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Research paper

Stress distributions in maxillary central incisors restored with different high-stiffness post models: 3-D FEA

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Abstract

Background: Dental root posts are recommended for endodontically treated weakened teeth.
Objectives: The present computational FEA study aims to evaluate the effect of material and design of the post on the stress distribution under load in different root canal shapes of endodontically treated maxillary central incisor (MCI).
Methods: Three-dimensional models of (MCI) were created by using CAD modeling software and divided into two groups. Group-I comprised five models of a weakened root restored using different post materials (stainless steel, titanium, gold-alloy, Ni-Cr, and zirconium). Group-II: involved four models of (MCI) with two different root canal shapes (small and wide) restored using cylindrical (C-Post) and two-stage tapered (T-Post) posts. Each tooth model was subjected to a 100 N oblique load at the palatal surface of the crown. Von Mises equivalent stresses on dentin and post, as well as shear stresses on the post cement, were evaluated.
Results: In Group-I: Ni-Cr produced the lowest stress values on the dentin, where titanium and gold-alloy posts produced the lowest stresses in the post and post/root interfaces. In Group-II: Roots restored with a T-Post showed a lower concentration stress in the dentin and lower shear stresses in the cement layer compared with those restored with a C-Post.
Conclusion: The geometry of the post and the corresponding material play an important role in the stress behavior of restored teeth. The use of titanium or gold-alloy T-Posts seems a good way to improve the stress distribution profile and reduce the risk of restoration failure.

Keywords: *Prefabricated Post; Tapered Post; Post Material; Stress Distribution; FEA*

1. Introduction

Root canal-treated teeth are weaker than vital teeth, and exhibit a high risk of biomechanical failures due to filling preparations, endodontic procedures, or extensive loss of tooth structure (De Castro Albuquerque et al. 2003; Tang et al. 2010). A root post is generally recommended for a tooth affected by a significant loss of coronal tissues, to provide higher retention to the core and the final restoration (Schwartz and Robbins 2004). Root posts can be classified into two categories; prefabricated and customized cast posts (can be created in a laboratory to fit the original shape of the root canal preparation). Recently, however, prefabricated posts have been used preferentially to cast posts because they are easier to use and less expensive to make (Gonzalez-Lluch et al. 2009). Prefabricated posts are available in a variety of materials and properties (such as metallic vs. non-metallic), as well as different diameters and designs (such as parallel vs. tapered) (Genovese et al. 2005; Schwartz and Robbins 2004).
The material type of the root post significantly influences the fracture resistance and stress distribution pattern of the final restoration (De Castro Albuquerque et al. 2003; Dejak and Mlotkowski 2011; Durmus and Oyar 2014; Maroulakos et al. 2015; Oyar 2014). Even though several studies have analyzed the biomechanical behavior of different post-and-core systems, the restoration of root canal-treated teeth still presents several unresolved aspects, and no consensus has been reached in the literature on the best material or technique to use for this purpose (De Castro Albuquerque et al. 2003; Li X et al. 2008; Ortega et al. 2004). However, because of their favorable performance in decreasing dentin stress during masticatory loads, many authors recommend using posts with a high modulus of elasticity to restore weakened endodontically treated teeth (Asmussen et al. 2005; Dejak and Mlotkowski 2011; Durmus and Oyar 2014; Seo et al. 2009). Furthermore, numerous in vitro studies showed that teeth restored with high-stiffness post materials have a higher fracture resistance than teeth restored with other post systems (Balkaya and Birdal 2013; Maroulakos et al. 2015).
In addition to the material type, the shape of the post can affect the amount of stress placed on the tooth. Also, the authors have different views on this subject: for instance, many studies showed conflicting in the outcomes of parallel versus tapered prefabricated posts. (Asmussen et al. 2005) find that the parallel post produced lower stress in dentin compared to the tapered shape, whereas (De Castro Albuquerque et al. 2003) conclude that the post shape has a small effect on the stress concentrations in dentin. However, (Uddanwadiker et al. 2007) demonstrate that the tapered post with a minimum taper induces lower stress in dentin and better retention compared to the parallel post. Moreover, according to (Maroli et al. 2017) the conical posts have higher fracture strength than those with the parallel shape.
Different methods have been used to evaluate the failure rate of teeth restorations based on various post systems, including clinical and experimental approaches, as well as theoretical methods such as finite element analysis (FEA). FEA is a computational method for the numerical analysis of complex structures based on the

properties of the materials involved. This powerful technique, which has been employed by several authors (Asmussen et al. 2005; Dejak and Mlotkowski 2011; Genovese et al. 2005; Gonzalez-Lluch et al. 2009; Li X et al. 2008; Seo et al. 2009), is extremely useful for analyzing mechanical features of biomaterials and human tissues that are difficult to inspect in vivo (Fu et al. 2010; Seo et al. 2009; Wakabayashi et al. 2008). FEA method provides different analysis tests on stress distribution under loads to predict failure pattern of the structures such as von Mises stress and shear stress criterions. The von Mises stress criterion is a strong indication of the possibility of damage occurrence (Asmussen et al. 2005; Durmus and Oyar 2014), where shear stresses can indicate the sliding effects between restoration components and post detachment (Genovese et al. 2005).
Several high-stiffness materials, including traditional materials such as stainless steel (Ss), gold alloy (Au), and nickel chromium (Ni-Cr) and comparatively the most recent titanium (Ti) and zirconium (Zr) were used in this filed to make various type of root posts. Therefore, additional studies are necessary to determine how different post designs and materials affect the stress distribution of the root-post and core system. The aim of this FEA study was to evaluate the stress behavior of maxillary central incisors restored with five high-stiffness post materials (Ss, Ti, Au, Ni-Cr, and Zr) and to compare the effect of two post designs (cylindrical and two-stage tapered posts (C-Post and T-Post, respectively)) on the stress distribution in different root canal configurations.

2. Material and methods

2.1. 3D models generation

A three-dimensional (3D) model of a maxillary central incisor was built using computer-aided design (CAD) software (Autodesk Inventor Professional 2012, Autodesk, Inc.) according to literature data (Nelson SJ and M. 2010). The crown was 10.5 mm long, 8.5 mm in mesio-distal width, and with a root length of 13 mm.

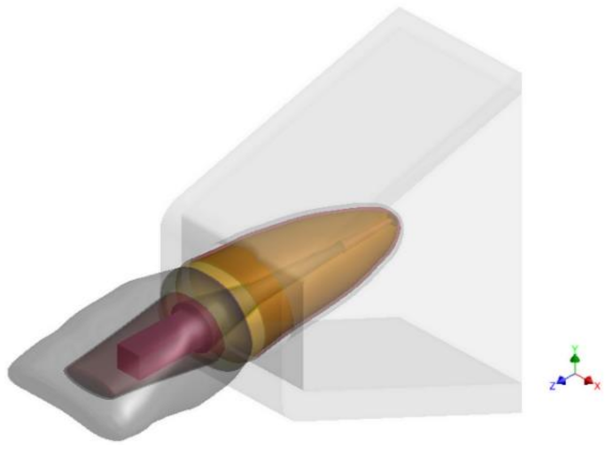

Fig. 1: 3D Tooth Model (SC2) with Bone and PDL.

Ten components [root, post, gutta-percha filling, post-cement, composite core, crown-cement, crown, periodontal ligament (PDL), cancellous bone, and cortical bone] were generated separately and then assembled in the final model (Fig.1). The root was simulated with 1 mm of ferrule high coronal to the cementoenamel junction and restored with a post, composite core and a leucite-reinforced ceramic crown (IPS Empress Esthetic; Ivoclar Vivadent AG). The crown was retained with a 0.1 mm-thick resin luting cement (Variolink II; Ivoclar, Vivadent AG). The average distance between the crest of the alveolar bone and the cementoenamel junction in young adults is almost 1mm (Newman MG et al. 2015). A 0.18 mm layer was modeled as PDL in adults (aged 32–50) (Newman MG et al. 2015). The cancellous bone was covered by 1.59 and 1.95 mm thicknesses of buccal and lingual cortical bone (Katranji et al. 2007), respectively, and a 0.25 mm thickness of compact bone was considered the lamina dura layer. The root canal was prepared according to the post shape with 0.1 mm wider size. The post-cement layer was created with a thickness of 0.1 mm and the remaining space between post and root canal wall was filled with cement. Zinc phosphate cement was used for the metal posts (Ss, Ti, Au, and Ni-Cr) whereas the resin luting cement was used for Zr post. The periodontal tissues supporting the tooth model were cut mesially and distally according to the widest width of the crown.

Table 1: Configuration of the FEA Models

Group	Model number	Model label	Post type	Post material	Root canal shape
I	1	SsP	T-Post	Ss	S-Canal
	2	TiP	T-Post	Ti	S-Canal
	3	GaP	T-Post	Au	S-Canal
	4	NcP*	T-Post	Ni-Cr	S-Canal
	5	ZrP	T-Post	Zr	S-Canal
II	6	SC1	C-Post	Ni-Cr	S-Canal
	7	SC2*	T-Post	Ni-Cr	S-Canal
	8	WC1	C-Post	Ni-Cr	W-Canal
	9	WC2	T-Post	Ni-Cr	W-Canal

* NcP and SC2 models correspond to the same configuration.

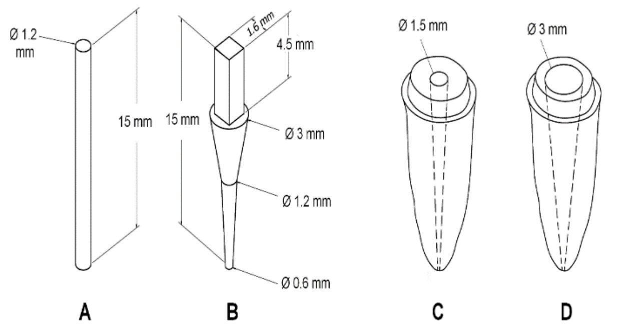

Fig. 2: Post Models and Root Canal Shapes Before Prepared. (A) C-Post. (B) T-Post. (C) S-Canal. (D) W-Canal.

According to the literature, the length of the post should be equal to 75% of the root length or at least match the length of the crown (Schwartz and Robbins 2004). In the present model, the total length of the post was set to 15 mm, and 10.5 mm (equal to the crown length) were inserted into the prepared root canal. At the root apex level, the model included 3.5 mm of gutta-percha filling as an apical seal (Abramovitz et al. 2001).
Nine 3D tooth models, divided into two groups, were created (Table 1). Group-I included five tooth models corresponding to five different root post materials (Ss, Ti, Au, Ni-Cr, and Zr) restored with a T-Post, composite core, and crown. Group-II included two different designs of prefabricated root posts (C-Post and T-Post) inserted in two different root canal configurations of the maxillary central incisor: small canal (S-Canal) and wide canal (W-Canal) (Fig.2 and Fig.3).

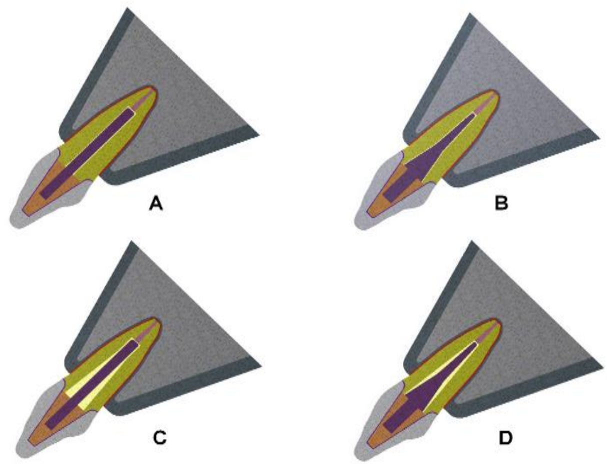

Fig. 3: Bucco-Palatal Sagittal Section View of: (A) SC1, (B) SC2, (C) WC1, and (D) WC2 Model.

Table 2: Isotropic Mechanical Properties of the Component Materials

Component/Material	Elastic modulus (MPa)	Poisson's Ratio	References
Stainless steel post	200000	0.33	(De Castro Albuquerque et al. 2003)
Dentin	18600	0.31	(De Castro Albuquerque et al. 2003)
Crown leucite ceramics	65000	0.19	(Dejak and Mlotkowski 2011)
Variolink II cement	8300	0.35	(Dejak and Mlotkowski 2011)
Gutta-percha	140	0.45	(Oyar 2014)
Zinc-oxide phosphate	22400	0.35	(Durmus and Oyar 2014)
Ni-Cr Alloy	205000	0.33	(Durmus and Oyar 2014)
Cortical bone	13700	0.30	(Gonzalez-Lluch et al. 2009)
Cancellous bone	1370	0.30	(Gonzalez-Lluch et al. 2009)
Periodontal ligament	68.9	0.45	(Gonzalez-Lluch et al. 2009)
Zirconia ceramic post	200000	0.23	(Seo et al. 2009)
Titanium post	120000	0.33	(Asmussen et al. 2005)
Gold alloy	93000	0.33	(Mahmoudi et al. 2012)
Composite	12000	0.3	(Mahmoudi et al. 2012)

2.2. Finite element analysis

The final 3D models were imported into the FEA software (ANSYS ver.15, Workbench; ANSYS, Inc.). All the materials and structures were assumed to be linear, elastic, homogeneous, isotropic, and bonded together with surface-to-surface contacts. The mechanical properties of all component materials were taken from the literature and are shown in Table 2.

Because of the complicated geometry of the tooth, a tetrahedral mesh is typically used in FEA studies of these systems (Pérez-González A et al. 2011). The SC1 tooth model was composed of 185546 elements, 316543 nodes; the SC2 model: 186213 elements, 318358 nodes; the WC1 model: 192297 elements, 327374 nodes; the WC2 model: 193989 elements, 330645 nodes. The accuracy of the models were checked by mesh convergence analysis of 2%.

Each model was constrained at the base and sliced along the mesial/distal surfaces to simulate the model, as in the mouth. A 100 N static occlusal was applied on the palatal face of the crown at a 45° angle (De Castro Albuquerque et al. 2003) with respect to the longitudinal axis of the tooth, as indicated in (Fig.4). The von Mises equivalent stress (VMS) on post and root (dentin) were investigated and the maximum shear stresses (τ) on the post cement were calculated on all directions (YZ, XZ, and YX) for all models of the two groups. A total deformation criterion was also adopted to evaluate the nodal displacements for each model.

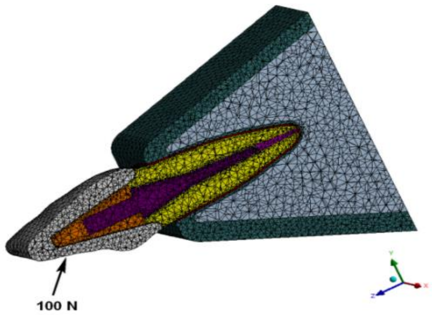

Fig. 4: Sagittal Section of the Finite Element Mesh of the SC2 Model, Showing the Load Conditions.

Table 3: Maximum Von Mises Equivalent Stress (VMS) Values in Root and Post (Mpa), and Maximum Shear Stress (T) in Post Cement (Mpa)

Group	Model number	Model label	VMS Root	VMS Post	τ (Post cement) (τ)yz	(τ)xy	(τ)xz
I	1	SsP	28.77	118.42	5.219	4.976	3.475
	2	TiP	30.25	70.35	5.088	4.635	2.835
	3	GaP	30.88	53.55	4.995	4.361	2.476
	4	NcP	28.69	121.35	5.224	4.982	3.517
	5	ZrP	29.05	125.15	5.327	3.094	3.179
II	6	SC1	31.75	93.92	7.892	3.427	3.459
	7	SC2	28.69	121.35	5.224	4.982	3.517
	8	WC1	31.81	92.08	8.353	3.083	3.741
	9	WC2	27.92	119.16	5.488	4.962	3.33

3. Results

We modeled teeth restored with post composed of Ss, Ti, Au, Ni-Cr, and Zr and simulated a crown pressure of 100 N. Table 3 lists the calculated values of maximum von Mises stress on the root and post and maximum shear stress on of the post-cement layer for the two groups, where the Table 4 shows the total deformation values of the post and tooth models. In all cases, the stress of dentin was concentrated on the facial surface of the coronal part of the root (Fig.5 and Fig.6).

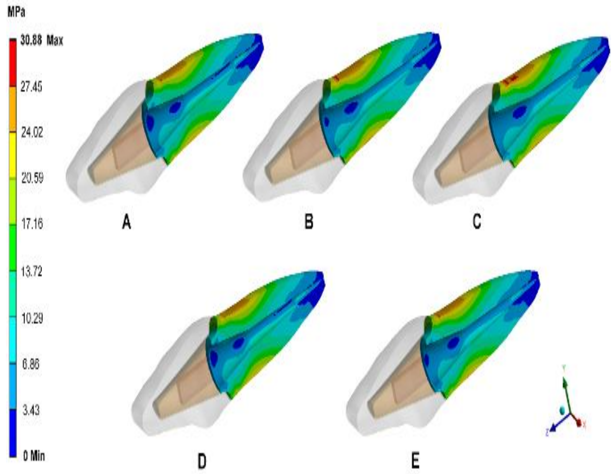

Fig. 5: Von Mises Equivalent Stress Comparison in Weakened Roots of Group-I: (A) SsP Model, (B) TiP Model, (C) GaP Model, (D) NcP Model, And (E) ZrP Model.

Table 4: Maximum Displacement Values of Post and Tooth Models (Mm)

Group	Model number	Model label	Post	Tooth
I	1	SsP	0.0405	0.0629
	2	TiP	0.0411	0.0640
	3	GaP	0.0414	0.0645
	4	NcP	0.0404	0.0629
	5	ZrP	0.0407	0.0633
II	6	SC1	0.0416	0.0651
	7	SC2	0.0404	0.0629
	8	WC1	0.0415	0.0648
	9	WC2	0.0404	0.0629

As discussed above, Group-I comprises models of a restored tooth involving T-Posts of different materials inserted in a small root canal (S-Canal); The Ni-Cr and Au posts produced the lowest and highest VMS on the dentin, respectively, with only a 7.7% difference between the two values. The stress values on the post increased with increasing modulus of elasticity of the post material. The lowest stress was recorded when the gold alloy was used, whereas the zirconium led to a 133% higher stress value on the post (Table 3. Fig.7). the maximum shear stress (τ) values on the post-cement layer also increased with increasing modulus of elasticity of the post material. The lowest shear stresses on the cement were recorded for Au and Ti materials, whereas Ni-Cr and Zr materials led to the highest stress values (YZ plan). The total deformations of the post and tooth models showed a slight increase with decreasing modulus of elasticity of the post material (Table 4).

The models in Group-II combined two post designs and two root canal shapes. Lower VMS on the root were obtained for the T-Post-based models. The stress values on the dentin were 10.6% lower in the SC2 and 14% in the WC2 model. Higher (τ) stresses on the post cement were found when the C-Post was used (YZ plan), and the highest values were recorded for the WC1 model. Severe interfacial shear stress concentrations were identified in two regions, active values at the coronal root and passive values at the apical third of the root interfaces (Fig.8). T-Post dissipated interface shear stress excellently on the coronal part of the root. Higher total deformations of the teeth and posts were recorded when using the C-Post and the highest deformation values were found for the SC1 model (Table 4).

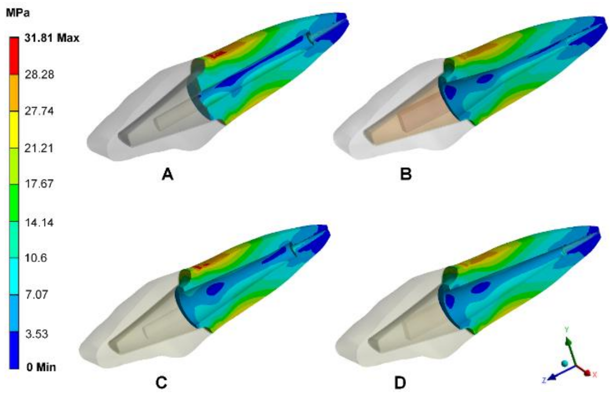

Fig. 6: Von Mises Equivalent Stress Comparison in Weakened Roots of Group-II: (A) SC1 Model, (B) SC2 Model, (C) WC1 Model, and (D) WC2 Model.

4. Discussion

The use of root post to restore endodontically treated tooth creates unnatural restoration components since the canal is filled with a material that has defined stiffness, unlike the natural pulp tissue, making it impossible to recreate the original stress distribution pattern within a tooth (Durmus and Oyar 2014). A proper stress distribution profile of the compound root, post, and core is necessary to minimize the probability of restoration failure. In this study, the FEA method was used to evaluate the influence of the post material and geometry on the stress distribution in endodontically treated teeth. Von Mises stress was the chosen criterion to assess the potential failure of the root and post, as well as shear stress criterion to evaluate the risk of post detachment.

In line with previous studies (Durmus and Oyar 2014; Mahmoudi et al. 2012; Oyar 2014; Uddanwadiker et al. 2007), the present analysis revealed higher dentin stress concentrations in the coronal third of the root on the facial surfaces of the teeth. This study found that the use of different high-stiffness post materials caused only minor changes in the stress on the dentin. This result is consistent with previous studies by (Genovese et al. 2005), (Fu et al. 2010), and (Mahmoudi et al. 2012) which reported a negligible influence of rigid post materials on the stress concentration in the remaining tooth structures. In contrast, the use of different post materials resulted in significantly different stresses on the post and post-dentin interfaces. The equivalent stresses on the posts increased with increasing elastic modulus of the material; similar results have been observed in other studies (Asmussen et al. 2005; Dejak and Mlotkowski 2011; Oyar 2014).

Due to the high modulus of elasticity of the posts, the occlusal loads were transmitted directly to the post and post-dentin interfaces. Stresses located at the post-dentin interface may negatively affect post retention (Fu et al. 2010; Seo et al. 2009), therefore reducing these stresses is vital to minimize the possibility of displacement of the post. As is clear, shear stresses will contribute to detach the post because they produce relative sliding between post-core and dentin (Genovese et al. 2005). This study showed that Au material recorded the lowest stress in the post as well as lowest shear stresses in the cement layer, this may lead to increases in retention of GaP post compared to the other tested models in Group-I. The result was consistent with the FEA finding of (Mahmoudi et al. 2012) in that a prefabricated gold alloy post generated lower stress at post-dentin interface compared with Ni-Cr and titanium posts, on stress distribution in posterior teeth. Furthermore, a retrospective clinical study evaluated the failure rate of custom cast posts and showed that the most common complication was loss of retention of the post and cores, and High-gold-content posts had a lower risk of failure than posts made from semiprecious alloy (Balkenhol et al. 2007).

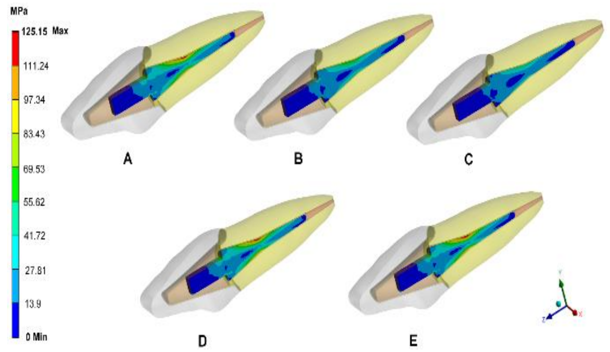

Fig. 7: Von Mises Equivalent Stress Comparison in the Posts of Group-I: (A) SsP Model, (B) TiP Model, (C) GaP Model, (D) NcP Model, and (E) ZrP Model.

The present work also found that the post geometry has a significant influence on the stress concentration in the dentin and post. The FEA results showed that the T-Post absorbed more stress, and caused a ~10–14% reduction in stress on the dentin under oblique load as well as a lower shear stresses on the cement layer, compared to the C-post. Furthermore, the T-Post provided more dissipation of the interface stress on the coronal part of the root, and distribute functional loading over a larger area of the remaining root structure compared to the C-Post. Therefore, more biomechanically favorable stress distribution in the root can be achieved when using T-post model. These different behaviors may be due to the two-stage tapered shape of the T-Post and to the 1.8 mm difference between the diameters of the two posts at the root ferrule level. In general tapered post provides superior adaptability to different root canal configurations, thus permitting optimal preservation of tooth structure and reducing the risk of post perforation in the apical region (Schwartz and Robbins 2004). Therefore, less cement needs to be used to fix the tapered post compared with the cylindrical shape.

Several FEA studies were conducted and compared the behavior of different post shapes on stress distribution of weakened roots; however, there are no data available on comparisons between the two- stage tapered post and the other root post models. However, the result is in line with the finding of (Asmussen et al. 2005) who demonstrated that a post with smaller diameter produces more stress on the root, and the author suggested to use a wide-diameter post as possible to restore weakened roots. Furthermore, the result conforms (Uddanwadiker et al. 2007) who concluded that a tapered post with a minimum taper produces lower stress and better retention compared with a cylindrical post. On the other hand, this result contradicted that of (De Castro Albuquerque et al. 2003) which stated that the maximum stress values in restored teeth were insensitive to the post shape.

The present theoretical study has some limitations, as all materials were assumed to be linearly elastic, homogeneous, isotropic, and ideally bonded together. However, the physical properties of biological structures are approximate, and the tooth structures are not homogeneous or isotropic (De Castro Albuquerque et al. 2003; Dejak and Mlotkowski 2011). Further experimental and clinical tests are necessary to evaluate the performance of different root post systems.

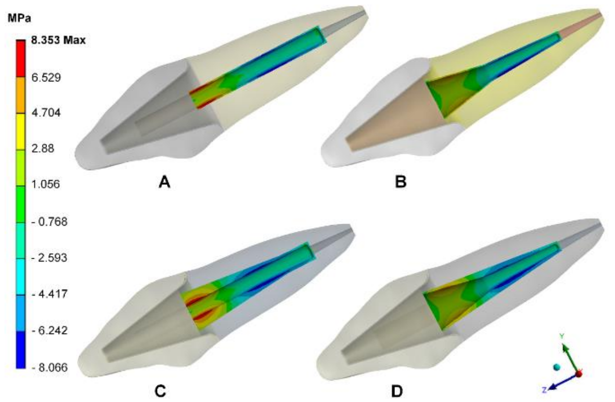

Fig. 8: Maximum Shear Stress Comparison in Post-Cement of Group-II (YZ Plan): (A) SC1 Model, (B) SC2 Model, (C) WC1 Model, and (D) WC2 Model-the Highest Values Are Marked in Red Color.

5. Conclusions

Within the limitations of this study, as discussed above, the following conclusions could be drawn:

1) The geometry of the post and the corresponding material play an important role in the stress magnitude and distribution in the post, dentin, and post/dentin interfaces.
2) Titanium and gold alloy appear to be the most reliable metallic materials for post systems because they generate lower amounts of stress at the post and post/dentin interfaces.
3) The shape of the post significantly alters the stress concentration in dentin, and the two-stage tapered post would be a very interesting choice to restore weakened teeth.

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