Identifying Optimal Composite Resin Depth to Maximize Fracture Resistance when Restoring Immature Endodontically Treated Teeth

David Poe
Marquette University

IDENTIFYING OPTIMAL COMPOSITE RESIN DEPTH TO MAXIMIZE FRACTURE RESISTANCE WHEN RESTORING IMMATURE ENDODONTICALLY TREATED TEETH

by

David E. Poe, D.M.D.

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ABSTRACT

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Introduction: This study compared stress distribution of an immature central incisor restored with intracanal composite resin placed at different depths.

Methods: Five pre-accessed models were prepared, to simulate immature central incisors, and endodontically treated using a mineral trioxide aggregate plug and different amounts of composite resin with gutta-percha in between the composite resin and mineral trioxide aggregate. (Group 1) Composite resin restored from the cemento-enamel junction, (group 2) composite resin restored from 2 mm apical to the cemento-enamel junction, (group 3) composite resin restored from 4 mm apical to the cemento-enamel junction, (group 4) composite resin restored from the mineral trioxide aggregate, (group 5) no material placed in the canal or access. Teeth were scanned and surface meshes were made for finite element analysis. Each model underwent a 240 Newton load at a 120-degree angle on the palatal fossa to provide evaluations for Von Mises stress distribution.

Results: The results showed that placement of composite resin 2 mm apical to the cemento-enamel junction produced the least amount of stress deformation, followed by, in order, composite resin placed 4 mm apical to the cemento-enamel junction, composite resin placed to the mineral trioxide aggregate, and composite resin placed to the cemento-enamel junction.

Conclusions: Placement of composite resin 2 mm apical to the cemento-enamel junction increased the fracture resistance of an immature endodontically treated tooth. Placement of composite resin at the cemento-enamel junction or more apical than 2 mm was determined to be unnecessary, as it decreased the fracture resistance.

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INTRODUCTION

Immature permanent teeth often need endodontic therapy due to trauma. One of the most affected teeth by trauma are the upper central incisors as these are one of the first adult teeth to erupt and are in a highly vulnerable location in the mouth (1). In vital teeth, apexogenesis is a treatment option to continue root development and increase dentinal wall thickness; in necrotic teeth, apexification is a treatment option to properly debride and disinfect the canal and establish an apical stop using an apical plug (2). Regeneration of pulp tissue is another option when treating necrotic teeth that can increase dentinal root thickness, however, Lin et al. reported that calcifications and discoloration are two complications associated with regenerative procedures (3). The apical plug technique has many advantages including fewer appointment, fewer follow-ups, and more predictability. However, using an apical plug does not increase dentinal wall thickness along the entire root and can lead to a higher risk of fracture (2,4).

Using mineral trioxide aggregate (MTA) as an apical plug in apexification has shown to be successful in healing periapical lesions and establishing a consistent apical barrier (5,6); however, it does not increase fracture resistance as it poorly bonds to root dentin, as does gutta-percha (GP) (7,8). A common intraradicular material used is composite resin (CR), which can bond to the root canal dentinal walls and increase fracture resistance (9-12). Although, drawbacks are associated with the use of CR as retreatments through CR can prove to be more difficult and have a higher risk of perforation than when done through GP.

Several studies have evaluated differences in fracture resistance between intracanal placement of CR and GP (10,13-16); however, none evaluated for multiple depths of CR placed into an immature canal using finite element analysis (FEA), which can allow for better understanding of stress distribution and fracture resistance.

The objective of this study was to evaluate, through FEA, the optimal depth of CR placed into the canal to maximize fracture resistance. The null hypothesis was that the depth of intracanal CR placement will not affect the fracture resistance of the tooth.

LITERATURE REVIEW

Goal of Endodontic Treatment

Prevention or treatment of apical periodontitis is the overarching goal of endodontic treatment (17). When bacteria occupy the dental pulp and progress into the root canal system apical periodontitis occurs (18,19). Infections of the dental pulp progress as bacteria form biofilms throughout the root canal system (20). A dental procedure known as root canal therapy (RCT) is used to reduce biofilms throughout the root canal system and by doing so, treating infection. Treatment is comprised of access, chemo-mechanical disinfection, and root canal system sealing (21). Residual biofilm is the main cause of endodontic failure stressing the importance of proper disinfection (22).

Trauma

Central incisors are the most affected teeth to trauma (1). Risk factors related to traumatic injuries include: boys, overjet over 5 mm, inadequate lip coverage, and obesity (2). After traumatic injures, pulp necrosis can occur within three months after concussion, one year after subluxation and extrusion, and two years after lateral and intrusive luxation. The type of injury that occurrs affects the risk of pulp necrosis with intrusive luxation being the highest risk followed by lateral luxation, extrusive luxation, subluxation, and concussion (3).

Endodontic Treatment for Immature Teeth

Endodontic treatment required for immature teeth, either caused from caries or trauma, can vary depending on the extent of pulpal injury. Apexogenesis should be completed if vital pulp tissue is still present after a pulp exposure. This will allow for continual root development. Apexogenesis includes the procedure of pulp capping, shallow pulpotomy, and conventional pulpotomy (2). In cases where immature teeth have become necrotic, other treatment methods are indicated, either apexification or regeneration (2). Apexification is defined as “a method of inducing a calcified barrier in a root with an open apex or the continued apical development of an incompletely formed root in teeth with necrotic pulp” (25). This can be completed with long-term use of calcium hydroxide (26). When done with calcium hydroxide the endodontic therapy was not completed until an apical seal was formed. Apexification can also be done using an apical plug (27-31), specifically using MTA (6, 32-33). Although the use of calcium hydroxide or an MTA plug have proven successful, they are not without their disadvantages. Calcium hydroxide includes unpredictability in treatment time or apical seal formation, delayed treatment, frequent follow-up with patients, and lack of root wall development. The MTA plug does not share the same disadvantages as calcium hydroxide except for the lack of root wall development (2).

Regeneration is defined as “biologically based procedures designed to replace damaged structures, including dentin and root structures, as well as cells of the pulp-dentin complex” (34). Ideally regeneration is an optimal method when treating immature necrotic teeth as it will regenerate functional pulpal tissue (35). It does so by creating an environment inside of the canal that is suitable for the repopulation of stem cells, regeneration of pulp tissue, and continual root development; the latter being an aspect that was missing from the apexification method (36). However, drawbacks also come with regenerative procedures including discoloration (37-41), treatment period (36), true regenerative histology (42-46), poor root development (39,41,47) , and root canal obliteration (39,48-49).

Fracture Resistance

Fracture resistance has been compared in teeth that have been treated endodontically and had different depths of intracanal CR placed after MTA and GP. Schmoldt et al. and Brito-Junior et al. both performed in vitro studies on bovine incisors and found no significant difference in fracture resistance between test groups (10, 14). Mello et al. also found, in their in vitro study done on mandibular incisors, that there was no significant difference in fracture resistance between test groups (13). A retrospective study completed by Danwittayakorn et al., as the previous in vitro studies, concluded that no significant difference was found in fracture resistance (15). An in vitro study done by Linsuwanont et al. contradicted the results found by the previous authors finding that CR placed more apical in a canal significantly increased fracture resistance (16).

Finite Element Analysis

The finite element method (FEM) is a numerical method of that solves differential equations and provides the groundwork for finite element analysis (FEA). This method can be applied in both two dimensions (2D) and three dimensions (3D), however after three decades of studies the 3D analysis has shown to be more accurate than the 2D analysis (50-51). After a geometric structure is built, it is divided into small elements that are then connected by nodes. To determine stress distributions between elements and nodes there are associated equations that form a finite set of equations (52).

FEA is a computer simulation technique to model stress distribution using FEM. FEM is able to quantify stresses and displacement in a 3D structure, unlike material methods like strain gauging. Computer tomography (CT) capabilities and computer-aid-design (CAD) software have greatly advanced the accuracy of FEA in dentistry since the first 3D FEA study. To perform FEA, models are created using CT, microCT, or magnetic resonance images (MRI). To create a mesh from the solid model, 2D slices obtained from the images are segmented. Discretization, which is the mathematical process that allows for numerical evaluation of the model, is from what the mesh is based. The final mesh model is then loaded into the FEA software where load, boundary conditions, and material properties are applied to the model. Stress distribution is then analyzed qualitatively and quantitatively using numerical values and gradient coloring (53).

The limitations contained within FEA inhibit its ability to mimic a clinical scenario. The sample geometry and surface structure must be accurate to ensure the accuracy of FEA modeling determine. FEA is confined to the extent of the model and the information included. Chewing functions and jaw movements can only be simulated under a static load (properties are set as isotropic and linearly elastic) as opposed to a dynamic function allowing for a more realistic movement (54).

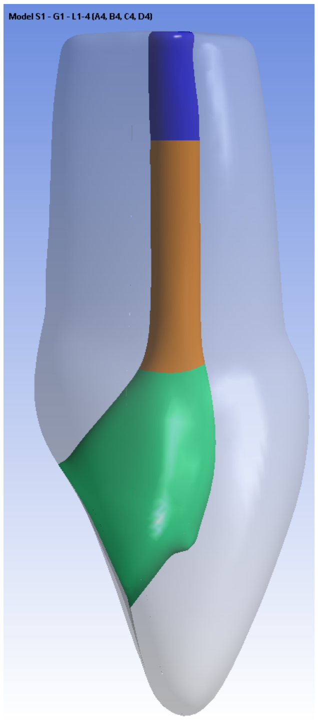
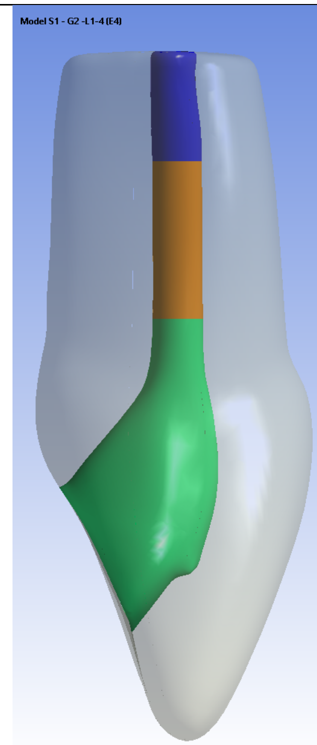
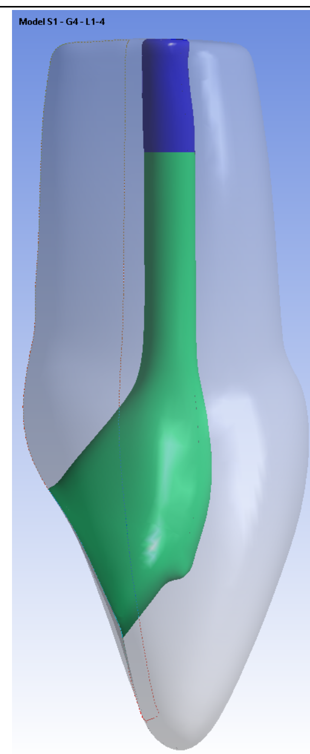
Despite the limitations, the benefits of using FEA outweigh its drawbacks. FEA is customizable as different stress points can be analyzed by adjusting the location, magnitude, and direction of applied forces (55). Physical properties of materials can be changed as well. Simulations of stress distribution are also repeatable as samples are not deformed in the analysis event (56). FEA can provide a reliable method for initial testing; if done alongside a clinical study FEA can be used as a more effective manner providing a detailed analysis of said study.

MATERIALS & METHODS

Sample Preparations

Five 3D printed pre-accessed, plastic central incisor teeth (tooth #9) were used for simulated endodontic treatment (Endo 3DP; Acadental, Lenexa, KS). The teeth were trimmed back from the apices using a diamond bur to establish a working length of 20 mm. The canals were then prepared to 1.1 mm with a 0-degree taper using a Gates Glidden #4 drill.

Obturation and restoration were then completed for each group. Group 1: 3 mm MTA plug placed at the apex. GP placed from the MTA to the cemento-enamel junction (CEJ). CR placed from the GP to the cavosurface margin. Group 2: 3 mm MTA plug placed at the apex. GP placed from the MTA to 2 mm apical to the CEJ. CR placed from the GP to the cavosurface margin. Group 3: 3 mm MTA plug placed at the apex. GP placed from the MTA to 4 mm apical to the CEJ. CR placed from the GP to the cavosurface margin. Group 4: 3 mm MTA plug placed at the apex. CR placed from the MTA to the cavosurface margin. Group 5: No material placed in the canal or access (Figure 1).

Group 1	Group 2
	
Group 3	Group 4
	

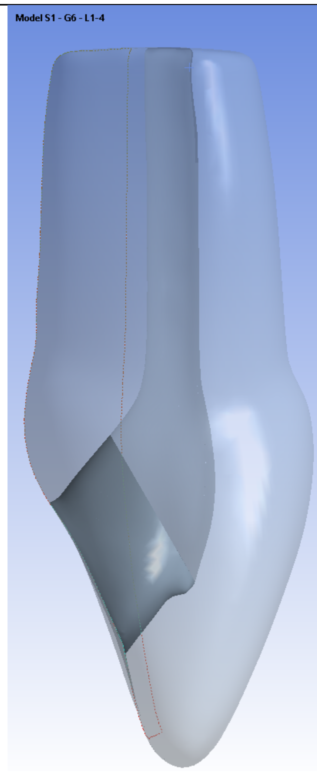
Group 5


Figure 1: Model Description. Green: Composite resin, Orange: Gutta-percha, Blue: Mineral trioxide aggregate, Grey: Simulated dentin (to be able to place stress on the occlusal surface).

Micro-CT and STL Construction

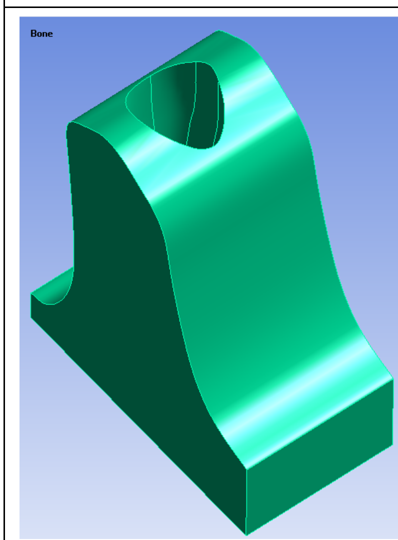
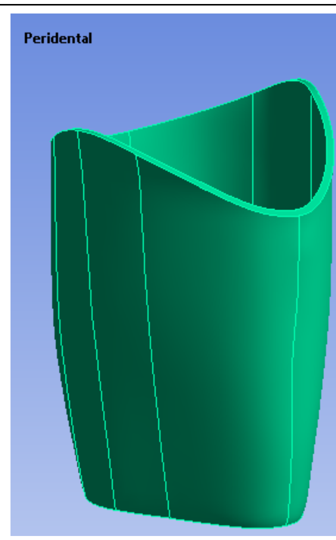
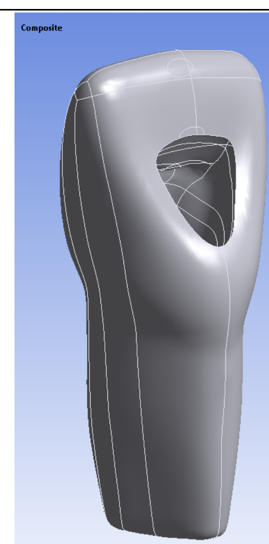
Materials and methods were like that done by Smoljan et al. (57). The micro CT-Scan and STL reconstruction were done by Exact Metrology (Brookfield, WI). A COM CT scanner was used at 25-uM voxel size, 150 kV Target X-Ray Voltage, 40 W X-Ray Target Power, Exposure Time: 1500 milliseconds, 750 exposure and GOM Inspect software (Braunschweig, Germany).

Meshing and Material Properties

In preparation for the finite element analysis, the STL files were imported to the 3-magic software (3-magic Medical v 13, Materialise N.V., Belgium). After the 3D models were processed, a virtual 3D uniform periodontal ligament and surrounding bone were added to each sample using the materials properties from an FEA study done by Belli (58) (Table 1) (Figure 2).

Material/Structure	Elastic Modulus (MPa)	Poisson ratio (v)
Dentin	18,600	0.31
PDL	0.689	0.45
Bone	1,370	0.30
Composite resin	16,400	0.28
Gutta-percha	140	0.45
Mineral trioxide aggregate	11,760	0.314

Table 1: Material Properties for finite element analysis

Bone	Periodontal Ligament	Tooth
		

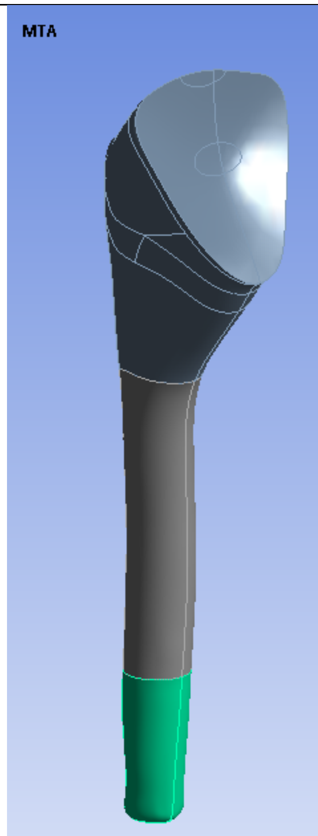
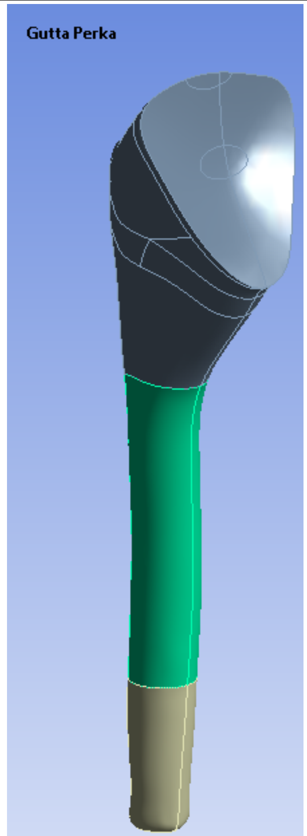
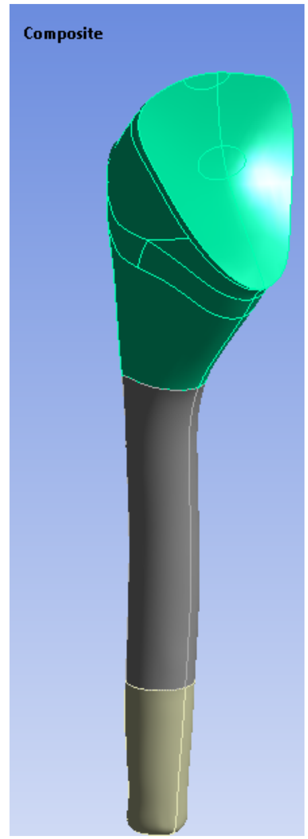
MTA	Gutta-Percha	Composite Resin
		

Figure 2: 3D models of separate components of overall model

All models were duplicated to make the root canal filling material the only variable between all the groups. The final volume meshes were then imported as finite element modeler files into the FEA software (ANSYS Workbench 2021R1, Canonsburg, PA, USA) (Figure 3). One value was used for the elastic modulus and Poisson's ratio for each body.

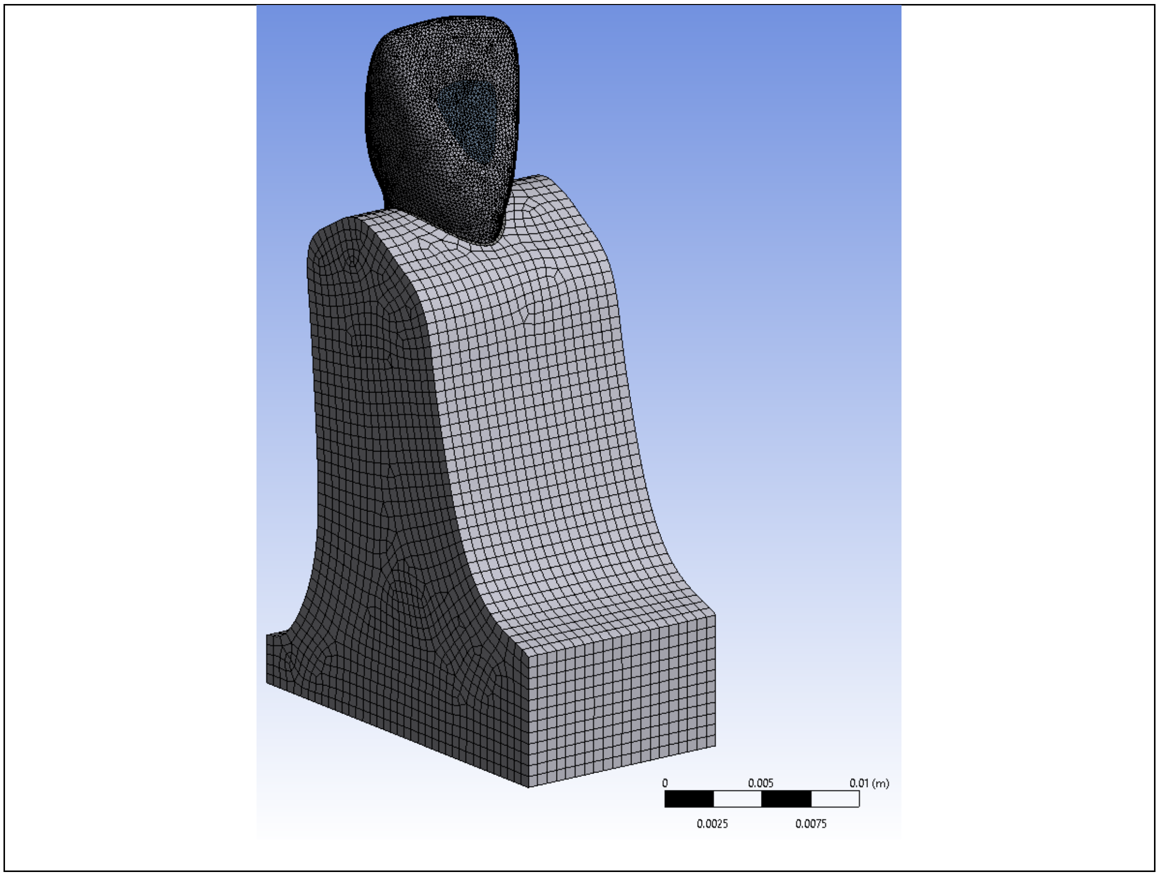


Figure 3: Final volume mesh of model

FEA

To simulate normal chewing function, a stress load of 240 Newtons was applied as a nodal force at a 120-degree angle (59). The force was applied to an ellipsoid like surface of 0.6 mm x 1.2 mm in the palatal fossa (60). Boundary constraints were set using bone (Figure 4).

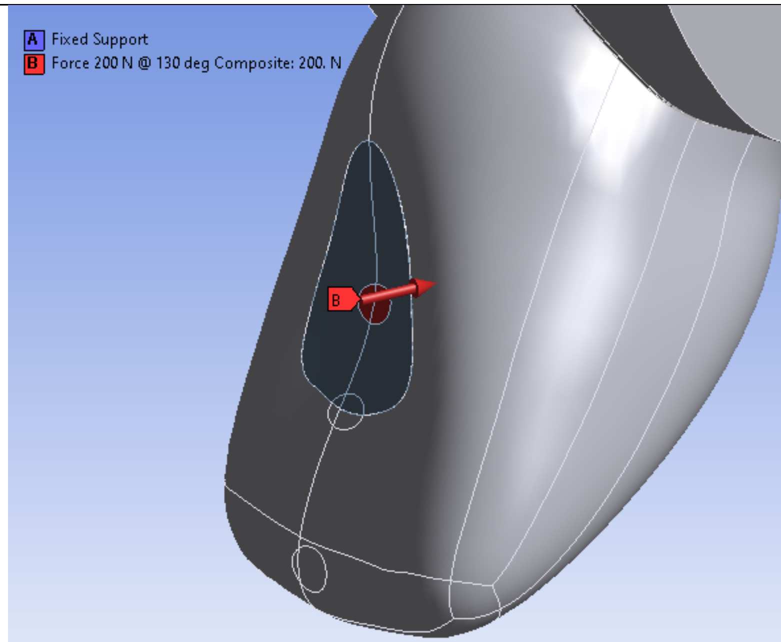
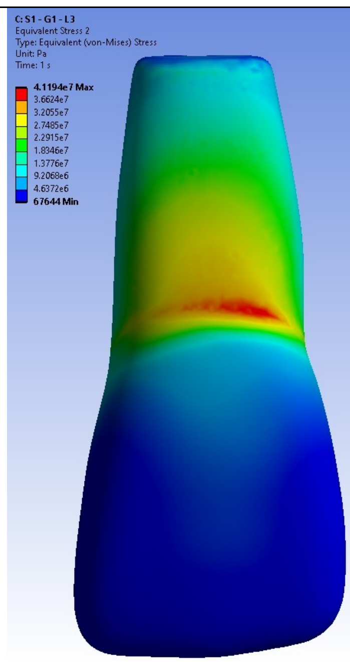
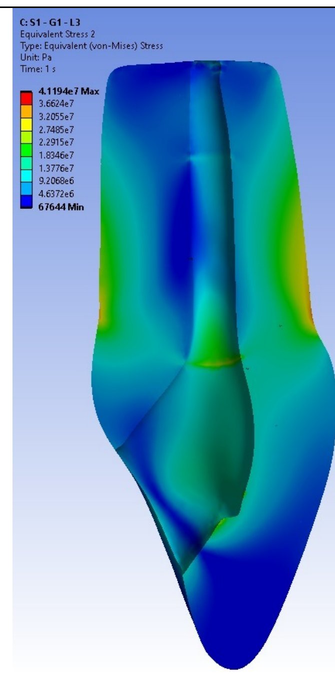


Figure 4: Stress load, shape, and angle.

The FEA results included the equivalent Von Mises (VM) stress (σ) and total deformation of the tooth structure in all the models. Maximum and minimum values were collected, along with figures with color-scale bar legends for qualitative and quantitative analysis and comparison. A buccal view was shown of all the models. A sagittal cross section was also taken of each model to show the stress distribution throughout the tooth.

RESULTS

Quantitative and qualitative results shown on the buccal portion of each model and in a sagittal slice (Figure 5). Each group showed maximum VM stresses on the buccal surface near the CEJ. The stresses then decrease in an apical and coronal direction from the cervical area. Group 2 had the lowest maximum VM stress value at 3.9631e7 Pa, followed by groups 3, 4 and 1, which had the highest VM stress value at 4.1194e7 Pa (Table 2).

Group 1 Buccal View	Group 1 Sagittal Slice
	

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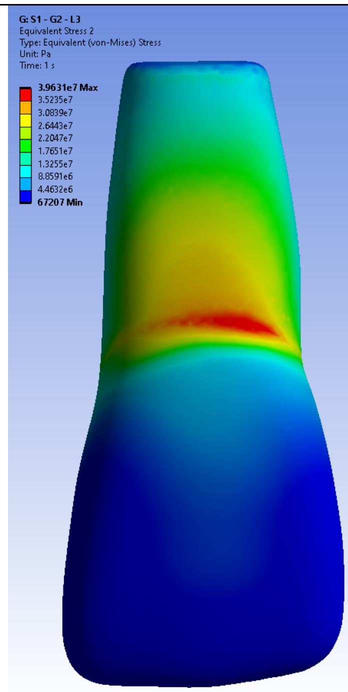
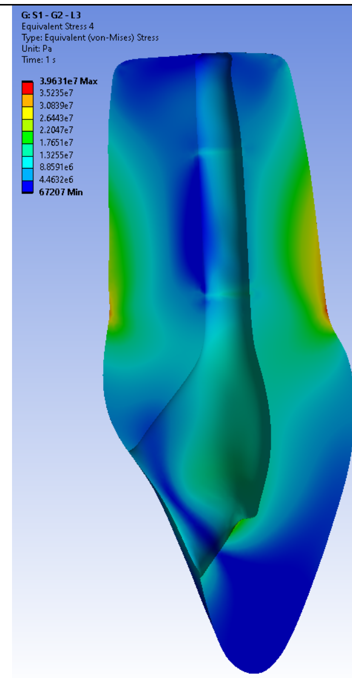
<tr><td>
</td><td>
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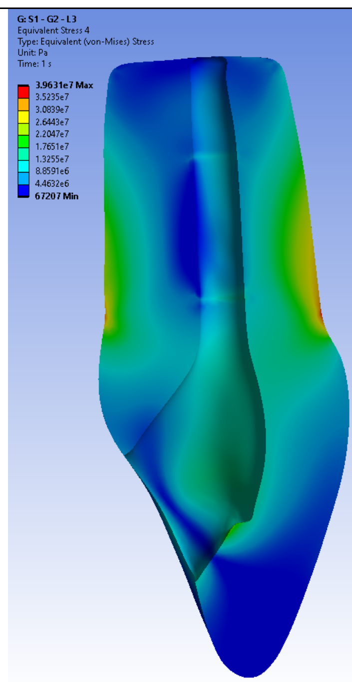
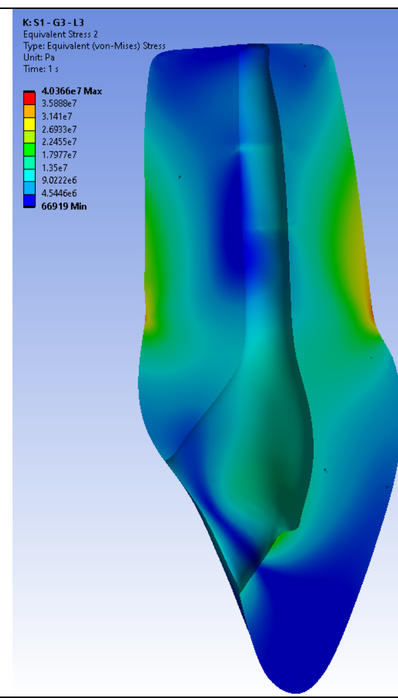
<tr><td>
</td><td>
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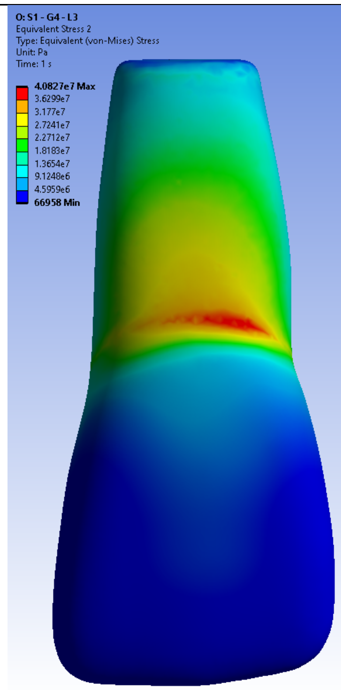

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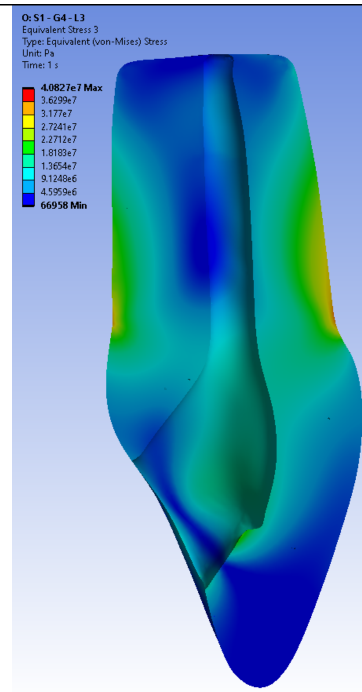

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<tr><td>Group 5 Buccal View</td><td>Group 5 Sagittal Slice</td></tr>
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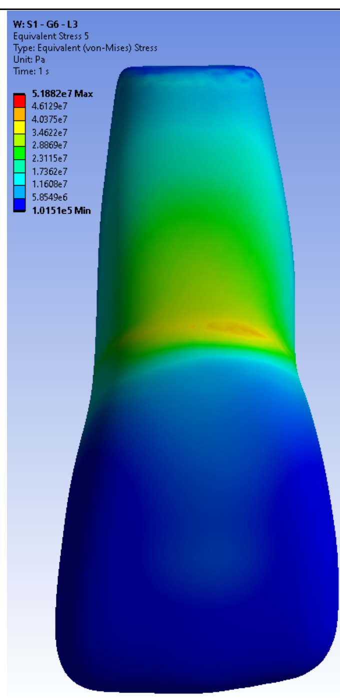

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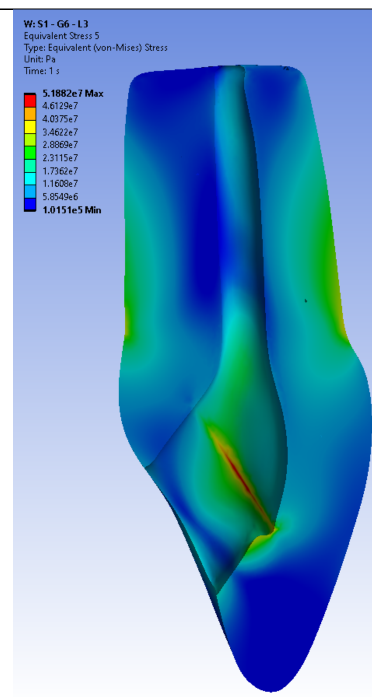

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Figure 5: Von Mises Stress (Pa) field distribution shown in a buccal view and sagittal slice

	Group 1	**Group 2**	**Group 3**	**Group 4**	**Group 5**
Maximum σ	4.1194e7	3.9631e7	4.0366e7	4.0827e7	2.5698e8
Minimum σ	6.7644e4	6.7207e4	6.6919e4	6.6958e4	1.0151e5

Table 2: Maximum and minimum Von Mises Stress values (Pa)

DISCUSSION

The objective of this study was to use FEA to determine the optimal depth of intracanal CR needed in an immature, endodontically treated tooth to maximize fracture resistance. The upper central incisor was chosen as it is the most affected tooth by trauma (1).

Fracture occurs when VM stress values exceed the yield strength of the tooth (61); and from our results we can reject our null hypothesis as group 2 generated the lowest stress values and can be assumed to be superior in fracture resistance. It is also of note that group 3 and group 4 generated the next lowest stress values, respectively. This was then followed by group 1 and group 5, respectively. This indicates that having CR apical to the CEJ is beneficial in improving fracture resistance, but that CR placed too far apically will begin to have a negative effect. This may be further understood as the results also showed that the point of maximum VM stress was in the cervical area, also shown in other studies done by Mello et al and Andreason et al. (13,62). This cervical area is the location where the fracture will begin and therefore, the most susceptible and important area to reinforce (57).

Non-FEA, in vitro and retrospective studies have been done comparing CR and GP as intracanal materials after placement of an MTA plug. Schmoldt et al. stated that there is no significant difference between the use of CR, placed from the MTA to the cavosurface margin, and GP, placed from the MTA to the CEJ and then restored with CR, when used as an intracanal material in primary bovine incisors (14). Brito Junior et al. also found similar results in their own study done on bovine incisors (10). Mello et al. found that there is no statistical difference in fracture resistance between GP placed from the MTA to the CEJ and restored with CR, and GP placed from the MTA to 3 mm apical to the CEJ and restored with CR, in this in vitro study (13). Danwittayakorn et al. performed a retrospective study of teeth treated with an MTA plug, which concluded that no significant difference was found between teeth with CR placed from the MTA to the cavosurface margin or GP placed from the MTA to 2 mm apical to the CEJ and then restored with CR (15).

Linsuwanont et al. was the outlier and concluded, in this in vitro study, that CR was significantly better at increasing fracture resistance than GP when placed from the MTA plug to the CEJ and both being restored with CR (16).

From the above studies, it can be noted that conclusions are not synchronous. They also do not compare CR against itself placed at different depths, but rather compare CR against GP. This further emphasizes the significance of this study and the value of stress analyses, lending to more detailed information about stress distribution and fracture resistance.

Limitations of this study include both the use of FEA and plastic teeth. FEA assumes that all materials are isotopic, and standardized plastic teeth are not as accurate a representation as natural dentition; however, the precision and accuracy gained from using FEA and standardized teeth can outweigh the the drawbacks. Smoljan et al. states that FEA can evaluate for a single variable in a standardized evaluation (57). The argument for the use of standardized plastic teeth is made by both Krikeli et al., who states that using standardized methods when performing in vitro studies is valuable, and Connert et al., who is in support for the use of 3D printed teeth for studies needing high levels of standardization (63-64).

From the information gathered we can see that the placement of only 2 mm of CR apical to the CEJ will create the least maximum stress as compared to the other groups. As stresses are highest at the CEJ, having CR placed apical to the CEJ to reinforce the cervical area is understood. However, what is surprising, is that CR placed too far apical to the CEJ can negatively impact the fracture resistance. There is an exact location that the CR must be placed to create maximum fracture resistance. This is, however, beneficial as it lessens the drawbacks of using more intracanal CR.

It must be noted that, although a trend was seen amongst the data, a further non-FEA, in vitro study using natural teeth, copying these exact variables, may provide more information and allow the data to be determined as significant or not. For the time being we can assume that placement of CR only 2 mm apical to the CEJ will allow for the greatest increase in fracture resistance.

CONCLUSIONS

Within the limitations of this study, it can be concluded the maximum stress values were lowest with the placement of CR 2 mm apical to the CEJ as compared to placing CR to the CEJ or further apically when performing apexification on an immature central incisor. These lower maximum stresses indicate a higher fracture resistance and lessen the drawbacks associated with placing more CR into the canal space.

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