tooth. However, the von Mises stress generated within the SSC was much greater than that within the zirconia crown thus indicating that the zirconia crown would be better suited to resist masticatory forces due to the inherently lesser stress development. An interesting consequence of this decreased stress generation in preformed zirconia crowns was the consequent decreased stress development in the underlying dentine. In the present study, all the scenarios showed decreased stress generation in the dentine by preformed zirconia crowns than by the SSCs. This directly indicates toward a greater protection conferred by the zirconia crown to the underlying tooth than is possible by SSCs. Furthermore, all the stresses generated by both SSC and preformed zirconia crowns were well below the maximal tensile strength of dentine. The greatest stress on the underlying dentine was caused by masticatory forces in the lateral direction, especially 90° as they are restricted to a smaller surface area. Hence, during preparation adequate tooth structure should be left at the cuspal inclines, which are most susceptible to lateral forces to withstand the resultant stress. Evidence suggests that when a tooth is restored with a crown, it is better able to withstand masticatory forces.

### Table 1: The number of elements and nodes of the finite element mesh model along with the extent of tooth reduction

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of nodes</th>
<th>Number of elements</th>
<th>% Reduction of enamel</th>
<th>% Reduction of dentine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>6882</td>
<td>35214</td>
<td>100</td>
<td>71</td>
</tr>
</tbody>
</table>

### Table 2: Mechanical properties of the materials and teeth used for the study

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mechanical properties</th>
<th>Modulus of elasticity (GPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel crown</td>
<td></td>
<td>200</td>
<td>0.33</td>
</tr>
<tr>
<td>Pre-formed zirconia crown</td>
<td></td>
<td>242</td>
<td>0.26</td>
</tr>
<tr>
<td>Enamel</td>
<td></td>
<td>80.35</td>
<td>0.33</td>
</tr>
<tr>
<td>Dentinell[2]</td>
<td></td>
<td>19.89</td>
<td>0.31</td>
</tr>
<tr>
<td>PULP[3]</td>
<td></td>
<td>2</td>
<td>0.45</td>
</tr>
<tr>
<td>GIC[4]</td>
<td></td>
<td>10.8</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Figure 3: Stress pattern on lateral loading - 45° through a stainless steel crown and a preformed zirconia crown as well as stress distribution on the underlying dentine of the primary tooth when restored with either of the two crowns. Areas of red represent maximal von Mises stresses while areas of blue represent minimal von Mises stresses. The maximal von Mises stress generated in a stainless steel crown and its underlying dentine was 287.8 and 11.13 MPa respectively while that generated by the preformed zirconia crown and its underlying dentine was 54.8 and 1.30 MPa. The above data imply lesser stresses were generated in the preformed zirconia crown and the restored tooth as compared to stainless steel crown. Thus, preformed zirconia confers more protection to the primary tooth than stainless steel crown.

Figure 4: Stress pattern on lateral loading - 90° through a stainless steel crown and a preformed zirconia crown as well as stress distribution on the underlying dentine of the primary tooth when restored with either of the two crowns. Areas of red represent maximal von Mises stresses while areas of blue represent minimal von Mises stresses. The maximal von Mises stress generated in a stainless steel crown and its underlying dentine was 290 and 18.05 MPa respectively while that generated by the preformed zirconia crown and its underlying dentine was 57.5 and 1.9 MPa. The above data imply lesser stresses were generated in the preformed zirconia crown and the restored tooth as compared to stainless steel crown. Thus, preformed zirconia confers more protection to the primary tooth than stainless steel crown.
CONCLUSION

• Pre-formed Zirconia Crowns are an excellent aesthetic alternative to Stainless Steel Crowns as full coverage restorations in the pediatric population

• It is essential to restore a grossly destructed tooth with a crown to ensure its function in the oral cavity.

Financial support and sponsorship
Nil.

Conflicts of interest
There are no conflicts of interest.

Table 3: A Tabulation of the magnitude of stress in each case and the ultimate tensile strength of the corresponding materials

<table>
<thead>
<tr>
<th></th>
<th>stainless steel crown (MPa)</th>
<th>pre-formed zirconia crown (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal Von Mises Stress</td>
<td>Vertical Loading: 173.8</td>
<td>Vertical Loading: 38.1</td>
</tr>
<tr>
<td></td>
<td>0°: 247.5</td>
<td>0°: 52.9</td>
</tr>
<tr>
<td></td>
<td>45°: 287.8</td>
<td>45°: 54.8</td>
</tr>
<tr>
<td></td>
<td>90°: 290</td>
<td>90°: 57.5</td>
</tr>
<tr>
<td>Maximal Tensile Stress</td>
<td>0.95</td>
<td>620[14]</td>
</tr>
</tbody>
</table>

Dentine

<table>
<thead>
<tr>
<th>Maximal Von Mises Stress</th>
<th>Vertical Loading: 9.98</th>
<th>Vertical Loading: 1.03</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°: 7.84</td>
<td>0°: 0.8</td>
</tr>
<tr>
<td></td>
<td>45°: 11.13</td>
<td>45°: 1.3</td>
</tr>
<tr>
<td></td>
<td>90°: 18.05</td>
<td>90°: 1.9</td>
</tr>
<tr>
<td>Maximal Tensile Stress</td>
<td>38.2</td>
<td>38.2</td>
</tr>
</tbody>
</table>

REFERENCES


