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Three-dimensional FEA of Effects of Two Dowel-and-Core Approaches and Effects of Canal Flaring on Stress Distribution in Endodontically Treated Teeth

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Keywords
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Abstract

Purpose: The aim of this 3D finite element analysis (FEA) was to assess stress distribution and levels in endodontically treated teeth restored with two dowel-and-core systems with differing root canal configurations.
Materials and Methods: Four 3D finite element models of a laser-digitalized maxillary central incisor embedded in alveolar bone were created. Internal morphology data and mechanical properties of the materials were obtained from the literature. Models included a (1) sound tooth (control) versus an endodontically treated maxillary central incisor with a crown ferrule preparation with two restorative approaches of a ceramic crown over a (2) gold alloy dowel-and-core or (3) glass-fiber dowels with composite cores (4) the latter with a flared root canal. A 100 N static load was applied in the center of the palatal surface at a 45° angle, and the stress distribution pattern was analyzed using ANSYS® software.
Results: In Model 1 (control), maximum stresses occurred at the coronal third of the buccal (2.32×10^7 Pa) and palatal aspects of dentin. The stress peak value of the model (2.45×10^7 Pa) occurred on the palatal aspect of the enamel at the level of the cementoenamel junction. With the insertion of dowels with thin cement layers (Models 2 and 3), stress concentrations in radicular dentin decreased, while they increased in the dowel/cement/dentin interface. These models exhibited the greatest stress peak values in the incisal margin of the gold alloy core (18.9×10^7 Pa) and in the cement layer (4.7×10^7 Pa). In Model 4, stress peak value was observed in the porcelain crown (4.62×10^7 Pa), and there was no stress concentration inside the cement layer.
Conclusions: Within the limits of this study, the results suggest that the use of dowels and cements with mechanical properties similar to those of dentin, and an increased cement layer thickness, results in mechanical behavior similar to the physiological behavior of a sound tooth.

Many endodontically treated teeth planned for restoration require dowel-and-core systems for retention purposes.[1,2] Previous 2D finite element analysis (FEA) and simultaneous laboratory/3D FEA studies have demonstrated that these systems do not always reinforce the endodontically treated tooth; instead, they may weaken it,[1,3] contradicting what was first stated by laboratory studies.[4,5] It has been suggested by 2D and 3D FEA studies that when an endodontically treated tooth is submitted to occlusal loads, stress is concentrated primarily at the cervical area,[6] where the placement of dowels could reduce the stress.[7,8]

In addition, remaining tooth structure still appears to be a key factor in the use of dowel-and-core restorations.[7,9] A particular situation in which reinforcement becomes a necessity involves the restoration of the tooth with a flared root canal and thin walls near the cervical region. A laboratory study[10] suggested that the ferrule on the final preparation of a tooth works as a reinforcement tool because it would reduce the wedge effect of the dowel on root walls and allow a redistribution and dissipation of occlusal forces. Peroz et al,[11] in a systematic review of the literature, concluded that the ferrule effect is more important to fracture resistance and stress distribution than dowel materials or design and the luting agent used; this statement is corroborated by previous fracture resistance laboratory studies[5,12,13] and finite element studies.[14]

Another resource employed to reinforce such teeth is the use of materials with mechanical properties similar to those of dentin. Some clinicians have reported favorable clinical results with resin reinforcement in structurally weakened teeth. In order to avoid the extraction of weakened roots, filling the radicular defects with adhesive materials has been suggested by 2D and 3D FEA studies.[15,16]

Some disparity of results relating to the way in which the dowel material affects the fracture resistance of restored teeth has been observed in the literature.[17] Some laboratory studies[18,19] state that metallic dowels perform better than fiber dowels, and these findings are confirmed by a 3D FEA study;[9] however, other 2D and 3D FEA studies argue that nonmetallic prefabricated dowels provide the best performance,[15,20-23] because more-rigid restorative materials are more stress resistant and transfer a large part of the burden onto less-rigid structures like dentin. Such dowels are conservative because deep insertion in the root canal is unnecessary due to the adhesive luting, and this is one reason for their increased use.[24] A clinical prospective observational study by Grandini et al[25] showed that the use of fiber dowels and direct resin composites is a short-term conservative treatment option. A 5-year randomized clinical trial by Manocci et al[26] comparing teeth restored either by amalgam or fiber dowels and composite concluded that restorations with fiber dowels and composite were found to be more effective than amalgam in preventing root fractures but less effective in preventing secondary caries. Because of this, clinicians are opting ever more frequently for materials with an elastic modulus similar to that of dentin, which would exclude metallic dowels.[27] Furthermore, 2D and 3D FEA studies[8,15,20] showed that dowel design seems to exert a great influence on the mechanical behavior of the tooth, and cylindrical dowels provide the best stress distribution while tapered dowels may create a wedge effect in the apical third of the root.

The purpose of this 3D FEA study was to assess the stress distribution and levels in endodontically treated maxillary central incisors restored with two dowel-and-core systems and with differing root canal configurations.

Materials and methods

Two dowel-and-core materials were applied to a maxillary central incisor with ferrule and with or without a flared root canal. Models analyzed in this study are shown in Figure 1.

Solid and FE model preparation

A sound maxillary central incisor with dimensions closely approximating those described in the literature[28,29] (23.56 mm in apico-incisal length) was chosen from a group of teeth extracted for periodontal or prosthetic reasons. First, the external shape was obtained by laser-based 3D digitizing (Digimill 3D, Tecnodrill®, Novo Hamburgo, Brazil). A file with the ".TXT" extension was generated and opened in the software Geomagic® v. 7.0 (Raindrop, Research Triangle Park, NC). Next, the 3D image of the tooth was mounted (Fig 2), and a new file with the ".STL" extension was generated. Finally, a file with the ".IGES" extension was generated and exported to Rhynoceros® v. 3.0 software (McNeel and Associates, Seattle, WA), where the dimensions of tooth anatomy obtained from the literature[28,29] were used to generate a solid model for each of the structures: dentin, pulp, enamel, root canal, cortical bone, cancellous bone, and periodontal ligament.

Due to the comparative aim of the structural evaluations, the arbitrary geometry shown in Table 1 was assigned to the dowel-and-core systems. For core retention purposes, the glass fiber dowel had an additional 1.0 mm in length on the coronal portion when compared to the gold alloy dowel. A 5.0 mm gutta percha point was retained in models with endodontic treatment to preserve the apical sealing,[11] and the same enamel dimensions (2.0 mm thickness at incisal region, 1.5 mm thickness at buccal and palatal aspects of cervical region)[29] were given to the ceramic crown. In the models of the endodontically treated teeth, the core just above the ferrule had the same dimensions as the sound tooth's coronal dentin model. The average thickness of the periodontal ligament, cortical bone around the root, and cortical bone covering the cancellous bone were 0.175, 0.3, and 2 mm, respectively.[29] The cement layer in Models 2 and 3 was considered to have an average thickness of 0.4 mm in this study because of its important mechanical properties.[16] All models of endodontically treated teeth also contained 2 mm circumferential ferrules and 1 mm shoulder margins.[5]

In Model 4, a simulated flaring of the root canal was performed. In order to weaken the root, the canal was extended at an angle of 1° from its most apical point just above gutta percha to the most incisal point of the ferrule. Thus, the root canal diameter increased progressively from the apical to the cervical third of the tooth, preserving the 1-mm thickness of dentinal walls around the root canal recommended in the literature.[11] The dentinal volume of Model 3 was 269 mm^3, while Model 4 had a volume of 246 mm^3, resulting in a dentinal volume reduction of 8.55%.

Stress analysis

The FEM was obtained by importing the solid models into ANSYS® v. 12.0 FEM software (Ansys Inc., Houston, TX) using the '*.IGES*' file format. Models were mounted in a tissue support block, and contacts between the solids were established. Solid tetrahedral elements were used for the mesh, and ideal adherence was assumed between adjacent components; that is, nodes from adjacent elements belonging to different components were shared to ensure continuity.

Mechanical properties of the models' materials were obtained from the literature (Table 2).[2,19,21,30,31] Materials were considered homogeneous, isotropic, and linearly elastic, except for the glass fiber dowel (properties are listed in Table 3), which was considered orthotropic, with different properties of fiber in parallel and perpendicular directions.[6] E_x, E_y, and E_z represent the elastic moduli along the 3D directions while υ_{xy}, υ_{xz}, and υ_{yz} and G_{xy}, G_{xz}, and G_{yz} are the Poisson's ratios and the shear moduli in the orthogonal planes (*xy*, *xz*, and *yz*), respectively.

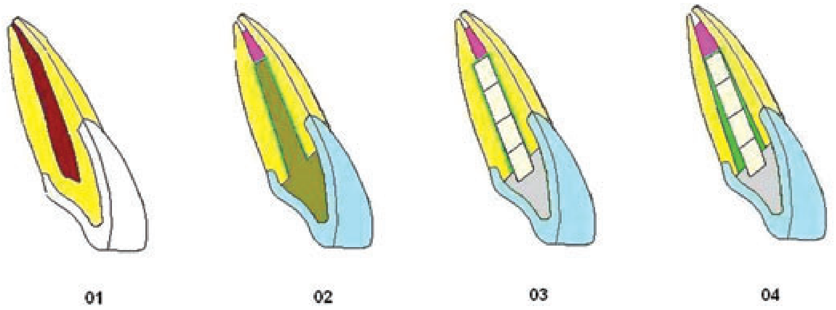

Figure 1 The four models. Model 1, sound tooth; Model 2, endodontically treated tooth with a crown ferrule preparation restored with ceramic crown and gold alloy dowel-and-core system; Model 3, glass fiber dowel and composite core system; and Model 4, glass fiber dowel and composite core system with flared root canal.

Fixation condition was determined for the cancellous bone and the lateral part of cortical bone. The software generated models as follows: Model 1, with 23,196 elements and 30,895 nodes; Model 2, with 30,478 elements and 39,284 nodes; Model 3, with 33,628 elements and 42,485 nodes; Model 4 with 33,226 elements and 42,026 nodes (Fig 3). A 100 N arbitrary static masticatory load was applied at a 45° angle, 2 mm below the incisal edge of the palatal surface of the crown (Fig 4). The 100 N load was determined from the current literature.[7,20]

The Von Mises stresses were to be analyzed according to location and distribution in the models, isolated from the support tissue block and with no specific points for comparisons; however, emphasis was given to the stress distribution in the radicular portion of the endodontically treated teeth, where irreversible failures such as root fracture are due to occur, as well as dowel decementation. Therefore, radicular dentin, cement layer, dowel, as well as the interfaces between the materials are to be further analyzed.

Results

The Von Mises stresses, which were estimated using the model for each point, are represented using a color scale (warmer colors represent higher stresses). The evaluation of the results took into account multiple views. To group the results of the four models, a standard view of a mid-saggital section from each model was provided (Fig 5). Most current FEA software does not allow scales for color coding to be predetermined by the user. The software is designed to enhance the detection of differences whether they are large or small. A related problem is that the scale provided with the output images usually includes a magnification factor. In the case of the current images, “1e7 Pa” and “1e8 Pa” are shorthand for 10,000,000 Pa (10 MPa)

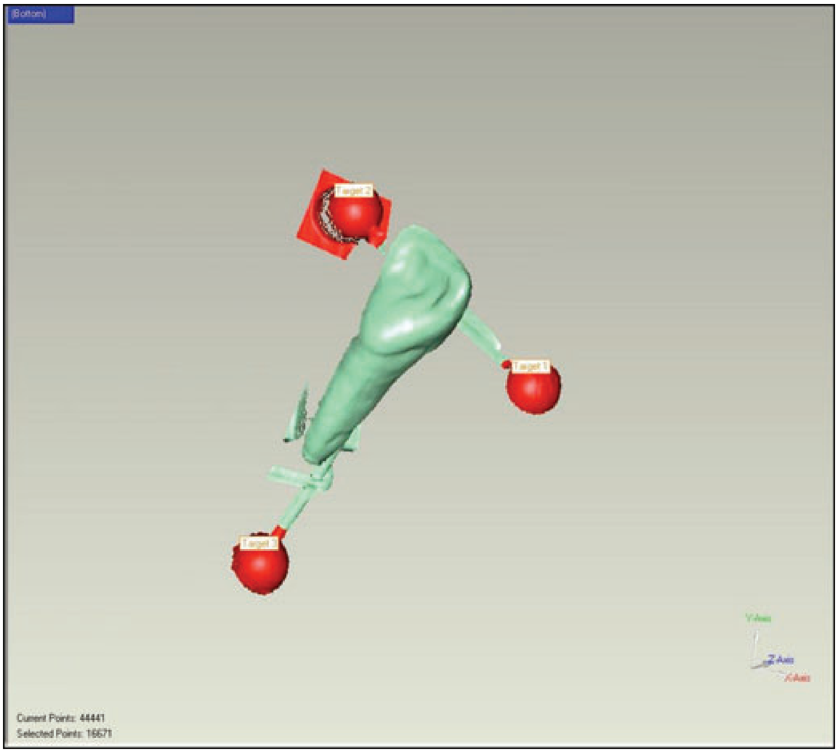

Figure 2 Three-dimensional image of the tooth mounted in the Geomagic® v. 7.0 software.

Table 1 Arbitrary geometry used for the dowel-and-core systems

Solid	Shape	Intra-canal length	Conicity	Diameter
Gold alloy dowel	Tapered	10 mm	1°	1.5 mm cervical region 0.8 mm apical region
Glass fiber dowel	Parallel-sided	10 mm	0°	1.5 mm

and 100,000,000 Pa (100 MPa), respectively, and so all results actually are presented as Mega Pascal.

All models exhibited a progressive decrease in stress from the outer to the inner part of the root and from the cervical third of root dentin towards the apical region and the incisal margin of the tooth crown as well. A medium (Models 1, 3, and 4) and medium-to-high (Model 2) stress concentration was observed on the palatal aspect of the enamel or the porcelain crown underneath the load application point.

In Model 1 (control), the maximum stresses were evidenced both at the mid and coronal thirds of the buccal (2.32×10^7 Pa) and palatal aspects of radicular dentin. The stress peak value of the model (2.45×10^7 Pa) occurred on the palatal aspect of the enamel at the level of the cementoenamel junction (CEJ) (Fig 6).

The stress peak value of Model 2 (18.9×10^7 Pa) occurred at the incisal edge of the core (Fig 7). The maximum stresses of the radicular portion were found in the two coronal thirds of the root on the buccal and palatal aspects of the dowel and dowel/cement/dentin interface (3.42×10^7 Pa). There was a decrease of stress on root dentin (peak = 1.92×10^7 Pa) in relation to Model 1.

In Model 3 (Fig 8), the maximum stresses were evidenced at the cement layer around the dowel in the coronal third of the root and on the buccal (peak = 4.7×10^7 Pa) and palatal aspects of the root canal. A relative increase in stress was observed in the buccal and palatal aspects of both the mid and coronal thirds of radicular dentin (2.12×10^7 Pa) in relation to Model 2, but the stress concentration in this region was lower than in Model 1.

Table 2 Mechanical properties of the materials analyzed in this study

Solid	Elastic modulus "E" (GPa)	Poisson's ratio "υ"
Enamel[31]	84.1	0.33
Dentin[31]	18.6	0.32
Gold alloy type IV[30]	120¶	0.44
Composite[21]	12§	0.33
Resin cement[31]	18.6¥	0.28
Feldspathic ceramic[31]	69†	0.30
Gutta percha[2]	0.69	0.45
Cortical bone[19]	13.7	0.30
Cancellous bone[19]	1.37	0.30
Periodontal ligament[2]	0.069	0.45

¶"E" value from commercial brand Veritas (Degussa Ney®, Bloomfield, CT). §"E" value from commercial brand BisCore (Bisco®, Schaumburg, IL). ¥"E" value from Panavia F (Kuraray CO®, Tokyo, Japan). †"E" value from commercial brand IPS Empress (Ivoclar Vivadent®, Schaan, Liechtenstein).

Model 4 (Fig 9) showed a small increase in stress on radicular dentin in comparison to Models 2 and 3, as well as a slightly lower stress concentration than in Model 1. The stress peak value of the model occurred in the porcelain crown (4.62×10^7 Pa) and of the radicular portion of the model, in the buccal aspect of the coronal third of the root (2.22×10^7 Pa). Stress concentration was significantly lower within the dowel and core in Models 3 and 4, and within the cement layer in Model 4.

Discussion

In this study, 3D FEA was used to analyze the stress distribution pattern of maxillary central incisors endodontically treated and restored with ceramic crown and two dowel-and-core systems. Under a simulated masticatory load, the sound tooth showed a concentration of Von Mises equivalent stress in the buccal and palatal aspects of coronal third of radicular dentin, where the peak occurred at the level of the CEJ, while the endodontically treated and dowel-restored teeth exhibited a slight decrease of stress concentration at that point. Dowel insertion and cement layer were of utmost importance in the changes of stress distribution pattern of endodontically treated teeth, and these factors seem to have contributed to the lower stress peak values in the radicular dentin. This parallels the evidence supported by previous 2D[4] and 3D[6,7] FEA studies. Maxillary central incisors were modeled, and the maximum stresses were evidenced at the level of the CEJ in the control models (either sound or nonrestored tooth), while the different restorative approaches used reduced the levels and changed the location of stress distribution at the radicular dentin.

When a dowel is inserted into the root canal, some occlusal forces are directed along the dowel length and may assist in protecting the remaining tooth structures, decreasing the Von Mises equivalent stresses in dentin.[7,8] In this study, the most favorable decrease in stress concentration on root dentin in

Table 3 Orthotropic properties of the glass fiber dowel: elastic moduli* (E expressed in GPa), Poisson's ratios (υ), and shear moduli* (G)[6]

E_x	37
E_y	9.5
E_z	9.5
υ_{xy}	0.27
υ_{xz}	0.27
υ_{yz}	0.34
G_{xy}	3.1
G_{xz}	3.1
G_{yz}	3.5

*"E" and "G" values from commercial brand FibreKor Dowel (Jeneric Pentron®, Wallingford, CT).

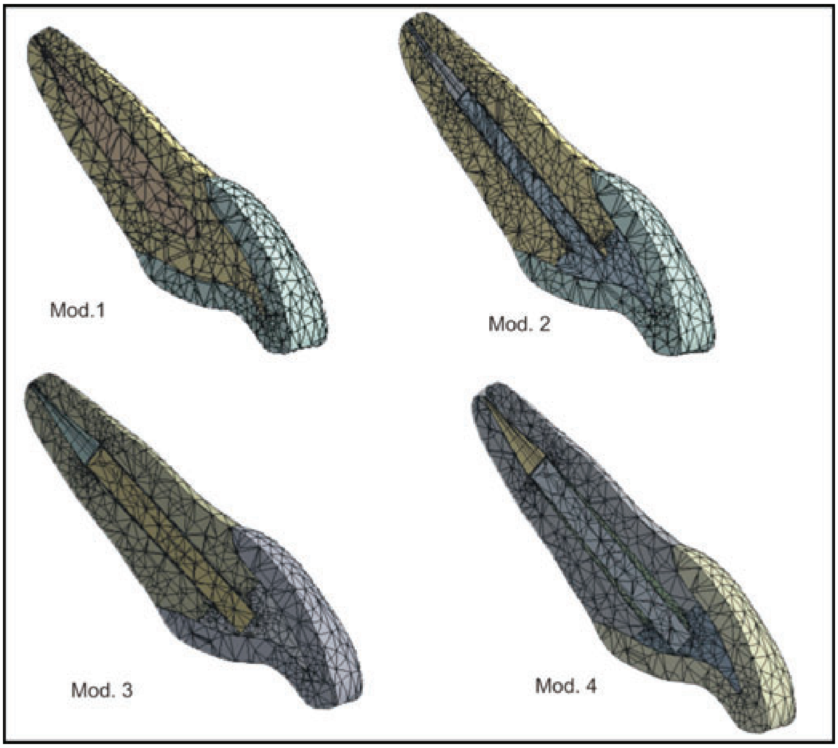

Figure 3 Mid-saggital view of the 3D meshes of the four models. Solid tetrahedral elements were used for the mesh, and nodes from adjacent elements belonging to different components were shared to ensure continuity.

comparison with sound tooth structure was observed with the gold alloy dowel-and-core system. This corroborates previous findings of both 2D[27] and 3D[9,32] FEA studies, which used maxillary central incisors as models, and where the insertion of a gold-alloy dowel resulted in a decrease in the stress concentration on root dentin. On the other hand, there are 2D[15,27] and 3D[1,21] FEA studies of maxillary central incisors reporting better behavior for glass fiber dowels and claiming that a

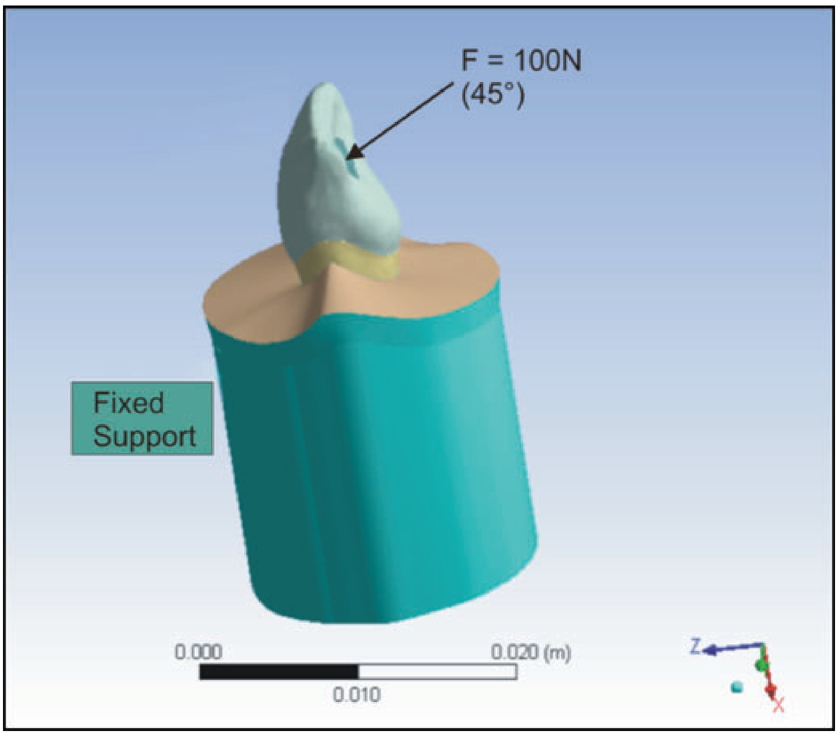

Figure 4 Fixation and loading conditions of the model. A support tissue block was postulated, including cortical bone, cancellous bone and periodontal ligament. A 100 N arbitrary static masticatory load was applied at a 45° angle in the center of the palatal surface of the tooth, 2 mm above the incisal margin.

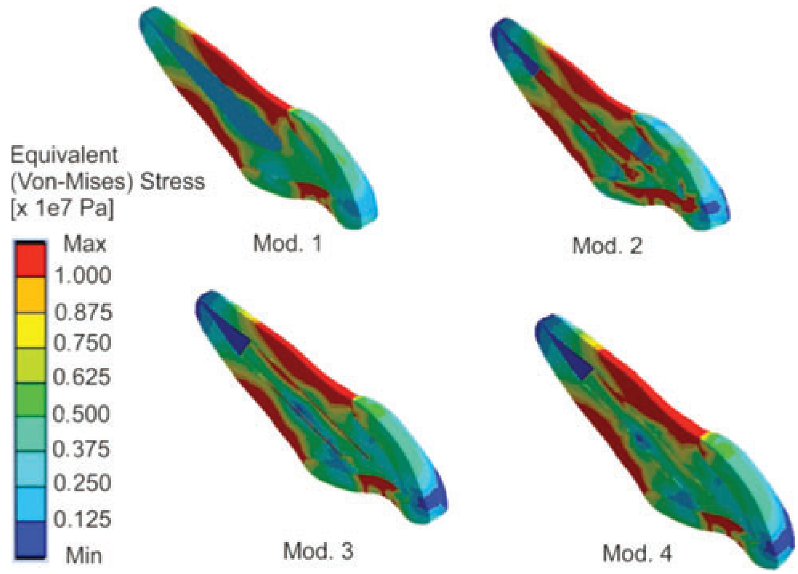

Figure 5 Equivalent (Von Mises) stress in the mid-saggital views of the four models (1e7 Pa = 10 MPa).

very stiff dowel would work against the natural function of the tooth. This good mechanical behavior of glass fiber dowels is also confirmed by clinical studies[25,26] that observed fewer incidences of fractures and a better conservation of the remaining tooth structure in a short-term evaluation. The findings of our study are in agreement with the findings of these previous FEA studies, once the glass fiber dowel showed similar deformation to that of the root, probably reducing the risk of fracture; however, our results counteract those of Toksavul et al,[7] who stated that a glass fiber dowel system may demonstrate deformations under simulated masticatory loading that could result in greater stress concentration in dentin, thus possibly leading to fracture.

The small reduction of stress concentration on radicular dentin observed in the models of endodontically treated and dowel-restored teeth was insignificant compared to the tensile zones created in the interfaces of the restorative system. Stress concentration occurs where a non-homogeneous material distribution is present, such as the interfaces of materials with varying moduli of elasticity, which in turn represent the weak point of a restorative system.[6] This could explain the high stress concentration in Models 2 and 3, considering the great

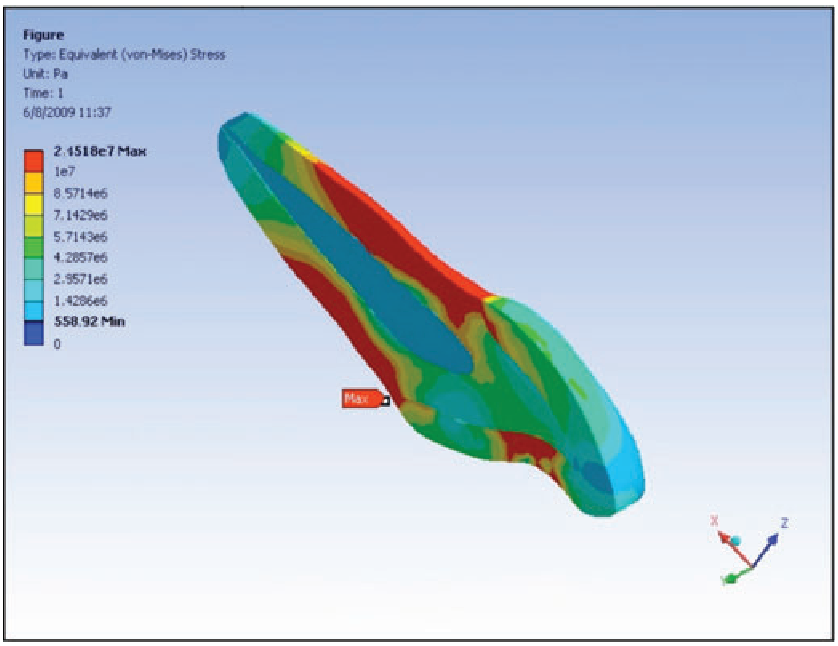

Figure 6 Saggital view of Model 1. The section was distally moved to show the point where maximum stress occurred (1e6 Pa = 1 MPa; 1e7 Pa = 10 MPa).

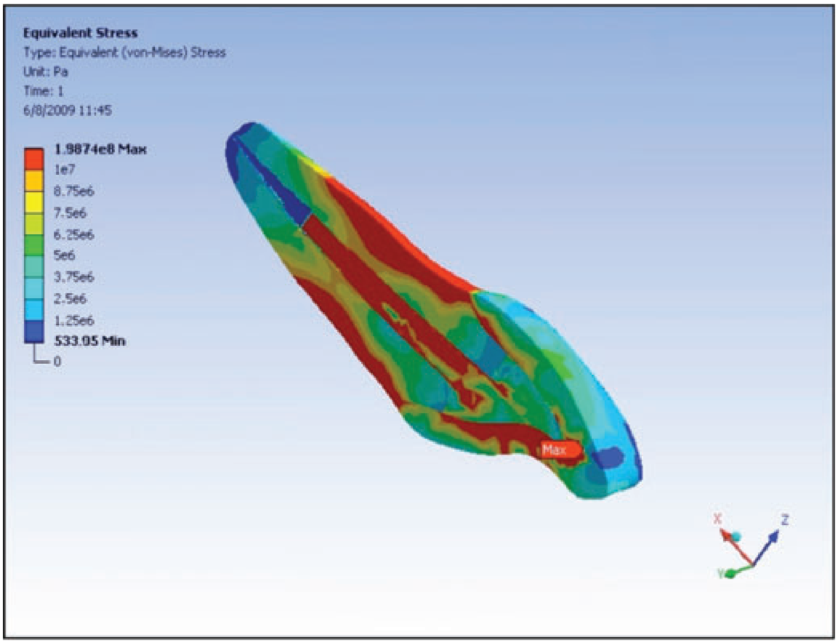

Figure 7 Saggital view of Model 2. The section was distally moved to show the point where maximum stress occurred. Observe the different unit used in the scale of this model, due to an unexpected high stress concentration, occurring in the incisal margin of the gold alloy core (1e6 Pa = 1 MPa; 1e8 Pa = 100 MPa).

discrepancy difference between dowels and dentin in elastic modulus. The dowel increases the rigidity of the root, reducing its deformability, and the lower dentin deformation determines a decrease in physiological stress concentration.[6]

Two main types of failures are most likely to happen with endodontically treated teeth restored with dowel-and-core systems. The first concerns a reversible but still undesirable failure, which is the decementation of the dowel, and can be predicted with higher stresses at the cement layer. Although new adhesive cements and cementation techniques have been developed to avoid it, the non-homogeneity of the materials inside the root leads to the creation of zones of higher stress concentration in the dowel/dentin interface, resulting in microfractures and consequently, decementation; however, the use of materials with similar mechanical properties seems to decrease the impact of such factors. In this study, the high stress concentration occurring in the dowel/cement/dentin interface in Model 2 could predict a higher potential for failure. The second type of

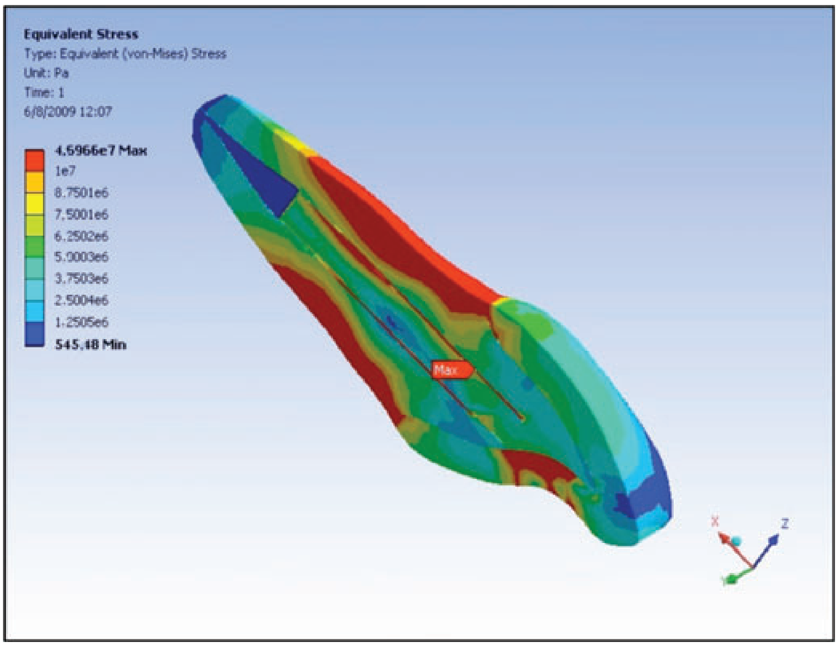

Figure 8 Saggital view of Model 3. The section was distally moved to show the point where maximum stress occurred (1e6 Pa = 1MPa; 1e7 Pa = 10 MPa).

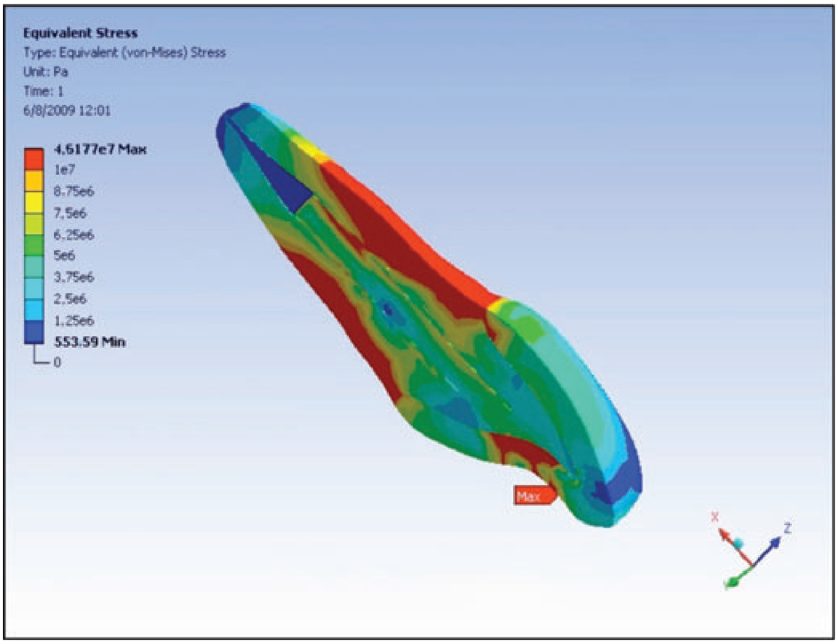

Figure 9 Saggital view of Model 4. The section was mesially moved to show the point where maximum stress occurred (1e6 Pa = 1MPa; 1e7 Pa = 10 MPa).

failure concerns a usually irreversible one—root fracture—and is associated with higher stress concentrations in the dentin. One mechanical study[18] showed that this type of fracture is most likely to occur with metallic dowels, which have a higher modulus of elasticity and leads to the creation of zones of high stress concentration in the root dentin, usually above the tooth endurance limit. In that study, nickel–chromium alloy was used and compared to glass fiber and carbon fiber as dowel materials. Even though the incidence of fractures of weakened roots of endodontically treated teeth was lower with the metallic dowels, the fractures were usually vertical towards the root apex and therefore irreversible, while the fractures observed on the glass fiber dowel, for instance, were usually horizontal and close to the cervical region, that is, reversible. Although different methodologies were used, these results corroborate the findings of the present study.

Peak stress values are related to area of the structures and to the modulus of elasticity of the materials. Tensions are calculated at one specific region of the model, dividing the applied force by the area, and the thin cement layer in Models 2 and 3 contributed to the greater stress peak values in the dowel/cement/dentin interfaces. The smaller the area of the cement layer, the greater is the stress concentration inside it and the smaller is the stress concentration in dentin. The option for materials with mechanical properties similar to those of dentin is favorable to success in the restoration of endodontically treated teeth.[6] Some authors[7,32] claim that the greater is the modulus of elasticity of dowels, the greater is the decrease in dentinal stress distribution during masticatory loading, and the findings of this study are in agreement with those of previous studies. Although a high stress concentration occurred in the incisal margin of the gold alloy core, possibly explained by its reduced area at that point, the stress distribution in the root dentin is not generated or altered by the stress concentration at that point in this static analysis, but it is influenced by the loading transmission towards to the apex. It was not observed with the resin cores, probably due to the different core materials, while the area was the same. The wedging effect attributed to tapered dowels reported in the literature[8,11,15,20] was not observed in this study, once the stress concentration in the apical region of the root, which was considerably low, was similar to sound tooth in both dowel systems.

This study was conducted using the 3D Von Mises criteria. The rationale for selecting this approach, which apparently results in a tensile-type normal stress, lies in the fact that brittle materials, of which the tooth is an example, fail primarily due to tensile-type normal stresses.[7]

Three-dimensional FEA is an additional research tool and is not able to prove anything per se. Results depend on the assumptions of the model, and while the assumptions seem to be reasonably true, they will ultimately require clinical confirmation. Although the reliability of the FEA is based basically on the accuracy of the model, it has great strengths in being able to simulate complex situations that could not be tested directly for practical reasons. Differences in tooth anatomy sizes, restorative material choices, occlusal loads, amount of remaining tooth structure, and effects of tooth structure defects (e.g., cracks) for instance, might alter the analysis, but the general outcomes should still be the same. This study was designed to make the models and simulations the closest recreation of the actual clinical practice (for instance, the gold dowel had a tapered shape, whereas while the glass fiber dowel had a cylindrical shape) with a cement thickness typical for dowel retention. An extremely accurate 3D model of the tooth has been provided, reproducing each detail of all structures that make part of a real endodontically treated tooth. On the other hand, the reproduction of bone should be more accurate, and additional views of the models should be provided to elucidate the results.

Further studies must be done considering endodontically treated teeth without dowel-and-core restorations and ferrule as well as examining variations in dowel diameter and cement layer thickness for comparison purposes. Even though in vitro or in vivo studies are necessary to validate the findings of this study, we believe that the level of evidence produced in this study may contribute to the current scientific evidence available.

Conclusions

Within the limitations of this 3D FEA study, the interpretation of the results from multiple views of the models could lead us to the following conclusions:

(1) Endodontic treatment and restoration with dowel and core and ceramic crown increases stress concentration in the dowel/cement/dentin interface and decreases stress concentration in root dentin; however, irrespective of the dowel-and-core system used, the stress distribution pattern on the three models of endodontically treated teeth was similar, when compared to the model of a sound tooth.

(2) Gold alloy cast dowel and core creates the lowest equivalent Von Mises stress in the dentin of maxillary central incisors and causes a great stress concentration in the dowel/cement/dentin interface.

(3) A thin cement layer tends to concentrate tensile stresses inside it, while a thicker layer tends to dissipate tensile stresses to radicular dentin.

(4) Among the analyzed models, the tooth restored with glass fiber dowel and composite core system with a thicker cement layer under masticatory loading exhibited the most similar mechanical behavior to the physiological behavior of a sound tooth.

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