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Analysis of Dentinal Stress Distribution of Maxillary Central Incisors Subjected to Various Post-and-core Applications

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Clinical Relevance

According to FEA analysis, under a simulated occlusal load, the cervical area of endodontically treated and crowned maxillary central incisors was the most stress concentrated area. Zirconia ceramic posts create slightly less dentinal stress concentration than titanium and glass-fiber posts.

SUMMARY

This study evaluated the stress distribution on an endodontically treated maxillary central incisor restored with different post-and-core systems by using a three-dimensional finite element analysis model. Seven three-dimensional finite element models were created. Each model contained cortical bone, cancelous bone, periodontal ligament, 3 mm apical root canal filling, post-and-core and all-ceramic crowns. Two different prefabricated zirconia ceramic post systems, a glass fiber-reinforced post system and a titanium post system were modeled. As a control, an all-ceramic crown on an endodontically treated maxillary central incisor without a post-and-core was modeled. Each model received a 45° oblique occlusal load at a constant intensity of 100 N. In each model, the ratio of Von Mises stress distribution was compared. The greatest stresses were observed in the coronal third of the roots on facial surfaces. The ratio of Von Mises stress distribution in dentin for the zirconia ceramic post (CosmoPost) and ceramic core (Cosmo Ingot), zirconia ceramic post (CosmoPost) and composite core (Tetric Ceram), glass fiber-reinforced post (FRC Postec) and composite core (Tetric Ceram), titanium post (Er post) and composite core (Tetric Ceram), zirconia ceramic post (Cerapost) and ceramic core (Cosmo Ingot), zirconia ceramic post (Cerapost) and composite core (Tetric Ceram) and the control group were 0.886, 0.889, 0.988, 0.924, 0.889, 0.893 and 1, respectively. The

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stress concentrations in dentin created by two different zirconia ceramic post systems were nearly the same. The zirconia ceramic post systems created slightly less stress concentration in dentin than the glass fiber-reinforced and titanium posts.

INTRODUCTION

Many endodontically treated teeth planned for fixed prosthodontic treatment require post-and-core restorations for retention purposes, because of extensive structural defects resulting from caries, cavity access and the excessive removal of radicular dentin during endodontic treatment. On the other hand, intact endodontically treated teeth can be restored with filling material without post-and-core restorations (Mannocci & others, 2002). It was believed that when an endodontically treated tooth is subjected to occlusal loads, stress is mostly concentrated at the cervical area (Hunter, Feiglin & Williams, 1989; Assif & others, 1989). The placement of posts in endodontically treated teeth reduces stress in this area (Assif & Gorfil, 1994; Ottl & others, 2002; Yang & others, 2001; Ko & others, 1992). When the post is inserted into the root canal, some of its force is directed along the post length. Thus, the placement of posts may assist in protecting the remaining tooth structures (Caputo & Standlee, 1987). Today, it is accepted that posts do not reinforce endodontically treated teeth (Robbins, Earnest & Schumann, 1993); however, in the case of substantial horizontal loss of the clinical crown, there is no restorative alternative other than fabricating a post-and-core buildup (Shillingburg & others, 1997a; Mannocci, Ferrari & Watson, 1999). A study suggested that posts should be used only when there is a need to retain the core, and they do not reinforce an endodontically treated tooth (Fernandes & Dessai, 2001). Therefore, the remaining tooth structure appears to be a key factor in the use of post-and-core restorations.

Posts can be divided into two categories: custom/cast posts with cast core and prefabricated posts, primarily with composite core. Metal alloys are generally used to fabricate custom/cast posts. Prefabricated posts are divided into two groups: metallic, such as titanium alloy posts, and non-metallic, such as zirconia ceramic, glass fiber-reinforced composite and glass-ceramic posts.

The prefabricated post-and-core system is one of the most popular systems, because it is less time-consuming (Shillingburg & others, 1997b). In this system, the root canal is prepared by using drills that have the same diameter as posts. Thus, the perfect fit of the post to the root canal is achieved. This increases the fracture resistance of endodontically treated teeth (Sorensen & Engelman, 1990a). In addition, it was reported that cast posts showed lower fracture resistance compared to prefabricated posts due to weakening of the posts during the casting process (Heydecke & others, 2002).

The use of all-ceramic restorations has increased considerably due to rising esthetic demands. The application of an all-ceramic crown after insertion of a metallic post-and-core compromises the esthetic appearance of the all-ceramic crown. In this respect, several tooth-colored post-and-core systems, as mentioned above, have been used. These systems have improved the esthetics of teeth restored with posts and cores. In addition, zirconia ceramic can offer superior strength compared to other post materials. In the zirconia ceramic post system, two different core materials, composite and zirconia-enriched glass-ceramic, are being used. The use of zirconia ceramic post with composite core simplifies the restorative procedure, because all steps can be completed chairside.

Finite element analysis (FEA) is a popular numerical method in stress analysis. FEA shows the internal stresses and, on that basis, predictions about failure can be made. The effect of post design (Sorensen & Martinoff, 1984), post material (Ukon & others, 2000) and core material (Combe & others, 1999) is very important on dentinal stress distribution. Therefore, this study compared the dentinal stress distribution of 3-D FE models of maxillary central incisors that received zirconia ceramic, glass-fiber reinforced composite and titanium posts.

METHODS AND MATERIALS

In this study, four different post systems, including two different core materials, were applied to a maxillary central incisor. Post-and-core systems modeled in this study are listed in Table 1. Two different zirconia ceramic post systems, CosmoPost (Ivoclar Vivadent, Schaan, Liechtenstein) and Cerapost (Komet, Gebr Brasseler, Lemgo, Germany), were used. As a result, the effect of the diameter and shape of these systems on dentinal stress distribution were also evaluated.

Seven 3-D FE models of a maxillary central incisor were designed for the analysis of stress distribution induced by applied loads by use of the ANSYS 7.0 (Swanson Analysis Inc, Houston, PA, USA) software program (Table 2). Six models contained posts-and-cores of the same height and all-ceramic crowns (IPS-Empress-2, Ivoclar Vivadent), periodontal ligament, cortical and cancellous bone and approximately 3 mm gutta-percha apical seal. The average thicknesses of the periodontal ligament and cortical bone were 0.3 mm and 0.4 mm, respectively. The all-ceramic crowns in each model were created by using the layering technique. In the layering technique, IPS-Empress-2 framework is covered with a layering ceramic that contains fluoroapatite crystal. The average thickness of the IPS-Empress-2 framework was 0.8 mm. These

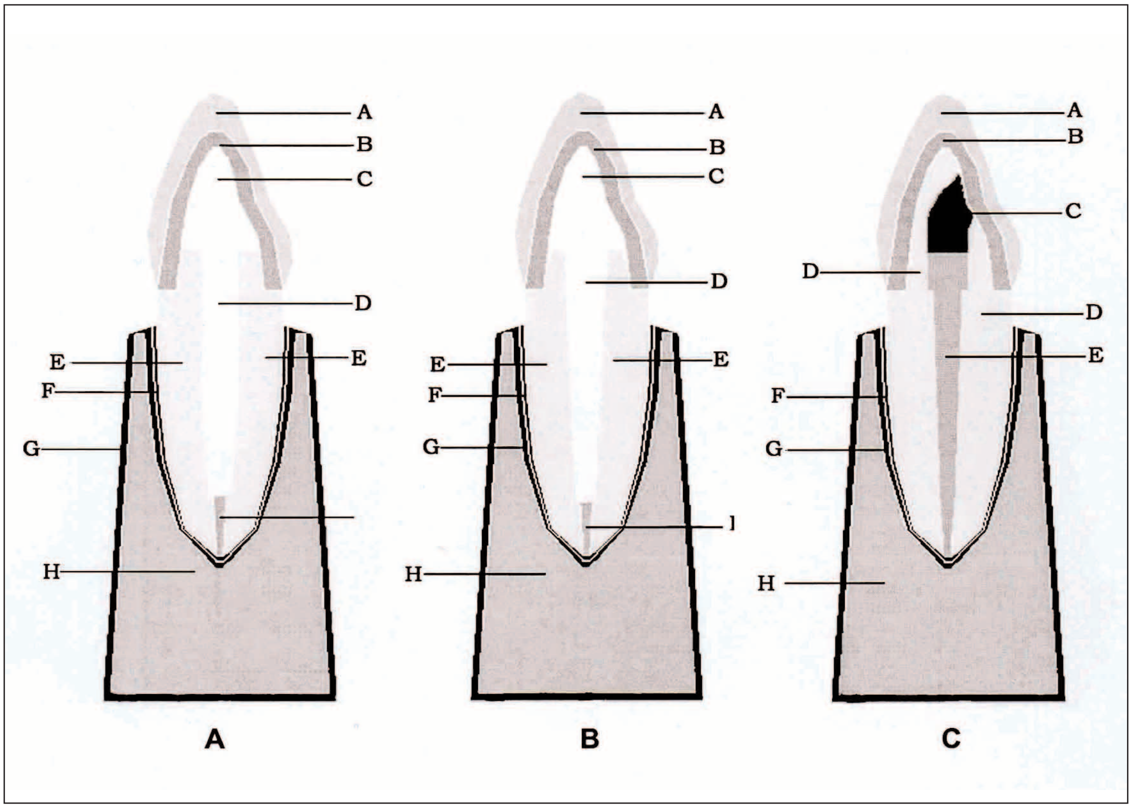

Figure 1: *A, Midlabiolingual section of models 1 and 2. B, Midlabiolingual section of models 3, 4, 5 and 6. Layering ceramic (A), ceramic framework (B), core (C), post (D), dentin (E), periodontal ligament (F), cortical bone (G), cancellous bone (H), remaining apical root canal filling (I). C, Midlabiolingual section of model 7. Layering ceramic (A), ceramic framework (B), composite filling (C), dentin (D), root canal filling (E), periodontal ligament (F), cortical bone (G), cancellous bone (H).*

Table 1: *3-D Modeled Post-and-core Systems*

Post System	Manufacturer	Core	Manufacturer
Cosmopost (yttrium-stabilized zirconia ceramic)	Ivoclar Vivadent	Tetric Ceram (light-cure Composite filling material)	Ivoclar Vivadent
FRC Postec (glass fiber-reinforced composite)	Ivoclar Vivadent	Cosmo Ingot (Zirconia contained pressable ceramic)	Ivoclar Vivadent
ER Post (Pure titanium)	Komet-Brasseler		
Cerapost (yttrium-stabilized zirconia ceramic)	Komet-Brasseler		

Table 2: *Properties of the Models in This Study*

	Post System	Core Material	Length of Post (mm)	Coronal Diameter of the Post (mm)	Tip Diameter of the Post (mm)	Length of the Core (mm)
Model 1	CosmoPost	Cosmo Ingot	14	1.7	1	4
Model 2	CosmoPost	Tetric Ceram	14	1.7	1	4
Model 3	FRC Postec	Tetric Ceram	14	2	1	4
Model 4	ER Post	Tetric Ceram	14	1.78	0.9	4
Model 5	Cerapost	Cosmo Ingot	14	1.78	0.9	4
Model 6	Cerapost	Tetric Ceram	14	1.78	0.9	4
Model 7 (control)	-	-	-	-	-	-

Table 3: *Material Properties Used in Finite Element Models*		
	Modulus of Elasticity (Mpa)	**Poison's Ratio**
Dentin**	18600	0.31
Periodontal ligament**	68.9	0.45
Cortical bone**	13700	0.30
Cancellous bone**	1370	0.30
Gutta Percha**	0.69	0.45
CosmoPost*	210000	0.23
ER Post*	120000	0.33
Cerapost*	200000	0.23
Cosmo Ingot*	85000	0.24
Tetric Ceram*	9400	0.28
IPS-Empress-2 layering Ingot*	100000	0.25
IPS-Empress-2 layering ceramic*	65000	0.19
FRC Postec		
Parallel to fibers*	45000	0.24
Perpendicular to fibers*	12000	0.30

**Information given by the manufacturers*

***Yang & others, 2001*

Table 4: *Information on Used Meshes*		
	Number of Elements	**Number of Nodes**
Models 1 and 2	22275	30698
Models 3-6	21804	30554
Model 7 (control)	20639	28663

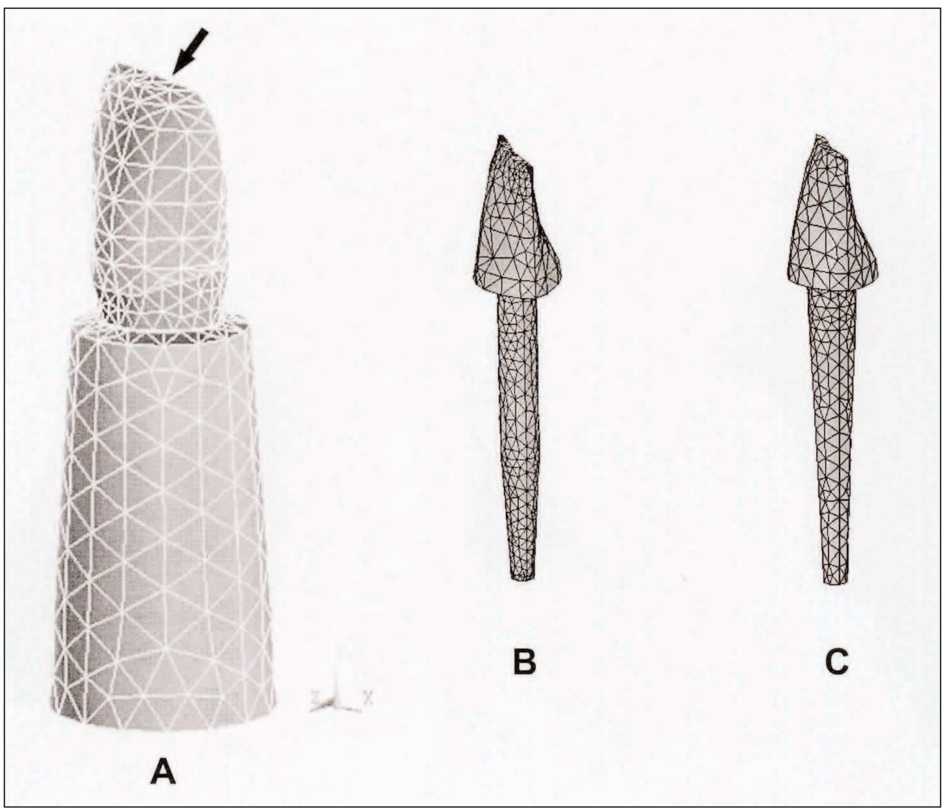

Figure 2: *A: 3-D Finite element mesh for the maxillary central incisor. B: post-and-core in models 1 and 2. C: post-and-core in models 3 through 6.*

models also contained ferrules that were 1 mm proximally and 2 mm buccally and lingually. In the modeling of the posts, two-dimensional models of the semi-cross-sections of the posts were spun 360° around the vertical axis, and 3-D FE models of the posts almost in actual sizes and shapes were created. The shapes and sizes of the ER Post (Komet, Gebr Brasseler), FRC Postec (Ivoclar Vivadent) and Cerapost were similar. The model of the endodontically treated tooth constructed for comparisons consisted of all the materials except for the post-and-core. All the models contained a 1 mm shoulder margin (Figure 1). For purposes of simplification, all materials were considered homogeneous, isotropic and linearly elastic, except the glass fiber-reinforced posts which were considered orthotropic, with different material properties on fiber in parallel and perpendicular directions. In this case, the fibers were aligned to the post on the longitudinal axis. The mechanical properties of materials used in this study are listed in Table 3. The influence of the cement layer on stress distribution was negligible. Since the cement layer was too thin, it was hard to simulate it on the model, and its modulus of elasticity is believed to be close to that of dentin (Ho & others, 1994). All materials were assumed to be rigidly bound together. Each layer of the structures was connected to the other by shared nodes.

In the modeling of FEM, each element was assigned a predetermined number of nodes. The elements were connected to each other by means of their nodes, and the numbers of the elements and nodes of the models are given in Table 4. The element type chosen was a solid, 3-D, ten-node, tetrahedral element (Figure 2).

A masticatory force of 100 N was applied at 45° 2 mm below the incisal edge of the palatinal surface of the modeled crown. The 100 N load was determined from the current literature, establishing the normal chewing force as a third of the maximum biting force (Kohal & others, 2002). All nodes on the outline of the bone surface were constrained in the vertical and labiolingual directions as boundary conditions. The Maximum Von Mises equivalent stresses in dentin for each group (Vm_{max}) was divided by the maximum Von Mises equivalent stresses in dentin of the control group (Vm_{max}*). Ratios of the maximum Von Mises equivalent stress values between each model and control group (Vm_{max}/Vm_{max}*) were obtained. From this viewpoint, since the ratio of the control group was 1, the created maximum Von Mises equivalent stresses would be less in groups having ratios of less than 1. This study was conducted by considering the 3-D Von Mises criteria. The Von Mises value for-mula is given below (Ugural & Fenster, 1977):

$$Vm = \frac{1}{\sqrt{2}} \sqrt{(St-S2)^2 + (S2-S3)^2 = (S3-S2)^2}$$

S_1, S_2 and S_3 are known as the principle stresses. The Von Mises formula results in a value that is always positive.

The results are presented in terms of Von Mises stress values. Because the tensile strength values of all the materials concerned are not available for comparison, the likelihood of a failure is determined by accepting the fact that a higher Von Mises stress value is a strong indication of a greater possibility of failure.

In order to analyze stress location and distribution, the tooth was isolated from the rest of the model.

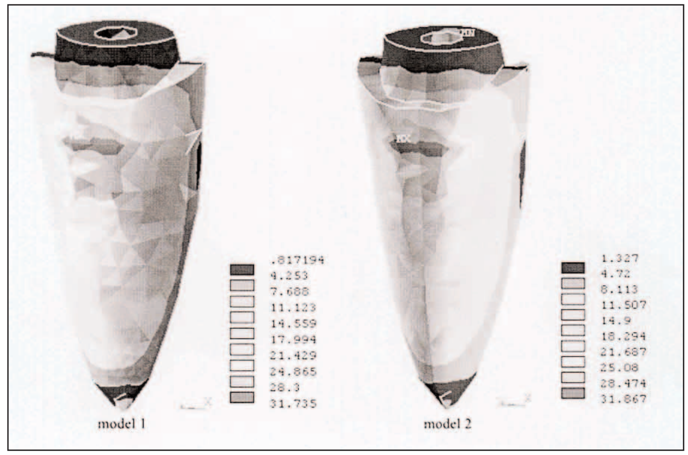

Figure 3*A: Maximum Von Mises equivalent stress distribution in dentin for models 1 and 2.*

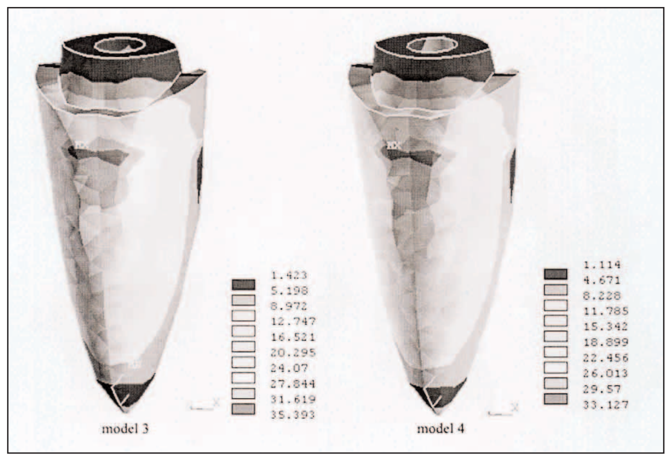

Figure 3*B: Maximum Von Mises equivalent stress distribution in dentin for models 3 and 4.*

RESULTS

When the 3-D models of maxillary central incisors were subjected to simulated masticatory loading, the maximum Von Mises equivalent stress in dentin was concentrated on the coronal third of the facial surface of the root. In the control group (model 7), the maximum Von Mises equivalent stress was slightly greater than the other models, and its ratio 1 concentrated on the coronal third of the facial surface of the root (Figures 3A-D). The ratios of the maximum Von Mises stress distributions in

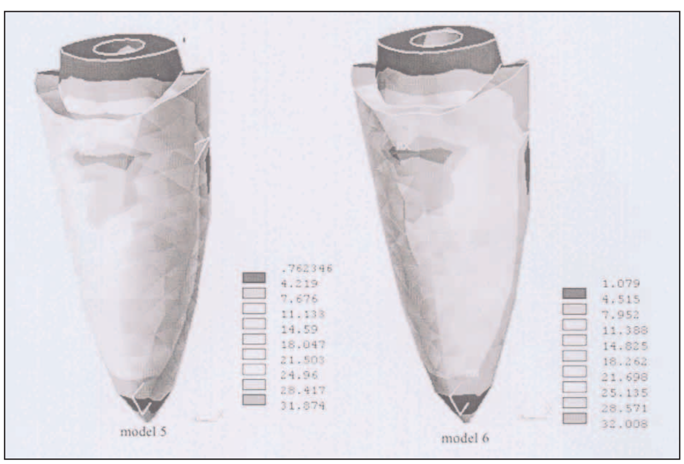

Figure 3*C: Maximum Von Mises equivalent stress distribution in dentin for models 5 and 6.*

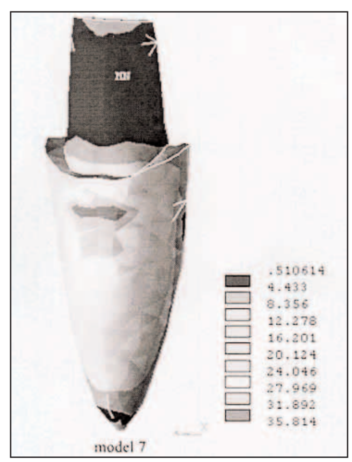

Figure 3*D: Maximum Von Mises equivalent stress distribution in dentin for model 7 (control).*

Table 5: *Ratios of Von Mises Stress Distribution in Dentin*

	Vmmax/Vmmax*
Model 1	0.886
Model 2	0.889
Model 3	0.988
Model 4	0.924
Model 5	0.889
Model 6	0.893
Model 7	1

Vm_{max} : Von Mises stress distribution in tooth model with post-and-core
Vm_{max}* : Von Mises stress distribution in the control group model (35.814 MPa)

dentin for models 1 through 6 were 0.886, 0.889, 0.988, 0.924, 0.889 and 0.893, respectively, and are listed in Table 5. Stress progressively decreased towards the apex. According to these values, zirconia ceramic posts created slightly less Von Mises stress concentrations in dentin than glass-fiber reinforced composite and titanium posts.

Zirconia ceramic posts with ceramic core exhibited slightly less stress concentration in dentin when compared with zirconia ceramic posts with composite core. The cosmopost system created slightly less dentinal stress concentration than the Cerapost system.

The insertion of posts into the root canal decreased the maximum Von Mises equivalent stresses in dentin.

DISCUSSION

FEA is a basic research tool that is widely being used in dentistry. When FE modeling is compared with laboratory testing, it offers several advantages. The variables can be changed easily, simulation can be performed without the need for human material and it offers maximum standardization. Although numerical results can be easily obtained in two-dimensional modeling and is not time-consuming, it has some significant shortcomings: the human tooth is highly irregular, such that it cannot be simulated without taking the third dimension into consideration. Distribution of various materials of the tooth structure does not show any symmetry; therefore, a 3-D model with actual dimensions should be preferred for a reliable analysis (Borchers & Reichart, 1983). However, due to the complexity of tooth structures (enamel, dentin), they cannot be considered as homogeneous. The physical properties of biologic structures (bone, tooth, soft tissues) are only approximations, since all materials are considered homogeneous and have a linear response to stress. However, in a living organism, the response of these structures to stress is more complex, and the accuracy of a 3-D FEA relies on the precision of the simulation model. FEA is used as an initial step and an aid for planning further laboratory tests and clinical studies that will reduce inaccuracies inherent with the FEA method. Clinical studies also need to show the longevity and success rates of post systems.

Because of the vast degree of variance in human tooth sizes, a maxillary central incisor believed to represent an average size was adapted from Wheeler (1962). The maxillary central incisor was selected because of its likelihood of being subjected to oblique occlusal stresses. The principle stresses are, in fact, normal stresses that act on principal planes on which the shearing stresses are zero. The reason for selecting the Von Mises criteria, which apparently results in a tensile type normal stress, lies in the fact that brittle materials, of which the tooth is a member, fail primarily due to tensile-type normal stresses.

One study (Sorensen & Engelman, 1990b) reported that coronal dentin above the shoulder decreased stress concentration in dentin, so, in the modeling process of this study, a ferrule design was created in the proximal, lingual and buccal surfaces at the cervical region. All FE models contained a periodontal ligament and cortical and cancelous bone, since it has been suggested that the periodontal ligament and alveolar bone should be considered in FE studies of teeth (Rees, 2001). The combination of a tooth-colored core and restorative material was chosen, considering that a ceramic crown should restore an endodontically treated tooth for optimum esthetic results. More esthetic results are achieved at the anterior region by using the layering technique rather than the staining technique.

Since the ratios would remain the same based on an increase or decrease in model size, the maximum Von Mises equivalent dentinal stresses of groups 1 through 6 were divided by the stresses of the control group.

All posts modeled in this study were tapered, except for the CosmoPost, which has a parallel-sided, tapered-end shape. The differences between the two different zirconia ceramic post systems (Cerapost and CosmoPost) were the diameter and shape. Parallel-sided tapered-end post design is the most favorable design biomechanically (Smith, Schuman & Wasson, 1998). Isidor and Brondum (1992) reported a wedging effect attributed to tapered posts, while other research could not demonstrate any differences between parallel-sided and taper-end posts (Assif & others, 1993).

This 3-D FE study demonstrated that zirconia ceramic resisted bending forces more than titanium and glass fiber reinforced composite due to a higher modulus of elasticity. As a result, a zirconia ceramic post is loaded more frequently than the latter two. Consequently, stresses acting on the dentin decrease. This finding in the current study is in accordance with a study reported by Ho and others (1994). In that study, 3-D models were created, and it was found that the greater the modulus of elasticity of posts, the greater the decrease in dentinal stress distribution during masticatory loading, and the greater the modulus of elasticity of posts, the greater the increase in dentinal stress distribution during traumatic loading. The same results were observed in a study reported by Yang and others (2001). Glass fiber-reinforced composite posts and titanium posts may demonstrate deformations under simulated masticatory loadings. This may result in greater stress concentration in dentin and may lead to fracture (Lambjerg-Hansen & Asmussen, 1997). Titanium posts showed less deformation than glass-fiber reinforced composite posts. However, Rosentritt and others (2000) reported that glass fiber posts exhibited a modulus of elasticity that was far better matched to teeth than zirconia and titanium. Due to the high modulus of elasticity of zirconia, forces were transmitted directly to the post/tooth interface without stress absorption (Mannocci & others, 1999). This may lead to a decrease in fracture resistance of the tooth.

If the modulus of elasticity of the core material is similar to the post material, a more uniform stress distribution within the entire post-and-core restoration and within dentin is achieved, while the restoration's resistance is increased against the high forces of mastication (Asmussen, Peutzfeldt & Heitmann, 1999). In this study, the maximum stress concentrations created in dentin were nearly the same as in the zirconia ceramic post with composite core groups and with the ceramic core groups.

When two different zirconia ceramic post systems were compared, the maximum stress concentrations created in dentin were nearly the same, although the diameter of Cerapost was greater than CosmoPost.

CONCLUSIONS

The results of this 3-D FEA indicated that the use of posts did not affect the region of dentinal stress concentration in endodontically treated maxillary central incisors. Zirconia ceramic posts used with the ceramic core created nearly the same dentinal stress concentrations when compared with those used with composite core.

Zirconia ceramic posts created slightly less dentinal stress concentration in the dentin of maxillary central incisors, although dentinal stress concentration in dentin created by glass fiber reinforced posts and titanium posts were nearly the same when compared with endodontically treated maxillary central incisors.

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