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ORIGINAL ARTICLE

The finite element analysis of the effect of ferrule height on stress distribution at post-and-core-restored all-ceramic anterior crowns

Oğuz Eraslan · Filiz Aykent · M. Tolga Yücel · Serhan Akman

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Abstract The purpose of this study was to compare the effect of ferrule with different heights on the stress distribution of dentin and the restoration-tooth complex, using the finite element stress analysis method. Three-dimensional finite element models simulating an endodontically treated maxillary central incisor restored with an all-ceramic crown were prepared. Three-dimensional models were varied in their ferrule height (NF: no ferrule, 1F: 1-mm ferrule, and 2F: 2-mm ferrule). A 300-N static occlusal load was applied to the palatal surface of the crown with a 135° angle to the long axis of the tooth. In addition, two post and core materials with different elastic modulus were evaluated. The differences in stress transfer characteristics of the models were analyzed. Maximum stresses were concentrated on force application areas (32.6–32.8 MPa). The stress values observed with the use of a 2-mm ferrule (14.1/16.8 MPa) were lower than the no-ferrule design (14.9/17.1 MPa) for both the glass fiber-reinforced and zirconium oxide ceramic post systems, respectively. The stress values observed with zirconium oxide ceramic were higher than that of glass fiber-reinforced post system. The use of a ferrule in endodontically treated teeth restored with an all-ceramic post-and-core reduces the values of von Mises stresses on tooth-restoration complex. At rigid zirconium oxide ceramic post system, stress levels, both at dentin wall and within the post, were higher than that of fiber posts.

Keywords Finite element analysis · Ferrule effect · All-ceramic anterior crown · Post–core · Stress distribution

O. Eraslan (✉) · F. Aykent · M. T. Yücel · S. Akman
Faculty of Dentistry, Department of Prosthodontics,
Selcuk University,
42079 Kampus,
Konya, Turkey
e-mail: oguzeraslan@selcuk.edu.tr

Introduction

The presence of a ferrule is hypothesized to protect the tooth from wedging stresses in post-restored teeth [16]. A band of restoration margin unattached to a post and core can produce a ferrule effect that increases resistance to fracture [16]. Restoration design must provide enough strength to restoration and the abutment tooth to resist occlusal forces.

The post-restored teeth have been the subject of numerous in vitro and in vivo studies and studies with a theoretical approach [2, 4, 7, 11, 15, 19, 20, 23, 31]. These studies did investigate effects of different post materials and ferrule heights on the fracture resistance of endodontically treated teeth. Asmussen et al. [2] and Boschian et al. [7] found that increasing the elastic modulus of the post causes decreased dentin stress. This result was in agreement with findings of an earlier in vitro investigation [23] and with a finite element (FE) analysis [15]. Furthermore, it has been reported that a cervical ferrule preparation creates a positive effect in terms of reducing stress concentration in endodontically treated teeth [4, 31]. However, there was not enough information about the effect of ferrule height on stress distribution pattern at tooth-restoration complex.

The FE method has been shown to be a useful tool when investigating complex systems [2, 8, 12]. A knowledge of stress distribution is important to the understanding of fatigue yielding [17]. Overall stress distribution within the tooth-restoration complex is determined by geometry and hard tissue/restorative material arrangement [18]. Therefore, to develop theories of prosthesis design, the amount of stress likely to be generated in the oral cavity must be quantified [10]. Thus, the purpose of this study was to develop a three-dimensional model of maxillary central incisor and evaluate the stress distribution caused by different ferrule heights on the restoration-tooth complex. The null hypothesis was that different ferrule heights do not affect the stress distribution within endodontically treated teeth.

Material and methods

The study was conducted using a three-dimensional FE method (FEM) and a FE structural analysis program (ANSYS ver.10.0; ANSYS, Houston, TX, USA). A three-dimensional FE model was fabricated to represent an endodontically treated maxillary central incisor restored with an all-ceramic crown restoration (Fig. 1a). The model contained a simulated periodontal ligament (PDL) and alveolar bone structure. The geometry used for the tooth model was previously described by Wheeler [28]. On the basis of the root-form geometry of teeth, a simplified 0.25-mm PDL, 0.25-mm lamina dura, and cortical shell (1.5 mm) were developed [24]. The remaining bone was modeled as trabecular bone.

In the FE analysis, the effects of ferrule height (NF: no ferrule, 1F: 1-mm ferrule, and 2F: 2-mm ferrule; Fig. 2) and two different post materials were evaluated, respectively. The post systems modeled for analysis were a glass fiber-reinforced (ParaPost Fiber White, Coltene Whaledent, Langenau, Germany) and a zirconium oxide ceramic (Cera-post, Brasseler, KG, Lemgo, Germany) post materials. The core material modeled was composite resin (Biscore; Bisco,Vancouver, Canada). A ceramic (IPS e-max Press; Ivoclar Vivadent AG) was simulated as the final crown material.

An average occlusal force of 300 N was determined from the literature [12]. Static occlusal load was applied from the palatal surface of the crown in a 135° angle to the tooth long axis. Nodes at basis of the alveolar bone was

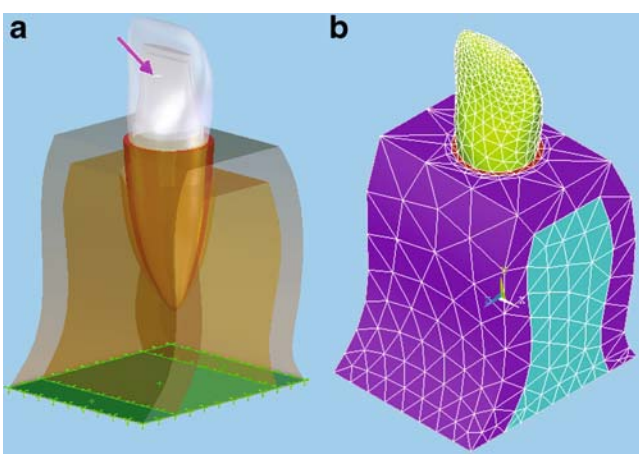

Fig. 1 **a** Three-dimensional FE model and illustration of materials involved, *arrow* represents load application, and *green area* was assumed fixed as boundary condition. **b** Three-dimensional mesh and material arrangement of FE model

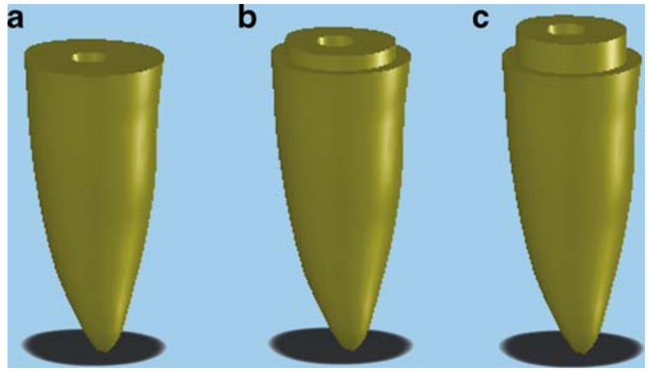

Fig. 2 Illustration of different ferrule height designs, **a** no ferrule, **b** 1 mm ferrule, and **c** 2 mm ferrule

assumed as fixed in all directions to calculate the stress distribution (Fig. 1a).

The mathematical models included 77,753 nodes and 56,914 tetrahedral solid elements (Fig. 1b). Materials used in study were assumed as homogenous and isotropic. The elastic properties of the materials (Young's modulus [E] and Poisson's ratio [μ]) were determined from the literature and are provided in Table 1. Results are presented by considering von Mises criteria [1, 6, 25, 26, 29]. A convenient way of reporting the stresses is in the form of a color representation of the stress distributions [2]. Calculated numeric data were transformed into color graphics to better visualize mechanical phenomena in the models.

The FEM results are presented as stresses distributed in the investigated structures. These stresses may occur as tensile, compressive, shear, or a stress combination known as equivalent von Mises stresses. von Mises stresses depend on the entire stress field and are a widely used indicator of the possibility of damage occurrence [19, 21]. As compressive strength of dentin is considerably higher than tensile strength, calculated tensile and von Mises stresses may be compared with the tensile strength of dentin to assess the risk of fracture [2]. Thus, von Mises stresses were chosen for presentation of results.

Results

The maximum stress values are presented as color figures. Stresses are present in all of the structures in Figs. 3 and 4, but only dentin stresses are reported in other figures. The section plots (Figs. 3 and 4) revealed that the maximum von Mises stresses were primarily located at the force application areas (32.6–32.8 MPa) for all models. Maximum dentin stress values were observed at buccal cervical preparation margins of teeth (14.9, 14.4, and 14.1 MPa) for the glass fiber-reinforced post system, for no ferrule, 1-mm ferrule, and 2-mm ferrule models, respectively (Fig. 5).

Table 1 Mechanical properties of investigated materials

Material	Elastic modulus (E; GPa)	Poisson's ratio (υ)
IPS e.max core[a]	95	0.24
IPS e.max veneer[a]	65	0.24
Zirconium oxide ceramic post [9]	200	0.33
Glass fiber-reinforced post [9]	23.6	0.32
Composite core [5]	12	0.30
Dentin [22]	18.6	0.31
Periodontal ligament [22]	0.0689	0.45
Gutta-percha [22]	0.00069	0.45
Trabecular bone [27]	1.37	0.30
Cortical bone [27]	13.7	0.30

[a] Acquired from manufacturer

Figure 6 shows that maximum von Mises stress value decreased with ferrule height in the order of no ferrule, 1-mm ferrule, and 2-mm ferrule (17.1, 16.9, 16.8 MPa, respectively) for zirconium oxide ceramic post system models. These values were located at dentin surface adjacent to the post. The stress values observed with the use of the 2-mm ferrule (14.1/16.8 MPa) were lower than the no-ferrule design (14.9/17.1 MPa) for both the glass fiber-reinforced and zirconium oxide ceramic post systems, respectively. Both stress values and its location were different between the two evaluated types of post systems. Furthermore, when the zirconium oxide ceramic and glass fiber-reinforced post system were compared, von Mises stresses at the dentin tissue were smaller for the glass fiber-reinforced post system (14.1–14.9 at glass fiber-reinforced post system, 16.8–17.1 at zirconium oxide ceramic post system).

Discussion

Although the maximum stress values and distribution in the tooth-restoration complex induced were different, the FE analysis showed similar stress values in the simulated dentin tissue stress, when the ferrule height varied for both post material models. Based on these results, the null hypothesis that the ferrule height would not affect the stress distribution for post-and-core-restored teeth was rejected.

The FEM has several limitations. The structures in the model were all assumed to be homogeneous and isotropic and to possess linear elasticity. The properties of the materials modeled in this study, particularly the living tissues, however, are different. For instance, it is well described that cortical bone of the mandible is transversely isotropic and inhomogeneous [12]. In addition, the stress distribution patterns simulated may be different depending on the materials and properties assigned to each layer of the model and the model used in the experiments. Thus, the inherent limitations in this study should be considered. Clinical experience indicates that most fractures in prosthodontic restorations occur after several years [14]. Generally, such failures are unrelated to episodes of acute

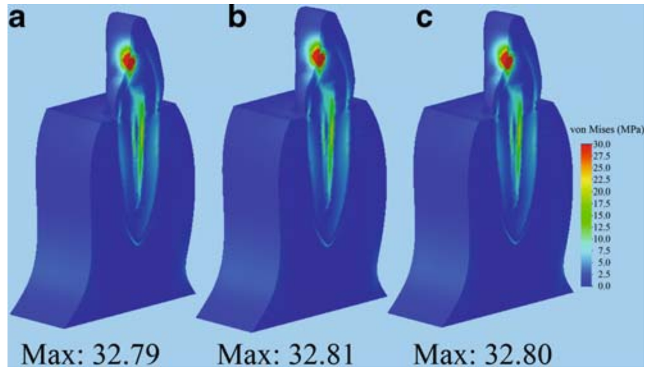

Fig. 4 Distribution of von Mises stresses (MPa) in bucco-lingual section of zirconium oxide ceramic post model, **a** no ferrule, **b** 1-mm ferrule, and **c** 2-mm ferrule. *Dark blue to red colors* represent stress values from lower to higher, respectively

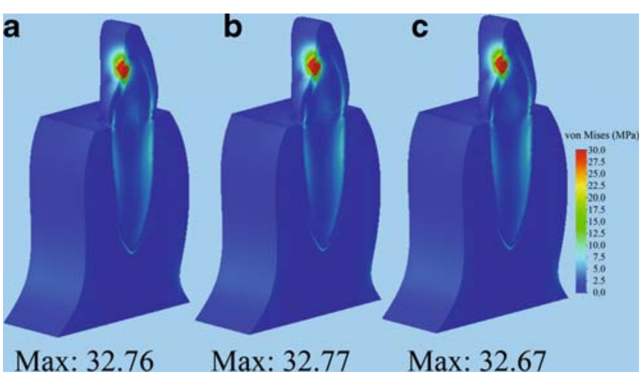

Fig. 3 Distribution of von Mises stresses (MPa) in bucco-lingual section of glass fiber-reinforced post model, **a** no ferrule, **b** 1-mm ferrule, and **c** 2-mm ferrule. *Dark blue to red colors* represent stress values from lower to higher, respectively

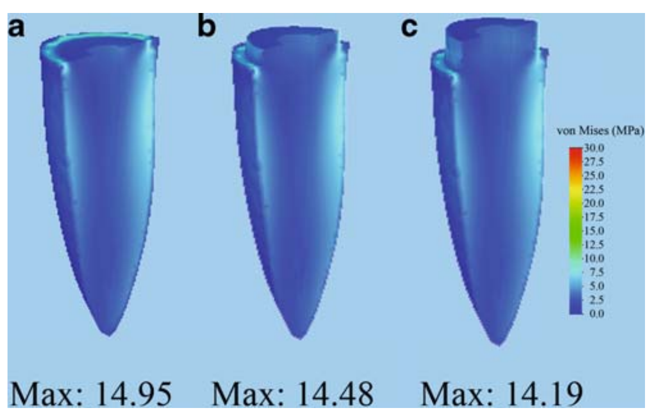

Fig. 5 Distribution of von Mises stresses (MPa) at dentin tissue in bucco-lingual section of glass fiber-reinforced post model, **a** no ferrule, **b** 1-mm ferrule, and **c** 2-mm ferrule. *Dark blue to red colors* represent stress values from lower to higher, respectively

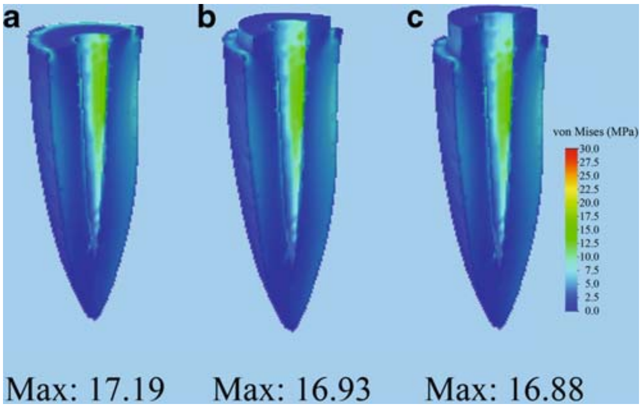

Fig. 6 Distribution of von Mises stresses (MPa) at dentin tissue in bucco-lingual section of zirconium oxide ceramic post model, **a** no ferrule, **b** 1-mm ferrule, and **c** 2-mm ferrule. *Dark blue to red colors* represent stress values from lower to higher, respectively

overload, but result from fatigue failure [14]. The absence of fatigue loading is another limitation of the study.

Previous photo-elastic analysis and progressive loading studies have reported that a cervical ferrule preparation created a positive effect in reducing stress concentration at the core–dentin junction for crowned and endodontically treated teeth subject to stress in the cervical region [3, 4, 31]. Pereira et al. [20] performed a fracture resistance test of post-and-core-restored teeth with variable ferrule height, and they reported that an increased ferrule length significantly increases the fracture resistance of endodontically treated teeth. Thus, current FE study confirmed that the stress was concentrated at the cervical region and the ferrule preparation was effective in reducing the stress values. In contrast Pierrisnard et al. [21] reported that ferrule preparation was more efficient when the post has a high elastic modulus; in the present study, the stress values did equally change with ferrule height for both the glass fiber-reinforced post system and zirconium oxide ceramic post, which has a greater elastic modulus.

The fracture resistance of post-and-core-restored teeth has been the subject of numerous in vitro and in vivo studies [2, 31]. Studies with a theoretical approach [2, 4, 11, 15, 19] did report contradictory results. One reason could be that in vitro studies cannot simulate many variables present clinically such as the elasticity and presence of PDL and supporting bone tissues. In addition, some studies used unrealistically high loads such as 600 N to register fracture [13, 23].

Because of the large variability of the results obtained from in vitro studies, an increasing number of investigations of post-and-core-restored teeth are based on FE analysis [2]. The FEM has been used in several previous investigations of the stresses generated in endodontically treated, post-and-core-restored teeth and has been shown to be a useful tool when investigating complex systems that are difficult to standardize in vitro and in vivo [2, 4, 11, 15, 19]. In addition, the FEM does not result in variability of the results and is restricted by the number of nodules and elements used in the model and the elastic constants attributed to the elements [2].

Boschian et al. [7] emphasized the effect of elastic modulus of the post material on stresses transferred to tooth structures as another factor. They reported that post materials that have higher elastic modulus than dentin are capable of causing dangerous and non-homogenous stresses in root dentin. That study concluded that the configuration that best preserves the integrity of the root, post, and core unit is when fiber posts are used for restoration [7]. Current study confirmed them with lower stress values at dentin structure by use of fiber post. Similarly, Zarone et al. [30] evaluated the biomechanical behavior of different restoring configurations compared to a sound tooth by FEM. They reported that high modulus materials used for the restoration strongly alter the natural biomechanical behavior of the tooth. In contrast, Asmussen et al. [2] found that increasing the elastic modulus of the post caused decreased dentin stress, and this result was in agreement with an earlier in vitro investigation of the resistance of post-and-core-restored teeth to cyclic loading [23] and with a theoretical study using FE analysis [15]. The results of the current study differ from previously mentioned investigation, because zirconium oxide ceramic posts that have a greater elastic modulus than glass fiber-reinforced post system produced slightly higher dentin stress values. This was pronounced at the dentin surface adjacent to the post. The higher elastic modulus of zirconium oxide ceramic post than other tooth structures could be the reason of higher stress values. Furthermore, high stress values were observed at the post material with the zirconium oxide ceramic post system. It is known that, when force is applied to composite or layered materials, stresses tend to maximize within the material with the highest elastic modulus [11]. Therefore, the stresses were more concentrated in the post of the zirconium oxide ceramic post model, as it has a higher elastic modulus than other structures. This finding was in agreement with the study by Eskitascioglu et al. [11]. The authors reported that stresses accumulated along the cast post-and-core system that has a high elastic modulus, and with the fiber post–core system (relatively low elastic modulus), stress accumulated along the cervical region of the tooth and the buccal bone. In addition, stresses located at the dentin may influence the risk of root fracture, and stresses located at post/dentin interface may influence the risk of loss of post retention. Thus, every effort should be made to reduce these stresses. Again, in agreement with Eskitascioglu et al. [11], using restorative materials of elastic modulus close to dentin rather than materials of high elastic modulus may create a mechanically homogenous unit.

The FE model created for this study was a multilayered complex structure involving an all-ceramic crown, a post-and-core-restored, endodontically treated maxillary central incisor, and supporting structures. It is important to note that the stress after loading may be influenced greatly by the materials and properties assigned to each material.

As with many in vitro studies, it is difficult to extrapolate the results of this study directly to a clinical situation. The finish line and ferrule were placed at a constant height around the periphery of the teeth. Further studies that better simulate the oral environment and including fatigue loading are recommended.

Conclusions

Within the limitations of this theoretical study, the following conclusions were drawn:

1. The presence of a ferrule resulted in less dentin stress than designs without a ferrule.
2. Dentin stress was reduced with increasing ferrule height.
3. The differences of the stresses with and without the ferrule are small.
4. An increase of the elastic modulus of the post material increased the dentin stress, but shifted the maximum stress location from the dentin surface (adjacent to the post) to the post materials.

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