Effect of Composite Resin and Restorative Technique on Polymerization Shrinkage Stress, Cuspal Strain and Fracture Load of Weakened Premolars

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Purpose: To compare shrinkage stress, cuspal strain and fracture load of weakened premolars restored with different conventional and bulk-fill composite resins and restorative techniques.

Materials and Methods: Fifty premolars received a 4.0 x 3.5mm mesio-occlusal-distal (MOD) class II preparation. The lingual and buccal cups were internally weakened. Specimens were restored according to the following 5 groups: Filtek Z350 XT/10 increments; Filtek Z350 XT/8 increments (both 3M Oral Care); Filtek Bulk Fill Flowable Restorative + Filtek Z350 XT (both 3M Oral Care); SDR + Spectra Basic (Dentsply Sirona); and Tetric N-Ceram Bulk Fill (Ivoclar Vivadent). Cuspal strains were measured using strain gauges ($n = 10$). After restoration, specimens were submitted to thermal/mechanical cycles and fractured. Post-gel shrinkage of the composites was determined. Additionally, residual shrinkage strains and stresses were analyzed using three-dimensional finite element analysis (3D-FEA). The data were statistically analyzed using one-way ANOVA and Tukey's HSD ($\alpha = 0.05$).

Results: One-way ANOVA revealed statistically significant differences among composite resins ($p < 0.001$) for the post-gel shrinkage. Filtek Z350 XT had the highest post-gel shrinkage and no difference was found between Spectra Basic and Tetric N-Ceram Bulk Fill ($p = 0.110$). The Filtek Z350 XT/10 increments, Filtek Z350 XT/8 increments and Filtek Bulk Fill Flowable Restorative/Filtek Z350 XT had statistically significantly higher cuspal deformation values when compared to the SDR/Spectra Basic and Tetric N-Ceram Bulk Fill techniques. 3D-FEA confirmed higher stress levels in the incrementally filled conventional restorations. Fracture loads were not statistically significantly different.

Conclusion: The bulk-fill restoration techniques resulted in less cuspal strain and stress than the incremental technique with conventional composite resin. Fracture resistance was not affected by the restorative techniques.

Keywords: biomechanics, cuspal strain, finite element analysis, fracture resistance, shrinkage stress.

J Adhes Dent 2020; 22: 503–514.
doi: 10.3290/j.jad.a45180

Submitted for publication: 17.03.20; accepted for publication: 03.06.20

Dental caries is a disease that causes the loss of dental structure and weakening of the remaining hard dental tissue through a demineralization process, especially in posterior teeth.[21] In most cases, the indicated treatment is a direct restoration with composite resins, due to their favorable physical and mechanical properties and their ability to restore the biomechanical behavior of teeth.[14,22] In posterior teeth, the use of composite resin restorations has

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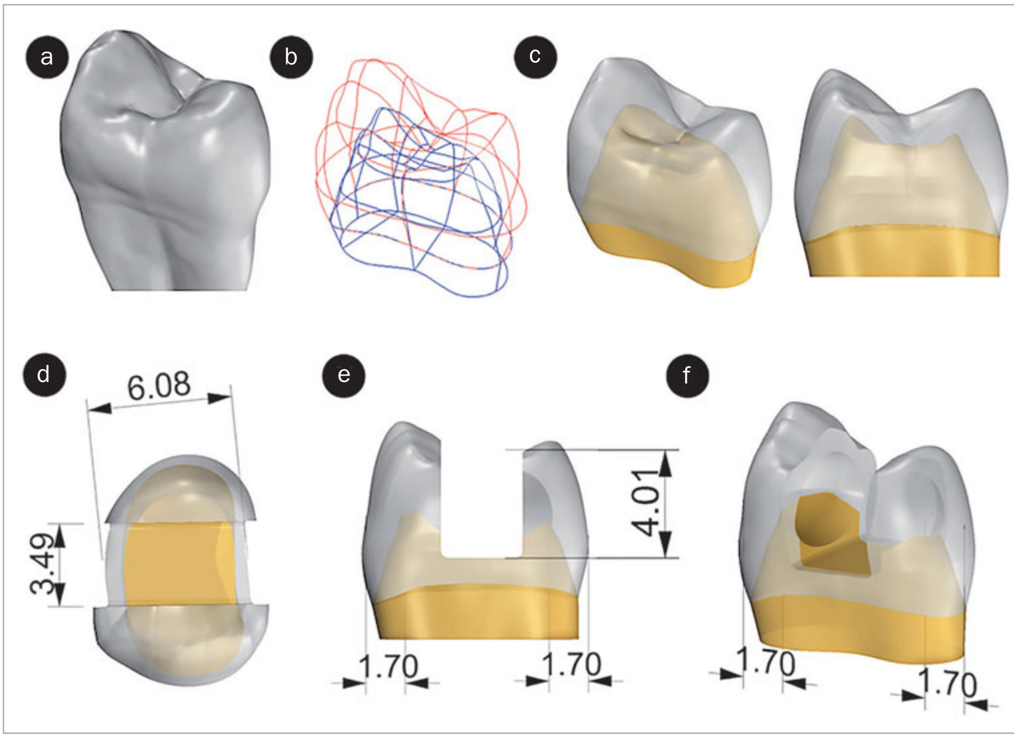

Fig 1 Bio-CAD three-dimensional modeling protocol. a. STL file of a scanned maxillary premolar; b. polylines created on the STL file; c. enamel and dentin surface model of the sound maxillary premolar; d. occlusal view and dimensions of the MOD class II preparation; e. proximal view of the MOD class II preparation; f. weakened cusps (buccal and lingual).

increased over the years compared to the placement of amalgam restorations.[14,36,38] Among the favorable biomechanical characteristics of composite resin materials is that they have an elastic modulus similar to dentin and they adhere to dental tissues.[41] However, composite resins undergo volumetric shrinkage during polymerization, which, in combination with bonding, creates residual stresses.

Polymerization shrinkage stress is still a clinical issue, long after it was first described by Bowen in 1967 and further discussed by Davidson and Feilzer during the mid-1980.[8,15,19] The origin of shrinkage is the formation of a polymer network during the polymerization reaction. This process results in a denser material, where the density change is manifested in volumetric shrinkage.[1,23,39] The bonding process, if strong enough, will limit the dimensional changes, leading to stress in the composite resin, tooth substrates and adhesive interfaces.[9,23] Composite resin shrinkage stress has been associated with cavity design, restorative procedures, characteristics of the composite resins, and polymerization processes.[23] If the stress generated exceeds the adhesive strength, debonding can occur.[23] On the other hand, if the adhesive is sufficiently strong, the tooth structure will suffer the consequences, leading to cusp flexure, crack formation and propagation, and fracture.[23] The magnitude of the generated shrinkage stress depends on several factors, such as monomer composition and extent of cure,[28] filler amount and stiffness,[13] and curing method.[20] These shrinkage stresses are also directly associated with the elastic modulus of the composite resin.[56,57] The elastic modulus is a material property that expresses the inherent stiffness of a material and determines how much stress is generated when the material is deformed.[45,57] Stresses created by polymerization shrinkage thus depend on both shrinkage and elastic modulus values.[12,16] Composite resins with a higher elastic modulus (which increases, for example, with filler content)[33] can generate higher residual shrinkage stresses in a restored tooth with the same amount of shrinkage.[17,44,49,54]

Several laboratory studies evaluated the effects of the shrinkage stress of composite resins. Although controversial, there is evidence from in vitro studies that higher shrinkage stress leads to a greater incidence of microleakage, cuspal deflection, gap formation, enamel cracks, and post-operative sensitivity.[23] Reducing the polymerization shrinkage stress of a composite resin restoration in a posterior tooth is a major challenge. The conventional layering technique has the advantage of a better cure throughout the depth of the composite.[25] However, the layering technique is not only more technique-sensitive and time-consuming, it is also associated with voids between the layers.[35] New restorative techniques and composite resins have been introduced to reduce polymerization shrinkage stress.[4,12,16,45] Among the new materials are the so-called bulk-fill composite resins that can be light cured at depths up to 5 mm,[16,28,31,35,52] and have the advantage of simplifying the clinical procedure, and reducing polymerization shrinkage stress as well as clinical chair time.[32] Bulk-fill composite resins have a composition very similar to conventional composite resins (regu-

Table 1 Characteristics of tested composite resins

Material	Shade	Batch number	Composite type	Increment size, light activation time	Organic matrix	Filler	Filler %wt/vol	Manufacturer
Filtek Z350 XT	A2	1634200773/ 10/2019	Nanofilled composite	2.0 mm, 40 s	Bis-GMA, bis-EMA, UDMA, TEG-DMA	Silica and zirconia nanofillers, agglomerated zirconia-silica nano clusters	82/60	3M Oral Care (St Paul, MN, USA)
Filtek Bulk Fill Flowable Restorative	A2	1715800547/ 10/2019	Bulk Fill Flowable composite	4.0 mm, 40 s	UDMA, bis-GMA, EBPADMA, procrylat resin	Silane treated ceramic and YbF_3	64/42.5	3M Oral Care
SDR	A2	1701000280/ 10/2019 1711000389/ 07/2020	Bulk Fill Flowable composite	4.0 mm, 40 s	Modified UDMA, dimethacrylate, dysfunctional diluents bis-GMA adduct, EBPADMA, TEG-DMA	Bariumand strontium aluminofluorosilicate glass	68/44	Dentsply Sirona (Konstanz, Germany)
Spectra Basic	A2	333662J/ 04/2020	Microhybrid composite	2.0 mm, 40 s	Bis-GMA-adduct, EBPADMA, TEG-DMA	Ba-F-Al-B-Si-glass, silica	76/60	Dentsply Sirona
Tetric N-Ceram Bulk Fill*	IVA	U03239	Bulk Fill Paste composite	4.0 mm, 40 s	UDMA, bis-GMA	Barium glass, ytterbium trifluoride, mixed oxide prepolymer	79/61	Ivoclar Vivadent (Schaan, Liechtenstein)

*marketed as Tetric Evoceram Bulk Fill in some countries.

lar-viscosity composite resins recommended for the incremental technique), but they have higher translucency and new types of photoinitiators that generate higher depth of cure.[16,27] In clinical studies, bulk-fill composite resins have shown excellent clinical behavior when compared to the incremental filling technique.[32] In vitro testing is indispensable for understanding the biomechanical aspects of such outcomes, especially the evaluation of polymerization shrinkage, cuspal strain, marginal infiltration, and fracture resistance.[5,6,37] Fracture tests are important for the biomechanical analysis of restorative materials because they determine the strength of materials, interfaces, and structures.[47] Nondestructive tests, such as the deformation measurements using strain gauges and finite element analysis (FEA) are also increasingly used because they allow assessment of stress and strain in restored tooth structures.[57]

The aim of this study was to compare shrinkage stress, cuspal strain and fracture load of weakened premolars restored with different conventional and bulk-fill composite resins and restorative techniques. These weakened premolars were restored with different conventional and bulk-fill composite resins and restoration techniques (incremental with conventional composite; incremental with conventional composite + flowable bulk fill and non-flowable bulk fill). The null hypothesis tested was that different restorative techniques and composite resins would not affect the buccal and lingual cuspal strain, polymerization shrinkage stress, and fracture load. A conventional incrementally (10 increments) placed composite resin was used as control.

MATERIALS AND METHODS

Tooth Selection and Cavity Preparation

Fifty extracted, intact, caries-free human maxillary premolars were used (Ethics Committee approval No. 93446218.8.0000.5145). The premolars had an intercuspal width within a maximum deviation of 10% from the determined mean. The intercuspal width varied between 6.5 to 7.9 mm (buccal-lingual direction). This standardization avoided pulpal chamber exposure. The roots were covered with a 0.3-mm layer of polyether impression material (Impregum, 3M Oral Care; St Paul, MN, USA) to simulate the periodontal ligament and embedded in polystyrene resin (Cristal; Piracicaba, SP, Brazil) up to 2 mm below the cementoenamel junction to simulate the alveolar bone. Using a cavity preparation machine,[46] standard class II mesio-occlusal-distal (MOD) cavities were prepared using a cylindrical diamond bur #1095F (KG Sorensen; Cotia, SP, Brazil) in a high-speed handpiece (Kavo do Brasil; Joinville, SC, Brazil) under copious air-water spray. The preparations were 4 mm deep (axio-pulpal) from the lingual cusp tip and 3.5 mm wide (mesio-distal). The dentin from the buccal and lingual cusps was internally removed to leave a 1.7-mm-thick undercut enamel wall (Figs 1e and 1f) using the same cavity preparation machine with a diamond bur #3168F (KG Sorensen). The final thickness of enamel was measured with a digital precision caliper (Mitutoyo; Tokyo, Japan).

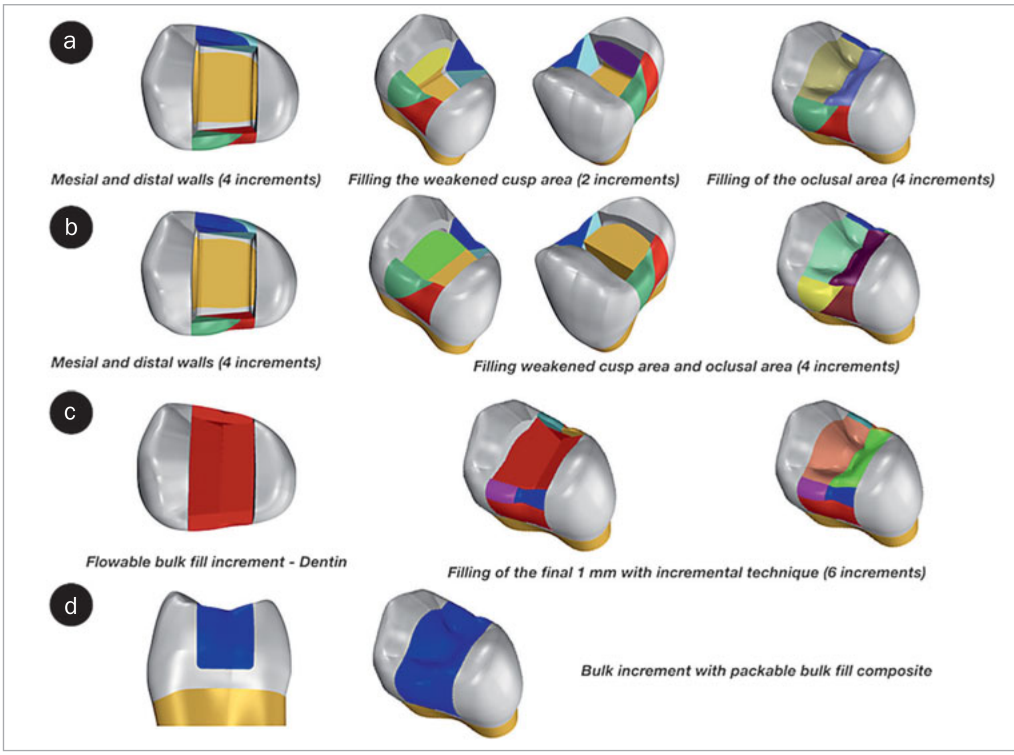

Fig 2 Overview of the simulated restorative techniques. a. Filtek Z350 XT/10 increments; b. Filtek Z350 XT/8 increments; c. Filtek Bulk Fill Flowable Restorative + Filtek Z350 XT and SDR/Spectra Basic; d. Tetric N-Ceram Bulk Fill.

Groups Division

The prepared teeth were randomized and divided into 5 groups (n = 10) according to the restorative techniques and composite resins used: group 1 iIncremental technique): Filtek Z350 XT/10 increments; group 2 (incremental technique): Filtek Z350 XT/8 increments; group 3 (incremental + bulk-fill flow technique): Filtek Bulk Fill Flowable Restorative + Filtek Z350 XT; group 4 (incremental + bulk-fill flow technique): SDR + Spectra Basic; group 5 (bulk-fill non-flowable technique): Tetric N-Ceram Bulk Fill. In groups 3 and 4, the conventional composite resin was incrementally placed over the flowable bulk-fill resin composite as an occlusal layer to replace the occlusal enamel portion. The Filtek Bulk Fill Flowable Restorative and SDR are flowable composite resins that require overlayering with a regular-viscosity composite resin. Tetric N-Ceram Bulk Fill is a sculptable non-flowable bulk-fill composite that can be used to restore the whole cavity in one single increment. The composite resins used and their properties are shown in Table 1.

Cuspal Strain during Restorative Procedures (CSt-Re)

Uniaxial strain gauges type PA-06-125AC-350L (Excel Sensores; Taboão da Serra, SP, Brazil) with a gauge factor of 2.14 were used (grid size: 3 x 3 mm). The gauges were attached on the middle third of the external faces of the buccal and lingual cusps, which corresponds to the weakened area. The gauges were oriented to measure strains in the axial direction. For strain gauge attachment, the buccal and lingual surfaces were conditioned with 37% phosphoric acid (Condac 37%, FGM; Joinville, SC, Brazil) for 30 s, washed with water for 15 s, dried with air jets and then bonded with cyanoacrylate glue (Super Bonder, Loctite; Itapevi, SP, Brazil). Two strain gauges were also attached to a dummy specimen, which did not undergo any restoration procedures to compensate for environmental effects. The strain gauges were connected to a data acquisition device (ADS2000, Lynx; São Paulo, SP, Brazil) to record strain (µε) during the restorative process.

Restorative Techniques (Fig 2)

Group 1: Filtek Z350 XT/10-increment technique

The increment volumes (25.66 mm^3) were calibrated using an acetate matrix and sequentially placed as follows: the first increment was inserted into the distal marginal ridge in the lingual/pulpal direction; the second increment was inserted into the distal marginal ridge in the buccal/pulpal direction; the third increment was inserted into the mesial marginal ridge in the lingual/pulpal direction; the fourth increment was inserted into the mesial marginal ridge in the buccal/pulpal direction, thus concluding the reconstruction of the mesial and distal walls. The fifth increment was inserted in the weakened area located in the inner part of the lingual cusp; the sixth increment was inserted in the weakened area located in the inner part of the buccal cusp. The occlusal surface was restored using four oblique increments: the first was inserted in the direction of the lingual/pulpal walls to the limit of the dentin area; the second was

Table 2 Mechanical properties examined in FEA for dental structures and materials

Material/structure	Elastic modulus (GPa)	Poisson's ratio	Reference for elastic modulus	Linear post-gel shrinkage*
Filtek Z350 XT	14.3	0.24	41	0.0025
Filtek Bulk Fill Flowable Restorative	10.1	0.24	41	0.0017
SDR	12.6	0.24	41	0.0011
Spectra Basic	9.8	0.24	Manufacturer's information	0.0013
Tetric N-Ceram Bulk Fill	12.3	0.24	7	0.0015
Enamel	84.1	0.30	56	
Dentin	18.6	0.30	43	

* Experimentally tested.

inserted towards the buccal/pulpal walls also to the limit of the dentin area; the third increment was inserted towards the lingual/pulpal walls filling the enamel area and the remainder of the occlusal/lingual face; and the fourth increment of the occlusal face was inserted towards the buccal/pulpal walls, filling the enamel area and the remainder of the occlusal/buccal face.

Group 2: Filtek Z350 XT/8-increment technique

The increments were also calibrated and inserted in the following order: the first increment was inserted into the distal marginal ridge in the lingual/pulpal direction; the second increment was inserted into the distal marginal ridge in the buccal/pulpal direction; the third increment was inserted into the mesial marginal ridge in the lingual/pulpal direction; the fourth increment was inserted into the mesial marginal ridge in the buccal/pulpal direction, thus concluding the reconstruction of the mesial and distal walls. Then the occlusal surface was restored using four oblique increments. Thus, the first increment was inserted in the direction of the lingual/pulpal walls up to the limit of the dentin area; the second increment was inserted towards the buccal/pulpal walls also up to the limit of the dentin area; the third increment was inserted towards the lingual/pulpal walls filling the area of the enamel, the remainder of the weakened area and the remainder of the occlusal/lingual surface; and the fourth increment of the occlusal surface was inserted towards the buccal/pulpal walls, thus filling the entire occlusal area.

Groups 3 and 4: Filtek Bulk Fill Flowable Restorative/ Filtek Z350 XT, SDR/Spectra Basic techniques

The flowable bulk-fill composite resins were inserted into a single increment throughout the dentin area. The enamel area was restored using six 1-mm increments of conventional composite resin following the conventional oblique technique. The conventional increments in group-3 and -4 specimens were inserted in the following order: the first increment was inserted into the marginal ridge distally in the lingual/pulpal direction; the second increment was inserted into the distal marginal ridge in the buccal/pulpal direction; the third increment was inserted into the mesial marginal ridge in the lingual/pulpal direction; the fourth increment was inserted into the mesial marginal ridge in the buccal/pulpal direction, thus concluding the reconstruction of the mesial and distal walls. The occlusal surface was restored with 2 oblique increments of 1 mm each, where the first was inserted in the direction of the lingual/pulpal walls, completing the occlusal/lingual area, and the second was inserted towards the buccal/pulpal walls, completing the buccal/lingual area.

Table 3 Post-gel shrinkage mean values (SD) measured by strain gauge method

Composite	Post-gel shrinkage (vol%)
Filtek Z350 XT	0.86 (0.02)^{A}
Filtek Bulk Fill Flowable Restorative	0.53 (0.03)^{B}
Spectra Basic	0.40 (0.04)^{CD}
SDR	0.34 (0.03)^{E}
Tetric N-Ceram Bulk Fill	0.45 (0.02)^{D}

Different superscript letters indicate a significant difference between restorative techniques ($p < 0.05$).

Group 5: Tetric N-Ceram Bulk Fill technique

A single bulk increment was inserted reconstructing the entire restoration.

All groups

The composite resins were light cured using an LED light-curing unit (VALO Cordless, Ultradent; South Jordan, UT, USA) with an intensity of 1297 (mW/cm^2) in standard mode

Table 4 Mean (SD) cuspal strain values (με) measured by strain gauge and calculated with 3D FEA

Group	Strain gauge method			3D FEA		
	Buccal strain	Lingual strain	Averaged cuspal strain	Buccal strain	Lingual strain	Averaged cuspal strain
Filtek Z350 XT/10 increments	124.2 (30.3)	143.8 (19.6)	134.0 (17.9)^{A}	129.7	203.4	166.6
Filtek Z350 XT/8 increments	72.6 (29.6)	99.2 (51.6)	85.9 (30.4)^{B}	56.4	127.5	92.0
Filtek Bulk Fill Flowable Restorative/Z350	94.1 (17.5)	107.5 (34.0)	100.8 (11.8)^{AB}	85.0	103.3	94.1
SDR/Spectra Basic	53.0 (15.2)	39.6 (10.8)	46.2 (10.6)^{C}	51.4	59.3	55.4
Tetric N-Ceram Bulk Fill	33.2 (16.7)	75.3 (43.8)	54.3 (22.2)^{BC}	44.7	54.4	49.5

Different superscript letters indicate a significant difference between the restorative techniques ($p < 0.05$).

Table 5 Mean (SD) fracture resistance values

Group	Fracture resistance (N)
Filtek Z350 XT/10 increments	531.0 (189.8)^{A}
Filtek Z350 XT/8 increments	453.7 (107.0)^{A}
Filtek Bulk Fill Flowable Restorative/Z350XT	494.2 (205.8)^{A}
SDR/Spectra Basic	462.5 (144.8)^{A}
Tetric N-Ceram Bulk Fill	436.7 (97.5)^{A}

Different superscript letters indicate a significant difference between the restorative techniques ($p < 0.05$).

for 40 s per increment. The irradiance (mW/cm^2) was measured using the MARC Resin Simulator (BlueLight Analytics; Halifax, NS, Canada). The light-curing unit was positioned on a support to standardize the 1.0-mm distance between the light tip and the tooth crown. To simulate clinical conditions, each tooth was fixed in a device with adjacent teeth to allow interproximal contact during restoration where wooden wedges and matrix strips could be positioned.[41] The strain values (με) were obtained with a data acquisition device (ADS2000, Lynx; São Paulo, SP, Brazil), which collected the buccal and lingual strain data at a frequency of 4 Hz.[41]

Thermomechanical Cycling

After the cuspal strain test, all restored teeth (n=10) were submitted to 10,000 thermocycles (5°C to 55°C, 15-s dwell time) in a MSCT-3 machine (Marcelo Nucci ME; São Carlos, Brazil). After thermocycling, a total of 100,000 mechanical cycles were performed in a water bath at room temperature in a mechanical cycling machine (Odeme Dental Research; Luzerna, SC, Brazil), with 50 N compressive load and 2 Hz frequency applied to the occlusal surface of the restoration with a flat load applicator. The thermal and mechanical cycling tests took one week per test, after which the teeth were subjected to the failure test.

Fracture Load and Failure Mode

The specimens were placed in a universal testing machine (EMIC, DL2000; São José dos Pinhais, PR, Brazil) and subjected to a compressive load with a 5-mm diameter spherical metallic tip at a crosshead speed of 0.5 mm/min until fracture. The force (N) at fracture was recorded with a load cell connected to acquisition software (TESC, EMIC). The fractured specimens were examined using a stereomicroscope (Leica; Wetzlar, Germany) at 10X and 40X magnification to determine the failure pattern, as follows:[10] (I) fractures involving part of the coronal tooth structure; (II) fractures involving a small part of the coronal tooth structure and cohesive failure in the restoration; (II) fractures involving part of the coronal tooth structure, cohesive failure in the restoration and root fractures reparable with periodontal surgery; (IV) severe fractures involving root and crown, for which extraction would be clinically indicated.

Post-gel Shrinkage

Post-gel shrinkage was quantified for each composite resin by the strain gauge method.[42] The composite resin was shaped into a hemisphere and placed on a biaxial strain gauge (CEA-06-032WT-120, Measurements Group; Raleigh, NC, USA) that measured shrinkage deformation in two perpendicular directions. A strain conditioner (ADS2000, Lynx) converted electrical resistance changes in the strain gauge into voltage variations through a quarter-bridge circuit with an internal reference resistance. The strain values measured along the two directions were recorded by the data acquisition software. The specimens were photoactivated for 40 s using an LED light-curing unit (VALO Cordless, Ultradent), the tip of which was fixed 1 mm from the specimens. The recorded strains, converted to percent volumetric shrinkage, represented the post-gel shrinkage. The post-gel shrinkage values were also used in the residual shrinkage stress calculation by finite element analysis.

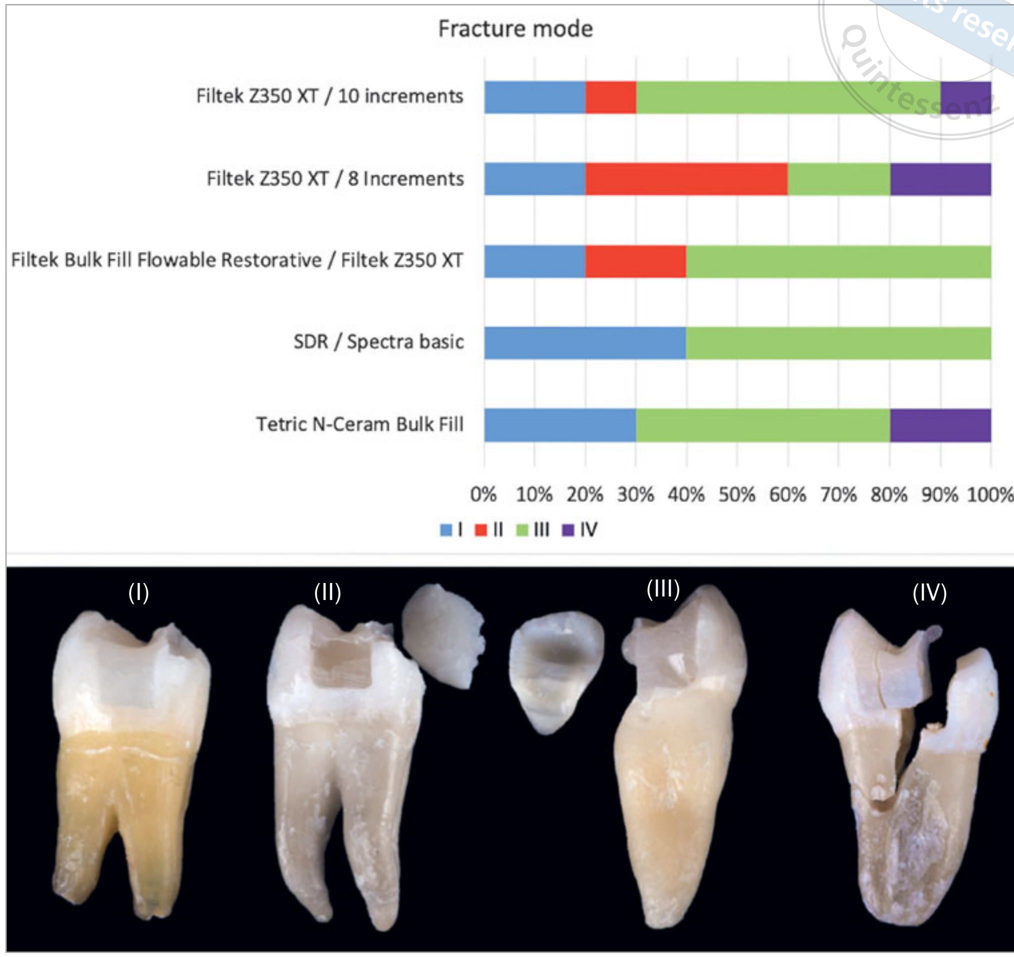

Fig 3 Failure pattern analysis frequency and examples. Type I: fracture involving part of the coronal structure; type II: fracture involving a small part of the coronal structure and cohesive in the restoration; type III: fracture with partial involvement of coronal structure, cohesive failure in restoration and reparable root fracture associated with periodontal surgery; type IV: severe fracture with indication for tooth extraction.

Residual Shrinkage Stress Calculation – Three-dimensional Finite Element Analysis (3D-FEA)

3D-FEA was carried out simulating the MOD tooth preparation and the restorative techniques used in the experimental test. The 3D model was created from an intact, sound, maxillary human first premolar (approved by the local ethics committee) CAD software (Rhinoceros 3D 5.0, McNeel North America; Seattle, WA, USA). The tooth's geometry was scanned (LPX600, Roland DG; Osaka, Japan) and saved in a stereolithography (STL) file (Fig 1a). Polylines were created on the scanned tooth using the anatomical markers on the crown (Fig 1b). Non-Uniform Rational Basis Spline (NURBS) surfaces were created using the lines (Fig 1c). The MOD preparation and cuspal weakening were created using Boolean differences with the same dimensions as in the experimental test (Figs 1d to 1f). Each composite resin increment of the restoration techniques was re-created using CAD (Fig 2).

The models were exported as Standard for the Exchange of Product Data (STEP) files to a preprocessing program (Patran, MSC software; Santa Ana, CA, USA) for the creation of a finite element mesh of each structure using solid 4-noded tetrahedral elements. The mesh of each structure was exported to the FEA program (Marc & Mentat, MSC software). Boundary conditions were applied, consisting of constrained nodal displacements in x, y, and z dimensions at the bottom surface of the model. Polymerization shrinkage was simulated by thermal analogy. Notional temperature was reduced by 1°C, while the post-gel shrinkage strain was entered as the coefficient of linear thermal expansion. Each composite resin increment was activated in the same sequence as the restoration technique employed in the experimental cuspal strain test. Material properties used in the FEA are shown in the Table 2.

Modified von Mises equivalent stress was used to express the stress conditions. Modified von Mises stress is an equivalent stress value that is calculated based on the whole 3D stress situation, giving more weight to tensile than compressive stress components, because tensile stresses are more critical for brittle dental tissues and materials.[57] Areas with predominantly tensile stresses therefore appear with higher modified von Mises values compared to areas that are predominantly compressed. Furthermore, strain values in the y-dimension (vertical) were obtained during the analysis at nodes on the buccal and lingual external surfaces of the model that corresponded to

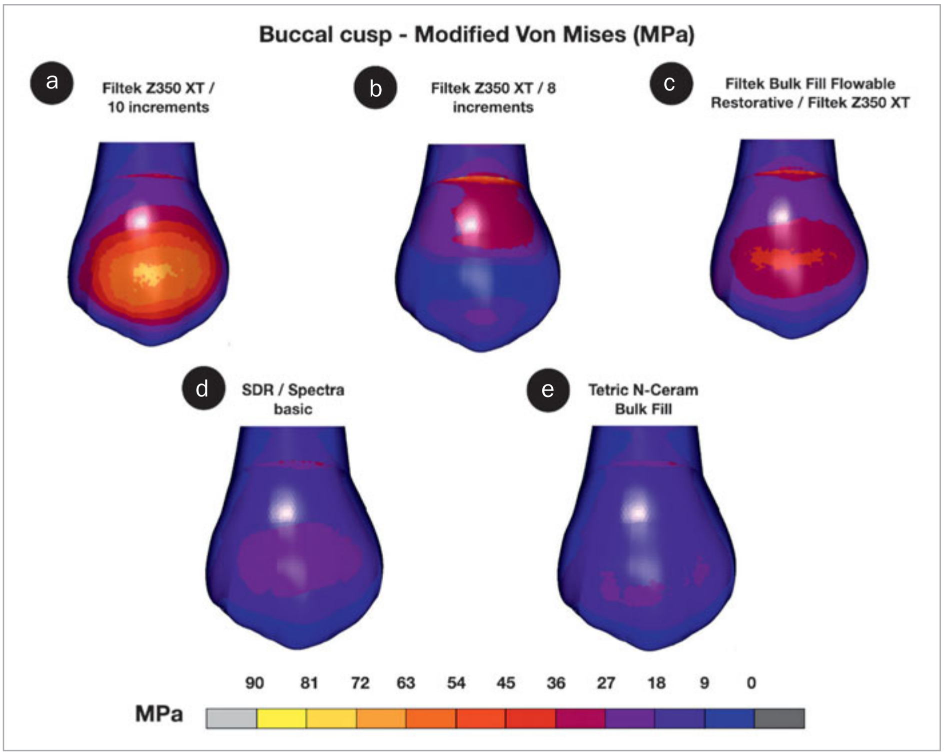

Fig 4 Polymerization shrinkage stress distributions in the buccal cusp. a. Filtek Z350 XT/10 increments; b. Filtek Z350 XT/8 increments; c. Filtek Bulk Fill Flowable Restorative + Filtek Z350 XT; d. SDR/Spectra Basic; e. Tetric N-Ceram Bulk Fill.

the position where the strain gauges (electrical resistance grid size: 3 x 3mm) were fixed in the laboratory tests. The strain values across the selected areas were averaged.

Statistical Analysis

The values obtained in the cuspal strain, fracture resistance, and post-gel shrinkage experiments were tested for normal distribution (Shapiro-Wilk, $\alpha = 0.05$) and equality of variances (Levene test). Normal distribution was confirmed, so parametric statistical tests were conducted. One-way ANOVA was performed for the cuspal strain, fracture resistance, and post-gel shrinkage. Multiple comparisons were made using Tukey's HSD test. All tests used a significance level of 0.05 and all analyses were performed with Sigma Plot statistical software package (version 14, Systat Software; San Jose, CA, USA).

RESULTS

Post-gel Shrinkage

Mean volumetric post-gel shrinkage values (vol%) and standard deviation for the different composite resins are shown in Table 3. One-way ANOVA revealed statistically significant differences between the restorative composite resins ($p < 0.05$). The composite resin Filtek Z350 XT had the highest post-gel shrinkage. There was no statistically significant difference between Spectra Basic and Tetric N-Ceram Bulk Fill ($p = 0.110$).

Cuspal Strain during Restorative Procedures (CSt-Re)

The mean buccal and lingual, as well as the averaged (lingual and buccal) cuspal strain mean values (μS) and standard deviations for the different restorative techniques measured with strain gauges are shown in Table 4. One-way ANOVA revealed statistically significant differences between the restorative techniques ($p < 0.05$). The highest mean values of cuspal strain were observed for the groups Filtek Z350 XT/10 increments, Z350 XT/8 increments, and Filtek Bulk Fill Flowable Restorative/ Filtek Z350 XT. Higher cuspal strain mean values were observed for the lingual cusp regardless of restorative technique. SDR/Spectra Basic and Tetric N-Ceram Bulk Fill had the lowest mean cuspal strain, with no statistically significant difference between these groups ($p = 0.956$). The buccal, lingual, and averaged cuspal strain means for the different restorative techniques calculated by the 3D-FEA are also shown in Table 4. For 3D-FEA, Filtek Z350 XT/10 increments, Filtek Z350 XT/8 increments, and Filtek Bulk Fill Flowable/Filtek Z350 XT exhibited the highest cuspal strain means, with the lingual cusp exhibitng the highest strain. The lowest cuspal strain means were observed for SDR/Spectra Basic and Tetric N-Ceram Bulk Fill.

Fracture Load and Failure Mode

The mean fracture load (N) and standard deviation for the different restorative techniques are shown in Table 5. One-way ANOVA revealed that there was no statistically signifi-

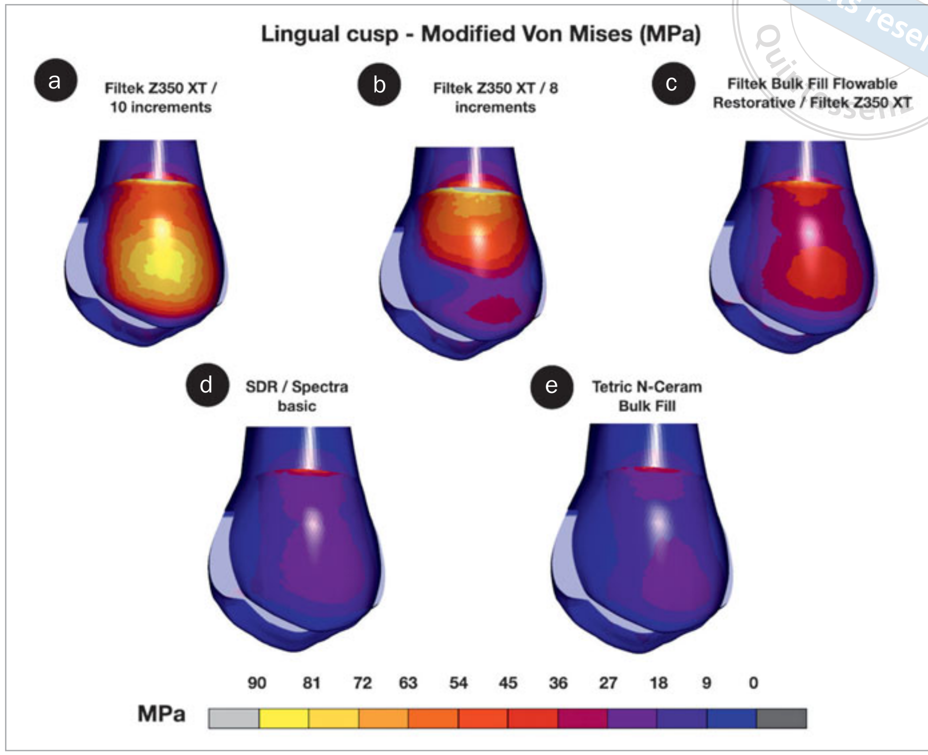

Fig 5 Polymerization shrinkage stress distribution in the lingual cusp. a. Filtek Z350 XT/10 increments; b. Filtek Z350 XT/8 increments; c. Filtek Bulk Fill Flowable Restorative + Filtek Z350 XT; d. SDR/Spectra Basic; e. Tetric N-Ceram Bulk Fill.

cant difference between the groups (p = 0.679). The fracture mode distribution for the experimental groups is presented in Fig 3. Type III fractures were prevalent with most of the restorative techniques. The SDR/Spectra Basic group showed a higher percentage of restorable fractures (type I).

Residual Stress Calculation – Finite Element Analysis (3D)

The modified von Mises shrinkage stress distributions at the buccal and lingual cusps for the different restorative techniques are shown in Figs 4 and 5. The stresses can be visualized using a linear color scale, in which blue indicates the lowest stress values, and yellow and light gray the highest stress values. The shrinkage stresses at the buccal cusp of the Filtek Z350 XT/10- and 8-increment groups were the highest (Fig 4). Filtek Z350 XT/10 increments had higher stress levels over a larger area of the buccal cusp, while the higher stresses in the Filtek Z350 XT/8-increment group concentrated in the cervical area of the buccal cusp. The SDR/Spectra Basic techniques and Tetric N-Ceram had lower stress values than Filtek Z350 XT/10- and 8-increment groups. For the lingual cusp (Fig 5), Filtek Z350 XT/10- and 8-increment groups exhibited higher shrinkage stresses than the SDR/Spectra Basic techniques and Tetric N-Ceram. The lingual cusp showed higher shrinkage stresses than the buccal cusp, regardless of restorative technique.

DISCUSSION

The results of present study confirmed that incremental, incremental + bulk fill flowable, and bulk regular paste filling techniques carried out with different composite resins affected the cuspal strain and residual stress generated by polymerization shrinkage. However, they had no significant effect on fracture resistance. Therefore, the null hypothesis that restorative techniques and composite resins would not affect the buccal and lingual cuspal strains and polymerization shrinkage stress was rejected.

Severe structural loss reduces structural integrity in premolars and increases their susceptibility to fractures.[2,34,40,48] Direct composite resin restorations conserve dental structure if the preparation is restricted to the carious area and the restorative material can restore the original coronal stress distributions.[14,22,56] Therefore, it is important to understand the biomechanical behavior of the restorative composite resin materials and techniques used to restore weakened premolars. The oblique layering technique associated with conventional composite resins generally involves the placement and curing of the composite resin in increments with a maximum thickness of 2 mm. This strategy is wellstablished in the literature and ensures optimal curing throughout the composite.[25,29,30] However, in a desire to simplify the clinical procedure for direct posterior restorations, bulk-fill composites were introduced.

Composite resins have been shown to be able to restore the original coronal stress distributions unless they introduce new residual stress. Residual shrinkage stress is generated by volumetric shrinkage during development of the elastic modulus in the polymerization process, when composite resin bonding to the tooth structure prevents contraction.[23,45,54,56] However, not all polymerization shrinkage causes shrinkage stress.[18,23,42,50] When the composite resin is still viscous (pre-gel phase) and can relieve stress, it does not generate residual shrinkage stress. Residual shrinkage stress is only generated after the composite resin has started to behave like an elastic solid, when it reaches the gel point.[18] The portion of the total shrinkage that is responsible for the development of residual stress is the "post-gel shrinkage".[42]

Post-gel shrinkage is measured using the strain gauge technique.[42] In the present study, the post-gel shrinkage of all the composite resins analyzed were statistically significantly different. Filtek Z350 XT had higher post-gel shrinkage values than the bulk-fill composite resins. Considering that the Filtek Z350 XT also had the highest elastic modulus, it had the potential of developing higher residual shrinkage stress compared to the bulk fill resin composites. The stress distributions were evaluated using the modified von Mises criterion. This modification of the von Mises criterion was used, because it takes differences between compressive and tensile strengths into account in the stress evaluations. Since the tensile stress is more critical for enamel, dentin, and composite resins than compressive stress, we decided to use the modified von Mises criterion to evaluate shrinkage stress.[56,57] The 3D-FEA showed that the Filtek Z350 XT/10-increment group, in which the undermined areas were filled first, resulted in the highest residual stress values. The stresses concentrated at the middle of the lingual and buccal cusps. On the other hand, the Filtek Z350 XT/8-increment group, in which the weakened area was restored to include the occlusal area of the preparation, showed a change in stress concentration location towards the cervical area of both the lingual and buccal cusps. The use of 8 increments thus generated lower stress than 10 increments. 3D-FEA results also showed that the position of the increment during a restorative technique affects the stress distribution, since filling the weakened area first (Filtek Z350 XT/10 increments) resulted in higher residual stress.

Shrinkage stresses were calculated using FEA because they cannot be measured directly; however, the resulting deformation (cuspal strain) can be measured experimentally.[5,6] In this study, the FEA stress outcomes, which depend on the properties and modeling choices of the material used, were validated by comparing the FEA-calculated cuspal strains with the experimental cuspal strain results. The experimental validation confirmed the adequacy of the material properties applied in the stress analysis. The cuspal strain tests showed similarly higher cusp deformation for Filtek Z350 XT/10 increments. Although the strain values of 3D-FEA and laboratory tests were similar, we did not expect them to be the same because of experimental and natural variations. For FEA validation, strain values should be in the same order and show similar behavior as the experimental results. Using Filtek Z350 XT (10 or 8 increments), the stresses and strains were higher at the lingual cusp; the same strain behavior was confirmed experimentally by the cuspal strain test.

The evaluation of the restorative techniques using both flowable bulk-fill and conventional composite resins showed that, although SDR and Filtek Bulk Fill Flowable Restorative are both flowable composite resins, the respective stress/strain results differed significantly. The SDR-Spectra Basic group generated lower cuspal strains and shrinkage stresses than Filtek Bulk Fill Flowable Restorative/Filtek Z350 XT. Combinations of a bulk-fill flowable composite resin with a conventional composite resin resulted in lower mean shrinkage stress only for the SDR-Spectra Basic combination. This may be explained by the lower post-gel shrinkage and elastic modulus of SDR and Spectra Basic. Furthermore, the SDR-Spectra Basic combinations had more favorable fracture modes. Lower values of cuspal strain and shrinkage stresses were observed for Tetric-N-Ceram composite resin. Since Tetric-N-Ceram is a high-viscosity/packable bulk-fill composite resin, the specimens from this group were restored in one single increment and received only one photoactivation of 40 s, following the respective manufacturer's instructions. Assuming that 40 s was enough to cure the restoration throughout its depth, the obtained lower cuspal strain and stress values with a bulk-filling technique support the theory that an incremental technique with a higher number of small increments can increase the cuspal strain and shrinkage stresses.[6] Although incremental techniques do not reduce shrinkage stresses, they should not be simply dismissed, because filling in smaller increments may be needed to improve restoration adaptation and curing. Some studies reported that the incremental technique reduced gap formation, which may be associated with higher fracture resistance values,[25] while even bulk-fill composites undergo light attenuation and thus have limits to the depth to which they can be cured adequately.[35] Therefore, the use of one single bulk-fill increment for a deep, wide preparation should be carefully considered. In this study, the large bulk-filled restoration generated the lowest fracture resistance, although the difference to incrementally filled restorations was not significant.

Several studies have compared shrinkage stress generated by bulk-fill composite resins and conventional incremental techniques.[3,5,6,11,12,26] The results of our study confirmed that bulk-fill composite resins were able to decrease the stress and cuspal strain compared to incremental techniques. Cerda-Rizo et al[11] showed that the use of a high-viscosity bulk-fill composite resin as an occlusal layer over a low-viscosity bulk-fill composite resin to restore posterior teeth can be a viable alternative, as it resulted in bonding interaction similar to that of conventional composite resins, as well as lower shrinkage stress at the enamel margin. Our results also showed that covering a low-viscosity bulk-fill composite resin (SDR or Filtek Bulk Fill Flowable Restorative) with a conventional composite resin can decrease the shrinkage stress and cuspal strain. The use of a conventional composite resin as a final layer is indicated to improve wear of a restoration, since more densely filled conventional composite resins usually have better wear resistance than flowable composite resins.[41] This strategy can also improve esthetics, because most bulk-fill composite resins are translucent.

The restoration of compromised posterior teeth is always a challenge for the clinician. During the restorative procedure, the cuspal strain test showed that the lingual cusp had higher deformation regardless of the restorative technique and composite resin used. This is explained by the lingual cusp retaining less tooth structure after MOD preparation, since all proximal faces converge to the lingual side. Clinically, during cavity preparation, attention should be given to the lingual cusp as it becomes more fragile.[2,48] The fracture modes reported in the present study confirm that most fractures occurred in the lingual cusps.

The fracture-resistance results of weakened premolars showed no statistically significant differences among the groups ($p = 0.679$). Although not statistically significant (so that the differences may be due to chance), higher fracture resistance was observed for the group restored with Filtek Z350 XT in 10 increments. This may be due to the fact that each increment was light cured more times than the others, allowing a higher degree of conversion. Most of the polymerization shrinkage occurs within the first 10 s, after which it continues at a decreasing rate. Shrinkage strain and stress increase at a low rate has been shown to continue for more than 24 h. However, over time, environmental conditions may cause stress relaxation due to water absorption and consequently hygroscopic expansion, while the composite resin elastic modulus may undergo a slow deterioration due to solubility and matrix softening effects.[53,55] In this study, specimens were also kept immersed in water during the thermomechanical cycling. Versluis et al[55] showed that initial cuspal deformation due to polymerization shrinkage decreased after one week and still continued decreasing after 8 weeks. This may explain why the strength test was not affected by the differences in stress levels found by the FEA among the different restoration materials and techniques. On the other hand, the fact that any harmful stresses may relax over time does not diminish the requirement that the tooth-restoration complex must survive the initial period, probably spanning more than a week for restorative composite resins, because debonding caused by initially high stresses is not reversed by hygroscopic expansion or stress relaxation. Therefore, concerns about shrinkage stress remain important.[55] The present results thus indicate that clinically, simplification of the restorative technique with bulk-fill composite resin may improve shrinkage stress and strain levels without compromising fracture resistance. These experimental observations have been confirmed by several clinical studies.[32,51] A recent randomized clinical trial of bulk-fill composite resin reported similar clinical performance for bulk- and incrementally placed restorations after 36 months.[32] Another randomized clinical study evaluated two restorative strategies associating a bulk-filll flowable composite as the base with a conventional composite occlusal layer in Class II restorations.[24] The authors concluded that the different restorative systems did not affect post-operative sensitivity after 90 days, and found satisfactory clinical performance after one year. However, they also reported a reduction of interproximal contact after one year for one of the tested combinations (Surefil SDR+TPH3). A recent literature review recommended more clinical studies of bulk-filling deep/large restorations to fully explore the clinical benefits of bulk-fill composites.[52]

Since the incremental filling technique is more time consuming, the use of bulk-fill composite resin can decrease the chair time and decrease the costs associated with the placement of a posterior restoration. Moreover, bulk-fill composite resins could reduce the chance of clinical errors during restoration, because it reduces the number of clinical steps. In vitro studies are indispensable for gaining knowledge of material responses, but clinical studies are equally vital in dental research, because not all clinical factors can be foreseen or simulated in vitro. Clinical evidence is, therefore, needed to determine the impact our findings will have on clinical longevity of direct composite resin restorations in severely compromised premolars.

CONCLUSION

The fracture resistance of weakened premolars was not affected by the restorative techniques tested. Flowable and regular viscosity/non-flowable bulk-fill composite resin restorative techniques resulted in less cuspal strain and stress than conventional incrementally-placed composite resins.

ACKNOWLEDGMENTS

This study was supported by grants from PAPE-UNIUBE and PIBIC-UNIUBE (Grant Number: 2016-030). The authors thank the Federal University of Uberlândia for Finite Element Analysis laboratory support at the CPBIO.

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Clinical relevance: The use of bulk-fill composites associated with conventional composite resins generated lower shrinkage stress and cuspal strain in vitro without compromising fracture resistance. A greater number of increments increased shrinkage stress and cuspal strain.