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Laboratory Research

Effect of Restorative Protocol on Cuspal Strain and Residual Stress in Endodontically Treated Molars

RAS Pereira • AA Bicalho • SD Franco
D Tantbirojn • A Versluis • CJ Soares

Clinical Relevance

The use of conventional or resin modified glass ionomers to fill the pulp chamber before cavity filling with an incremental direct composite restoration reduced cuspal deflection and residual shrinkage stress and increased the fracture resistance of endodontically treated molars.

Renata Afonso da Silva Pereira, DDS, MS, Biomechanics Research Group, Department of Operative Dentistry and Dental Materials; and School of Dentistry, Department of Operative Dentistry, Federal University of Uberlandia, Uberlandia, Minas Gerais, Brazil

Aline Aredes Bicalho, DDS, MS, PhD, Biomechanics Research Group, Department of Operative Dentistry and Dental Materials; and School of Dentistry, Federal University of Uberlandia, Uberlandia, Minas Gerais, Brazil

Sinésio Franco, Eng, MS, PhD, professor, Department of Mechanical Engineering, Federal University of Uberlandia, Uberlandia, Minas Gerais, Brazil

Daranee Tantbirojn, DDS, MS, PhD, associate professor, Department of Restorative Dentistry, College of Dentistry, University of Tennessee Health Science Center, Memphis, TN, USA

Antheunis Versluis, PhD, professor and director, Biomaterials Research, Department of Bioscience Research, College of Dentistry, University of Tennessee Health Science Center, Memphis, TN, USA

*Carlos José Soares, DDS, MS, PhD, professor and chairman, Biomechanics Research Group, Department of Operative Dentistry and Dental Materials; and School of Dentistry, Department of Operative Dentistry, Federal University of Uberlandia, Uberlandia, Minas Gerais, Brazil

*Corresponding author: Av. Pará, n° 1720, CEP 38400-902, Bloco B, 2B24, Uberlândia, Minas Gerais, Brazil; e-mail: carlosjsoares@umuarama.ufu.br

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SUMMARY

Objectives: To evaluate the effect of the restorative protocol on cuspal strain, fracture resistance, residual stress, and mechanical properties of restorative materials in endodontically treated molars.

Methods: Forty-five molars received mesio-occlusal-distal (MOD) Class II preparations and endodontic treatment followed by direct restorations using three restorative protocols: composite resin (CR) only (Filtek Supreme, 3M-ESPE), resin modified glass ionomer cement in combination with CR (Vitremer, 3M-ESPE in pulp chamber and Filtek Supreme in MOD cavity), conventional glass ionomer cement in combination with composite resin (CGI-CR) (Ketac Fil, 3M-ESPE in pulp chamber and Filtek Supreme in MOD cavity). Cuspal strain was measured using strain gauges, and fracture resistance was tested with an occlusal load. Elastic modulus (EM) and Vickers hardness (VH) of the restorative materials were determined at different depths using dynamic microhardness indentation. Curing shrinkage was measured using the strain gauge technique. The restorative protocols were also simulated in finite element analysis (FEA).

The shrinkage strain, cuspal strain, EM, VH, and fracture resistance data were statistically analyzed using split-plot analysis of variance and Tukey test (p=0.05). Residual shrinkage stresses were expressed in modified von Mises equivalent stresses.

Results: Shrinkage strain values (in volume %) were Ketac Fil (0.08±0.01) < Vitremer (0.18±0.01) < Filtek Supreme (0.54±0.03). Cuspal strain was higher and fracture resistance was lower when using CR only compared with the techniques that used glass ionomer. The EM and VH of the materials in the pulp chamber were significantly lower for glass ionomer. The FEA showed that using CR only resulted in higher residual stresses in enamel and root dentin close to the pulp chamber than the combinations with glass ionomers (RMGI-CR and CGI-CR).

Conclusions: The choice of restorative protocol significantly affected the biomechanical behavior of endodontically treated molars. Using glass ionomer to fill the pulp chamber is recommended when endodontically treated molars receive direct composite restorations because it reduces cuspal strain and increases fracture resistance.

INTRODUCTION

Multisurface restorations in permanent premolars and molars are the most frequent type of dental restorations.[1] Posterior direct restorations have been frequently placed in endodontically treated teeth that have a sizable amount of the cusp remaining.[2] Avoiding indirect restorations with cuspal coverage is recommended because they necessitate substantial removal of tooth structure and have a high cost.[2]

Endodontically treated teeth are more susceptible to fracture compared with intact teeth.[3] This has been attributed to structure loss and changes in the mechanical properties of dentin after endodontic treatment.[4] Restoring the strength of endodontically treated teeth requires restorative materials that can resist masticatory forces. Composite resins have been shown to provide fracture resistance when used as direct restorations for posterior teeth.[5] Composite restored teeth are also subjected to residual stresses due to polymerization shrinkage induced during the restorative process or with thermal changes. In a restored tooth, these stresses from different origins can either amplify or compensate each other.[6] Depending on the geometry of the structure, mechanical properties of the materials, and intensity of the applied load, the stress may generate elastic and plastic deformations that can promote failure in the structure.[7]

Masticatory loading can cause deformation of cusps in posterior teeth.[8] Endodontic treatment weakens cusps which results in higher structural deformation under masticatory loads[9] and, in turn, can lead to increased stress concentrations and fracture of the dental structure.[2] Restorative techniques that combine different materials have been suggested to reduce the stress generated at adhesive interfaces.[10,11] Whereas composite resin has been the material of choice for restoring endodontically treated posterior teeth,[1,12] a combination of composite resin and another material with lower elastic modulus (EM), such as glass ionomer, may reduce the shrinkage stress. Moreover, the use of conventional glass ionomer cement or resin modified glass ionomer cement as a substructure will reduce the composite resin volume needed to fill the cavity, which may diminish the residual shrinkage stress.[13] To date, no studies have evaluated the effect of the material combinations on cusp deflection and residual shrinkage stress.

This study evaluated the hypothesis that the use of conventional glass ionomer or resin modified glass ionomer to fill the pulp chamber of endodontically treated molars restored with composite resin will reduce cusp deflection, increase fracture resistance, and improve stress conditions.

METHODS AND MATERIALS

Tooth Selection and Cavity Preparation

Forty-five extracted, intact, caries-free human third molars were used (Ethics Committee in Human Research approval no. 06257012.1.0000.5152). The teeth were selected to have an intercuspal width within a maximum deviation of 10% from the determined mean.[14] The intercuspal width varied between 4.81 mm and 5.98 mm. The roots of the teeth were covered with a 0.3-mm layer of a polyether impression material (Impregum, 3M ESPE, St Paul, MN, USA) to simulate the periodontal ligament and then embedded in a polystyrene resin (Cristal, Piracicaba, Brazil) up to 2 mm below the cementum-enamel junction to simulate the alveolar bone.[15]

The teeth were cleaned using a rubber cup and fine pumice water slurry. Class II mesio-occlusal-distal (MOD) cavities with 4/5 of the intercuspal

Table 1: *Materials Tested in the Study* [a]

Materials	Manufacturer	Material Type	Presentation	Composition	Matrix
Filtek Supreme	3M-ESPE, St Paul, MN, USA	Nanofilled composite resin	Syringe	Silica nanofillers (75 nm), zirconia nanofillers (5-10 nm), and agglomerated zirconia-silica nanoclusters (600-1400 nm)	Bis-GMA, Bis-EMA, UDMA, TEGDMA
Vitremer	3M-ESPE, St Paul, MN, USA	Resin modified glass ionomer	Hand mixed	Fluoroaluminosilicate glass, microencapsulated	Poly (acrylic-itaconic acid) with pendent methacrylate, H_2O
Ketac Fil	3M-ESPE St Paul, MN, USA,	Conventional glass ionomer cement	Hand mixed	Fluorosilicate glass strontium, aluminum, lanthanum, and pigments	polycarbonic acid, tartaric acid, H_2O

Abbreviations: Bis-EMA, bisphenol-A hexaethoxylated dimethacrylate; Bis-GMA, bisphenol-A glycol dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.
[a] *Information provided by the manufacturers.*

width and 5-mm depth were prepared in all specimens with a diamond bur (#3099 diamond bur, KG Sorensen, Barueri, Brazil) with copious air-water spray using a cavity preparation machine.[16] This machine consisted of a high-speed handpiece (Extra torque 605 C, KaVo do Brasil, Joinvile, Brazil) coupled to a mobile base. The mobile base moves vertically and horizontally with three precision micrometric heads (152-389, Mitutoyo Sul Americana Ltda, Suzano, Brazil), attaining a 0.002-mm level of accuracy. The endodontic access was manually performed with a diamond bur (#1016 HL KG Sorensen) in a high-speed handpiece with copious air-water spray.

The composition and manufacturer information of the restorative materials used in this study are listed in Table 1. The specimens were distributed into three groups (n=15). In the composite resin (CR) group teeth were restored with an incremental filling technique using composite resin (Filtek Supreme, Shade A2, 3M-ESPE, St Paul, MN, USA) to fill the pulp chamber and MOD cavity. In the resin modified glass ionomer cement in combination with composite resin (RMGI-CR) group, teeth were restored using resin modified glass ionomer cement to fill the pulp chamber (Vitremer, Shade A2, 3M-ESPE) followed by the same composite resin technique to fill the MOD cavity; In the conventional glass ionomer cement in combination with composite resin (CGI-CR) group, teeth were restored using conventional glass ionomer cement to fill the pulp chamber (Ketac Fil, 3M-ESPE) followed by the same composite resin technique to fill the MOD cavity. Ten restored teeth per group were used for measuring cuspal deflection with strain gauges and afterward for compressive fracture resistance test. The other five restored teeth were used for Vickers hardness (VH) and elastic modulus (EM) measurements using the dynamic indentation method.

Cuspal Deformation

Cuspal deformation was measured with strain gauges (PA-06-060CC-350L, Excel Sensores, Embú, Brazil), which had an internal electrical resistance of 350 Ω, a gauge factor of 2.07, and a grid size of 21.02 mm^2. The gauge factor is a proportional constant between electrical resistance variation and strain. The strain gauges were placed on 10 teeth in the region where a finite element model had indicated the presence of the highest polymerization strains.[17] One strain gauge was placed on the external surface of the lingual cusp next to the height of the pulp chamber. The other strain gauge was placed on the external surface of the buccal cusp next to the base of the Class II MOD cavity. In addition, two strain gauges were fixed to another intact tooth to compensate for dimensional deviations due to temperature effects. The strain gauges were bonded with cyanoacrylate-based adhesive (Super Bonder, Loctite, Itapeví, Brazil), and the wires were connected to a data acquisition device (ADS0500IP, Lynx, São Paulo, Brazil).

For the RMGI-CR and CGI-CR groups, the glass ionomer cements were manipulated as recommended by the manufacturer and used to fill the pulp chamber, thereby creating a flat surface of the pulpal floor level with the gingival wall of the proximal boxes. The conventional glass ionomer was covered with wax for 5 minutes to achieve complete setting. The resin modified glass ionomer was light cured for 40 seconds using a light source with 600 mW/cm^2 output (Demetron Kerr, Orange, CA, USA). Selective etching of enamel was done for 15 seconds, and a two-step self-etching adhesive system (Clearfil SE Bond, Kuraray America, New York City, USA) were used for hybridization procedures in all groups. The average volume of composite per increment used was 24.3 mm^3 (no more than 2-mm thick) defined by a Teflon matrix to standardize before insertion into the cavity. For the CR group, the pulp chamber was filled in two resin increments and the coronal cavity for all groups was filled with eight resin increments (two at the mesial box, two at the distal box, and four at the occlusal box). Each increment was light cured for 40 seconds from the occlusal direction closest to the cavity.

The cuspal deformation data were obtained from the strain gauges through data analysis software (AqDados 7.02 and AqAnalisys, Lynx Tecnologia Eletrônica, São Paulo, SP, Brazil). The strain values were recorded at 4 Hz during the restorative procedure and continued for 10 minutes after curing the last increment.

Fracture Resistance Test

After cuspal deformation measurements, teeth were subjected to axial compressive loading with a metal sphere 6 mm in diameter at a crosshead speed of 0.5 mm/min in a universal testing machine (DL2000, EMIC, São Jose dos Pinhais, Brazil). The load required (N) to cause catastrophic fracture of specimens was recorded by a 500 N load cell hardwired to a computer with control and data acquisition software (TESC 3.04, EMIC). The failure mode of each specimen was analyzed under a stereomicroscope (Leika Ecafix, Tokyo, Japan) at 40× magnification, and then assigned to one of four categories, using a modified classification system based on that proposed by Burke[18]: (I) fractures involving a small portion of the coronal tooth structure; (II) fractures involving a small portion of the coronal tooth structure and cohesive failure of the restoration; (III) fractures involving the tooth structure, cohesive and/or adhesive failure of the restoration, with root involvement that can be restored in association with periodontal surgery; and (IV) severe root and crown fracture, which determine extraction of the tooth.

Vickers Hardness and Elastic Modulus

The remaining five specimens from each group were used for analysis of the mechanical properties (VH and EM) of the composite resin/glass ionomer restorations at eight depths. Each restored tooth was sectioned in the buccal-lingual direction into two halves using a precision saw (Isomet 1000, Buehler, Lake Bluff, IL, USA). One section per tooth was randomly selected for assessment of the mechanical properties. The specimens were embedded with methacrylate resin (Instrumental Instrumentos de Medição Ltda, São Paulo, Brazil). Before testing, the surfaces were finished with silicon-carbide papers (#600, 800, 1200, and 2000 grit, Norton, Campinas, Brazil) and polished with metallographic diamond pastes (6-, 3-, 1-, and 1/4-μm, Arotec, São Paulo, Brazil). After polishing, the specimens were cleaned using ultrasound for 10 minutes with distilled water. Using a Vickers indenter (CSM Micro-Hardness Tester, CSM Instruments, Peseux, Switzerland), indentations were made every 1.0 mm from 0.5 mm to 7.5 mm, starting from the base of the pulp chamber of the restorations. The indentations were carried out with controlled force, whereby the test load was increased or decreased at a constant speed ranging between 0 and 500 mN in 20-second intervals. The maximum force of 500 mN was held for 5 seconds. The load and the penetration depth of the indenter were continuously measured during the load-unload hysteresis. The universal hardness was defined as the applied force divided by the apparent area of the indentation at the maximum force. The measurements were expressed in VH units by applying the conversion factor supplied by the manufacturer. The indentation modulus was calculated from the slope of the tangent of the indentation depth curve at the maximum force and is comparable to the material's EM.[19]

Post-Gel Shrinkage

Post-gel linear shrinkage was determined using the strain gauge method.[20] Ten specimens were tested for each restorative material. The materials were shaped into a hemisphere on top of a biaxial strain gauge (CEA-06-032WT-120, Measurements Group, Raleigh, NC, USA) that measured shrinkage strains in two perpendicular directions (X and Y axes). A strain conditioner (ADS0500IP, Lynx Tecnologia Eletrônica) converted electrical resistance changes in the strain gauge to voltage changes through a quarter-bridge circuit with an internal reference resistance. The strains measured along the two axes were averaged because the material properties were homogeneous and isotropic on a macro scale. Filtek Supreme (composite resin) and Vitremer (RMGI) were light-cured using a quartz-tungsten-halogen unit (Demetron, Kerr, Orange, CA, USA) with the light tip held at a 1-mm distance from the surface of the composite and monitored for 10 minutes. The radiant exposure was set at 18 J/cm^2 (600 mW/cm^2 ×30 s). Ketac Fil (conventional glass ionomer) was positioned on the strain gauge after mixing and was monitored for 30 minutes. The mean shrinkage strain was used as linear post-gel shrinkage input for the finite element analysis and could be converted to volumetric percentage by multiplying by 3 and 100%.

Residual Stress Calculation: Finite Element Analysis

To calculate corresponding residual stresses in the tooth, a two-dimensional (2D) finite element model was analyzed for the MOD restoration with endodontic access. The geometry of the model was based on a digitized buccolingual cross-section of a third molar with similar dimensions as the teeth selected for laboratory tests. Coordinates were obtained using digital image processing software (ImageJ 1.48, National Institutes of Health, Bethesda, MD, USA). The applied mechanical properties were EM of enamel 84 GPa and Poisson ratio 0.30 as well as EM of dentin 18 GPa and Poisson ratio 0.23.[21] The EM values of the three restorative materials measured in this study were also used for the analysis (Table 4). The Poisson ratios used were 0.24,[22] 0.35,[23] and 0.33,[24] respectively for Filtek Supreme, Vitremer, and Ketac Fil. A plane strain condition was assumed for the tooth cross-sections. Because of this 2D strain condition and consequently 2D finite element model, no distinction was made between the mesial and distal increments.

The finite element analysis (FEA) was performed using MSC.Mentat (preprocessor and postprocessor) and MSC.Marc (solver) software (Version 2010r2, MSC Software Corporation, Santa Ana, CA, USA). One FEA model was generated for each experimental group to simulate the three restorative protocols of the experimental study. Polymerization shrinkage was simulated by thermal analogy. Temperature was reduced by 1°C, while the linear shrinkage value (post-gel shrinkage) was entered as the coefficient of linear thermal expansion. Modified von Mises equivalent stress was used to express the stress conditions using compressive-tensile strength ratios of 37.3,[22] 3.0,[22] and 5.82,[14] respectively for the enamel, dentin, and Filtek Supreme as well as 3.55,[25] and 11.3,[26] respectively, for the Vitremer and Ketac Fil. Stress values were recorded in the integration points of each element and in nodes along material interfaces at either aspect (tooth and restoration).

Statistical Analysis

The cuspal deformation (strain), fracture resistance, post-gel shrinkage, EM, and VH data were tested for normal distribution (Shapiro-Wilk, $p>0.05$) and equality of variances (Levene test), followed by parametric statistical tests. One-way analysis of variance (ANOVA) was performed for cuspal deflection in each cusp, fracture resistance, and post-gel shrinkage. One-way ANOVA was performed in a split-plot arrangement, with the plot represented by restorative protocol and the subplot represented by the depth of the cavity. Multiple comparisons were made using a Tukey test. The data of fracture mode were subjected to a χ^2 test. All tests used $\alpha = 0.05$ as the significance level, and all analyses were carried out with the statistical package Sigma Plot version 13.1 (Systat Software Inc, San Jose, CA, USA).

RESULTS

Cuspal Strain (CS)

The values of cuspal deformation (strain) for the three filling techniques are shown in Figure 1 and Table 2. For the lingual cusp, the CR filling technique had the highest cuspal deformation values, followed by the RMGI-CR and CGI-CR techniques, respectively. For the buccal cusp, the CR filling technique also had the highest cuspal deformation values. Buccal deformation was not significantly different between the RMGI-CR and CGI-CR groups.

Fracture Resistance and Failure Mode

The mean fracture resistance and standard deviation for the three restorative techniques are shown in Table 2. One-way ANOVA showed significant difference among groups ($p=0.02$). The CR group had significantly lower fracture resistance than the other two filling techniques that used glass ionomer to fill the pulp chamber. No differences were found between the RMGI-CR and CGI-CR groups. Failure mode distribution is shown in Table 3. No significant differences in failure modes were found among the three groups.

Vickers Hardness

The VH of the three filling techniques at various depths of the restorations are shown in Figure 2A and Table 4. The VH of the CR filling technique was constant through the entire restoration. For the RMGI-CR and CGI-CR filling techniques, the VH was constant on coronal restoration (composite resin portion) and decreased significantly in the pulp

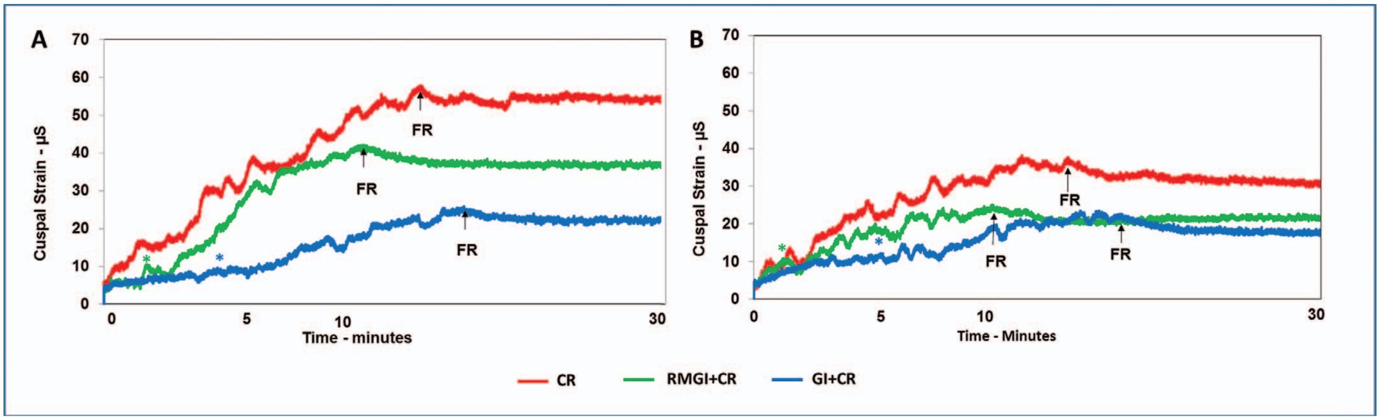

Figure 1. *Cuspal deformation in microstrains (μS) measured with strain gauges. (A): Lingual cusp. (B): Buccal cusp. *Indicates finishing glass ionomer insertion and activation. FR indicates finishing composite curing.*

chamber (glass ionomer–based materials). No differences were found between the VH on the coronal portion of the three filling techniques (Table 4). The VH measured in the pulp chamber was significantly lower for the RMGI-CR and CGI-CR restorative techniques (Table 4).

Elastic Modulus

The EM of the three filling techniques at various depths of the restorations are shown in Figure 2B and Table 4. The EM of the CR filling technique decreased significantly only after the 6.5-mm depth. For the CGI-CR and RMGI-CR filling techniques, the EM was constant in the coronal restoration (composite resin portion). The EM decreased significantly in the pulp chamber for the RMGI-CR and CGIRC techniques (Figure 2B). The EM values measured in the pulp chamber were significantly lower for the RMGI-CR and CGI-CR groups (Table 4).

Post-Gel Shrinkage

The mean values and standard deviations for the post-gel shrinkage of three restorative materials are presented in Table 5. One-way ANOVA revealed statistical difference among the composites ($p<0.001$). Filtek Z350 XT had significantly higher mean volumetric shrinkage value than Ketac Fil and Vitremer.

Finite Element Analysis

Stress distribution for all groups is shown in Figure 3. The filling technique influenced the stress distribution and stress intensity. The CR filling technique resulted in higher stresses in the enamel and in root dentin close to the pulp chamber than the CGI-CR and RMGI-CR filling techniques. For comparison, Figure 4 shows cuspal deformation calculated with the FEA in the same buccal and lingual locations where the strain gauges were placed in the experiments (Figure 1). Experimentally measured cuspal deformation values were similar to the deformation values calculated by FEA.

DISCUSSION

The results of the present study confirmed that the use of conventional glass ionomer or resin modified glass ionomer to fill the pulp chamber reduces the cusp deflection, increases fracture resistance, and improves shrinkage stress distribution in endodon-

Table 2: *Cuspal Deformation (μS) Measured by Strain Gauges and Fracture Resistance [a] Measured by Axial Compression Test (n=10)*

Filling Technique	Cuspal deformation, μS (Mean ± Standard deviation) Buccal	Lingual	Fracture Resistance, N
Filtek Supreme (CR)	30.9 ± 18.7^{B}	54.1 ± 23.4^{C}	943.7 ± 134.1^{B}
Filtek Supreme + Vitremer (RMGI-CR)	23.2 ± 12.1^{A}	36.8 ± 17.3^{B}	1502.8 ± 444.0^{A}
Filtek Supreme + Ketac Fil (CGI-CR)	19.8 ± 8.6^{A}	22.2 ± 10.8^{A}	1882.1 ± 371.4^{A}

[a] *Different uppercase letters indicate significant difference between the restorative techniques for each mechanical property (p<0.05).*

Table 3: *Failure Mode Distribution* [a]

Groups	Failure Mode, %			
	I	II	III	IV
Filtek Supreme (CR)	10	10	80	0
Filtek Supreme + Vitremer (RMGI-CR)	0	0	90	10
Filtek Supreme + Ketac Fil (CGI-CR)	0	20	80	0

[a] Failure modes are defined as follows: (I) fractures involving a small portion of the coronal tooth structure; (II) fractures involving a small portion of the coronal tooth structure and cohesive failure of the restoration; (III) fractures involving the tooth structure, cohesive and/or adhesive failure of the restoration, with root involvement that can be restored in association with periodontal surgery; and (IV) severe root and crown fracture, which determine extraction of the tooth.

tically treated molars restored with composite resin. Therefore, the hypothesis tested in this study was accepted.

The study of mechanical behavior involves examination of the relationship between a body of a given material or combination of materials and the forces acting on it, as well as the consequences of their interaction. Different materials respond differently to the application of these forces. The interactions with materials selection, bonding procedures, and restorative techniques are already complex for vital teeth but are even more complex for endodontically treated teeth. Endodontically treated teeth are weakened by alteration of mechanical properties and moisture content of the dentin,[3] loss of strategic tooth structure through restorative procedures, and caries.[27,28] A direct restoration should recover the stress/strain conditions of the original intact tooth.[21] Therefore, a restorative procedure using materials with mechanical properties distribution similar to an intact tooth is most desirable.

The present study investigated several aspects of the materials and restorative techniques that are involved in the biomechanical behavior of an endodontically treated tooth. To calculate the shrinkage stresses, the polymerization shrinkage responsible for the shrinkage stress had to be determined. The shrinkage component that causes stresses (post-gel shrinkage) was measured using the strain gauge technique.[20] Post-gel contraction is characterized by the development of internal forces in the material, resulting in molecular rearrangement (viscoelastic properties) and their inability to compensate for the polymerization shrinkage by plastic flow and deformation.[29] Contraction of conventional glass ionomers, which also start out as materials that can relieve stress by flow in their uncured stage, were measured by the same strain gauge technique. The post-gel shrinkage of Filtek Supreme (0.54%) was significantly higher than the post-gel shrinkage of Vitremer (0.18%) and the corresponding value for Ketac Fil (0.07%). The low post-gel shrinkage values of Vitremer could be explained by the lower resin component and the prolonged setting reaction in comparison to composite resin. The Ketac Fil had a low post-gel shrinkage value because its initial reaction is based on a relatively slow acid-base reaction that allows more stress relief during setting. Although it was not considered in this study, restorative materials are known to swell because of hygroscopic expansion. Swelling can compensate setting shrinkage, but hydrophilic materials, such as the glass ionomers, may continue to expand,[30] which may have more significance over the lifetime of a restoration than shrinkage. On the other hand, these materials were used only to fill the pulp chamber in the present study, and were not in direct contact with water. The higher shrinkage stress in the CR model may be explained by the higher post-gel shrinkage of the Filtek Supreme in combination with its

Table 4: Elastic Modulus (GPa) and Vickers Hardness (N/mm^2) Averaged from Eight Measurement Points[ba]

Filling technique	Mean ± Standard deviation			
	Elastic Modulus, GPa		Vickers Hardness, N/mm^2	
	Coronal Cavity	Pulp Chamber	Coronal Cavity	Pulp Chamber
Filtek Supreme (CR)	14.4 ± 0.2[Aa]	13.1 ± 1.1[Aa]	115.1 ± 1.1[Aa]	113.5 ± 3.1[Aa]
Filtek Supreme + Vitremer (RMGI-CR)	14.5 ± 0.2[Aa]	10.7 ± 0.5[Bb]	118.6 ± 3.6[Aa]	59.9 ± 2.0[Bb]
Filtek Supreme + Ketac Fil (CGI-CR)	14.6 ± 0.1[Aa]	11.8 ± 0.2[Bb]	116.8 ± 57.1[Aa]	57.1 ± 4.9[Bb]

[a] *Different uppercase letters in columns compare restorative technique for each mechanical property. Lowercase letters in rows compare restoration location for each mechanical property ($p<0.05$).*
[b] *The coronal cavity was filled with composite resin in all groups, but the pulp chamber was either composite resin, conventional glass ionomer, or resin-modified glass ionomer.*

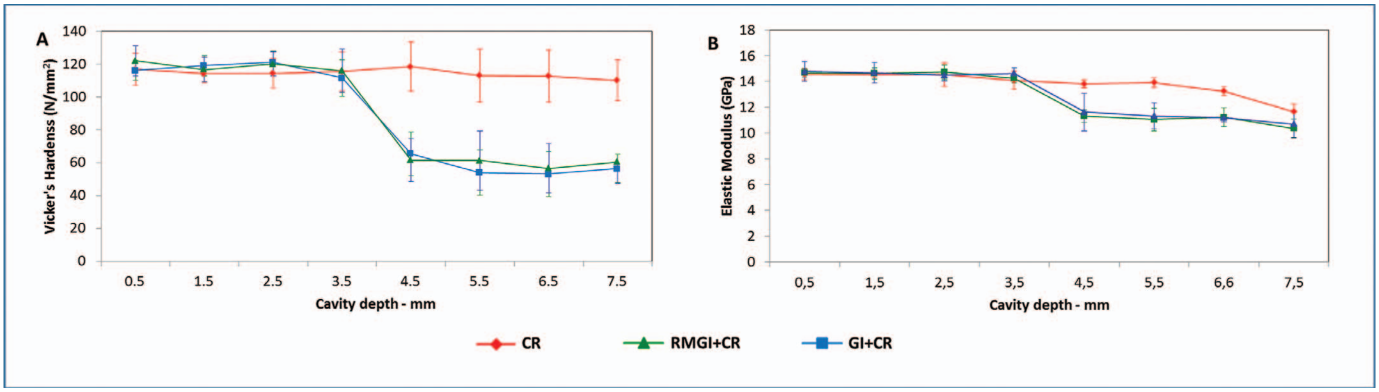

Figure 2. *Mechanical properties of the restorative materials used measured with dynamic indentation. (A): VH at various restoration depths on coronal portion and pulp chamber. (B): EM at various restoration depths on coronal portion and pulp chamber.*

higher EM. The main difference between the models was the material used to fill pulp chamber. Therefore, the residual shrinkage stress was generated in the tooth region where structural dentin was lost, resulting in higher cusp deflection and lower fracture resistance, as will be discussed later.

Microhardness

Hardness has been used as an indicator of degree of conversion (ie, extent of polymerization of monomers to polymers) and curing depth in resin-based dental materials.[31-33] Filtek Supreme inserted incrementally showed constant values of VH at all depths of the restorations, suggesting adequate polymerization and degree of conversion.[14] The Ketac Fil and Vitremer had similar VH, which was significantly lower than that of Filtek Supreme. This may be explained by the different compositions of these materials. Glass ionomer cements are mechanically weaker compared with composite resins because of the weak bonding between the particles of glass and polyacid matrix.[34] Resin-modified glass ionomers essentially consist of conventional glass ionomer components combined with organic photopolymerizable monomers for the initial setting reaction.[35] The VH values of the materials in the pulp chamber were constant for both glass ionomers, demonstrating that their curing process was efficient. The VH of the Filtek Supreme is very similar to the value for human dentin. However, when a correlation is made with the intact tooth, the pulp chamber is similar to an empty, not a load supporting, space. The use of materials with lower stiffness may thus explain the better biomechanical performance of the two groups that used glass ionomer to fill pulp chamber.

Table 5: *Mean (± Standard Deviation) Volumetric Post-Gel Shrinkage* [a]

Materials	Volumetric Post-Gel Shrinkage, %
Filtek Supreme	0.54 ± 0.03[B]
Vitremer	0.18 ± 0.002[A]
Ketac Fil	0.08 ± 0.00[A]

[a] *Different uppercase letters indicate significant difference between the composites* ($p<0.05$).

Elastic Modulus

The EM represents the relative stiffness of a material and gives information about how occlusal forces will be supported by the materials. The incrementally inserted Filtek Supreme showed constant values of EM up to 6.5 mm depth. At the bottom of the restoration the VH was maintained but EM decreased, demonstrating that VH and EM have no direct correlation.[14] The distance between the light positioned, even with limited access by the cusps was apparently sufficient to cure the very deep region of the cavity but not to attain the same EM.

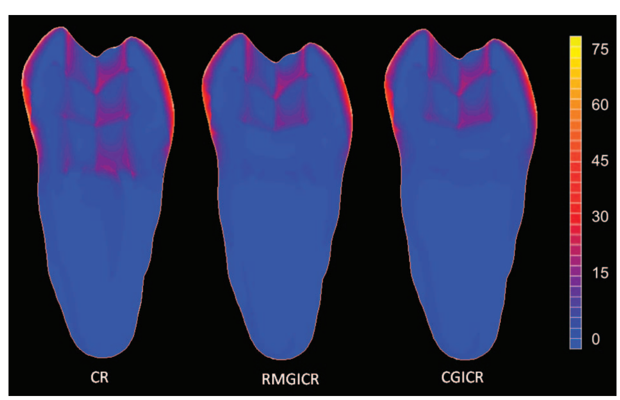

Figure 3. *Stress distribution calculated by FEA (modified von Mises equivalent stresses, MPa).*

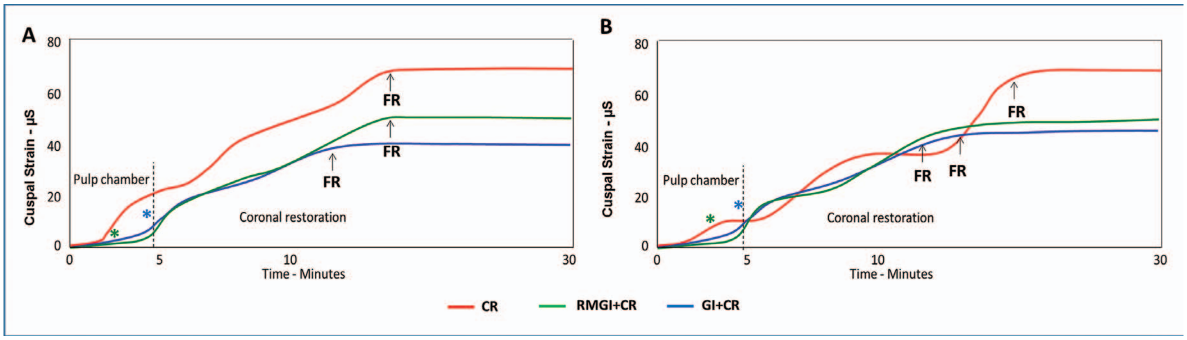

Figure 4. *Cuspal deformation in microstrains (µS) calculated with FEA in the same region where the strain gauges were attached in the experimental test. (A): Lingual cusp. (B) Buccal cusp. *Indicates the CGI and RMGI. FR indicates the end of the restoration.*

Filtek Supreme had the same EM in the coronal restoration in all tested groups, confirming that the biomechanical differences found among the three groups were related to the restorative material in the pulp chamber. The low EM of glass ionomers can be explained by their composition. Particle type and size as well as the flexible matrix of glass ionomers contribute to their relative weakness.[34,36,37]

Cuspal Strains

Cuspal deformation in restored teeth is affected by many factors, including the size of the cavity, the properties of the restorative material, and the filling technique.[14] In this study the size of the cavity was standardized for all specimens. Assuming similar tooth properties, shapes, and sizes, the main variables causing differences in cuspal deformation were therefore the properties of the materials and the filling techniques. We used strain gauges to measure cuspal deformation. Because strains vary across the tooth surfaces, the attachment location is important for the results. FEA was used to identify the areas where the highest strains occurred. The lingual cusp had more cusp deformation than the buccal cusp, irrespective of the restorative protocol. This result can be explained by the amount of remaining tooth structure. Third molars had thinner cervical areas lingually than they had buccally, and, thus, the lingual cusps can be expected to be less stiff and deform more than the buccal cusps. The cuspal deformation values were significantly different among the restorative protocols tested. Using a glass ionomer material to fill the pulp chamber and overlaying it with composite resulted in lower cuspal strain than using composite for the whole restoration. The reduction this gave in cuspal strains can be attributed to the lower shrinkage in combination with the lower EM of the glass ionomers. For the same reason glass ionomers have been recommended as cavity lining to reduce shrinkage stress of the restoration.[28]

Fracture Resistance

The fracture resistance values showed significant differences between the restorative protocols, with significantly lower resistance for the CR group. According to Reeh and others,[27] endodontic procedures have only a small effect on the tooth, reducing the relative rigidity by 5%, which is contributed entirely to the access opening. Restorative procedures and, particularly, the loss of marginal ridge integrity were the greatest contributors to the loss of tooth rigidity. Despite the lower mechanical properties of glass ionomer cement compared with composite resin, placement of a glass ionomer into the pulp chamber resulted in higher fracture strength than restoration with composite alone. A relatively stiffer restoration, in this case with the all-composite resin technique (CR), will transfer and distribute the occlusal loads deeper into the restoration and pulp chamber,[38] making the endodontically treated tooth more vulnerable around the compromised pulpal area. Furthermore, anatomically the lingual cusp seems to be more prone to fracture, which has been attributed to an unfavorable distribution of stresses during mastication.[39] The failure modes observed in this study confirm that most of fractures were concentrated on the lingual cusp (failure mode III). This area was also where shrinkage stresses were more concentrated along the pulp chamber, which may have contributed to this type of fracture.

Validation

The validation and correlation of experimental and computational methods is an important step in a comprehensive research approach and is essential to justify conclusions drawn from *in vitro* analyses.[6] Although FEA was essential to assess the stress conditions, the validity of stress calculations depends on the correct input of material properties, anatomic shape, and restraints of the restored tooth structure.[40] A validated finite element model can be further used to predict mechanical failures or investigate questions that cannot be accessed as well in laboratory tests.[6] Although the calculated stresses could not be validated directly from the laboratory experiments, they could be verified indirectly from the deformation and its consequences.[40] In our study, cuspal strains calculated by the FEA were similar to the cuspal strain data collected experimentally using strain gauges placed on cuspal surfaces (Figures 1 and 4). This close similarity supports the validity of our FEA models and stress results.[38,40,41]

Shrinkage stress is a serious concern, as has been demonstrated clinically by a high incidence of secondary caries in endodontically treated teeth restored with resin composites over a 5-year period.[12] The finding of this study could be important when direct composite restoration is the treatment of choice because of cost or conservative approach. Using conventional or resin modified glass ionomer to fill the pulp chamber under composite restoration may improve the longevity of the endodontically treated molars.

CONCLUSIONS

The restorative protocols significantly affected the deformation, stress, and fracture resistance of endodontically treated molars. Using glass ionomer to fill the pulp chamber under the composite resin restoration resulted in the most favorable conditions by reducing cuspal strain and increasing fracture resistance.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the human subjects oversight committee guidelines and policies of the Federal University of Uberlândia in Brazil.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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