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Evaluation of Stress Distribution in Endodontically Weakened Teeth Restored with Different Crown Materials: 3D-FEA Analysis

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This study evaluated the stress distribution in endodontically treated teeth, weakened (W) or not weakened (NW), restored with different materials of prosthetic crown using 3D-FEA. Models of a maxillary canine were constructed based on micro-CT images and divided into the groups: G1 (control) – sound tooth; G2 to G7 – endodontically treated teeth restored with glass fiber post (GFP); which G2 to G4 simulated NW root and G5 to G7 simulated W root. For crown material the teeth were restored with: G2 and G5: metallic coping and ceramic veneering, G3 and G6: zirconia coping and ceramic veneering, G4 and G7: alumina coping and ceramic veneering. Load of 180 N was applied at the incisal third of lingual surface at 45º. Models were supported by the periodontal ligament (x=y=z=0). The von Mises stress (VMS) values were calculated. The W teeth presented higher VMS at coping when compared to NW teeth and group G1 showed lower VMS value. For crown material, for both W or NW teeth, increasing VMS was found at metallic, zirconia and alumina coping, respectively. Metallic coping showed a better performance despite its unfavorable esthetics, suggesting as an appropriate material for prosthetic restoration of endodontically treated teeth.

Key Words: endodontically treated teeth, weakened, ceramic, finite element analysis.

Introduction

The restoration of endodontically treated teeth is one of the main challenges in Restorative Dentistry since the weakened tooth structure is more prone to biomechanical failures as a result of significant tooth loss (1). The major cause of tooth weakening are extensive caries, erosion, abrasion, previous restorations, trauma, fractures, iatrogenic procedures, pulp pathologies, as well as endodontic access and prepare for intracanal retainer (2).

Assuming the complete loss of coronal structure, intracanal retainers and cores are needed in order to provide retention for prosthetic crowns. In this sense, several materials have been suggested for intracanal and coronal restoration of endodontically treated teeth. However, those materials must provide adhesion to dentine and core and appropriate distribution of masticatory forces along root long axis (3).

In vivo and in vitro studies have demonstrated that glass fiber posts (GFP) associated with composite resin cores are an excellent approach for restoration of endodontically treated teeth compared to metallic post-and-core and prefabricated metallic posts as a result of excellent clinical performance (1,3,4). The GFPs present mechanical properties, such as elasticity modulus, similar to dentine which reduces the risk to root fracture (4). In addition, those retainers are more esthetic, practical, efficient and less invasive (5). However, using GFP in enlarged roots can be a challenge since the post is not completely adapted at coronal level. The thick layer of resin cement in this condition increases the risk to failure as a consequence of debonding or decementation (6).

The correct selection of restorative materials and preservation of remaining tooth structure are essential to achieve appropriate biomechanical performance of endodontically treated teeth (7). A lack of studies has been compared different types of prosthetic crowns about resistance to fracture and compression, success and survival (6,8). The porcelain-fused-to-metal crowns are materials widely used for restoration of endodontically treated teeth. However, assuming the modern esthetic requirements, all-ceramic systems have been introduced in order to provide better light transmission and esthetics without using metallic frameworks (9).

Although several materials can be indicated for prosthetic restoration of endodontically treated teeth, there is little information about the biomechanical performance when associating different materials for restoration of weakened roots. The studies usually evaluate tooth performance under excessive loading using destructive mechanical testing (10). However, a non-destructive method (finite element analysis – FEA) has been widely used as an excellent tool for analysis of internal structural performance in order to predict long-term failures in specific regions and provide additional data to in vitro destructive testing. The FEA allows to numerically simulate the behavior of several materials, techniques and designs about displacement and stress distribution under specific loading (11).

So, in order to evaluate the performance of different materials for restoration of endodontically treated teeth, the aim of this study was to assess stress distribution in endodontically treated teeth, weakened or not, restored with different combination of prosthetic materials using the three-dimensional finite element analysis (3D FEA). The null hypotheses assumed that: (i) there is no difference in stress distribution among the different combinations of restorative materials, and (ii) there is no difference in stress distribution between weakened or non-weakened roots.

Material and Methods

This study was approved by the Ethics Committee (C.A.A.E.: 22249113.7.0000.5498). A total of 7 three-dimensional finite element models were constructed representing a maxillary canine (C) surrounded by periodontal ligament and restored with glass fiber post and full-length crown with weakened root or not in order to simulate the different combinations of restorative materials. A total of 7 groups were designed (Table 1).

Construction of Finite Element Models

A sound canine, indicated for exodontia because of periodontal pathology or orthodontic treatment, was used in the present study based on the following inclusion criteria: root with 15 mm in length and cervical diameter ranging from 5 to 5.5. mm at mesiodistal direction and 7 to 7.5 mm at buccal-palatal direction; no caries, cracks, fractures, atresic canal, apical dilacerations, fissures or surface defects. The three-dimensional (3D) geometry of the tooth was based on a micro computed tomography (μCT) (SkyScan 1174v2; Bruker-microCT, Kontich, Belgium). Then, 0.5 mm-slices were get along the tooth structure.

The μCT data were transferred to the software Simpleware 4.1 (Simpleware Ltd, Exeter, UK) for geometry construction of a 3D solid model for the 7 experimental groups. Based on the tomographic image, the periodontal ligament was included into all 3D models with 0.2 mm in thickness. The endodontic treatment and reconstructive techniques of root internal walls were simulated according to the real procedures performed clinically.

The working length of 14 mm was reproduced in all experimental groups and maintained 1 mm far from the root apex. Canal instrumentation with manual K file up to #50 and root filling with gutta-percha were also simulated. Additionally, the restoration of root canal with a prefabricated parallel glass fiber post with 1.5 mm in diameter and 14 mm in length was simulated, preserving 4 mm of gutta-percha sealing at apical area. The cement layer thickness was maintained in 50 μm for the groups G2 to G4. The groups G5 to G7 presented a thicker cement layer as simulated in weakened roots (12).

A composite resin core was simulated in all models to restore the coronal region assuming a tooth prepare with reduction of 1.5 mm at buccal and lingual surfaces and 2 mm at the incisal edge. For prosthetic restoration, it was simulated a full-length crown presenting a coping with 0.5 mm in thickness and esthetic veneering with 1 mm in thickness at buccal and lingual surfaces and 1.5 mm at the incisal edge.

The weakened roots in the groups G5 to G7 were reproduced by root enlargement with 10 mm in length, 1.8 mm in apical diameter, 5 mm at mesiodistal direction, 3 mm at buccal-palatal direction, and 1 mm in thickness of remaining cervical walls.

Material Properties and Interface Conditions

The material mechanical properties (elasticity modulus [E] and Poisson's ratio [v]) were defined in the software Simpleware, using ScanFE and based on the literature; as shown in Table 2. All materials were assumed as homogeneous, isotropic and linearly elastic. The GFP was assumed as orthotropic since it presents different mechanical properties along fibers direction (x direction)

Table 1. Design of experimental groups

Groups	Material
G1 (Control)	Sound tooth
G2	Endodontically treated root restored with glass fiber post and porcelain-fused-to-metal crown
G3	Endodontically treated root restored with glass fiber post and all-ceramic crown with zirconia coping
G4	Endodontically treated root restored with glass fiber post and all-ceramic crown with alumina coping
G5	Enlarged endodontically treated root restored with glass fiber post and porcelain-fused-to-metal crown
G6	Enlarged endodontically treated root restored with glass fiber post and all-ceramic crown with zirconia coping
G7	Enlarged endodontically treated root restored with glass fiber post and all-ceramic crown with alumina coping

and other two normal directions (y and z directions). So, the material mechanical properties were represented by elasticity modulus along the 3 directions (Ex, Ey, Ez), Poisson's ratio (vxz, vxz, vyz) and shear modulus (Gxz, Gxz, Gyz) at orthogonal planes (xy, xz and yz) (Table 3). All model structures were assumed as completely joined, which means no failure in adhesion and interposition between them.

Finite Element Mesh

The finite element mesh was constructed using linear tetrahedral elements type C3D4 and the final models presented a specific number of nodes and elements (35,816 nodes and 174,838 elements for G1; 234,824 nodes and 1,243,290 elements for G2 to G4; and 392,069 nodes and 2,157,784 elements for G5 to G7). Mesh refinement was based on the convergence analysis of 6%.

Definition of Boundary and Loading Conditions

The finite element mesh of each model was transferred to the finite element software (Abaqus 6.10-EF1, Dassault Systèmes Simules Corp., Providence, RI, USA) for simulation of static occlusal loading of 180 N at the incisal third of the lingual surface at 45° in relation to tooth long axis in all models. As boundary condition, the nodes of periodontal ligament were fixed in the three axes of Cartesian plane (x, y and z), assuming values of x=y=z=0.

The results were generated by the finite element software as stress maps (hot colors represent the highest stress values while cold colors represent the lowest stress values) and numerical analysis. After loading, the maximum von Mises stress (VMS) was calculated.

Table 2. Mechanical properties of materials

Material	E (GPa)	v	Reference
Resin cement	18.6	0.28	Sorretino et al. (13)
Ceramic	69.0	0.30	Dejak & Młotkowski (14)
Metallic coping	200.0	0.33	Pierrisnard et al. (15)
Zirconia coping	269.0	0.25	Imanishi et al. (16)
Alumina coping	418.0	0.22	Jones et al. (17)
Composite resin	12.0	0.30	Ausiello et al. (18)
Dentin	18.6	0.31	Reinhardt et al. (19)
Periodontal ligament	6.89×10^{-5}	0.45	Reinhardt et al. (19)
Gutta-percha	1.4×10^{-1}	0.45	Friedman et al. (20)

Table 3. Orthotropic mechanical properties of glass fiber post

E (GPa)	v	Shear modulus (GPa)	Reference
X = 37.0	Xy = 0.27	Gxy = 3.1	
Y = 9.5	Xz = 0.34	Gxz = 3.5	Lanza et al. (21)
Z = 9.5	Yz = 0.27	Gyz = 3.1	

Results

Among all restorative materials, there was difference on both VMS distribution and value at coping and core, regardless the condition of endodontic treatment (weakened roots or not) (Table 4 and Fig.1). The results showed that the greater elasticity modulus of coping material (metal: 200 GPa, zirconia: 269 GPa, and alumina: 418 GPa) was been proportional the higher VMS value (MPa) (metal: G2: 7.8 MPa and G5: 9.1 MPa; zirconia: G3: 28.8 MPa and G6: 37 MPa; alumina: G4: 42 MPa and G7: 53 MPa). The different combinations of restorative materials showed similar stress distribution along root length.

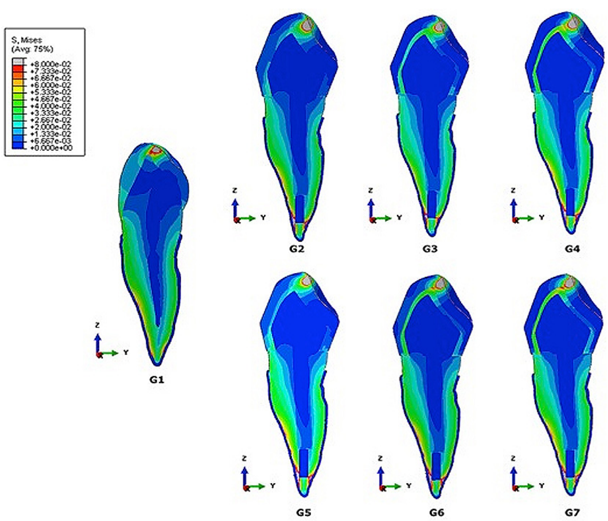

Figure 1. von Mises stress (VMS) distribution (MPa) in all groups.

Table 4. von Mises stress values (MPa) of the groups

Structures	G1	G2	G3	G4	G5	G6	G7
Ceramic	31.02	108.0	108.0	108.0	75.0	75.0	75.0
Coping	-	7.8	28.8	42.0	9.1	37.0	53.0
Composite resin core	-	1.0	1.7	2.0	2.2	3.6	5.9
Glass fiber post	-	2.82	2.8	2,8	2.9	2.9	2.9
Root dentin	-	13.0	13.0	13.0	13.0	13.0	13.0
Cement	-	4.1	4.1	4.1	4.1	4.1	4.1
PDL	0.3	0.3	0.3	0.3	0.4	0.4	0.4

PDL: Periodontal ligament

The sound tooth presented lower concentration of maximum von Mises stress when compared to the endodontically treated teeth (Table 4 and Fig. 1).

Comparing the endodontically treated teeth, it was found similar and homogeneous VMS distribution and value (MPa) along the root, glass fiber post, cement and periodontal ligament in all groups; reduced VMS value (MPa) at veneering; and higher VMS value at coping and core in the weakened groups G5 to G7 compared to the non-weakened groups G2 to G4.

Discussion

Endodontically treated teeth present higher risk to biomechanical failure in comparison to sound teeth as a consequence of excessive tooth loss because of root and/or coronal caries, extensive restoration, occlusal unbalance, and prepare for intracanal retainers (22). This information was confirmed in the present study since the results showed lower values of maximum von Mises stress (MPa) in sound tooth compared to endodontically treated teeth restored with glass fiber post and prosthetic crown. Thus, it can be suggested that restoration of endodontically treated teeth remains a challenge in Restorative Dentistry.

The first null hypothesis was rejected since there was difference in VMS distribution and value between the different combinations of restorative materials. Coping properties; such as elasticity modulus, hardness and toughness; are known to predict the reliability of single crowns. In the present study, it was found direct relation between elasticity modulus and VMS values of coping; assuming an elasticity modulus of 200 GPa for metal, 269 GPa for zirconia and 418 GPa for alumina. Additionally, the literature reports strong correlation between elasticity modulus and fracture strength for prosthetic restorations (23), showing higher fracture strength (8) and reliability under cyclic loading (24) for porcelain-fused-to-metal crowns when compared to all-ceramic systems.

When a structure is under loading, stress concentrates in the region presenting the highest elasticity modulus, transferring the load with higher intensity to the surrounding structures (7). In this sense, the different combinations of restorative materials showed similar stress distribution along the root in the groups G2 to G7 because the coping presented the highest elasticity modulus, absorbing the greatest amount of stress in the whole system. In clinical scenario, it can be predicted that the highest VMS values in those structures would increase the risk to mechanical failure; which could be restored although the present study did not evaluate failure pattern. A retrievable failure is intended for good restorative materials since it represents a favorable prognosis for teeth restored with fiber posts (4).

The second null hypothesis was partially accepted. Although some studies have concluded that prepare on root dentine becomes the root thinner and more prone to fatigue and fracture (25), the present study showed similar stress along the root, glass fiber post and resin cement in all groups for both weakened and non-weakened roots; which is in accordance with Gomes et al. (12). Probably, the similar elasticity modulus of the structures was assumed as a monoblock system and provided uniform stress distribution (12), regardless the amount of remaining root dentine. Furthermore, restorative materials with elasticity modulus similar to oral tissues generate lower stress in the remaining tooth structure (22).

Nevertheless, it was found overload in coping and core in the weakened groups (G5 to G7) in comparison to the non-weakened groups (G2 to G4). This result suggests that, regardless root fragility, the restorative material influences the coronal area but not the root region since teeth restored with glass fiber post and composite resin core show homogeneous stress distribution along root dentine (7). In addition, all-ceramic crowns protect the remaining tooth structure (4) because of association between low elasticity modulus of glass fiber post and ceramic and also bonding between ceramic, composite resin core and resin cement. These features create a flexible complex restorative system with mechanical properties similar to sound teeth (4).

It is noteworthy that the present study is a limited computer simulation that cannot reproduce the dehydration and loss of collagen in ligament experienced after endodontic treatment; which affects the resistance to tooth fracture (22). Additionally, the materials were assumed as isotropic, homogeneous and linearly elastic; except for the glass fiber post. Another limitation was static loading that does not simulate the real forces occurring in oral cavity. So, further studies simulating resistance to fracture and thermal and mechanical cycling loading are required to predict the biomechanical performance of endodontically treated teeth, weakened or not, restored with different materials.

According to the results of the present study, it was concluded that regardless the condition of remaining root dentine, metallic coping showed a better performance despite its unfavorable esthetics, suggesting as an appropriate material for prosthetic restoration of endodontically treated teeth; sound teeth present lower values of maximum von Mises stress when compared to endodontically treated teeth; simulation of weakened root after endodontic treatment did not influence the values of maximum von Mises stress.

Resumo

Este estudo avaliou a distribuição de tensão em dentes tratados endodonticamente, fragilizados (F) ou não fragilizados (NF), restaurados com diferentes materiais para a coroa protética utilizando 3D-FEA. Modelos de um canino maxilar foram construídos baseados em imagens de micro-CT e divididos em grupos: G1 (controle) - dente hígido; G2 a G7 - dentes tratados endodonticamente com pino de fibra de vidro (PFV), sendo que G2 a G4 simularam raízes NF e G5 a G7 simularam raízes F. Para o material das coroas os dentes foram restaurados com: G2 e G5: coping metálico e revestimento cerâmico, G3 e G6: coping de zirconia e revestimento cerâmico, G4 e G7: coping de alumina e revestimento cerâmico. Carregamento de 180 N foi aplicado na superfície lingual em seu terço incisal com 45 graus de inclinação. Os modelos foram suportados pelo ligamento periodontal (x=y=z=0). Os valores da tensão de von Mises (VMS) foram calculados. Os dentes F apresentaram maiores valores VMS para o coping quando comparados aos dentes NF, sendo que o G1 apresentou menores valores VMS. Para o material das coroas, ambos F ou NF aumentaram VMS no coping metálico, zirconia e alumina, respectivamente. Copings metálicos apresentaram melhor comportamento mecânico apesar de não favorecerem a estética, o que sugere ser um material apropriado para a restauração de dentes tratados endodonticamente.

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