Three-dimensional finite element analysis of a maxillary central incisor restored with different post-core materials

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Purpose: To provide a theoretical guidance to post-core choice by analyzing dentinal stress of post-restoration with six types of post-core materials.
Materials and Methods: A three-dimensional (3D) finite element model (FEM) of maxillary central incisor restored with porcelain fused to metal crown (PFM) was constructed using spiral CT scan technology. By comparing the restored incisor with PFM as a control model, the stress distribution pattern in the dentine after post restoration was analyzed upon using six types of post-core materials, cast Ni-Cr alloy, cast titanium alloy, cast gold alloy, glass fiber reinforced composite resin, and polyethylene fiber reinforced composite resin, as well as common composite resin.
Results: Compared to the control model, the maximum principal and von Mises stresses in coronal dentin decreased by 26% and 27.8% respectively, while those in post-apex dentine increased by 152% and 162% respectively in post-apex when cast Ni-Cr alloy was used as a post-core. Significant change in maximum stresses was also found in dentin when the first four restoration materials were used as post-core.
Conclusion: Material with low elastic modulus similar to that of dentin, such as polyethylene fiber reinforced composite, may be more ideal for post restoration with respect to the stress distribution in dentin.
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Key Words: dentin, elastic modulus, finite element analysis, post-core material, stress.

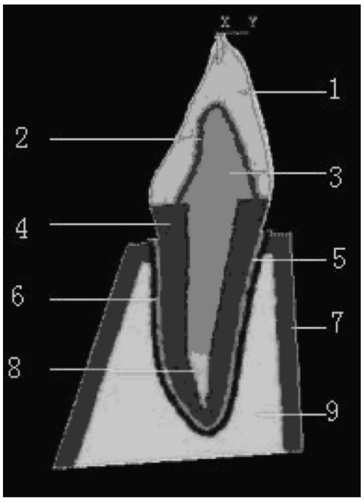
Introduction

Post and core build-ups represent an important pre-prosthetic procedure prior to the restoration of an endodontically treated tooth. The dental practitioner is often presented with the dilemma of selecting post-core materials from an ever increasing variety of available materials, many of which are harmful or controversial in use. Materials used for post-core include both metal and nonmetal. Metal post-cores are generally made of gold alloys, stainless steel, titanium alloys, pure titanium, and brass alloys. Nonmetal post-cores are generally produced with zirconium oxide,[1] composite and other types of fiber reinforced composites. Many researchers have investigated the physical, chemical and biomedical characteristics of different types of materials and suggested ideal post-core build-ups by considering their mechanical properties. However, the conclusions are diverse.[2,3] Ko et al.[2] suggested that the materials with high elastic modulus can be made small in diameter. In this case, a small amount of dentin is removed so as to retain more usable dentin. On the other hand, Pegoretti et al.[3] recommended that it is ideal for the post-core materials to have a similar elastic modulus to that of dentin, because such materials do not significantly change the stress distribution characteristics of the dentin and are convenient for re-restoration if the initial restoration is failed.

The finite element method (FEM) is based on a mathematical model which approximates the geometry, loading, and constraint conditions of a structure to be analyzed. Deformations and stresses at any point within the model can be evaluated and highly stressed regions can then be identified. Research is limited in the area of three-dimensional (3D) finite element analysis (FEA) of stress distribution in post restored teeth.[3-6] In particular, little work is published in relation to the materials used as post-core build-ups in clinical practice. The aim of the present work is thus to analyze the stress distribution characteristics in dentin with different post-core models. The outcome of this research is to provide a theoretical guidance for the dental clinicians in selecting appropriate post-core materials in their practice.

Materials and Methods

A volunteer with a near standard maxillary central incisor consisting of a dental corona of 11.1 mm and a root of 11.5 mm was selected. The subject was given an informed consent prior to the commencement of this study. The maxillary bone and tooth of the volunteer were scanned by a spiral CT (GE Medical Systems, Milwaukee, WI, USA). The image data were saved in a bitmap format and imported into an in-house computer program. Following a series of process (preprocessing, image subdivision, and outlining), a contour data were obtained and subsequently imported into the general purpose software SolidWorks (Solidworks Corp., Boston, MA, USA). Through a sequential processing (lofting, shelling, Boolean calculus, etc.), a solid model of the maxillary central incisor with PFM was produced. The solid model consisted of nine components; porcelain, metal base, post-core, dentin, cementum, periodontal ligament, gutta-percha, cancellous bone, and cortical bone (Fig. 1). The length and diameter of the post-core was respectively 2/3 and 1/3 of those of the dental root. The shape of the post-core was identical to the root canal. A computer aided engineering software FEMAP (UGS Corp., Plano, TX, USA) was used for mesh generation of the solid model. The complete finite element model contained 126,912 nodes and 86,369 tetrahedron elements.



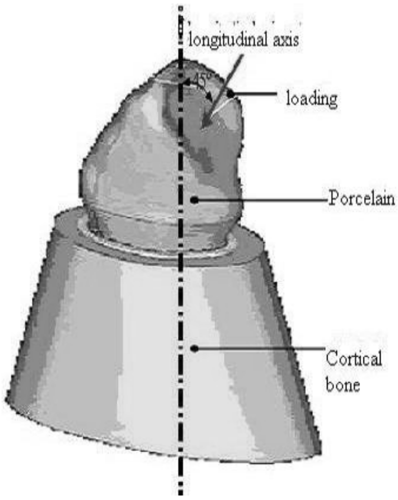


Fig. 1. (left) Vertical section of solid model with PFM crown. 1, porcelain; 2, metal base; 3, post-core; 4, dentin; 5, cementum; 6, periodontal ligament; 7, cortical bone; 8, gutta-percha; 9, cancellous bone).

Fig. 2. (right) Loading condition.

To simulate the functional masticatory force, a 100 N load was applied at 45° with respect to the longitudinal axis of the tooth. The concentrated load was converted to a uniformly distributed load which was applied through five nodes on the boundary of incisal 1/3 and middle 1/3 in lingual surface (Fig. 2).[7,8] A fixed restraint was applied to all the nodes on the bottom surface of each model.[9] All materials were assumed to be homogeneous, isotropic and have linear elastic behavior. The material properties are summarized in Table 1.[3,10-13]

In this study, six types of post-core materials with different elastic moduli were selected for the finite element analysis. Amongst the six, three metal materials were often used in clinical practice, cast Ni-Cr alloy, cast titanium alloy and cast gold alloy. The other three nonmetal materials have also been used in recent years, glass fiber reinforced composite, polyethylene fiber reinforced composite, and common composite. The same model with ideal post-core material, whose elastic modulus is equal to dentin, will be considered as a control model.

Table 1. Material properties used in FEA models.

Restoration materials	Modulus of elasticity (GPa)	Poisson's ratio
Cancellous bone[10]	1.37	0.30
Cast gold alloy[10]	96.6	0.35
Cast Ni-Cr alloy[11]	210	0.33
Cast titanium alloy[12]	120	0.33
Cementum[10]	13.7	0.30
Common composite[10]	8.3	0.28
Cortical bone[10]	13.7	0.30
Dentin[10]	18.6	0.31
Enamel[10]	84.1	0.30
Glass fiber reinforced composite[3]	45	0.32
Gutta-percha[10]	0.00069	0.45
Periodontal ligament[10]	0.0689	0.45
Polyethylene fiber reinforced composite[13]	23.6	0.32
Porcelain[10]	96	0.29

A total of seven 3D FEA models including the control model and those with six different post-core materials were established and analyzed using the finite element software ANSYS (Swanson Analysis Systems, Inc., Pittsburgh, PA, USA). The maximum principal (tensile) $\sigma_{11,max}$ and von Mises stresses $\sigma_{vM,max}$ in dentine were obtained for different models with different post-core materials.

Results

Regardless of the model with any post-core material, $\sigma_{11,max}$ were mainly found in dentin at around coronal 1/3 of the root on the lingual side; whereas $\sigma_{vM,max}$ mainly occurred on the outer layer of dentin at the same location on both the facial and lingual sides. Details of $\sigma_{11,max}$ and $\sigma_{vM,max}$ at around the coronal part of the root are given in Table 2, while those at the root apex are presented in Table 3. It can be seen that the magnitudes of both $\sigma_{11,max}$ and $\sigma_{vM,max}$ are higher at around the coronal part of the root than those at the root apex. Further, both $\sigma_{11,max}$ and $\sigma_{vM,max}$ are considerably low at the root apex for models restored with polyethylene fiber reinforced composite and common composite. Note that in Table 2, a reduction ratio was calculated in relation to the stresses of the control model. Table 3, on the other hand, shows an increase rate as compared to the control model.

Table 2. $\sigma_{11,max}$ and $\sigma_{vM,max}$ (MPa) in dentin at coronal part of the root.

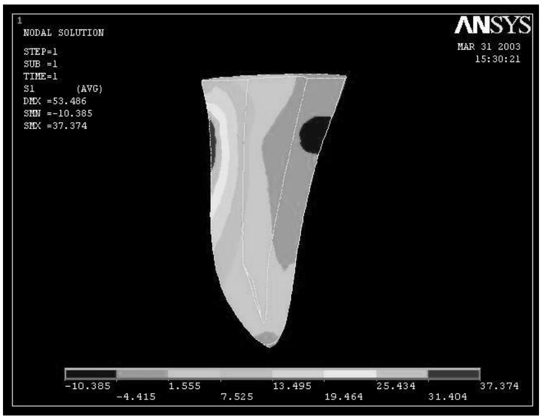
Restoration materials	$\sigma_{11,max}$		$\sigma_{vM,max}$	
	Magnitude	Reduction ratio	Magnitude	Reduction ratio
Control model	37.61		33.46	
Cast Ni-Cr alloy	27.84	-26.0	24.15	-27.8
Cast titanium alloy	31.24	-16.9	27.33	-18.3
Cast gold alloy	32.32	-14.0	28.44	-15.0
Glass fiber reinforced composite	35.25	-6.3	31.42	-6.1
Polyethylene fiber reinforced composite	37.04	-1.5	32.98	-1.4
Common composite	39.25	4.4	34.21	2.2

Reduction ratio (%) = (maximum stress of restored model - maximum stress of control model) x 100/ maximum stress of control model

Table 3. $\sigma_{11,max}$ and $\sigma_{vM,max}$ (MPa) in dentin at root apex.

Restoration materials	$\sigma_{11,max}$		$\sigma_{vM,max}$	
	Magnitude	Increase rate	Magnitude	Increase rate
Control model	9.2		7.53	
Cast Ni-Cr alloy	24.11	162.0	18.95	151.8
Cast titanium alloy	20.84	127.0	16.52	119.0
Cast gold alloy	18.30	99.0	12.12	61.1
Glass fiber reinforced composite	15.76	71.3	10.60	40.9
Polyethylene fiber reinforced composite	14.08	53.0	4.82	-36.0
Common composite	13.55	47.3	3.09	-59.0

Increase rate (%) = (maximum stress of restored model - maximum stress of control model) x 100 / maximum stress of control model



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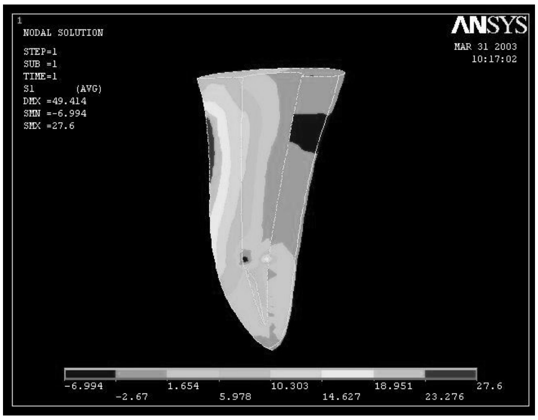

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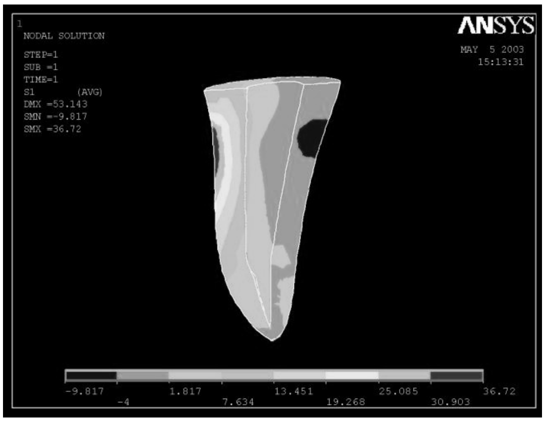

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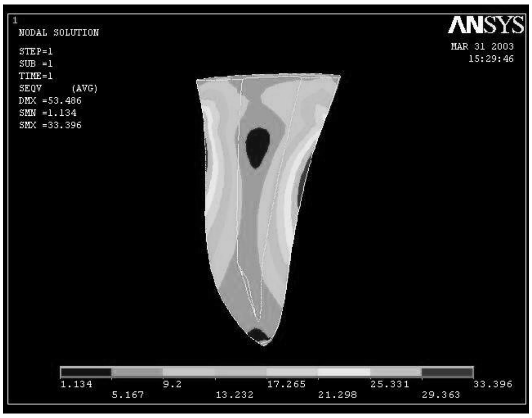

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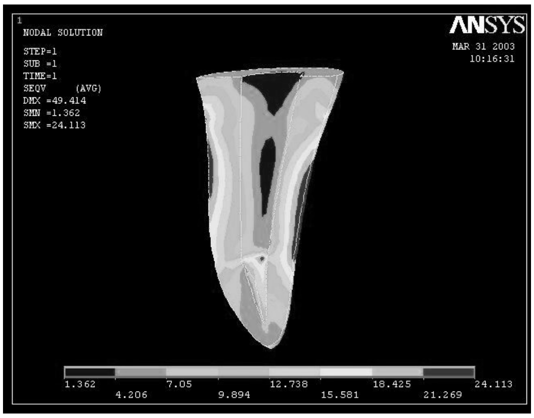

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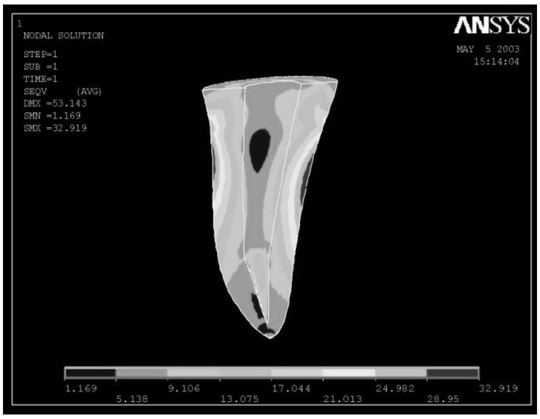

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Fig. 3. Stress distribution contour of maxillary central incisor in different models.
a, Control model (σ_{11}); b, Ni-Cr post (σ_{11}); c, Polyethylene fiber reinforced composite post (σ_{11}); d, Control model (σ_{vM}); e, Ni-Cr post (σ_{vM}); and f, Polyethylene fiber reinforced composite post (σ_{vM})

When cast Ni-Cr alloy was used as a post-core, the $\sigma_{11,max}$ and $\sigma_{vM,max}$ in dentin at around the coronal 1/3 of the root decreased by 26% and 27.8% respectively, while significantly increased by 151.8% and 162% respectively at the root apex, as compared to the control model. When the post-core material was glass fiber reinforced composite, cast gold alloy and cast titanium alloy, the $\sigma_{11,max}$ and $\sigma_{vM,max}$ decreased by 6.3%-16.9% and 6.1%-18.3% respectively at the coronal part of the root whereas increased by 40.9%-119.0% and 71.3%-127% respectively at the root apex. However, when the nonmetal materials, the polyethylene fiber reinforced composite or the common composite was used, both $\sigma_{11,max}$ and $\sigma_{vM,max}$ had little change at around the coronal part of the root. Note that $\sigma_{vM,max}$ had a small increase at the root apex (13.55 MPa and 14.08 MPa versus 9.2 MPa in the control model); but such an increase (47.3%-53.0%) was insignificant as compared to metal post-core models (99.0%-163% increase). Further, $\sigma_{11,max}$ at the root apex decreased showing negative increase rates (-36.0% and -59.0% for polythene fiber reinforced and common composites, respectively).

Fig. 2 shows the stress distribution patterns of the control model, the cast Ni-Cr alloy and the polyethylene fiber reinforced composite post models. Shown in Figs. 2(a) and (d) are the distribution of σ_{11} and σ_{vM} for the control model. The $\sigma_{11,max}$ were mainly found in the outer layer of the coronal dentin - at around coronal 1/3 of the root on the lingual side; whereas the $\sigma_{vM,max}$ mainly occurred at the same location on both the facial and lingual sides. The maximum stress locations were similar in models with Ni-Cr and polyethylene fiber reinforced composite posts, except that the maximum stress regions expanded towards the apex in the Ni-Cr post models.

Discussion

The FEM has been used extensively in dental biomechanics research. The method is powerful and versatile in that it can provide detailed information on stresses, strains and displacements within complex structures such as teeth and restored teeth with post-core materials. Previous research[3-6] has demonstrated that 3D modeling is effective in analyzing stress distribution characteristics in dentin and post, and such a technique is used in this study.

In this study, six types of representative post-core materials were selected and their elastic moduli ranged from 8.3 GPa to 210 GPa, covering a wide range of available post-core materials used in clinical practice. The post-core systems studied herein consisted of components (dentin and the post-core material) of different elastic moduli. This study has demonstrated that the stress distribution patterns in dentin of a restored tooth are similar if the elastic modulus of the post-core material is close to that of dentin. Hence the elastic modulus is one of the important parameters to evaluate when choosing an appropriate post-core material for dental restoration. The outcome of this study can be used as a reference when other materials are chosen to be post-cores, for example carbon fiber reinforced composites, pure titanium, and zirconium oxide.

The study also demonstrated that when the elastic modulus of the post-core material increased, the maximum stresses in the coronal part of the root dentin deceased, whereas the maximum stresses in the post-apex increased. It is evident from the stress distribution contour shown in Fig. 3 that the post-core with high elastic modulus reduced the maximum stress values in the coronal part of the root dentin, but the highly stressed region expanded along the surface of the root towards the apex. The higher the elastic modulus of the post-core material, the larger the expanded high stress region and more stress concentration at around the post-apex. When the cast Ni-Cr alloy (with the highest elastic modulus) was used as post-core, the highly stressed region on the root surface covered form the coronal part of the root dentin all the way to the level of post-apex. This, together with the two stress concentration areas, formed a large highly stressed region over the entire cross section of the root (Fig. 3(e)). This in turn increased the likelihood of fracture of the dentin. The post with low elastic modulus, on the other hand, did not reduce the maximum stress values of the coronal part of the root dentin; neither caused stress concentration at the post-apex. When the polyethylene fiber reinforced composite, of which the elastic modulus was similar to that of a dentin, was used as a post-core, the stress distribution characteristics were very similar to those of the control model restored with PFM.

The above FEM results can be elaborated from the mechanics point of view. When the elastic modulus of the post is high, the load carrying capacity of the post itself is also high. In other words, the post absorbs more loading which in turn reduces the stress in dentine at the post level, and shifts the stress concentration region to the post-apex level. Considering the fact that the coronal part of the root dentin is much thicker than the post-apex, the likelihood of fracture of the post-apex is much higher than the coronal part under the same stress condition. Hence it is more important to reduce the stresses in the post-apex region.

The placement of the post-core changes the stress distribution patterns within the dentin, which largely correlated with the elastic modulus of the post. Before post restoration, the induced stresses transfer from the coronal part to the apex along the surface of the root. The interior part of the root where the post is placed is lowly stressed. This situation is changed when placing a post with high elastic modulus where the post itself attracts a large amount of the load. As a result, the stresses within the root decrease except the post-apex region. When the elastic modulus of the post is low, the load absorbed by the post is small and the remaining load must be supported by the out layer of the dentin. This study showed that, when the elastic modulus of the post was high, the primary load supporting element is the post and stress concentration was high. When the elastic modulus of the post was small, the post did not attract much load which caused little change on the stress distribution within the root dentin. The finding of this study is also supported by the work of Albuquerque et al.[14] and Toparli et al.[15] who claimed that stainless steel posts presented the highest level of stress concentration.

Although the stress distribution characteristics in root dentin restored with different post-core materials have been successfully evaluated in this study, certain limitations are recognized by the authors. These include the assumptions made on the properties of the post materials and tissues used in the finite element analysis, as well as the simplified loading scenarios. Note that this study was not intended to determine the absolute numerical stress levels created within the restoration but to examine the stress distribution patterns due to different post-core materials. Note also that failure of the models was outside the scope of this study, therefore the magnitude of the load would only proportionally alter the magnitude of the stresses. Moreover, the theoretical study conducted herein should be validated in relevant clinical and in vitro experimental work, which will help further develop key principles for post restoration.

In conclusion, this study successfully demonstrated that the FEM was effective in analyzing stress distribution characteristics in dentin and post. The study has verified that the elastic modulus is one of the important parameters to evaluate in post restoration. The results have provided some useful guidance for clinical practice. Within the limitations of this study, the results suggested that the polyethylene fiber reinforced composite with elastic modulus similar to that of a dentin is more suitable for post-core restoration. The extensively used cast Ni-Cr alloy, cast titanium alloy, and cast gold alloy are considered to be less appropriate. Results of this study further confirmed the principle that the elastic modulus of the restoration material should be as close as that of a dentin. This is supported by the recent move of the dentists who have changed from using very rigid materials to those that closely resemble dentin in an attempt to produce a mechanically homogenous unit.[16,17]

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