Stress distribution in luting agents with different post and core systems

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Purpose: Collapse of luting agent is one of the main causes of post and restoration detachment, but the stress distribution of luting agent is still unknown. The aim of this study was to analyze the stress distribution in the marginal area of the luting agent.
Materials and Methods: Two types of 3-dimensional root canal treated premolar finite element models were established; one was restored with composite resin core and glass fiber post (GFP), the other was cast post and core (MP). Both models were assumed to be restored with the metal restoration. In each model, two kinds of luting agents, composite resin luting agent (CC) and methyl methacrylate (MMA)-based luting agent (MMA), were applied.
Results: In the same post system, the stress in the CC had a more moderate attenuation amplitude from the restoration side to the dentin side. In contrast, the stress distribution in the MMA was concentrated on the restoration and dentin side, and the middle area suffered relatively little stress.
Conclusion: The stress concentration in the luting agents at the tooth cervical area is lower with an MP than with a GFP, while the stress concentrations in the luting agents at the post apexes are higher with an MP than with a GFP. At the cervical margin, the stress distribution in the CC gradually decreased from the restoration side to the dentin side and showed an even distribution with MMA.

(Asian Pac J Dent 2017; 17: 15-22.)
Key Words: core, nonlinear finite element analysis, post, root fracture, von Mises stress, Young's modulus

Introduction

A metal post and core are often used when restoring large tooth defects after root canal treatment due to excellent retention and force resistance [1-4]. In prosthetic restorations, luting agents play a vital role. As the capabilities of luting agent have improved, many types of luting agent have recently become available. The adhesive properties and Young's moduli substantially vary among different luting agents [5,6]. Due to differences in the Young's moduli of different luting agents, dental tissues and restorative materials, the stress applied to the luting agent is not evenly distributed. Highly focused stress within the luting agent may collapse certain parts of the luting agent or accelerate its aging process. Collapse of luting agents therefore one of the main causes of post and restoration detachment [6-10]. In a crown restoration, the luting agent serves as the mediator to transfer and disperse the stress from a dental prosthesis to an abutment tooth, and the adhesive properties of luting agent and Young's modulus are the key factors that affect the long-term durability of the dental restoration.

Among the various types of luting agents, resin-based luting agent has been increasingly applied in clinical practices due to its excellent adhesive properties and low micro-leakage rate [5,6,11]. It is commonly thought that a preferred luting agent should have a Young's modulus close to a natural tooth [12,13]. A matching Young's modulus allows a more even distribution of stress to the abutment tooth, luting agent and restorative materials, thereby reducing the possibility of crushing the luting agent due to stress concentration.

Fracture testing, photoelastic stress analyses and finite element analysis have often been used to analyze the distribution or the intensity of the stress in various parts of the tooth. However, because the luting agent is very thin compared with the abutment tooth and the prosthesis, it is difficult to measure the distribution and intensity of stress in the luting agent using the first two methods. Finite element analysis is currently one advanced method for stress measurement. With finite element analysis, the distribution and intensity of the stress in any part of the tooth can be measured. We measured the magnitude and direction of the occlusal force using a small three-dimensional occlusal force sensor. The obtained value of the occlusal force was used in this standard three-dimensional nonlinear finite element model for the mandibular first premolar [14]. The purpose of this study was to analyze the stress distribution and intensity in different types of luting agent on different post-and-core systems.

Materials and Methods

Finite element analysis software (MSC Marc Mentat 2013, MSC Software Corp., Santa Ana, CA, USA) was used to establish and analyze the three-dimensional nonlinear finite element model. Two different types of first mandibular premolar models were established. They were both set to represent a first mandibular premolar with complete restoration after root canal treatment, and palladium-silver alloy was used as the restoration material. A glass fiber post (GFP) and composite resin core were used in one model, while a cast-metal post and core (MP) were used in the other model. Two different types of luting agent, namely, a composite resin luting agent (CC) and a methyl methacrylate-based luting agent (MMA), were used to bond the restoration in each model. CC was used as the luting agent for the post in both models.

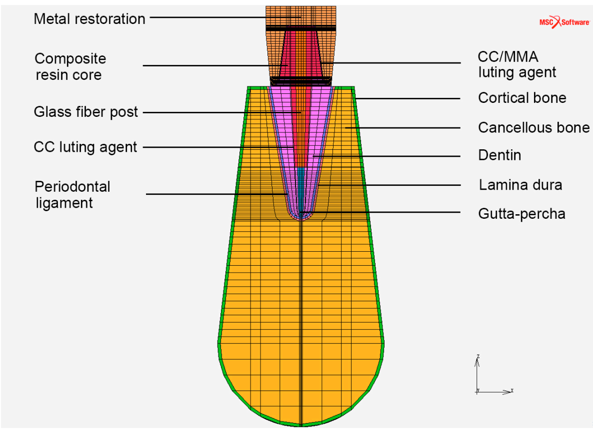

Fig. 1 Finite element analysis models

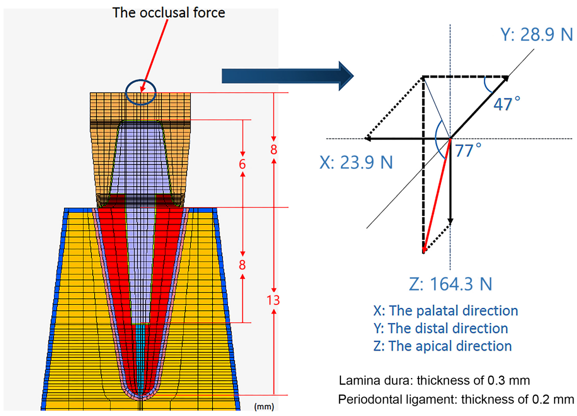

Fig. 2 The three-dimensional occlusal force

Each model comprised 57,904 elements and 58,643 nodes, including a metal restoration, luting agents, a post-and-core system, dentin, a gutta-percha point, a lamina dura, periodontal ligaments, cortical bone and cancellous bone. The thickness of the luting agent under the restoration was set to 100 µm. To obtain an accurate stress distribution in the layer of luting agent, the luting agent portion of the model was subdivided into a double-layered structure in each model to obtain 4,240 finite elements, thereby accounting for 7.3% of the finite elements in the overall model. The thickness of the lamina dura near the roots was set to 0.3 mm, and the thickness of the periodontal ligament was set to 0.2 mm. To more accurately simulate the actual situation, a shoulder-type tooth preparation was designed at the cervical margin of the abutment (Fig. 1).

The size of the model was set to the true proportion with the dental fixed on the lamina dura through the periodontal ligament of the mandibular first premolar. Additionally, the cortical bone and cancellous bone in the lower region of the model were established by imitating the morphology of the mandible. At the bottom surface of the model, all of the nodes of the cortical bones were set as restrained nodes. Furthermore, the contact points between each of the parts in the model were set as glued. The luting agent of the restoration and other small parts were treated with mesh refinement to avoid the phenomenon of element penetration during the phase of model analysis.

Table 1 Mechanical properties of materials

	Young's modulus (MPa)	Poisson's ratio	Reference
Dentin	15,000	0.31	[16]
Periodontal ligament	Nonlinear elastic	Nonlinear elastic	[18]
Lamina dura	13,700	0.3	[15]
Cancellous bone	345	0.31	[16]
Cortical bone	13,700	0.3	[15]
Gutta-percha	0.69	0.45	[19]
Composite resin core	12,000	0.33	[12]
Glass fiber post	29,200	0.3	[21]
Gold-silver-palladium alloy	86,000	0.33	[17]
CC	18,000	0.3	[20]
MMA	4,500	0.4	[14]

In all of the models, each unit was assigned an individual elastic property that matched the property of the material in the corresponding tooth part (Table 1) [12,14-21]. Corresponding linear elasticity values were assigned to all portions of the model except the periodontal ligament. The elastic property of the luting agent for the restoration was set as follows. CC (18,000 MPa) has a Young's modulus similar to dentin (15,000 MPa), while the Young’s modulus of MMA (4,500 MPa) is different from that of dentin. Because of its viscoelasticity, the periodontal ligament was individually assigned a nonlinear elastic property [18,22].

The three-dimensional occlusal forces measured using the occlusal force sensor during beef jerky chewing were 28.9 N (distal), 23.9 N (palatal), and 164.3 N (apical) (Fig. 2) [14]. These occlusal forces were applied to the central node of the occlusal surface with a reaction time of one second using the finite element software. This analysis obtained the distribution of the von Mises stress in various parts of the tooth and prosthesis and revealed the intensity of the von Mises stress in the luting agent at the cervical margin and at the post apexes.

Results

As shown in Figs. 3 and 4, the distributions of the von Mises stress in the luting agents of all the models were mainly concentrated in the post apexes and at the cervical margins of the teeth. Neither the material for the post-and-core system nor the luting agent type changed the concentration areas of the von Mises stress in the luting agents. When using the same luting agent, the von Mises stresses in the luting agents at the post apexes with a GFP were lower than at the apexes with an MP, while the results at the cervical margin showed the opposite pattern.

As observed in Fig. 5, the magnitude of the stress in the luting agent of each model gradually decreased in the cervical margin area with increasing distance from the cervical side to the post apex; that is, the attenuation curve on the restoration side of the stress within the luting agent remained approximately the same, while the attenuation rate of the stress in the middle of the luting agent was higher than that on the dentin side. When using the same post-and-core system, the stress in the middle of the MMA luting agent rapidly declined in the anterior segment but exhibited a stable trend in the posterior segment; meanwhile, the rates of decline in the stress in both the middle part and the dentin side of the CC luting agent were nearly constant.

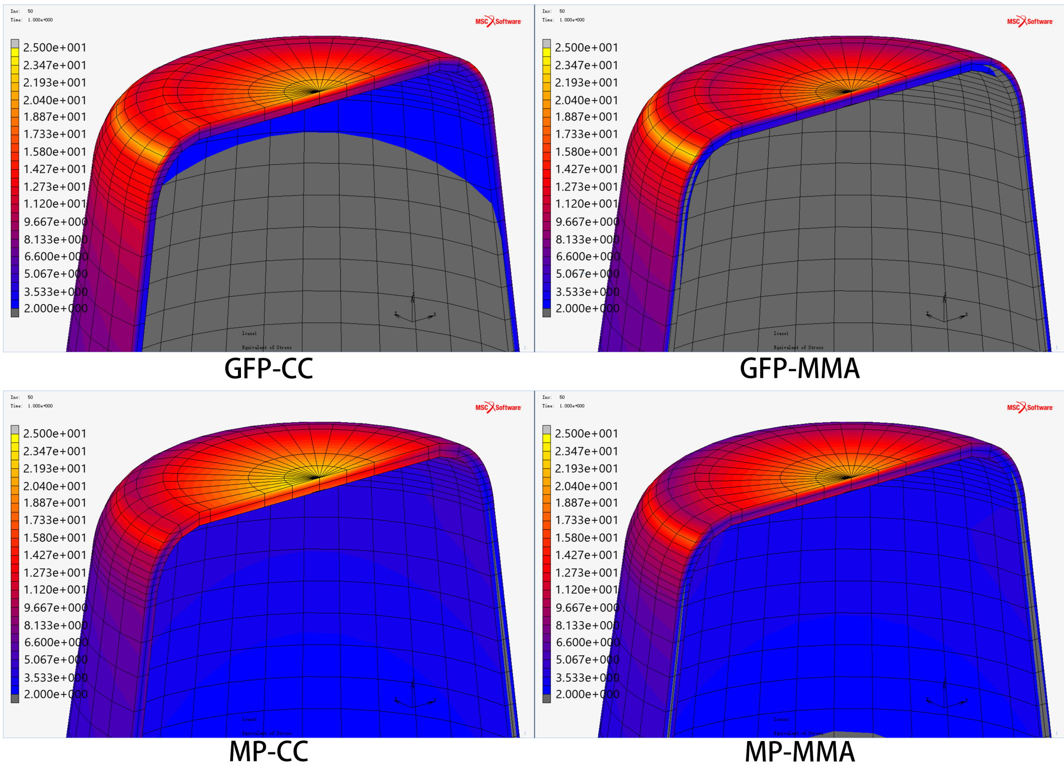

Fig. 3 Stress distribution in the luting agent at post apexes

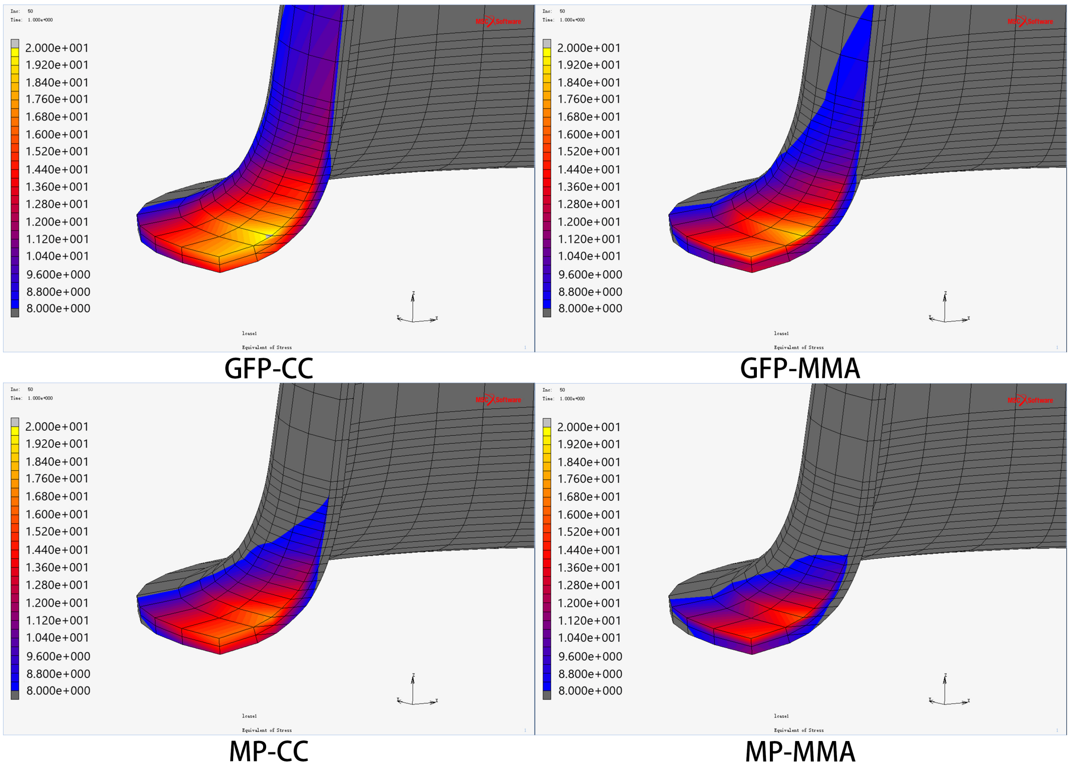

Fig. 4 Stress distribution in the luting agent at cervical area

As shown in Tables 2 and 3, when using the same post-and-core system, the stress in CC showed a moderate decrease from the restoration side to the dentin side. In contrast, the distribution of the stress in MMA was focused on the restoration side and the dentin side, with relatively lower stress in the intermediate portion of the luting agent.

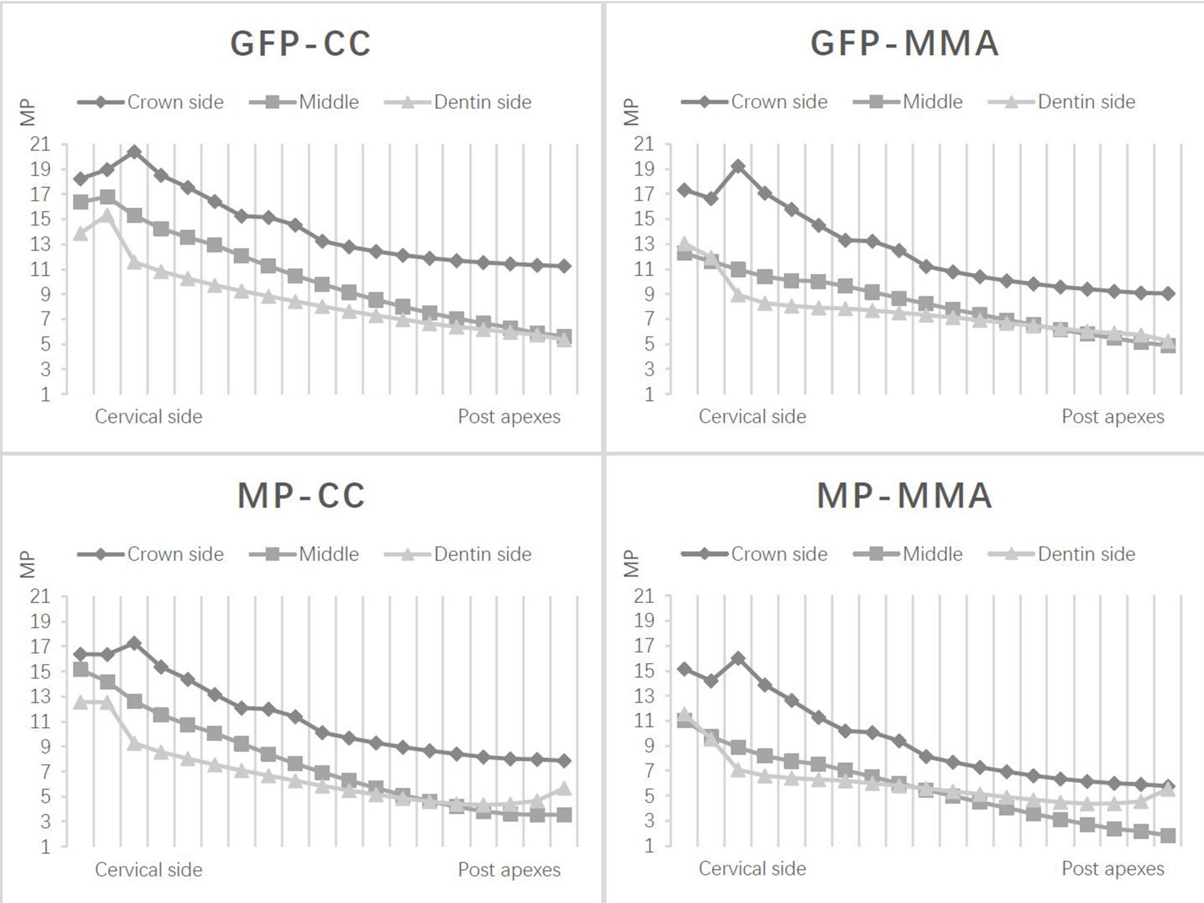

Fig. 5 Stress distribution in luting agent at the margin area from cervical side to post apexes side

Table 2 Von Mises stress in the luting agents at post apexes (MPa)

	GFP-CC	MP-CC	GFP-MMA	MP-MMA
Restoration side	22.24	23.46	20.1	21.36
Middle	11.05	14.85	4.51	7.12
Dentin side	9.74	17.41	5.87	10.86

Table 3 Von Mises stress in the luting agents at cervical area (MPa)

	GFP-CC	MP-CC	GFP-MMA	MP-MMA
Restoration side	18.23	16.37	17.33	15.15
Middle	16.38	15.14	12.27	11.03
Dentin side	13.88	12.56	13.05	11.57

Discussion

The collapsing of luting agents is the main cause of restoration dislocation [8,10]. In most of the currently available finite element studies that are relevant to luting agent stress, the distribution and intensity of the stress at the cervical margin, inside the root canal, on the root apex, or at other locations were measured using different types of luting agents; an appropriate luting agent was then selected according to the analytical results [12-14]. However, the stress on the luting agent itself was ignored, and consequently, the interior intensity and distribution of the stress in the luting agent have never been understood. Measurement of the stress distributions in luting agent with different Young's moduli can aid in selecting the optimal luting agent and restorative material for a specific circumstance in clinical practice, thus improving the long-term success rates of dental restorations.

Currently, typical finite element studies directly set luting agents as single layer elements or ignore the luting agent layer [23,24]. In such cases, the luting agent is treated only as a conductive medium for the occlusal force, and the interior intensity and distribution of the stress within the luting agent cannot be resolved. Luting agents are often treated as normal single layer elements because most finite element models are generated using the direct input of data from computed tomography (CT) scans into the modeling software. Such finite element models are limited by the resolution of the CT and, thus, cannot completely and accurately reconstruct the interior structures of the tooth and prosthesis. Therefore, a three-dimensional analytical nonlinear finite element model was manually established in this study. During the process of model analysis, because the luting agent layer is too thin, the luting agent finite element units may interpenetrate with the restoration units, the prosthesis units, or the dentin units, resulting in lower resolution or even making the model impossible to resolve. Thus, we increased the number of finite element units in the luting agent and increased the density of the units for the other finite elements in direct contact with the luting agent. Although the resolution time was substantially increased, the overall resolution was enhanced.

The advantages of using a CT scan to construct dental models for stress analysis are that the corresponding finite element model can be built quickly and that the finite element model using CT scan data closely resembles the shape of the actual teeth. However, because it is limited by the precision of the CT, some small portions of the finite element model inside the teeth, such as the luting agent layer, the root canal orifice and the shoulder margin, are difficult to fully scan, resulting in the loss of detail in the model and a reduced resolution. Manual modeling using finite element software can optimize the details based on the requirements of the experiment and can establish a more precise model to solve the above-mentioned problems. However, there are also some disadvantages to manual modeling. For example, it is difficult to simulate the morphology of the actual root canal, and it is difficult to restore the tooth shape with grooves and ridges on the occlusal surface.

In this study, an established model was used to manually subdivide the 100-μm-thick luting agent layer so that the interior intensity and distribution of von Mises stress in the luting agent could be accurately resolved. According to the experimental results, having luting agents with different Young's moduli on the same post-and-core system did not change the stress concentration area in the luting agents but could change the distribution pattern of the stress in the concentration area of the luting agents. The use of different post-and-core systems did alter the intensity of the stress in different areas of the luting agent.

Unlike the linear elastic models used in many other finite element analyses [23,25-27], a nonlinear elastic model was used in this study because the periodontal ligament is viscoelastic [18,22], and a nonlinear model produces more accurate analytical results for compression and tension. In addition, it has been reported that the deformation of the periodontal ligament when exerting occlusal force during chewing is nonlinear [22]. Deformation of the periodontal ligament easily occurs at a relatively low occlusal force, while it becomes less deformable as the occlusal force increases, in accord with the process of nonlinear analysis [22]. Compared with linear analysis, nonlinear analysis can better simulate the forces on the periodontal ligament during the chewing motion.

The results showed that the intensity of the stress concentrated in the luting agent of CC was higher than that for MMA for a given post-and-core system. However, whether at the post apex or in the cervical area, these stresses were far below the maximum stresses that the luting agents can bear [5,6]. Therefore, not only the adhesive properties but also the stress distributions among different luting agents should be considered. Because the chewing process is a repeated cycling process in an oral environment, adhesiveness will decline with time, and thus, a concentration of stress on a certain part is not conducive to the long-term stability of the restoration. Because the Young’s modulus of CC more closely resembles that of dentin, it can better transfer and disperse the stress.

The experimental results demonstrated that when using the same post-and-core system, different luting agents presented different attenuation curves in the shoulder margin from the cervical area to the post and core apexes, suggesting that adhesives with higher Young's moduli were associated with more homogeneous and more stable attenuation curves, especially in the immediate vicinity of the margin area. Additionally, it was found that the distribution of stress from the restoration side to the middle to the dentin side was more homogeneous in these cases. During chewing, the occlusal force is not consistently directed vertically downward; as a result, the tooth bears not only an axial force but also a lateral force. Furthermore, the shoulder margin produces similar fulcrums that, when combined with microleakage and other contributing factors, result in the observation that the luting agent in the margin area readily collapses. Clinically, in addition to the preparation of a reasonable shoulder margin shape and a homogeneous adhesive layer with a moderate thickness based on different repair materials.

Meanwhile, when using a given luting agent, an MP was better than a GFP at reducing the stress concentration in the luting agent at the cervical margin; the MP has a high Young's modulus, so the stress is concentrated inside the MP and is transmitted to the root canal. When a GFP was used, the stress of the luting agent was lower at the post and core but higher in the cervical margin. This result was consistent with the findings of other studies with respect to the stress-conduction characteristics of MPs and GFPs [27-29]. For any post-and-core system and any luting agent, the concentrated stress at the restoration side was greater than the concentrated stress at the dentin side, as the stress tends to concentrate in the material with a higher Young's modulus.

The analysis in our study can help clinicians to better choose appropriate luting agents depending on the patient situation and the materials that are used for the restoration. According to our results, a luting agent with a high Young's modulus allows more concentrated stress in the luting agent, thereby reducing the stress that is applied to the remaining tooth structures. However, a high Young's modulus will also cause a heavily concentrated stress in the luting agent, more easily resulting in the crushing and failure of the luting agent. A luting agent with a low Young's modulus cannot sufficiently buffer the stress to protect the remaining tooth structures. Additionally, if the Young's modulus of the restoration material is much higher than the Young’s modulus of the luting agent, it will cause the stress to be focused on the bonding interface at the restoration side; therefore, a luting agent with a Young's modulus that matches the Young’s moduli of both the dentin and the restorative material is preferred.

Because the Young's modulus of dentin is 15,000 MPa, the Young's moduli of all of the restoration materials, except a temporary restoration, are often higher than the Young’s modulus of dentin, so for a given adhesive strength, a composite resin luting agent is close to ideal. If the hard and soft tissues of the root are healthy, a cast-metal post-and-core system is ideal. In future experiments, in addition to further enhancements to the resolution of the finite element model, the impacts of different restoration materials on the stress distribution in luting agents will be investigated. Additionally, a greater number of luting agents can be tested to clarify the stress distribution patterns of different luting agents.

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Accepted November 22, 2016.

 Online ISSN 2185-3487, Print ISSN 2185-3479