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Root Canal Filling: Fracture Strength of Fiber-Reinforced Composite-Restored Roots and Finite Element Analysis

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The aims of this study were to evaluate the effect of root canal filling techniques on root fracture resistance and to analyze, by finite element analysis (FEA), the expansion of the endodontic sealer in two different root canal techniques. Thirty single-rooted human teeth were instrumented with rotary files to a standardized working length of 14 mm. The specimens were embedded in acrylic resin using plastic cylinders as molds, and allocated into 3 groups (n=10): $G_{(lateral)}$ - lateral condensation; $G_{(single\text{-}cone)}$ - single cone; $G_{(tagger)}$ - Tagger's hybrid technique. The root canals were prepared to a length of 11 mm with the #3 preparation bur of a tapered glass fiber-reinforced composite post system. All roots received glass fiber posts, which were adhesively cemented and a composite resin core was built. All groups were subjected to a fracture strength test (1 mm/min, 45°). Data were analyzed statistically by one-way ANOVA with a significance level of 5%. FEA was performed using two models: one simulated lateral condensation and Tagger's hybrid technique, and the other one simulated the single-cone technique. The second model was designed with an amount of gutta-percha two times smaller and a sealer layer two times thicker than the first model. The results were analyzed using von Mises stress criteria. One-way ANOVA indicated that the root canal filling technique affected the fracture strength (p=0.004). The $G_{(lateral)}$ and $G_{(tagger)}$ produced similar fracture strength values, while $G_{(single\text{-}cone)}$ showed the lowest values. The FEA showed that the single-cone model generated higher stress in the root canal walls. Sealer thickness seems to influence the fracture strength of restored endodontically treated teeth.

Key Words: rot canal filling, post, stress, finite element analysis.

Introduction

Vertical root fracture (VRF) has been the cause of failure of many endodontically treated teeth. The possible causes of this condition have been examined and recent evidence indicates that VRFs are most likely caused by the propagation of small, critical and less pronounced defects rather than the force exerted during the canal preparation or filling (1).

These incomplete fractures may occur in areas of high stress concentration when force is applied during the restorative procedure or from occlusal stresses during mastication (2). These fractures begin from small defects (1) that propagate through low and constant impulses, which result in a root fracture.

The quality of root canal filling has been widely evaluated by determining the percentage of voids and filling material with different filling techniques (3,4). It has also been demonstrated that endodontic and prosthodontic procedures may increase the incidence of vertical root fracture (5). Saw and Messer (6) studied the influence of root canal techniques (lateral condensation, Obtura and Thermafil) on the tension of roots and concluded that the lateral condensation and Obtura withstood more than twice the load than with Thermafil obturation, which is a thermoplastic technique.

Another important factor to be considered as a cause of stress concentration in the root canal apart from the filling technique is sealer expansion. Few studies have been carried out on the dimensional stability of sealers. The American Dental Association (ADA) states that no sealer should have contraction greater than 1%, but there is no consideration regarding how much a sealer may expand. However, research indicates that endodontic sealers undergo expansion that could weaken the root (7).

Restoration of endodontically treated teeth with an extensive loss of coronal dental structure may involve placement of an intraradicular post to retain a core (8). Various types of posts are available, but fiber posts have been widely used because they offer several advantages compared with the traditional cast metal dowel systems, including better esthetics and biomechanical behavior. It has been reported that use of fiber posts can reduce the incidence of irreversible root fracture compared with cast metal posts (9).

The placement of posts creates an interface between restorative materials and dental structure (9), and the rigidity of the restorative materials strongly influences the mechanical behavior of endodontically treated teeth (10).

A comparative evaluation of fracture strength of teeth restored with different posts found that the teeth restored with composite resin or glass prefabricated posts present favorable failure patterns compared with the metal cast post and core approach (11-13).

The aim of this study was to evaluate the effect of the root canal filling techniques on the fracture strength of roots and the type of failure. The other objective was to evaluate by finite element analysis (FEA) if sealer expansion with different thicknesses affects the stress distribution in different manners inside the root canal. The first research hypothesis was that the endodontic filling technique would affect the fracture strength and the specimens's fracture type. The second research hypothesis was that the single cone technique would generate the highest fracture strength. The third research hypothesis was that the sealer thickness would not influence the stress concentration inside the root canal.

Material and Methods

The study was approved by the Ethics Committee of the Federal University of Santa Maria and the teeth were obtained from the Human Tooth Bank of the same institution.

Experimental Design

The sample was composed of 30 extracted human permanent mandibular premolars, and mandibular and maxillary canines with straight root, single canal and complete root formation. After disinfection, the teeth were randomly allocated into 3 groups, according to the root canal filling technique (3 levels), resulting in 3 testing groups (n=10). Teeth with extensive caries lesions, calcifications and previous endodontic treatment were excluded. To evaluate these two last parameters, all the teeth were radiographed in both mesiodistal and buccolingual directions. In order to standardize the root dimension, dentin thickness was measured on the radiographs with a ruler. Also, root surface was examined with a stereoscopic magnifying glass (EyeMag Pro S, 4x; Carl Zeiss, Germany) and transillumination to discard teeth with cracks or fracture lines. The coronal portion of all teeth was removed using a low-speed diamond saw, leaving roots approximately 15 mm long.

Root Canal Preparation

A single operator instrumented all specimens to a standardized working length of 14 mm, using nickel-titanium rotary files (NRT NiTi; MANI, Inc., Nakaakutsu, Takanezawa-Machi, Japan) driven by an Endo Pro Torque engine (Driller, Jaguaré, São Paulo, SP, Brazil) with 1.5 N/cm torque and 300 rpm speed. The cervical third of the canals was shaped with 35 (0.12), 30 (0.10), 25 (0.10) rotary files, in that sequence. Then, the sequence of rotary files was 35 (0.04), 35 (0.06) and so on up to 15 (0.04) and 15 (0.06). This sequence was repeated until a 35 (0.06) rotary file reached the working length. The canals were irrigated with 2.5% NaOCl during instrumentation.

Periodontal Ligament Simulation and Root Embedding

After root canal preparation, the roots were placed inside plastic cylinders (15 mm high x 25 mm diameter). For periodontal ligament simulation, the root surfaces were dipped into melted wax (Newwax; Technew, Rio de Janeiro, RJ, Brazil) up to 3 mm below the most coronal portion of the specimen, resulting in an approximately 0.3-mm-thick wax layer. Then, the 35 (0.06) rotary file was attached to an adapted surveyor and the prepared root was fixed on that file. So, the long axis of the file, specimen and a plastic cylinder were parallel to each other and perpendicular to the horizontal plane. Next, a chemically cured acrylic resin (Dencrilay; Dencril, Caieiras, SP, Brazil) was prepared and poured into the cylinder up to 3 mm of the most coronal portion of the specimen. After polymerization, the teeth were removed from the resin and the wax was removed from the root surface.

For the periodontal ligament simulation, the resin "alveolus" was filled with a polyvinyl-siloxane material (Elite Light Body Normal Set; Zhermack, Rovigo, Italy), the tooth was inserted into the "alveolus" and excess material was removed with a scalpel blade.

Root Canal Filling Technique

After embedding, 3 groups (n=10) were formed, according to the technique used for the root canal filling:

- *Lateral condensation technique* ($G_{lateral}$): First, a size 35 (0.02) master gutta-percha (GP) cone (Dentsply Maillefer, Ballaigues, Switzerland) was selected and tug-back was checked. Sealer 26 sealer (Dentsply Ind. e Com. Ltda., Petrópolis, RJ, Brazil) was mixed according to the manufacturer's instructions, and the master cone was coated with the sealer and positioned in the root canal. Size 25 (0.02) accessory cones were laterally compacted using a size 30 (0.02) Mani Dental Spreader (Zhengzhou Shengxin Medical Instrument Co., Ltd., Japan), until it could not be introduced more than 5 mm into the canal. The force applied to the spreader was controlled using a digital scale (Kern 440-53; Kern & Sohn GmbH, Balingen-Frommern, Germany) and kept up to 3 kg. The extension of root canal filling was limited to 14 mm from the apex.

- *Single cone technique* ($G_{single\ cone}$): First, a size 35 (0.06) GP cone was firmly fitted into the root canal at the working length. Sealer 26 sealer was mixed according to the manufacturer's instructions, and the master cone was coated with the sealer and positioned in the root canal.

- *Tagger's Hybrid technique* (G_{tagger})*:* First, the apical 5 mm of the root canals were filled with laterally condensed GP, as described in $G_{lateral}$. Then, thermomechanical compaction was performed with Gutta Condenser #55 (Dentsply Maillefer). The plugger was carried apically up to 5 mm from the apical stop and then was activated. After GP plasticization, the GP condenser was slowly removed and GP was compacted vertically with a cold plugger.

In all groups, the coronal GP was removed with a heated instrument and the canal opening was sealed with a temporary restorative material (Coltosol, Coltène/Whaledent, Cuyahoga Falls, OH, USA). In order to allow complete endodontic sealer setting, the specimens were stored in water (37 °C) for 12 h.

Post Cementation Procedures

Using size #4 Largo drill (Dentsply Maillefer), 10 mm of the GP was removed, leaving a 5-mm long apical obturation. The post space was prepared with the preparation bur of a tapered glass fiber-reinforced composite post system (Macro-Lock™ post #3; RTD, St Egreve, France). The canal was then irrigated with 2.5% NaOCl and dried with paper points. Before cementation, the fiber post was cleaned with isopropyl alcohol, and a silane coupling agent (Prosil; FGM, Joinville, SC, Brazil) was applied on its surface, according to the manufacturer's instructions and the literature (17). A two-step self-etch adhesive system (AdheSE + AdheSE DC Activator; Ivoclar Vivadent, Schaan, Liechtenstein) was applied to the canal walls and to the cervical dentin surface, according to the manufacturer's instructions. Next, the dual cure resin cement Allcem (FGM) was mixed and inserted into the canal using a lentulo spiral #40 (Dentsply Maillefer), as recommended by the manufacturer. The post was also covered with cement and immediately inserted into the canal space. Light curing (RadiiCal; SDI, Bayswater, VIC, Australia) was performed through the incisal surface for 40 s.

The core was built with a composite resin (Filtek™ Z350 Universal Restorative; 3M ESPE), using a plastic matrix standardized (5 mm height). The composite resin was applied directly on the post and light-cured in order to avoid failures in the post/composite resin interface at the time of matrix placement. Then, the matrix was filled with composite resin and placed on the post. The buccal, lingual, mesial and distal surfaces of the core were light cured for 20 s each and then the specimens were stored in water (37 °C) for 7 days.

Fracture Strength Testing

Each specimen was positioned in a mounting device on a universal testing machine (DL-1000; Emic, São José dos Pinhais, PR, Brazil) and aligned at a 45° angle to the tooth long axis. A constant load was applied on the lingual face by a 2.5 mm diameter tip from the testing machine, at a crosshead speed of 1 mm/min, until the failure occurred.

Fracture Type Analysis

The fracture type was classified as: (F1) core facture; (F2) radicular fracture up to or above the simulated bone level; (F3) radicular fracture up to 1 mm below the simulated bone level; and (F4) radicular fracture more than 1 mm below the simulated bone level; "F1" and "F2" were considered reparable failures and "F3" and "F4" irreparable failures. The failure analysis was performed using a stereoscopic loupe at 4× magnification (EyeMag Pro S; Carl Zeiss, Germany) and transillumination.

FEA

FEA was done as a complementary analysis to verify if different thicknesses of the Sealer 26 cement would cause different stress distribution and concentrations after its setting expansion.

Two models were created, one represented the lateral condensation and Tagger´s hybrid techniques and the other represented the single cone technique. FEA models were developed by digitizing a single-rooted premolar in STL format. In order to simulate the lateral compaction technique and Tagger's hybrid technique, a GP cone was drawn with volume two times larger than the GP drawn for single cone model, with the aim of simplifying the design. The sealer thickness was inversely proportional to the GP cone volume in each model, i.e., the sealer thickness in the simulation of lateral condensation and Tagger´s hybrid techniques was less than twice the thickness of the single cone.

The modeling process was performed in Rhinoceros 4.0 software (McNeel North America, Seattle, WA, USA). After surface formation, they were transformed into solids and had their mechanical properties, such as elastic modulus and Poisson's ratio established according to the literature. The full images (Fig. 1) were exported in STP format (Standard for the Exchange of Product model Data) for the software Ansys Workbench v13 (ANSYS Inc., Canonsburg, PA, USA). Pre-and post-processing finite element was employed to generate the analysis. All the structures and materials used in the models were considered linear, elastic, homogeneous and isotropic (Table 1), except for the fiberglass fiber posts, which were considered orthotropic (Table 2). To simulate adhesion between the structures, all interfaces were considered completely bonded.

The setting expansion and moisture absorption of the endodontic sealer were simulated by thermal analogy. The linear thermal expansion coefficients were adjusted using as parameter to the Sealer 26 the value of expanding polymerization at 3%, according to the literature. The expansion value calculated from Equation 1 was 0.01×10^{-3} $^{\circ}C^{-1}$. The tensions were structurally analyzed based on the stress generated by this expansion.

Equation 1: $V-Vo = y.(T-To)$, where $y=3\alpha$, and α=linear thermal expansion coefficient $(a=1-(1-y)^{1/3})$

The endodontic sealer properties were determined by a non-destructive characterization from natural vibration frequencies obtained by the technique of pulsed excitation. For this test, a single beam of sealer was prepared and tested 10 times in order to determine both the average modulus of elasticity and the standard deviation of these measurements. During the test, the rectangular beam was supported on a suitable table and excited by the impact of a hammer specially made for this purpose (ATCP Sonelastic, Physical Engineering, Ribeirão Preto, SP, Brazil).

The numerical models were plotted and meshed with isoparametric elements, and the results were analyzed using von Mises stress and maximal principal stress criteria. Von Mises criterion was used to evaluate the model coherence to check, by the isochromatic line, if the stress field flows from the one geometry to another. The maximum principal stress was also used as a qualitative criterion because it showed not only the values of maximum tension and compression, as well as the tension field behavior.

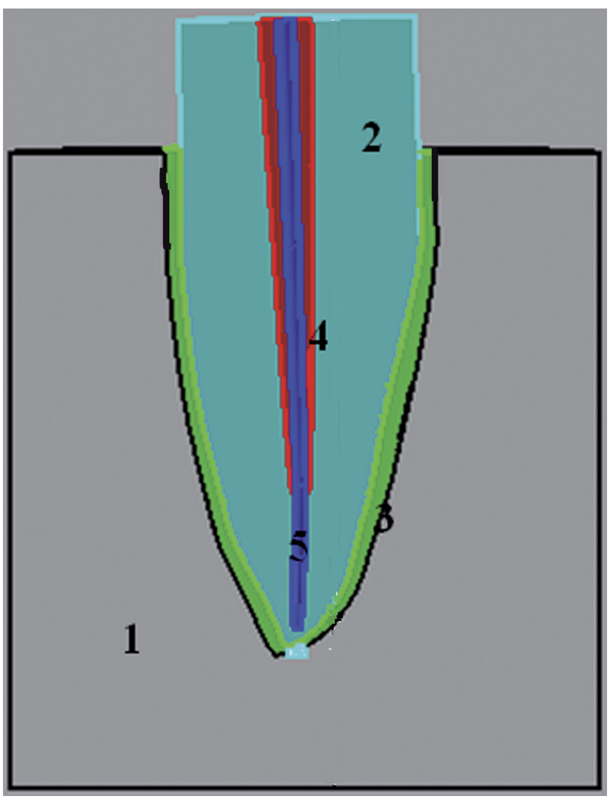

Figure 1. Geometrical delimitation and meshing of numerical models, where: 1=acrylic resin; 2=root; 3=ligament; 4=sealer; 5=gutta-percha.

Table 1. Elastic properties of isotropic materials

Structure	Elastic modulus (Mpa)	Poisson ratio	Reference
Acrylic resin	2600	0.38	*
Ligament	68.89	0.45	Holmes et al (14).
Dentin	18600	0.31	Ko et al. (15)
Gutta-percha	0.69	0.45	Ko et al. (15)
Sealer 26	4520	0.45	*

* data obtained from the technique of pulsed excitation (ATCP Sonelastic, Physical Engineering, Ribeirão Preto, SP, Brazil).

Statistical Analysis

The fracture strength data (N) were analyzed using one-way analysis of variance. Statistical analyses were not performed for the fracture type analysis.

Results

One-way ANOVA indicated that the filling technique ($p=0.0044$) affected the fracture strength. $G_{(lateral)}$ and $G_{(tagger)}$ had similar fracture strength values, while $G_{(single-cone)}$ showed the lowest fracture strength values (Table 3).

Table 4 presents the type of failure that occurred after fracture strength testing.

According to the FEA analysis, the von Mises criteria showed a correct flux of stress field from one geometry to another. The two groups (Fig. 2) showed different stress distributions as function of the cement thickness. The maximal principal stress showed that the single cone model presented a stress concentration two times the lateral condensation and Tagger's hybrid techniques. In addition, the stress distribution model of the single cone technique reached a large area, suggesting an increased tendency to fracture.

Table 2. Elastic properties of orthotropic materials (16)

Property	Fiberglass post
E_x (GPa)	37
E_y (GPa)	9.5
E_z (GPa)	9.5
V_{xy}	0.27
V_{xz}	0.34
V_{yz}	0.27
G_{xy}	3.10
G_{xz}	3.50
G_{yz}	3.10

Discussion

In this study, $G_{(lateral)}$ and $G_{(tagger)}$ did not show statistically significant differences and presented the highest values of fracture strength. $G_{(single\text{-}cone)}$ presented the lowest value of fracture strength and was significantly different from the other groups. Hence, the first hypothesis was partially accepted and the second hypothesis was rejected. There was a greater amount of endodontic sealer than GP in $G_{(single\text{-}cone)}$ compared with the $G_{(lateral)}$ and $G_{(tagger)}$, which influenced the occurrence of higher stress according to the FEA (Fig. 2) and consequently a possible negative impact on fracture strength (Table 3). The FEA was performed to confirm if the expansion caused by the sealer resulted in a concentration of stress at the root and if this stress would be proportional to the thickness of the cement, thus decreasing the resistance to root fracture.

The FEA showed that the group with greater sealer thickness [$G_{(single\text{-}cone)}$] generated greater stress on the canal walls, rejecting the third hypothesis. This stress may have generated cracks that possibly contributed to the lower fracture strength values of the single-cone group. The compression techniques of GP are most used because they maximize the amount of GP, which is dimensionally stable, resulting in a thin layer of cement covering the root canal walls (sealer is soluble and susceptible to infiltration). Additionally, GP is a low-modulus material and this property may reduce the volume of the root canal affected by sealer expansion and can be expected to absorb some of the generated stress (7). However, not all the sealers do expand because this phenomenon depends on the sealer composition (7).

The present study used the Sealer 26, which is composed of calcium hydroxide and bismuth oxide agglutinated with epoxy resin. According to Garrido et al. (18), Sealer

Table 3. Mean and standard deviation of fracture strength data (N)

Root canal filling technique	Mean±SD
$G_{(lateral)}$ - Lateral condensation	544.8±93.2^{A}
$G_{(single\text{-}cone)}$ - Single cone	423.7±136.1^{B}
$G_{(tagger)}$ - Tagger's hybrid technique	610.1±114^{A}

Same letters indicate statistical similarity; p<0.05.

Table 4. Failure analysis (%) of the specimens

Group	Failure type			
	Reparable		Irreparable	
	F1	F2	F3	F4
Lateral condensation	90	-	10	-
Single cone	70	10	10	10
Tagger's hybrid technique	70	20	10	-

F1: core fracture; F2: root fracture up to simulated bone level; F3: root fracture up to 1 mm below the simulated bone level; F4: root fracture more than 1 mm below simulated bone level.

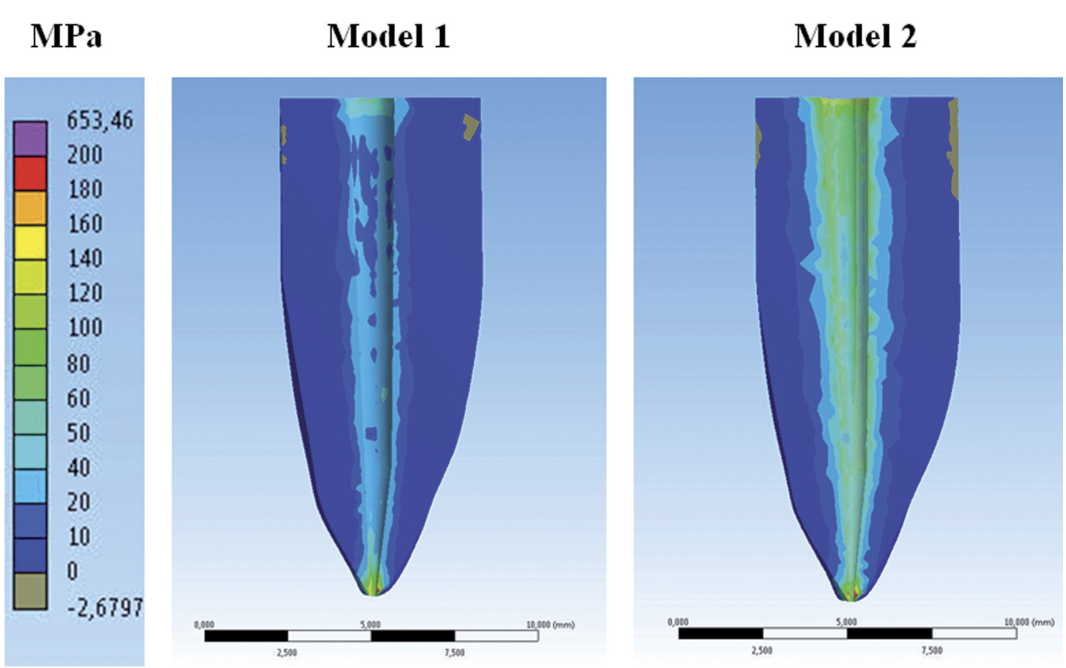

Figure 2. von Mises (MPa) stress distributions in the pre molar. Model 1=lateral condensation technique with thinner sealer thickness. Model 2=single cone technique with thicker sealer thickness.

26 presented the greatest dimensional alterations (3% expansion) compared with other sealers. These dimensional alterations could be explained by the resin water sorption after its polymerization (19). According to Orstavik et al. (7), if the sealer expands, there may be a risk of root fracture because the setting and the storage expansion of root canal sealers induces radial pressure on the pulpal aspect of dentin. Thus, expansion of the endodontic sealer may have contributed to decrease the fracture strength of $G_{(single\text{-}cone)}$, in the present study.

Lateral condensation and Tagger's hybrid techniques are different in terms of load application for root canal filling. In the present study, in $G_{(tagger)}$, only the apical portion was filled using a finger spreader, and the filling material in the middle and cervical thirds was mechanically plasticized. In the $G_{(lateral)}$, the finger spreader applied internal wedging forces to the entire length of the canal walls. However, the stress generated by lateral condensation and Tagger's hybrid techniques during root canal filling seemed to be less important than the sealer expansion that occurred in the single cone technique, in terms of fracture strength.

According to Telli et al. (20), the warm vertical compaction technique, when skillfully performed, does not create premature root fractures in a large rooted maxillary anterior tooth with straight root canal anatomy, even when containing severe weaknesses in itself and its supporting structures. Onnink et al. (2) evaluated three different filling techniques (lateral condensation and two different thermoplasticized GP filling techniques) on the incidence of incomplete vertical root fracture, and did not find statistical differences between the groups, corroborating the present study.

In the present study, no significant difference was found between $G_{(lateral)}$ and $G_{(tagger)}$. This is probably due to both techniques providing a similar amount of GP, when compared with the single cone technique. Although some studies (21) demonstrated that thermo-plasticized GP root canal filling techniques result in denser GP, the present study speculated that the difference of sealer quantity between this technique and lateral condensation is insignificant and was not enough to decrease the root fracture strength.

In this study, the adhesive cementation of the post was performed with self-etching adhesive and dual-curing cement. This approach was chosen because of the difficulty to perform bonding procedures within the root canal. The self-etching adhesive was used according to the manufacturer's instructions, which recommends no photoactivation of the adhesive inside the root canal to prevent the influence of the cured adhesive layer on the fit of the post and also because of the difficulty of the light reaching the most apical part of the post. Dual Cement was used for the same reason, i.e., the difficulty of light to reach the most apical part of the post; where the light does not activate the cement, the chemical cure takes part. However, according to Kanehira et al. (22), acidic monomers on the oxygen-inhibited surface layer of adhesives interact with the aromatic tertiary amine in the redox- or dual-curing overlying resin, thus preventing them from generating free radicals. Nevertheless, despite this limitation, the study did not aim to evaluate the bonding between post and the root canal, so that cementing would not influence the results.

In this study, the compressive load was applied directly on the core, since no crown was used in accordance with a previous study (23), for simplification purposes. However, the use of complete crowns has been shown to have significant influence on stress distribution in endodontically treated teeth (24). The use of no crown might have affected the stress distribution within the tooth and also the magnitude of fracture loads and the fracture modes of the specimens (25).

From a clinical standpoint, the findings of this investigation demonstrate that a greater amount of GP in relation to amount of sealer is better in terms of resistance, when restoring teeth that need fiber post and composite core. Teeth filled by lateral condensation or Tagger's hybrid technique present a more uniform stress distribution when occlusal loads are applied, which may mean a lower risk of root fracture.

The filling technique influenced the fracture strength of restored endodontically treated teeth but it did not influence the fracture type. The lateral condensation and Tagger's hybrid techniques produced the highest values for fracture strength. The FEA showed that the greater the sealer thickness, the greater the concentration of stress in the root canal.

Resumo

O objetivo deste estudo foi avaliar o efeito da técnica de obturação na resistência à fratura de raízes e analisar, por meio de análise de elementos finitos (AEF), a expansão do cimento endodôntico em duas diferentes técnicas de obturação. Trinta dentes humanos unirradiculares foram instrumentados com limas rotatórias, com um comprimento de trabalho padronizado (14 mm). Os espécimes foram embutidos em um cilindro plástico com resina acrílica, e distribuídos em 3 grupos (n=10): $G_{(lateral)}$ - condensação lateral; $G_{(cone\ único)}$ - cone único; $G_{(tagger)}$ - técnica híbrida de Tagger. Os canais radiculares foram preparados num comprimento de 11 mm com a broca de preparo do sistema de pinos de fibra reforçado por compósito. Todas as raízes receberam pinos de fibra de vidro, as quais foram adesivamente cimentadas, e a reconstrução do núcleo foi realizada com resina composta. Todos os grupos foram submetidos ao teste de resistência à fratura (1 mm/min, 45º). Os dados foram submetidos ao teste de análise de variância 1 fator. A AEF foi executada através de dois modelos: um simulou a técnica da condensação lateral e a técnica híbrida de Tagger, e o outro simulou a técnica do cone único. O último foi desenhado com a guta-percha duas vezes menor e com a espessura de cimento duas vezes maior que o primeiro modelo. Os resultados foram analisados usando o critério de tensão Von Mises. A análise de variância a um fator indicou que a técnica de obturação afetou a resistência à fratura (p=0.004). $G_{(lateral)}$

e $G_{(tagger)}$ obtiveram similares valores de resistência à fratura, enquanto $G_{(cone\ único)}$ apresentou os menores valores. A AEF mostrou que o modelo do cone único gerou um aumento de tensão nas paredes do canal radicular. A espessura do cimento pareceu influenciar a resistência à fratura dos dentes tratados endodonticamente e restaurados.

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