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Mechanical behaviour of endodontically restored canine teeth: Effects of ferrule, post material and shape

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Abstract

Objectives: To assess the effect of a ferrule design with specific post material-shape combinations on the mechanical behaviour of post-restored canine teeth.

Methods: Micro-CT scan images of an intact canine were used to create a 3-D tessellated CAD model, from which the shapes of dentin, pulp and enamel were obtained and geometric models of post-endodontically restored teeth were created. Two types of 15 mm post were evaluated: a quartz fiber post with conical-tapered shape, and a carbon (C) fiber post with conical-cylindrical shape. The abutment was created around the coronal portion of the posts and 0.1 mm cement was added between prepared crown and abutment. Cement was also added between the post and root canal and a 0.25 mm periodontal ligament was modeled around the root. Four models were analysed by Finite Element (FE) Analysis: with/without a ferrule for both types of post material and shape. A load of 50 N was applied at 45° to the longitudinal axis of the tooth, acting on the palatal surface of the crown. The maximum normal stress criterion was adopted as a measure of potential damage.

Results: Models without a ferrule showed greater stresses (16.3 MPa) than those for models with a ferrule (9.2 MPa). With a ferrule, stress was uniformly distributed along the abutment and the root, with no critical stress concentration. In all models, the highest stresses were in the palatal wall of the root. Models with the C-fiber post had higher stress than models with the quartz fiber posts. The most uniform stress distribution was with the combination of ferrule and quartz fiber post.

Significance: The FE analysis confirmed a beneficial ferrule effect with the combination of ferrule and quartz fiber post, with tapered shape, affording no critical stress concentrations within the restored system.

Introduction

It is widely recognised that to reduce fracture risk under physiological conditions and to preserve a seal against fluid access from the coronal end, endodontically treated teeth need to be restored with adhesive techniques [1-3]. A decrease in tooth rigidity often accompanies endodontic procedures as a consequence of the loss of one or both proximal ridges in posterior teeth and pulp chamber opening [4,5]. However, endodontically treated teeth may be successfully restored using adhesives without a post. The type of restored tooth, the shape of the residual cavity and the **adhesive-material** combination will influence fracture strength [6,7]. But especially in larger posterior teeth subject to compressive forces, if one or two cavity walls still remain, posts may help to reinforce weakened teeth [8,9]. For anterior endodontically treated teeth with a veneer, adhesive restoration should improve fracture resistance when a fiber post is placed and cemented in the root canal [10].

Further studies have shown that post placement may cause problems as a consequence of a mismatch between post stiffness and the residual dental structure, thus negatively affecting the mechanical resistance of teeth [11]. Compared to a sound tooth, an endodontic post may create a non-physiological stress and strain distribution as evaluated by **finite element (FE)** analysis [11–14].

Some authors analysed the effects of different combinations of restorative materials in anterior endodontically treated teeth [14]. It was evidenced that the level of stress and strain along the dentin-cement-post interfaces and the position of concentration areas were strongly related to the mechanical properties of the crown and core materials [14].

Under loading conditions, many differences have been found between endodontically treated anterior teeth and sound teeth [15].

The number of interfaces in the restored system, the cement modulus and its thickness, the post shape and its modulus can influence shock absorbance and stress distribution, also promoting crack propagation and fracture of the root [16,17]. Moreover, as experimentally evaluated, a combination of metal post and a resin composite core reduces the fracture resistance, compared to a fiber post, under static and fatigue loading [18]. To avoid this effect, a cement layer alone or in combination with dental adhesives may be considered. Even with low rigidity posts, it may not be possible to reproduce a physiological stress distribution, as in a sound tooth [12]. In a finite element analysis of the mechanical behaviour of a post-restored upper canine tooth, all the analyzed models exhibited a high stress gradient, because of interfaces with different material stiffnesses [1]. Nevertheless, when supragingival structures are badly damaged and subject to fracture during mastication, and when the tooth has been endodontically treated, posts and cores are widely employed [19]. The strength and

longevity of a post-and-core restored tooth is influenced by several factors. These are: the post material and its length, the post attachment to tissues, the root wall length and width, and the presence of a ferrule [19,20].

Post shape slightly affects the mechanical behavior of the restored teeth as reported in the literature [1]. Specifically, whereas small variations of post diameter or conicity do not affect the stress behavior in the modelled canine, variations in crown material strongly influences the “degree of fracture” [1].

With regard to the post material, it was previously shown that a fiber-glass post with a stiffness similar to that of the employed composite crown provided suitable results [1]. For a fiber-glass post, the post shape did not affect the stress distribution, when both conical and cylindrical shapes were adopted [1].

Thus, length, diameter, shape and stiffness of the post has been widely discussed by means of FE analysis for anterior teeth, showing that stiffness influences the length of the post that can be employed and a shorter fiber-glass post may successfully replace a longer metal post [1, 21].

A 3D FE analysis of the mechanical behavior of post-restored upper canine teeth evidenced a high stress gradient in multicomponent models consisting of materials with different stiffness at various interfaces and the combination of a composite crown and a conical or cylindrical fiber-glass post provided a mechanical behaviour which was similar to that of a sound tooth [1].

On the other hand, a ferrule is a metal ring or cap employed for strengthening. The “ferrule effect” is the consequence of a crown encircling the remaining supragingival tooth structure, which greatly enhances fracture resistance [20–24]. A ferrule may be a part of the artificial crown or core reinforcing root-filled teeth, that resists lever forces, lateral forces related to the post insertion and the wedging effect with a tapered post under functional loading [25]. Positive strengthening influences of ferrules have been reported [26–28]. As a consequence of the ferrule effect, post/core ratios are increased, fluid erosion of the luting cement is reduced and post retention is improved. Some controversies exist about the optimum height of remaining tooth structure and the location of supragingival structures [29–33].

Currently, custom cast metal posts-and-cores or fiberglass-reinforced composite posts are recommended [34]. However, compared to metal posts, composite posts show different mechanical properties [35]. For example, fiberglass-reinforced composite posts and cast gold alloys have, respectively, four times (879 MPa) and seven times (1542 MPa) the flexural strength of dentin (213 MPa). The optimum sizes of metal posts and cores have been investigated using experimental and

theoretical methods [36] and the influence of the ferrule effect and the length of cast and fiberglass-reinforced composite posts on the stresses of anterior teeth have been evaluated [19].

In particular, Dejak and Młotkowski [19] showed that the ferrule effect resulted not only in reduction of modified von Mises stresses in posts, in luting cement and in dentin, but also in a decrease of contact tensile stresses around posts: in teeth without a ferrule these were 1.7–3.0 times higher than those in teeth with a ferrule. Lower modified von Mises stresses were found in teeth with cast posts, compared to fiberglass-reinforced composite posts. Independently from the post material, in teeth restored with posts of several lengths, the modified von Mises stresses were similar [19]. It was also shown that post length had a small effect on stresses in tooth structure [19].

Anyway, with regard to post-core crown restorations, even though the use of rigid posts concentrates stresses at the interfaces, flexible posts provide stress concentration at the dentin.

To overcome the drawbacks related to both rigid and flexible posts, functionally graded materials (FGMs) have been proposed as an ideal choice to develop inhomogeneous dental posts with tailored properties [37].

In this context, the influence of different functionally graded posts on the stress distribution of endodontically treated teeth was analyzed. Specifically, if compared to homogeneous zirconia or titania posts, a better stress distribution was found in the case of FGM posts consisting of alumina/zirconia, titanium and hydroxyapatite, where the elastic modulus varied longitudinally [38]. Furthermore, a reduction of stress concentration was found at the apex of the post in a study focused on the use of a functionally graded composite post and core, with an elastic modulus varying in the longitudinal direction [39].

A recent 3D FE analysis [40] was also carried out to assess the influence of inhomogeneous dental posts on the stress distribution in tooth root and interfaces, evidencing how such devices can reduce dentin and interface stresses and resolve the weakness of both rigid and flexible posts.

However, the aim of the current research was to assess the effect of ferrule and of specific material-shape combinations for the post on the mechanical behaviour of post-endodontically restored canine teeth.

The null hypothesis was that the material-shape combination for the post and the presence of a ferrule would not affect the levels of the maximum tensile stress in the different components of the restored tooth.

Materials and Methods

Generation of a tooth solid model

A 3D CAD model of an intact canine was built-up using micro-CT scan images, from which the shapes of dentin, pulp and enamel were obtained. The tooth was digitized with a micro-CT scanner system (Bruker microCT, Kontich, Belgium). 3D tessellated model of the tooth was created using the methodology adopted previously [1]. Image data sets were processed by using the ScanIP® 3.2 module (Simpleware Ltd). Starting from cross-sections, generated by intersecting the tessellated model and cutting-planes, lofting surfaces were created using Rhinoceros® 5.0. Boolean operations were carried out to ensure the congruence of interfacial boundaries of tooth tissues. The tooth was 25 mm long, with about 10 mm crown height and 7 mm buccolingual crown diameter. The tooth geometric model was located in the system of coordinates such that the Z axis was oriented apically, the X axis mesiodistally and the Y axis buccolingually. Starting from the sound tooth model, the geometric models of post-endodontically restored tooth were created using Rhinoceros® 5.0. For crown preparation, tooth reduction was performed according to standardized specifications [41]: 2.0 mm-thickness of incisal edge, 1.0 mm-thickness of facial edge and 0.5 mm-thickness of lingual edge. Models without and with a 2.5 mm long and 0.5 mm wide ferrule were created. The crown margin was designed to simulate the boundary of the free gingival tissue. Two types of post were considered: a 15 mm-long quartz fiber post with conical-tapered shape, comparable to TokuPost (h15r – 0.95, Tokuyama Dental Corporation), and a 15 mm-long carbon fiber post with conical-cylindrical shape and 0.90 mm cylinder diameter. In all models, the abutment was created around the coronal portion of the posts. A 0.1 mm-thick layer cement was added between the prepared crown and the abutment, and cement was added between the post and the root in the root canal. Finally, a 0.25 mm-thick periodontal ligament was modeled around the tooth root for all models.

Numerical simulation

The geometric models of post-endodontically restored teeth were imported into the HyperWork® 14.0 (Altair Engineering Inc) environment, using the IGES format, where the finite element (FE) analyses were performed. Four models of post-endodontically restored teeth were built-up and analyzed (Fig. 1):

Model 1A (a tooth without ferrule and with quartz fiber post with conical-tapered shape),

Model 2A (a tooth without ferrule and with carbon fiber post with conical-cylindrical shape),

Model 1B (a tooth with a ferrule and a quartz fiber post with conical-tapered shape),

Model 2B (tooth with ferrule and carbon fiber post with conical-cylindrical shape).

Fig. 1 – Components of the constructed geometric models.

For the tooth models each component was defined in term of its mechanical properties. The Young's moduli and Poisson's ratios used are listed in Table 1.

Material	Young's modulus (GPa)	Poisson's ratio
Lithium disilicate crown	70	0.30
Crown cement	8.2	0.30
Abutment	12	0.30
Quartz fiber Post	$E_1 = E_2 = 15; E_3 = 50$	0.30
Carbon fiber Post	130	0.30
Post cement	8.2	0.30
Root	18.6	0.31
Periodontal ligament	$0.15 (x 10^{-3})$	0.45
Food (apple pulp)	$3.41 (x 10^{-3})$	0.10

Table 1 – Mechanical properties of materials: Young's modulus and Poisson's ratio.

A 3D mesh was created and each tooth model was divided into 3D solid CTETRA elements with four grid points. To minimize the mesh dependent results, a mesh size of 0.5 mm was adopted inside all the components of the tooth and mesh refinement techniques were used at the bonding interface (min mesh size: 0.05 mm). Table 2 summarizes the features of the analyzed models. The analyses were

focused on the closing phase of the chewing cycle. The variability of the chewing function was taken into account as it depends upon the contact between food and tooth surface. Solid food (apple pulp [42]), with values of the Young's modulus and Poisson's ratio of 3.41 MPa and 0.1, respectively, was modelled onto the palatal crown surface (Fig. 2) and slide-type contact elements were used between the tooth surface and the food.

Model	Ferrule	Post	Total # of Grids	Total # of Elements	Total # of Contact Elements	Total # of Degrees of Freedom
1A	Without	Quartz fiber	51552	213361	14094	188127
2A	Without	Carbon fiber	61833	264122	15326	205359
1B	With	Quartz fiber	56026	234011	14997	223578
2b	With	Carbon fiber	64967	277802	15618	233535

Table 2 – Analyzed tooth models and technical features.

Fig. 2 – FE models according to the components of the constructed geometric models, material properties and technical features.

In the FE models, nodal displacements on the external surfaces of the periodontal ligament were constrained in all directions. In contact with the food, a load of 50 N was applied at 45 degrees to the longitudinal axis of the tooth, acting on the palatal surface of the crown (Fig. 2). Static linear analyses were carried out. As the analyses were performed considering a non-failure condition, all the materials were assumed to behave as elastic materials.

Results

Except for the post component, this study involved materials that exhibit brittle behavior. So the maximum normal stress criterion was adopted as a measure of damage. The analyzed models exhibited a high stress gradient in the tooth components, due to the different stiffness of the materials present in the system. Interesting results were detected in the stress distributions. Fig. 3 depicts the contour plot of the first principal stress in the abutment, post, post cement, root and periodontal ligament. Cross sections along the buccolingual direction of the tooth were considered.

Fig. 3 - First principal stress distributions in the abutment, post, post cement, root and periodontal ligament (MPa): (a) Model 1A. (b) Model 2A. (c) Model 1B. (d) Model 2B. The false-colour scales vary from model to model, so the exact scale-range for each model should be noted carefully.

As seen in Fig. 3, models without a ferrule (1A and 2A) showed greater stresses than those for models with a ferrule (1B and 2B). In all models, the highest stresses were detected in the palatal wall of the

root. In models without a ferrule the maximum tensile stress was 16.3 MPa (Fig. 3b), compared to 9.2 MPa for models with a ferrule (Fig. 3d). Taking into account the same approach for the crown preparation, models with a C-fiber post and conical-cylindrical shape had greater stress than models with quartz fiber posts and a conical-tapered shape. For models without a ferrule, a maximum tensile stress of 16.3 MPa was found in the tooth with the C-fiber post (Fig. 3b), whereas 14.0 MPa was found with the quartz fiber post (Fig. 3a). Analogously, for models with a ferrule, the maximum tensile stress was 9.2 MPa with a C-fiber post (Fig. 3d) and 6.7 MPa with a quartz fiber post (Fig. 3c). In models with a ferrule, stress was uniformly distributed along the abutment and the root, with no critical stress concentration. Conversely, in the models without a ferrule, high stress concentrations were detected in the crown, the crown cement and in the root. Among the investigated models, the most uniform stress distribution was obtained for the combination of ferrule and quartz fiber post with tapered shape in the coronal portion (Fig. 3c).

More quantitative results are presented as maximum tensile stresses for each component (Fig. 4). The presence of the ferrule reduced tensile stresses in the root, where the maximum tensile stresses with ferrule were 1.8-2.1 times smaller those without a ferrule. Furthermore, in the crown cement, the maximum tensile stresses with ferrule were 6.2-32.1 times smaller than those obtained without ferrule.

Fig. 4 – Maximum tensile stress (MPa) in the components of the restored tooth.

Discussion

As reported in the literature, FE analysis has been frequently employed to study stress and strain distributions in teeth restored with adhesive techniques involving different approaches and materials [43-45].

The current study investigated different systems, with or without ferrule, and quartz fiber posts with conical tapered shape or C-fiber posts with conical-cylindrical tapered shape (Table 2), taking into account a more complex load application on the crown surfaces. All the results were reported in terms of stress values.

Compared to the C-fiber post with conical-cylindrical shape, the quartz fiber post with tapered shape gave lower stresses in all components of the restored tooth, except in the crown for the system with ferrule. Furthermore, the quartz fiber post with tapered shape improved the anchoring of the coronal restoration and provided an appropriate stress distribution, reducing tensile stress concentrations in the crown cement and root, compared to the C-fiber post with conical-cylindrical shape.

In agreement with the Dejak and Młotkowski [19], the current research also demonstrated the important role of the ferrule, as it was found that in a post-restored tooth a ferrule reduced the maximum tensile stresses in the crown, the crown cement and the root. Specifically, in the root the maximum tensile stresses with ferrule were 1.8-2.1 times smaller than those obtained without ferrule. In the crown cement, the ferrule gave maximum tensile stresses from 6.2 to 32.1 times smaller than those achieved without a ferrule.

Moreover, in systems with a ferrule no critical stress concentration was observed and the stress was uniformly distributed along the abutment and the root. This was different from models without ferrule where high stress concentrations were detected. The most uniform stress distribution was achieved for the combination of ferrule and quartz fiber post with a tapered shape of coronal portion (Model 1B) as a result of the synergistic contribution of the ferrule effect and the specific material-shape combination for the post.

Thus, the null hypothesis that in the different components of the restored tooth the material-shape combination for the post and the presence of a ferrule would not affect the levels of the maximum tensile stress was rejected.

However, a recent advanced study on a post-core crown restoration was properly performed with and without a ferrule. Metallic, fiber-reinforced composite and inhomogeneous posts were investigated by FE analysis, then comparing the results in terms of stress distribution [40]. Such analysis demonstrated the crucial role of the FGM post in reducing the values of the maximum tensile stress, both with or without a ferrule, whereas the presence of ferrule caused fewer dentin and interface stresses.

For this reason, also considering the results recently obtained for the FGM posts [40], the potential limitations of the current study were the uniform cement thickness, the constant value for the elastic modulus of the periodontal ligament as well as the approach related to the modelling of the post.

Conclusions

Taking into account the limitations of the present research, the following conclusions were drawn:

1. Different models of tooth restored with posts were analyzed especially focusing on the presence of ferrule and a specific material-shape combination for the post.
2. The absence of critical stress concentration and presence of uniform stress distributions along the abutment and root are evidently consequences of the ferrule effect and the specific material-shape combination for the post.
3. The synergistic combination of ferrule and quartz fiber post, with tapered shape, provided the most uniform stress distribution.

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Material	Young's modulus (GPa)	Poisson's ratio
Crown	70	0.30
Crown cement	8.2	0.30
Abutment	12	0.30
Quartz fiber Post	$E_1 = E_2 = 15; E_3 = 50$	0.30
Carbon fiber Post	13	0.30
Post cement	8.2	0.30
Root	18.6	0.31
Periodontal ligament	$0.15 (x 10^{-3})$	0.45
Food (apple pulp)	$3.41 (x 10^{-3})$	0.10

Model	Ferrule	Post	Total # of Grids	Total # of Elements	Total # of Contact Elements	Total # of Degrees of Freedom
1A	Without	Quartz fiber	51552	213361	14094	188127
2A	Without	Carbon fiber	61833	264122	15326	205359
1B	With	Quartz fiber	56026	234011	14997	223578
2b	With	Carbon fiber	64967	277802	15618	233535