A finite element analysis of stress distribution in roots with different types of post systems

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Purpose: The purpose of this study was to evaluate the stress distributions of various post and core systems and determine which post and core system contributes to preventing stress concentration and root fracture.
Materials and Methods: Following seven models were fabricated; a natural tooth model (NT), a vital tooth with preparation for a crown model (VT), a cast metal post and core model (CP), and composite resin core with four types of prefabricated post models. These prefabricated post materials were stainless steel post (SP) and three types of glass fiber posts (FP3, FP29, FP45) with different Young's modulus. In all models, stress distribution during function was calculated.
Results: Around base of the post and end of the post, SP and CP gave rise to higher stress concentration and FP3, its Young's modulus was the lowest among all types of posts, is the exhibited the lowest stress concentration.
Conclusion: Within the limitation of this study, FP3 was found to be the most suitable candidate.
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Key Words: nonlinear finite element analysis, post and core, root fracture, von Mises stress, Young's modulus

Introduction

Cast metal post and cores have traditionally been used to restore endodontic treated teeth, because they are superior in mechanical strength compared to other post and core systems [1-3]. However, a large difference in Young's modulus between metal and dentin may cause stress concentration around the end of the post, sometimes resulting in vertical root fracture [2,4,5] which leads to the extraction of teeth [6]. Recently, composite resin cores have been used instead of cast post and cores. The reason for the replacement is that a similarity in Young's modulus between composite resin and dentin [4,5] may lead to reduce the stress concentration within the root and prevent serious vertical root fractures. Other advantages using composite resin cores include the prevention of the elution of metal ions that can cause metal allergy [7] and the satisfaction of aesthetic demand, for example, shade and translucency when all ceramic crowns or polymer-based restorative material crowns are chosen as the final restoration [8,9]. On the other hand, there has been reported that the stress is concentrated around the cervical area [10-12]. Therefore composite resin cores will sometimes lead to repairable horizontal root fracture [4]. The composite resin core is usually built up in conjunction with a post. There are various kind of post materials such glass fiber [4,9,13], carbon fiber [14], stainless steel [4], quarts fiber [4,15] and titanium [15]. The large difference in Young's modulus among these materials may influence the magnitude and distribution of stress within the root. Above all, glass fiber posts with Young's modulus similar to dentin have been more commonly used with composite resin cores. Furthermore, there are many kinds of glass fiber posts with various Young's modulus [4,5,16-18]. However, no consensus of opinion exists on which post system is most suitable for composite resin cores.

The purpose of this study was to evaluate the stress distributions of various kinds of post and core systems during function and determine which post and core system contributes to preventing stress concentration and root fracture.

Materials and Methods

In this study, three-dimensional nonlinear finite element simulation model of a premolar was fabricated and analyzed using finite element analysis software (MSC Marc Mentat 2003, MSC Software Corp., Santa Ana, CA, USA) in accordance with previous reports [10,11]. The simulation tooth model was 18 mm long with a diameter of 6 mm at the crown margin level. The apical 12 mm of the root was modeled as invested in a socket of lamina dura 0.3 mm thick and had a uniform periodontal ligament thickness of 0.2 mm. The remaining bone was modeled as cancellous bone and cortical bone (Fig. 1).

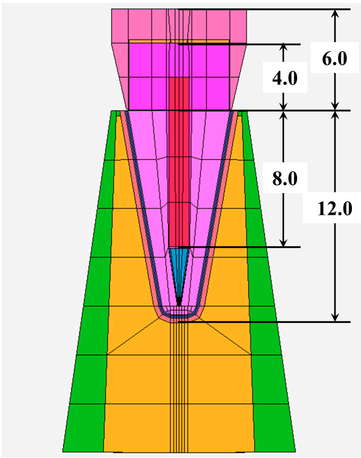

Fig. 1
The dimensions and elements of the complete model (mm)

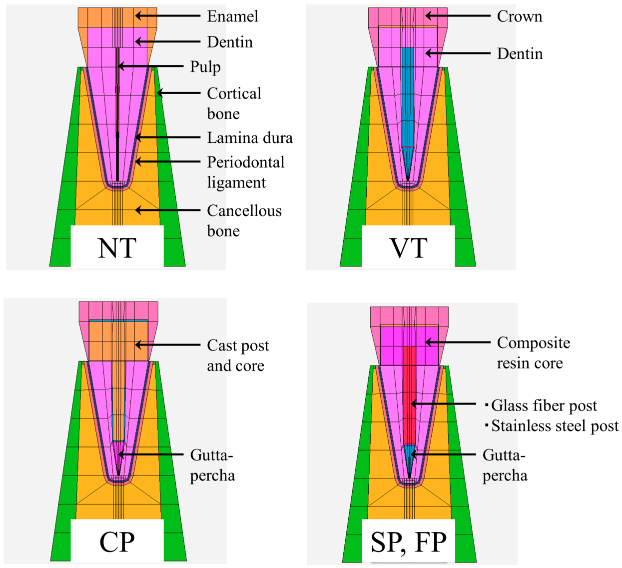

Fig. 2 Finite element analysis models
NT, a natural tooth model;
VT, a vital tooth with preparation for a crown model;
CP, a cast metal post and core model;
SP, a composite resin core with stainless steel post;
FP, a composite resin core with glass fiber post

Following the criteria of the simulation tooth model, seven models were fabricated; a natural tooth model (NT), a vital tooth with preparation for a crown model (VT), a cast post and core model (CP), and composite resin core with four types of prefabricated post models. These prefabricated post materials were stainless steel post (SP) and three types of glass fiber posts with different Young's modulus (FP3, 3,000 MPa; FP29, 29,200 MPa; and FP45, 45,000 MPa) (Fig. 2).

The CP, SP, FP3, FP29, and FP45 models, it was assumed that they were endodontically treated. Therefore, these models consisted of a crown, luting agent, post and core, dentin, gutta-percha, periodontal ligament, lamina dura, cancellous bone, and cortical bone (Fig. 2). On the other hand, in NT and VT, it was assumed that they were vital teeth. Therefore, only the dental pulp was included in the composition materials (Fig. 2).

Each element was assigned unique elastic properties to represent the modeled materials (Table 1) [8,13,19-26]. Homogeneity, isotropy, and linear elasticity were assumed for all materials except for the periodontal ligament, including continuous interfaces between materials. A nonlinear elastic property was applied to the periodontal ligament because it has viscoelastic properties (Fig. 3) [23,27]. The approximate function for periodontal ligament used in this study was adapted from a previous research [23].

Table 1 Mechanical properties of materials

	Young's modulus (MPa)	Poisson's ratio	Reference
Enamel	80,000	0.3	[20]
Dentin	15,000	0.31	[20]
Dental pulp	2	0.45	[22]
Periodontal ligament	Nonlinear elastic	Nonlinear elastic	[23]
Lamina dura	13,700	0.3	[19]
Cancellous bone	345	0.31	[20]
Cortical bone	13,700	0.3	[19]
Gutta-percha	0.69	0.45	[8]
Gold-silver-palladium alloy	86,000	0.33	[21]
Composite resin core	12,000	0.33	[25]
Glass fiber post (FP3)	3,000	0.3	
Glass fiber post (FP29)	29,200	0.3	[13]
Glass fiber post (FP45)	45,000	0.3	
Luting agent	4,500	0.4	[20]

Abbreviations as in Fig. 2

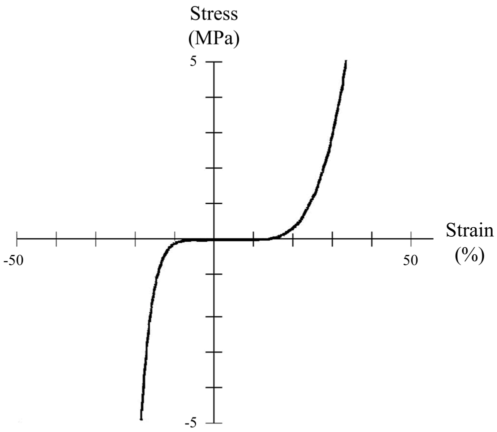

Fig. 3
Material property of periodontal ligament [28]

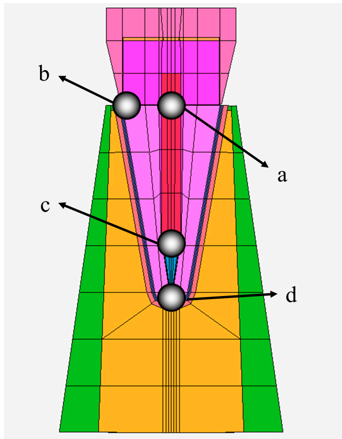

Fig. 4 Measurement points (a-d)
a, base of the post; b, cervical area;
c, end of the post; d, apex of the root

During function, the amount of distortion of the periodontal ligament was larger compared to other components. Therefore, the number of layers of the periodontal ligament was determined as three to improve the accuracy of finite element analysis results [10]. The model was absolutely restrained at all nodes on the bottom surface of the cortical bone and cancellous bone. In general, the shape of elements was tetrahedron, but we developed the hexahedral shape of element to increase the precision of finite element analysis results.

The information obtained in previous studies of occlusal force during beef jerky mastication measured with the three-dimensional occlusal force sensor [10,11] was used in this study. The data of three dimensional occlusal forces used as reference for the palatal, distal, and apical directions were 23.9 N, 28.9 N, and 164.3 N respectively [10,11]. That data was applied to a node located at the center of occlusal surface. Stress produced in the dentin of each root was calculated as von Mises stress, and stress distribution in the root was analyzed. Magnitude of von Mises stress around base of the post, cervical area, end of the post, and apex of the root were compared (Fig. 4).

Results

The von Mises stress distributions within the root of seven models during masticating beef jerky were observed (Fig. 5). The von Mises stress around the base of the post, the cervical area, the end of the post, and the apex of the root were analyzed (Table 2).

The magnitude of von Mises stress of composite resin core with four types of prefabricated post models (SP, FP3, FP29, FP45) were higher than that of CP around the cervical area. On the other hand, SP and CP produced higher stress concentration than composite resin core with three types of fiber post models (FP3, FP29, FP45) around the base of the post and the end of the post.

Among the vital tooth models, VT showed high-stress values around the cervical area of root compared with NT. In addition, at almost all of the points, the magnitude of von Mises stress of NT tended to be the lowest among all models.

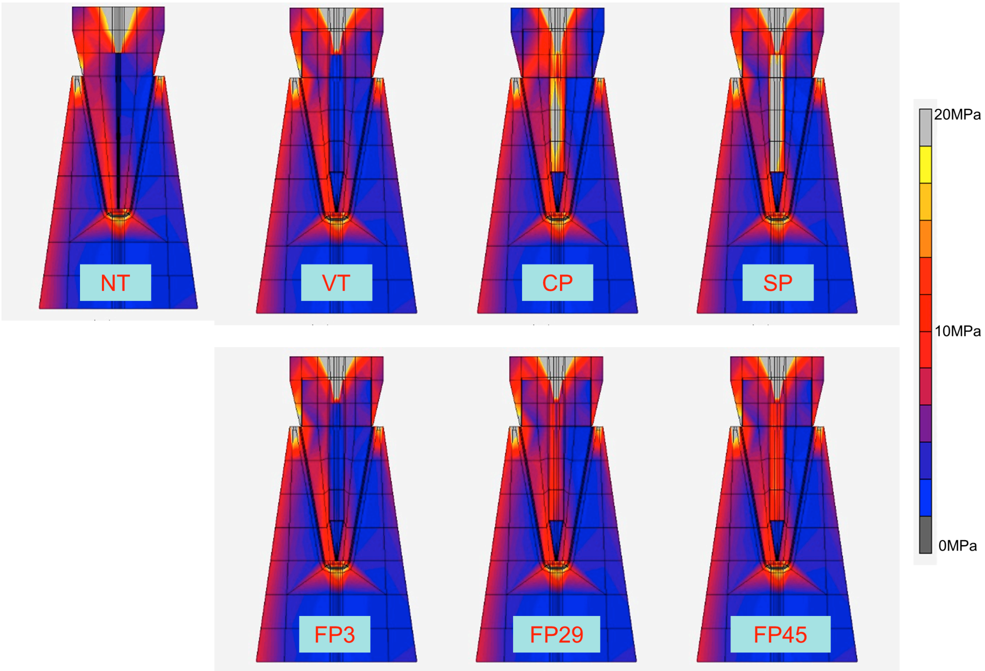

Fig. 5 Comparison of von Mises stress distributions for seven models

Table 2 Magnitude of von Mises stress at each analysis point by finite element analysis (MPa)

	NT	VT	FP3	FP29	FP45	SP	CP
Base of the post	2.1	1.7	1.9	6.3	8.6	25.7	15.5
Cervical area	6.2	15.3	14.6	14.3	14.2	13.4	10.5
End of the post	10.6	11.2	4.9	9.6	11.8	23.4	16.0
Apex of the root	14.5	14.7	14.5	14.5	14.5	14.5	14.6

Abbreviations as in Fig. 5

Discussion

The strain gage methods [6,12,28], loading tests [13,28,29], photoelastic analyses [30,31], and finite element methods [1,18,32,33] have been used to evaluate the possibility of root fractures. Each method has its own suite of advantages and disadvantages. With the strain gage method, it is possible to accurately measure the magnitude of the strain on the teeth or restorations surface under loading; however, it can't directly measure the internal strain. Although loading tests can measure failure load and mode, they cannot analyze the stress distribution within teeth. Photoelastic analyses allow stress distribution to be observed in two or three-dimensional mode, but it is difficult to make models in detail and to analyze the magnitude of internal stress in teeth accurately.

The results of finite element analyses depend on its modeling methods, values assigned to the material properties, the position of restraint and the direction of occlusal force. However finite element analyses have been used for many investigations, because they can reproduce structures of various shapes of teeth with many elements defined with specific Young's modulus and Poisson's ratio values and the distribution and magnitude of stress at any point within the root can be precisely analyzed. In this study, finite element analyses were selected to investigate stress distributions within the root in three dimensions.

The probability of root fracture of endodontically treated teeth is higher than that of vital teeth. In clinical restorations, composite resin cores with prefabricated posts sometimes caused horizontal root fracture which is repairable, but cast posts and cores sometimes caused vertical root fracture which leads to extraction of the teeth.

To prevent catastrophic vertical root fracture, it is important to investigate stress distribution within the root in various kinds of post materials, especially around the end of the post because of vertical root fracture surface included around the end of the post [13,28,29]. This means there are stress concentrations around the end of the post. Horizontal root fracture is also undesirable incident for patients and dentists, although the horizontal root fracture can be retreated [4] in many cases. Therefore, it is necessary to investigate the stress distribution within the root around the cervical area also because stress around this area might be related to horizontal fracture. In this study, the magnitudes of von Mises stress of cast metal post and core and composite resin cores with three types of glass fiber posts and stainless steel post during function were calculated. The natural tooth model was assumed to be a control.

Composite resin core models with four types of prefabricated post material (FP3, FP29, FP45, SP) and VT produced higher stress levels around the cervical area compared with CP and NT. This result was corresponding to the previous reports [10,11]. It suggested that composite resin core cause to the horizontal root fracture regardless of prefabricate post materials. To prevent the horizontal root fracture, stress concentration around the cervical area should be reduced. Taking into consideration that there were no differences in the magnitude of von Mises stress around the cervical area among the composite resin core with four types of prefabricated post material models (FP3, FP29, FP45, SP), the crown materials, luting agent [11] and ferule [34] would affect the magnitude of stress.

In reconstructing endodontically treated teeth, the kind and combination of materials for restoration and marginal shape and position is important to prevent the root fracture [35]. For VT, the stress concentration around the cervical area cause to wedge-shaped defect which produce pain, thus there would to be little case of serious root fracture. SP and CP which were the models with metal cast posts, produced high stress concentration around the base of the post and the end of the post. In the case of SP and CP, there is a high possibility of root fracture compared with other restorations. Especially, SP produced the high stress concentration around both cervical area and the end of the post. This suggested that SP was at the greatest risk of vertical and horizontal root fracture in this study.

Among composite resin core models with three types of glass fiber post (FP3, FP29, FP45), stress concentration around the base of the post and the end of the post was decreased as the Young's modulus of glass fiber posts became small. That is, the model with the lowest Young's modulus of glass fiber posts (FP3) showed the lowest stress concentration around the base of the post and the end of the post. This also meant that FP reduced the most possibility of vertical root fracture. In the case of FP, stress distribution within the root of restored tooth was similar to that of NT and the risk of root fracture would be reduced. If the Young's modulus of fiber post is under 29,000 MPa, it might prevent root fracture since magnitude of von Mises stress of FP29 around end of the post was lower than NT.

In this study, it was assumed that the prefabricated post materials adhered completely to composite resin and the cast post and core adhered completely to the luting agent. The adhesive properties might have an effect of on the distribution of stress within the root [36-41]. Furthermore, the stress concentration to composite resin and luting agent might cause to interfacial failure between composite resin or adhesive agent and post materials.

Therefore, it was necessary to consider not only adhesive properties, but Young's modulus and Poisson's ratio of materials as choosing composite resin and luting agents. Result of this study revealed that the Young's modulus of post and core materials might affect distribution of stress within the root. Within the limitation of this study, FP3 (the lowest Young's modulus of glass fiber posts), was found to be the most suitable candidate in the viewpoint of avoiding catastrophic vertical root fracture. Also, the following conclusions were obtained:

1. Around base of the post, SP and CP gave rise to higher stress concentration and the magnitude of von Mises stress of VT and FP3 was about the same as that of NT.
2. As for VT, a larger stress was also concentrated around cervical area.
3. SP and CP produced high stress concentration around end of the post. It suggested that SP and CP cause to the vertical root fracture.
4. Composite resin core models with any post material produced high stress levels around cervical area. Consequently, it suggested that composite resin core cause to the horizontal root fracture.
5. Among composite resin core models with three types of fiber post, with a higher Young's modulus of glass fiber post, a larger stress tended to be concentrated around end of the post.

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