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Stress and Strain Distribution in a Single Root Canal Post Made of Polyether Ether Ketone Using Three-Dimensional Finite Elements Method

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Abstract: This study was conducted to analyse the mechanical behavior of radicular posts made of Polyether ether ketone (PEEK) and carbon fiber-reinforced Polyetheretherketone (CFR-PEEK) materials in an anterior tooth subjected to oblique forces and compare them with the mechanical behavior of a cast metallic post and a sound tooth model as a control case. Four 3D FEA models of a maxillary central incisor were designed using SolidWorks software. An oblique force of 150 N was applied to the palatal surface of the crown and the simulation of the stress distribution was conducted by Ansys software to study maximum principal stress, equalivent stress, stress intensity and safety factor and compare them all between the four models. Results no systems of post and core threatened the safety of the dentin. PEEK and CFR-PEEK posts showed similar stress distribution to sound tooth model, but the system of PEEK post showed the highest stress concentration in adhesive cement layer while CFR-PEEK post showed the best stress distribution in adhesive cement layer.

Key words: Post and Core · Polyether Ether Ketone · Carbon-Fiber Reinforced Ployether Ether Ketone · Finite Element Analysis · Stress Distribution

INTRODUCTION

An advanced stage of a tooth decay promotes an extremely damaged tooth that needs endodontic treatment to be restored and the treatment of seriously damaged tooth often require an endodontic post [1]. While some cases of deep dentinal lesions could be saved by more conservative treatments such as step-wise excavation procedure [2]. The intra-radicular posts are required to ensure retention of the indirect restoration after endodontic treatment [3]. Post restorations are complex systems where the stress distribution within the structure is multiaxial, non-uniform and depending on the magnitude and direction of the applied external loads [4]. It has been suggested by 2D and 3D FEA studies that when an endodontically treated tooth is submitted to occlusal loads, stress is concentrated primarily at the cervical area [5] where the placement of posts could reduce the stress [6]. On the other hand, some studies suggested that stiff systems of posts work against the natural function of the tooth creating zones of tension and shear in the dentin, which can cause cracks or fractures both in the tooth and core reconstruction [4]. For this reason, it was presumed that the use of posts with mechanical properties similar to those of dentin results in mechanical behavior similar to the physiological behavior of a sound tooth [7].

Cast posts and cores were the standard for many years and are still used by clinicians [8] they presented a great versatility because they can be obtained through several metal alloys, as well as clinical longevity proved by scientific evidence. However, they exhibit some features unfavorable to tooth remnant preservation, such as irregular stress dissipation and stress concentration at apical area favoring the wedge effect, the possibility of oxidation and corrosion and tooth structure pigmentation. Currently, aesthetics is one of the main disadvantages of cast metal post use, mainly in anterior teeth receiving all-ceramic crowns with high translucency [9].

The adoption of Polyetheretherketone (PEEK) biomaterials has been facilitated in the recent years for the medical device industry. Due to its relative inertness and mechanical properties, PEEK has had the greatest clinical impact in the field of spine implant design and PEEK is now broadly accepted as a

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radiolucent alternative to metallic biomaterials in the spine community [10]. This material is a promising candidate for high temperature Direct methanol fuel cell (DMFC) in chemical engineering and industry [11]. Considering mechanical and physical properties similar to bone, PEEK can be used in many areas of dentistry. It has been explored for a number of applications [12] for example, PEEK dental implants exhibited lesser stress shielding compared to titanium dental implants due to closer match of mechanical properties of PEEK and bone [13, 14]. Also modified PEEK is a promising material for a number of removable and fixed prosthesis [12] it has been used for fabrication of removable prosthesis framework for the patients allergic to metals, or who dislike the metallic taste, the weight and the unpleasant metal display of the denture framework and retentive clasps. They found that modified PEEK is a biocompatible, nonallergic, rigid material, with flexibility comparable to bone, high polishing and low absorption properties, low plaque affinity and good wear resistance [15]. Another application of modified PEEK was a framework veneered with composite resin used as an alternative material for the fabrication of an interim 3-pontic resin-bonded fixed dental prosthesis after implant placement. The low modulus of elasticity of PEEK combined with the use of indirect light-polymerized resin as a veneering material provided an advantage over metal ceramics or ceramics in dampening the occlusal forces and reducing debonding rates, also further long-term clinical evidence is required before recommending the application as a substitute material [16]. PEEK can be modified easily by incorporation of other materials. For example; incorporation of carbon fibers can increase the elastic modulus up to 18 Gpa [17, 18]. The modulus of carbon-reinforced PEEK (CFR-PEEK) is also comparable to those of cortical bone and dentin [19] so the polymer could exhibit lesser stress shielding when compared to titanium which used as an implant material [20, 21]. Biomaterials point of view, there is no artificial material that can be used for all mineralized tissues, the materials properties have to be modified to match with the properties of the tissue to be replaced [22].

The aim of this study is to analyse the mechanical behavior of radicular posts made of Polyetheretherketone (PEEK) and carbon fiber-reinforced Polyetheretherketone (CFR-PEEK) materials in an anterior tooth subjected to oblique forces and compare them with the mechanical behavior of a cast metallic post, considering a sound tooth model as a control case.

MATERIALS AND METHODS

Four three-dimensional models were built of a maxillary central incisor embedded in the bone socket using Solid Works 2017 (SP 2.0 premium) software. First model was a sound tooth as a control case, second model was an endodontically treated tooth restored with metallic post and core, third model was an endodontically treated tooth restored with a post and core made of Polyetheretherketone (PEEK) material, fourth and last model was an endodontically treated tooth restored with a post and core made of carbon fiber-reinforced Polyetheretherketone (CFR-PEEK) material.

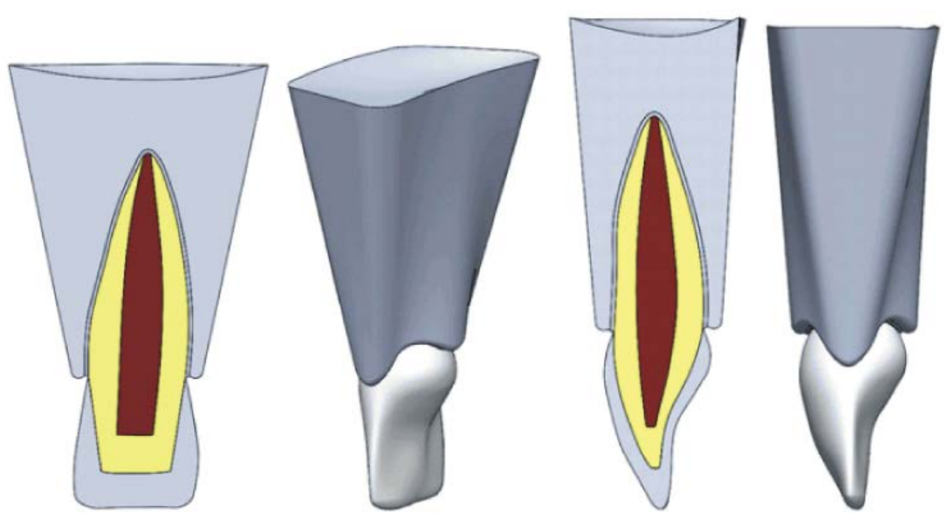

Fig. 1: Sound tooth model

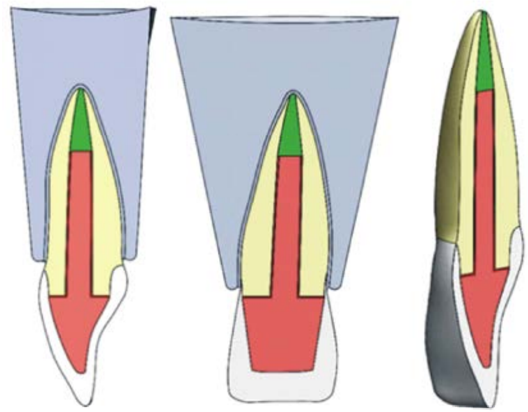

Fig. 2: Restored tooth models

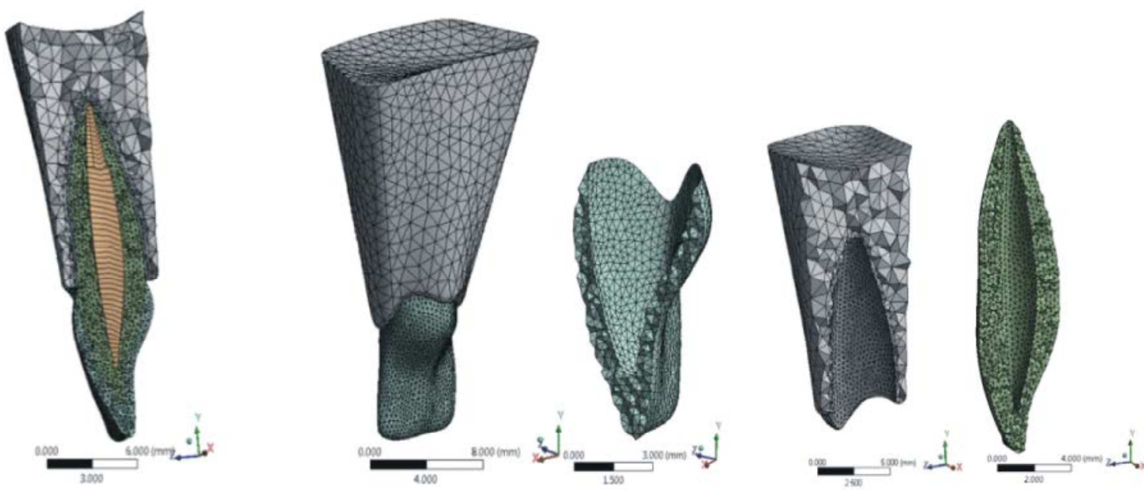

Fig. 3: Meshing of sound tooth model

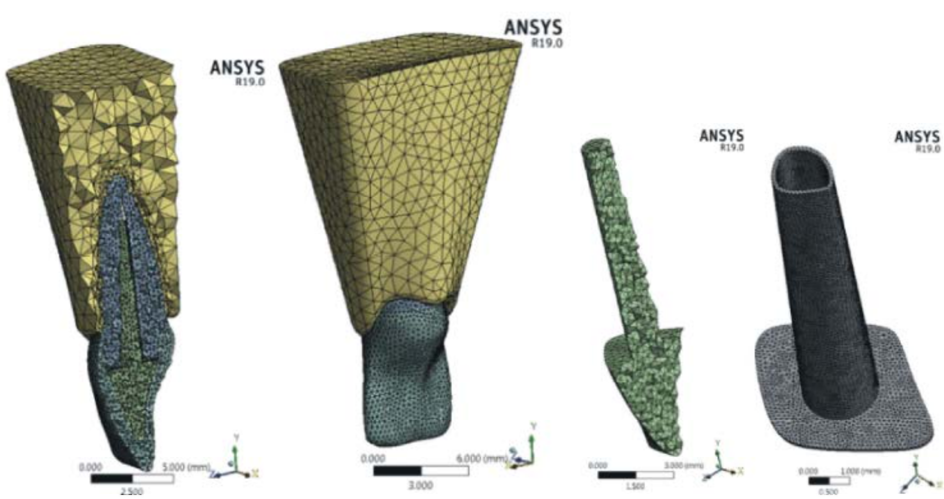

Fig. 4: Meshing of restored tooth model

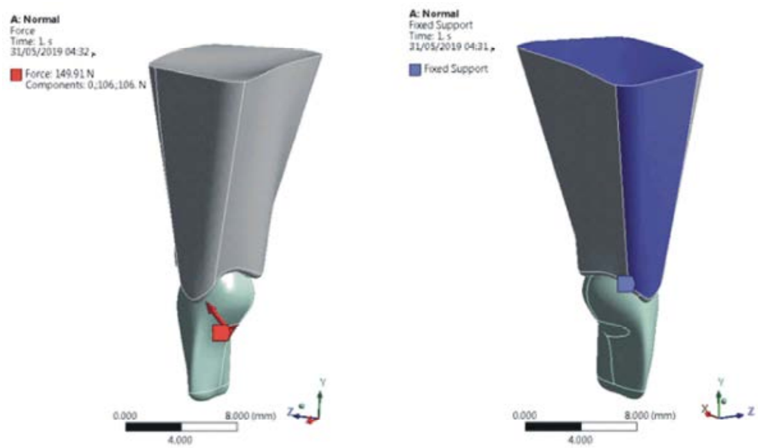

Fig. 5: Boundary conditions

Table 1: Mechanical properties of the materials

	E (MPa)		$_{ut}$(MPa)	$_{uc}$(MPa)	$_{yt}$(MPa)	$_{yc}$(MPa)
Enamel	84100	0.33	47.5	371	-	-
Dentin	18600	0.31	104	282		-
Pulp	20	0.45	-	-	-	-
Sponge Bone	E_x=1148	$_{xy}$=0.055	50	62	-	-
	E_y=210	$_{yz}$=0.055				
	E_z=1148	$_{xz}$=0.311				
Periodontal Ligament	0.0689	0.45	-	-	-	-
Feldspathic Porcelain	64000	0.27	271	360	-	-
Ni-Cr	200000	0.3	800	-	690	690
PEEK	4100	0.4	95.2	138.6	-	-
CFR-PEEK	18000	0.35	101.4	137.1	-	-
Mineral Trioxide Aggregate (MTA)	15000	0.314	-	-	-	-
Resin Cement	18300	0.3	12	-	-	-

After the generation of the models, they were exported to Ansys Workbench 19.0 software and meshing of each structure was performed using solid quadratic tetrahedral elements, the total numbers of elements were 99056 for the sound tooth model and 157288 for the restored tooth model.

All components were assumed to be perfectly bonded without any gaps between the components. An oblique load of 150 N, angled at 45°, was chosen to simulate the masticatory force. Rigid constrains have been considered at the bottom and lateral sides of the bone.

Mechanical properties of the materials used in the geometric models are represented in Table 1.

Afterwards, the solution of each model was run. Von Mises equalivent stresses, maximum principal stresses, stress intensity and safety factors were determined for stress assessment.

RESULTS

The primary focus of the numeric results was on the stress concentration at the dentin. Table 2 shows the equalivent stress at the dentinal ferrule area, while Table 3 shows it at the buccal surface of the radicular dentin.

Table 4 represents the safety factor of the dentin for all the models.

Stress concentration in the adhesive cement layer was also studied in several areas, Table 5 shows stress intensity at the buccal surface of the adhesive cement layer, Table 6 shows it at the palatal surface, Table 7 shows it at the apical area and Table 8 shows stress intensity at the palatal crown margin of the adhesive cement layer.

Table 9 represents the safety factor of adhesive cement layer at the least values for all the models.

Table 2: Equalivent stress at dentinal ferrule area

	Ni-Cr	CFR-PEEK	PEEK	Sound tooth
Equalivent stress (MPa)	2.849	7.963	14.791	15.169

Table 3: Equalivent stress at radicular dentin

	Ni-Cr	CFR-PEEK	PEEK	Sound tooth
Equalivent stress (MPa)	27.265	34.339	35.155	37.571

Table 4: Safety factor of the dentin

	Ni-Cr	CFR-PEEK	PEEK	Sound tooth
Safety factor (>1)	2.76	2.58	2.5	1.98

Table 5: Stress intensity at buccal surface of cement layer

	Ni-Cr	CFR-PEEK	PEEK
Stress intensity (MPa)	15.472	21.353	19.39

Table 6: Stress intensity at palatal surface of cement layer

	Ni-Cr	CFR-PEEK	PEEK
Stress intensity (MPa)	11.085	5.649	4.1

Table 7: Stress intensity at apical area of cement layer

	Ni-Cr	CFR-PEEK	PEEK
Stress intensity (MPa)	22.052	12.38	13.274

Table 8: Stress intensity at palatal crown margin of cement layer

	Ni-Cr	CFR-PEEK	PEEK
Stress intensity (MPa)	8.891	12.38	28.564

Table 9: Safety factor of cement layer

	Ni-Cr	CFR-PEEK	PEEK
Safety factor (>1)	0.75	1.35	0.75

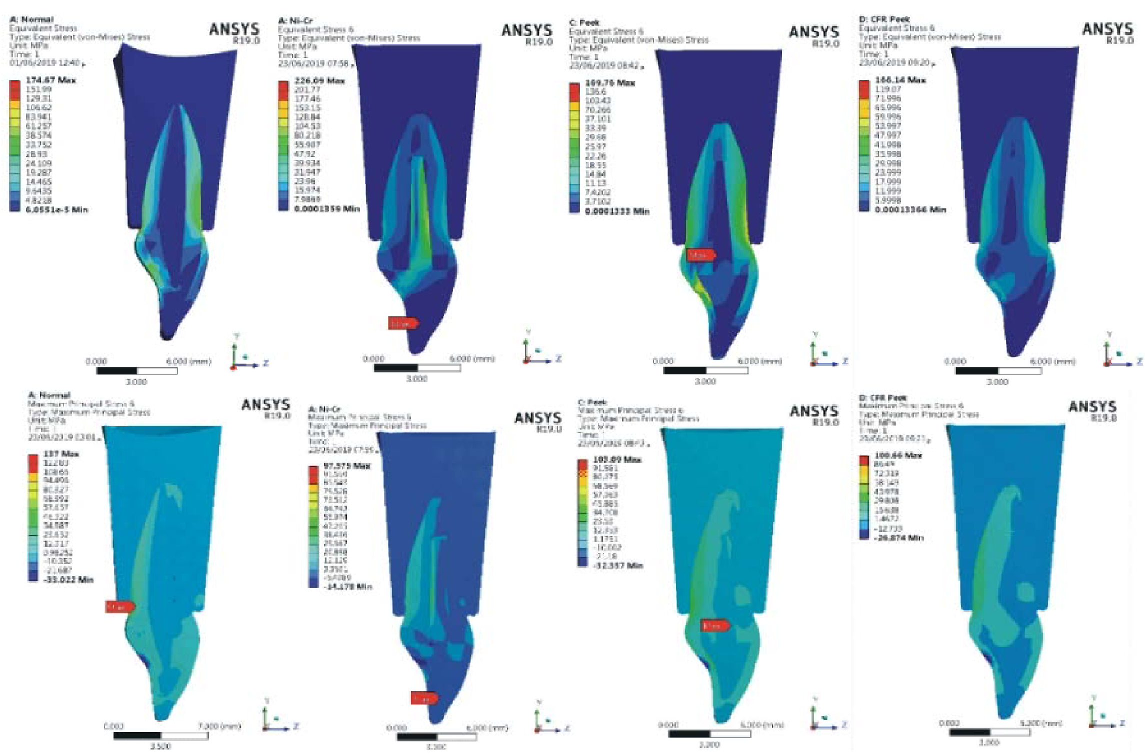

Fig. 14: Simulation of the models

Figure 14 represents the simulation of the four models.

DISCUSSION

The results of the present study were evaluated by von Mises equalivent stress and maximum principal stress (MPS). Von Mises stress is a failure criterion that shows the energy transmission in the structure, whilst MPS shows the locations of the structure that are more prone to failure by tensile stress [23].

Stress distribution in the dentin under oblique loading was evaluated, the stresses were lowest for the metallic post, followed by CFR-PEEK post and PEEK post. However, the mechanical behavior of the tooth restored with either PEEK or CFR-PEEK post was similar to that in sound tooth model. Safety factor of the dentin in all the models was >1 which means that the regular physiological occlusal forces applied on the tooth do not reach the limit that can cause dentinal failure or root fracture. These results are consistent with Madfa *et al*. [24] also found that posts with a higher elastic modulus were found to cause amplification of stress within the post itself but a reduced stress distribution in the root dentin. Dejak *et al*. [25] reported a similar result too, which indicates that cast metal posts resulted in lower stresses of the restored teeth than did glass fiber-reinforced composite resin posts. However, Lanza *et al*. [26] reported a different result which claims that steel posts are the most dangerous for the root, potentially leading to its fracture, but they failed to mention whether the stress was found in the dentin or within the post itself.

By studying the stress distribution within the adhesive cement layer and calculating the safety factor of it, it was found that both models restored with metallic and PEEK posts were more prone to decementation than CFR-PEEK model. Because the safety factor of cement layer in the models of both metallic and PEEK posts was <1, while the safety factor of this layer in the model of CFR-PEEK post was 1.35. This result can be interpreted by the resemblance of the elastic modulus of CFR-PEEK with these of both dentin and adhesive cement layer, resulting in giving the best stress distribution within this layer. Teshigawara *et al*. [27] found that the initial failure of cement was observed at the palatal crown margin regardless of the material, this agrees with the present study by only one material which was PEEK, while initial failure of cement in metallic post was observed at the apical area.

CONCLUSION

Within the limitation of this 3D FEA study, the interpretation of the results from multiple views of the models could lead to the following conclusions:

- No systems of post and core threatened the safety of the dentin under the regular physiological occlusal forces.
- PEEK and CFR-PEEK posts showed similar stress distribution to sound tooth model.
- The system of PEEK post showed the highest stress concentration in adhesive cement layer, while CFR-PEEK post showed the best stress distribution in adhesive cement layer.

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