3D Interfacial Gap and Fracture Resistance of Endodontically Treated Premolars Restored with Fiber-reinforced Composites

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Purpose: To evaluate interfacial gap and fracture resistance of endodontically treated maxillary premolars, restored with different glass-fiber reinforced materials.

Materials and Methods: Eighty-four extracted intact premolars were endodontically treated and MOD cavities prepared. Specimens were divided into 7 groups (n = 12 for each) as follows: sound teeth (G1); no restoration (G2); direct composite restoration with fiber-reinforced composite (everX Posterior GC) (G3); direct composite restoration (Filtek Supreme XTE, 3M Oral Care; “FSXTE”) (G4); a horizontal layer of high-viscosity flowable composite (G-ænial Flow, GC) was placed on the pulp chamber floor, 10 mm x 3 mm glass fibers (everStick NET, GC) were inserted into the cavity (G5); same procedure as in group 5 except the direct restoration was made incrementally with FSXTE (3M Oral Care) (G6); composite overlays were placed (G7). Specimens were scanned with micro-CT to evaluate 3D interfacial gaps before and after chewing simulation using Mimics software to calculate voids between restoration and tooth (dentin and enamel). These data (in mm^3) were collected for statistical analysis. Thereafter, specimens were loaded to fracture using a universal testing machine. Maximum breaking loads were recorded in Newton (N). The data obtained were analyzed using two-way ANOVA and post-hoc Tukey’s test ($p < 0.05$).

Results: ANOVA showed that horizontal glass-fiber insertions statistically significantly reduced interfacial gaps after chewing simulation. No differences in fracture resistance were found between Filtek Supreme XTE and everX Posterior; moreover, glass-fiber insertion did not significantly improve fracture resistance in either case. Composite overlays achieved significantly better fracture toughness than did direct restorations.

Conclusions: For the direct restoration of endodontically treated premolars, the insertion of glass fibers into direct composite restorations was unable to guarantee a significant increase in the fracture resistance or a significant change in the fracture pattern. However, it significantly reduced interfacial gap volume after cycling fatigue.

Keywords: 3D gap, endodontically treated teeth, fiber, fracture resistance, micro-CT.

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Restoration of endodontically treated teeth remains a challenge for clinicians, since non-vital posterior teeth are generally less stiff and more susceptible to fracture than vital teeth. This can be due to the loss of a large amount of tissue through carious lesions, making endodontic access, and root canal preparation.[30,51] Fracture resistance further decreases when such endodontic treatment is associated with mesio-occlusal-distal (MOD) cavities, since

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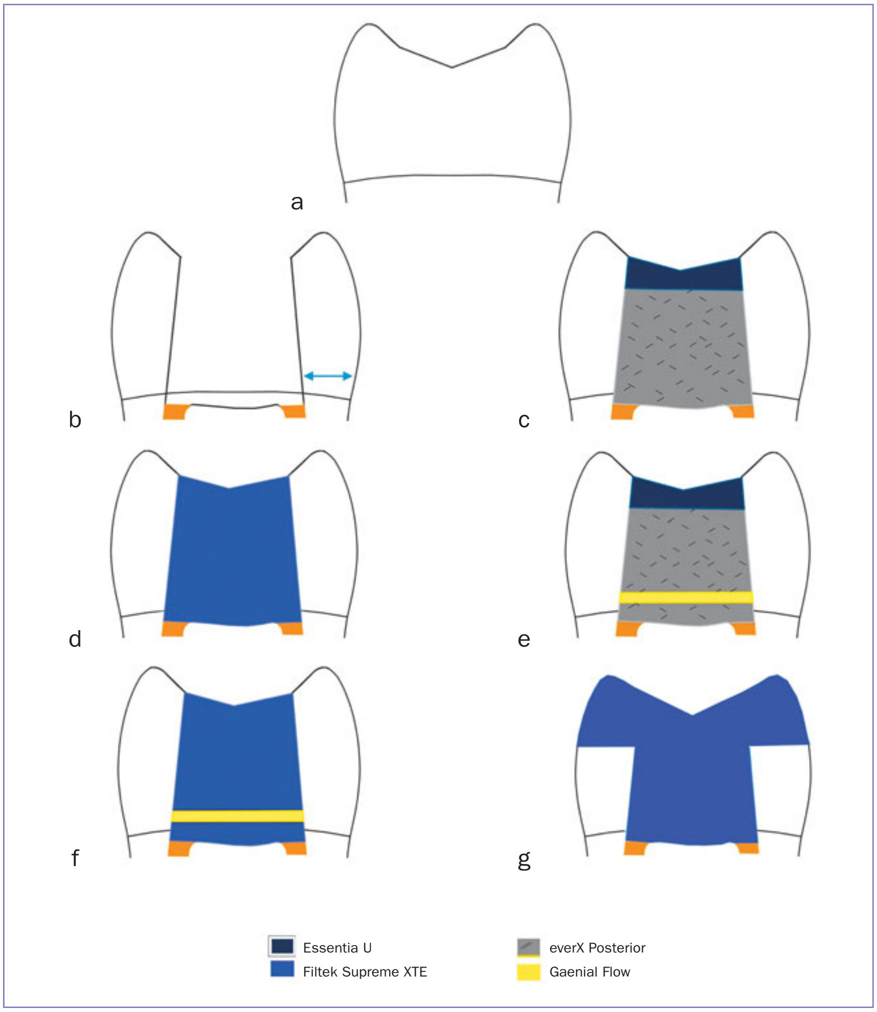

Fig 1 Sample preparation with wall thickness measurement area for all groups. a) group 1: sound teeth; b) group 2: MOD cavity without restoration; c) group 3: direct restoration with everX Posterior; d) group 4: direct restoration with Filtek Supreme XTE; e) group 5: direct restoration with everStick NET in the bottom of the cavity; f) group 6: direct restoration with Filtek Supreme XTE and fiber (EverStick NET) on the bottom of the cavity; g) group 7: overlay on Filtek Supreme XTE buildup.

the loss of marginal ridge integrity decreases the tooth's stiffness. Based on in vitro studies, maxillary premolars with deep MOD cavities are susceptible to fracture if extrinsic forces are applied.[65,67] In particular, fractures of the palatal cusps occur more frequently due to their anatomic form, an unfavorable crown:root ratio, dental arch position, and exposure to shear and compressive forces.[50,61] Thus, the remaining tooth structure and the efficacy of the restorative procedures to replace lost structural integrity are crucial for the longevity of endodontically treated teeth.[19] Different treatment strategies have been proposed, including intra-coronal post systems, modified directly placed restorations, different core materials and designs, and adhesive techniques, all of which exhibit certain advantages and disadvantages.[37,73] Regardless of the foundation core, a full-crown restoration remains the most proven solution in literature owing to its high longevity.[59,68] However, less invasive bonded clinical solutions such as indirect onlays, overlays, or endocrowns have been suggested as more conservative approaches for full-coverage restorations.[36,52]

Despite the significant development of bonded restorations, composite resins fail predominantly due to occlusal wear or secondary caries.[45,46] A common complication potentially contributing to the loss of integrity and influencing the resistance of a restored tooth is interfacial microleakage.[57,64] This can be caused by polymerization of composite resin, which is accompanied by contraction stress. The concomitant volume reduction generates a tensile force at the weakest area of the tooth-restoration interface, and stress-relieving gaps form which promote microleakage. If these gaps exceed ca 60 µm in width, postoperative sensitivity and secondary caries may form at the outer margin of the restoration.[28] Furthermore, during oral function, the tooth-restoration complex is exposed to fatigue stress resulting from cyclic loading, with the progressive onset of gap formation and interfacial microleakage.[42] A recent method to detect interfacial gaps is x-ray micro-computed tomography (µCT). Without destroying the original specimen, x-rays penetrate through it and images are collected by a detector slice-by-slice. This two-dimensional information is processed using special algorithms; a three-dimensional reconstruction is generated. Studies using μCT in restorative dentistry are increasingly being performed, since this technique has proven effective for the evaluation of the internal adaptation of composite resin restoration,[31,71] as well as the magnitude and direction of polymerization shrinkage.[14,20] Furthermore, it quantifies interfacial leakage with silver nitrate infiltration.[12,72]

Nowadays, direct resin composite restorations are the most widespread, useful, and least invasive approach to restore endodontically posterior teeth.[13,48] To increase fracture resistance, glass fibers and a fiber post have been inserted into direct composite restorations.[2,33] Particularly, ultrahigh-molecular-weight polyethylene fiber (PWT) with an ultrahigh elastic modulus was tested to reinforce the polymer-based materials.[11,15] Some studies showed that their network changed the stress dynamics at the enamel-composite interface;[35] therefore, their effect on fracture resistance reported in literature is contradictory.[7,54] Moreover, knowledge is still limited about interfacial gap progression after fatigue stress and fracture resistance of glass-fiber-reinforced composite restorations in endodontically treated posterior teeth. Thus, this in vitro study aimed to evaluate the interfacial gap, fracture resistance, and failure pattern of endodontically treated maxillary premolars restored with glass-fiber–reinforced composites. The null hypothesis was that glass fibers do not increase the fracture resistance of direct composite restorations in endodontically treated teeth (1) and do not influence interfacial gap (2).

MATERIALS AND METHODS

Specimen Preparation

Eighty-four extracted intact maxillary premolars with mature apices, extracted for orthodontic and periodontal reasons, were selected. The inclusion criteria were: sound teeth with nearly similar crown sizes (7 ± 1 mm mesio-distally, 10 ± 1 mm bucco-orally) and no cracks under transillumination and magnification, extracted within 1 month of testing. Scaler and a hand-scaling instrument were used for surface debridement, followed by cleaning with a rubber cup and pumice slurry. The teeth were stored in distilled water at room temperature until required.

Endodontic treatment was carried out in all specimens, except in the control group (intact teeth). Samples were endodontically instrumented using Pathfiles (1-2-3) and ProTaper Next X1 and X2 (Dentsply Maillefer; Ballaigues, Switzerland) to a working length set at 1 mm short of the visible apical foramen. Irrigation was performed with 5% NaOCl (Niclor 5, Ogna; Muggiò, Italy) alternating with 10% EDTA (Tubuliclean, Ogna) using a 2-ml syringe and 25-gauge needle. Thereafter, specimens were obturated with gutta-percha (gutta-percha points, medium, Inline B.M. Dentale; Torino, Italy) using the Down Pack heat source (Hu-Friedy; Chicago, IL, USA) and an endodontic sealer (Pulp Canal Sealer EWT, Kerr; Orange, CA, USA). Backfilling was performed with the Obtura III system (Analytic Technologies; Redmond, WA, USA).

After 48 h of storage in distilled water, a standardized MOD cavity was prepared by the same operator in all specimens, except in the positive control group. For cavity preparation, cylindrical diamond burs (#806314014; Komet; Schaumburg, IL, USA) under copious air-water cooling were used in a high-speed handpiece (Kavo; Biberach, Germany). The residual thickness of the buccal and oral cusps at the height of the contour was 1.5 ± 0.2 mm in all specimens, with the medial and distal cervical margins located 1 mm coronal to the CEJ. After preparation, all internal edges were smoothed and rounded.

Standardized adhesive procedures were performed in all specimens. The enamel margins were etched with 36% phosphoric acid (Ultraetch, Ultradent; South Jordan, UT, USA) for 40 s, while dentin was etched for 15 s. Thereafter, specimens were washed and gently air-dried with an air syringe, preventing the dentin from dehydrating. A multi-mode adhesive (G-Premio Bond, GC; Tokyo, Japan) was applied following the manufacturer's instructions and cured for 20 s with an LED curing light (Valo, Ultradent) at 1400 mW/cm^2. Later, specimens were randomly assigned to 7 groups (n = 12 each) according to the restorative material employed (Fig 1):

- Group 1 (G1, positive control): sound teeth (no cavity preparation or root canal treatment);
- Group 2 (G2, negative control): the MOD cavity was not restored;
- Group 3 (G3): the MOD cavity was incrementally restored with short-fiber–reinforced composite (EverX Posterior, GC; Tokyo, Japan), curing each 1.5- to 2-mm-thick layer with an LED curing light (Valo) at 1400 mW/cm^2, leaving 2 mm for placement of top layer using microhybrid composite (Essentia U, GC);
- Group 4 (G4): the MOD cavity was restored with a nanohybrid resin composite (Filtek Supreme XTE, 3M Oral Care; St Paul, MN, USA, FSXTE) applied in 1.5- to 2-mm layers using an oblique incremental technique. Each layer was light cured with an LED curing light (Valo) at 1400 mW/cm^2;
- Group 5 (G5): a horizontal layer of high-viscosity flowable composite (G-ænial Flow, GC) was placed over the pulp chamber floor. The glass fibers (everStick NET, GC) were cut to measure 10 mm long and 3 mm wide, inserted into the cavity, and adapted onto the pulpal floor in a buccal-oral direction, remaining 1 mm from the occlusal enamel margins. After light curing for 20 s with an LED lamp (Valo), a direct composite restoration was constructed as described in Group 3;
- Group 6 (G6): specimens were restored with the same procedure described for Group5 except for the material used. Direct restoration was performed with FSXTE, applied in 2-mm layers following an incremental oblique technique. Each layer was light cured with an LED curing light (Valo) at 1400 mW/cm^2;
- Group 7 (G7): a buildup with nanohybrid composite (Filtek Supreme XTE, 3M Oral Care) was performed with a 2-mm oblique layering technique. Thereafter, a standardized overlay preparation with 2-mm cusp reduction

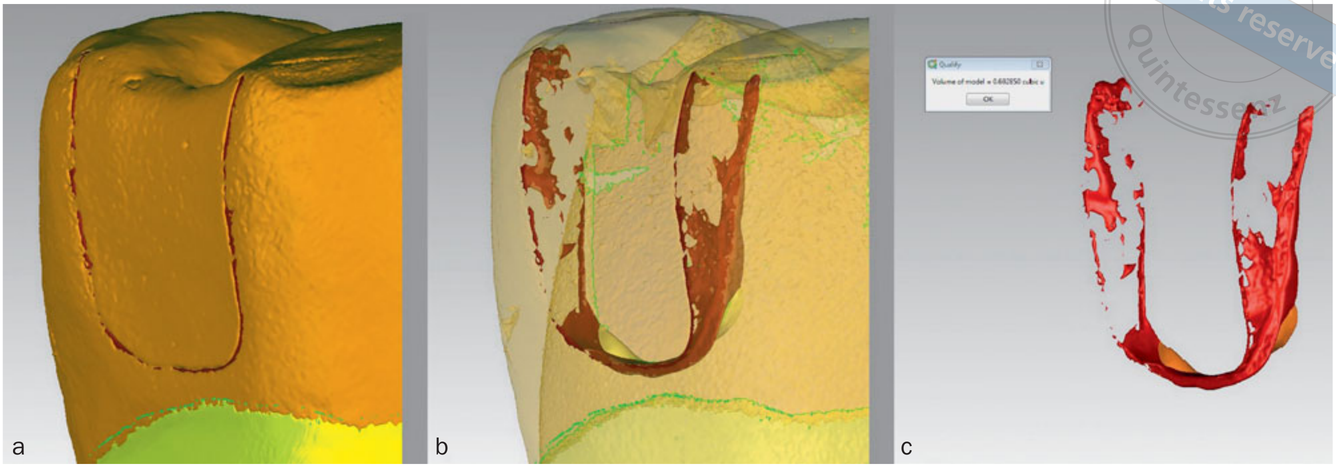

Fig 2 Micro-CT 3D images of specimens to calculate interfacial gap volume. a: Every specimen was 3D reconstructed dividing enamel, dentin, restoration, and voids using Hounsfield-scale spikes on Mimics software. Optimal quality STL images were then imported into Geomagic Qualify for analysis. b: Same view with enamel, dentin, and restoration set to 60% transparency to better visualize void areas at the interface. c: Volume calculation was automatically performed by Geomagic Qualify on void STL images, setting units in millimeters.

Table 1 Means and SD of interfacial gap, expressed as mm^3, before and after chewing simulation obtained in different groups

	everX Posterior (G3)	Filtek Supreme XTE (G4)	everX Posterior + Fiber (G5)	Filtek Supreme XTE + Fiber (G6)	Composite overlay (G7)
Before	0.415^{Aa} (±0.123)	0.499^{Aa} (±0.145)	0.424^{Aa} (±0.156)	0.434^{Aa} (±0.172)	0.322^{Ba} (±0.112)
After	0.705^{Ab} (±0.189)	0.788^{Ab} (±0.175)	0.568^{Ba} (±0.145)	0.551^{Ba} (±0.199)	0.398^{Ca} (±0.982)

Differences were considered significant at $p < 0.05$. Groups with the same superscript letters were not statistically significantly different ($p > 0.05$).
Fiber = everStickNET.

was performed. Composite overlays of equal thickness were prepared on a gypsum cast obtained after taking a mono-phase bicomponent impression with a light-body putty silicone material (Flexitime; Heraeus Kulzer). Overlays were post-cured (Labolight LV-III; GC, Tokyo, Japan) for 5 min and cemented using a dual-curing luting system (G-Cem Link Force, GC) following manufacturer's instructions. The overlays were inserted into the cavities and fixed in place manually, applying pressure to the occlusal surface with a large plugger. Excess luting composite was removed with a fine spatula along all sample margins. Polymerization was performed with an LED curing unit (Valo) for 60 s/surface. The luting composite was cured for an additional 10 s/surface after applying a thin layer of glycerin gel to eliminate the oxygen-inhibition layer on the surface of the luting composite.

All restorations were made by the same experienced operator, who aimed to obtain an intercuspidal angle of 90 degrees to standardize the cusp inclination, thus allowing reproducible positioning of the steel sphere during compressive tests. All restored specimens were finished using a fine diamond bur (8379314016, Komet, Gebr. Brasseler; Lemgo, Germany) and polished with fine Sof-Lex disks (3M Oral Care) and silicone cups (Dimanto, Voco; Cuxhaven, Germany). They were then stored in distilled water at 37°C for 1 week.

Micro-CT Analysis and Fatigue Cycling

The marginal integrity of each restoration was evaluated using a Micro-CT scan (SkyScan 1172 Micro-CT, Bruker Optik; Ettlingen, Germany). Specimens were scanned with parameters set for high resolution: voltage = 100 kV, current = 100 μA, aluminum and copper (Al+Cu) filter, 10 μm pixel size, averaging = 5, rotation step = 0.1 degree, total scan duration = 6 h. NRecon software (Bruker Optik) and Data Viewer software (Bruker Optik) were used to reconstruct specimens and obtain 3D images.

Specimens were stored in distilled water at 37°C for 24 h and then cleaned for 10 min by sonication. A CS-4.4 chew-

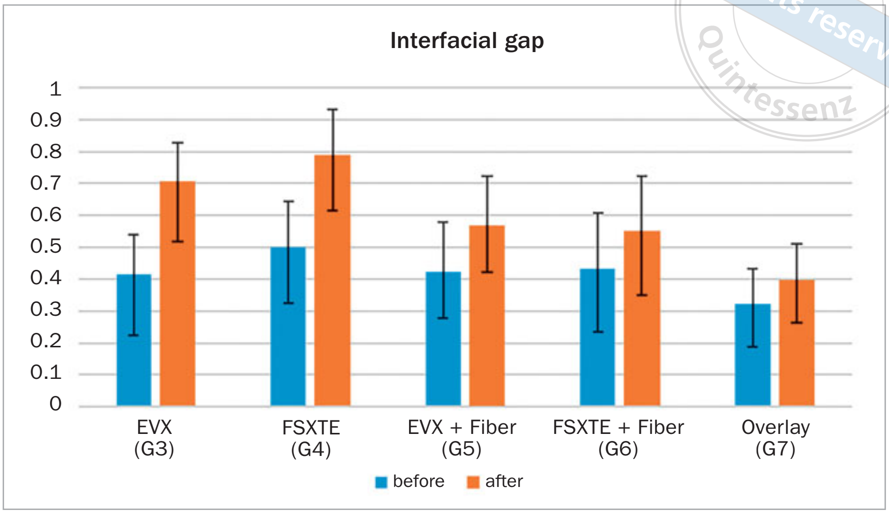

Fig 3 Mean interfacial gap of each group, expressed as mm^3 of volume, before and after fatigue loading in chewing simulator. EVX = everX Posterior; FSXTE = Filtek Supreme XTE; Fiber = everStickNET.

ing simulator (SD Mechatronik; Feldkirchen- Westerham, Germany) performed fatigue cycling to mechanically age specimens, which were embedded in light-curing acrylic resin. Resilience of the human periodontium was simulated by coating the tooth roots with a 1-mm layer of polyether (Impregum, 3M Oral Care)[55] before embedding them in light-curing acrylic resin. A 6-mm-diameter steatite sphere was applied using an occlusal load of 50 N, a frequency of 1 Hz, a downward speed of 16 mm/s, and a 2-mm sliding movement over the palatal triangular crest. All restored specimens possessed a standardized anatomy and were similarly positioned for the sphere to apply pressure onto the mesio-buccal, disto-buccal, and palatal cusps (tripod contacts). The test was performed for 500,000 cycles in distilled water.

To reveal the marginal gap progression between the restoration and tooth structure after cycling fatigue, specimens were scanned a second time with the same baseline parameters to ensure consistency in the greyscale values. Initial scans were aligned with post-chewing scans using the DataViewer software (Bruker microCT) and reconstructed with Nrecon using the same protocol. Thresholding was performed automatically with the Mimics Medical 20.0 software (Materialise; Leuven, Belgium), to obtain a void mask representing the voids between the restoration and the tooth (dentin and enamel). Using the dynamic region growing function, only the external gap was considered in this analysis. Volume data, expressed in mm^3, were calculated and collected for statistical analysis (Fig 2).

Fracture Resistance Test

Specimens were submitted to a static fracture resistance test using a universal testing machine (Instron; Canton, MA, USA) with a 6-mm-diameter steel-sphere crosshead welded to a tapered shaft and applied to the specimens at a constant speed of 0.5 mm/min and an angle of 30 degrees to the long axis of the tooth. Load was applied perpendicular to the triangular crest of the palatal cusp. Samples were loaded until fracture; the maximum breaking loads were recorded in Newton (N).

Failure Mode Analysis

Broken specimens were analyzed under a stereomicroscope (SZX9, Olympus Optical; Tokyo, Japan). The types of failure were determined and compared, particularly with a distinction made between catastrophic (irreparable, below the CEJ) and non-catastrophic fractures (reparable, above the CEJ).

Statistical Analysis

Interfacial gaps and fracture resistance are expressed as means ± standard deviation (SD). The Kolmogorov-Smirnov test for normality revealed a normal data distribution. Statistical analysis was conducted with a two-way ANOVA to examine the effects of the factors “fibers” and “restoration” (Filtek Supreme XTE vs everX Posterior vs Overlay) and their interactions on fracture resistance and interfacial marginal gap progression. Post-hoc pairwise comparison was performed using Tukey’s test. For all statistical analyses, statistical significance was pre-set at $p < 0.05$. All statistical analyses were performed using Stata 12.0 (StataCorp; College Station, TX, USA).

RESULTS

Means (± SD) of interfacial gaps, expressed in mm^3, before and after fatigue loading, obtained in different groups are displayed in Table 1 and Fig 3. Two-way ANOVA showed a significant increase in marginal gaps after chewing simulation

Table 2 Mean fracture load (in N) obtained in different groups

Group	n	Fracture load (mean ± SD)	Minimum	Maximum
Sound tooth (G1)	12	934.91 ± 143.1[a]	569	1039.45
Unrestored cavity (G2)	12	100.80 ± 12.3[d]	86.51	120.10
everX Posterior (G3)	12	465.36 ± 66.7[b]	376.01	630.01
Filtek Supreme XTE (G4)	12	451.92 ± 60.4[b]	383.70	587.24
everX Posterior with glass fibers (G5)	12	515.96 ± 72.5[b]	480.79	773.19
Filtek Supreme with glass fibers (G6)	12	499.79 ± 66[b]	307.77	699.43
Composite overlay (G7)	12	705.70 ± 123.6[c]	519.86	939.46

Groups with the same superscript letters were not statistically significant ($p > 0.05$).

in G3 ($p = 0.0001$), G4 ($p = 0.0001$), and G7 ($p = 0.00001$). Thus, the insertion of horizontal glass fibers reduced interfacial gap propagation after chewing simulation and with composite overlays.

Fracture resistance values (in N) obtained in different groups are listed in Table 2. Two-way ANOVA showed a significant difference for the variable restoration ($p = 0.00001$). The post-hoc Tukey test showed that sound teeth had a significantly higher fracture resistance than other groups, while non-restored cavities presented significantly lower values. No differences in fracture resistance were found between Filtek Supreme and everX; fiber insertion did not significantly improve the fracture resistance of either. Additionally, composite overlays achieved significantly better fracture toughness than the direct restoration techniques tested, regardless of materials used.

The fracture analysis revealed that in all fractured restorations, the origin of the fracture was always at the occlusal surface, mainly from the major contact loading area of the sphere in the stepwise fatigue test. The direction of fracture propagation was corono-apical. The number of fractures per group is shown in Fig 4. Reparable fractures started from the occlusal surface and ended above the CEJ, while irreparable fractures progressed in a mesio-distal vertical direction, which split the restoration and ended under the CEJ. In groups with a direct restoration (G3, G4, G5, G6), the main fractures were always adhesive. Debonding of the restoration, which started from the occlusal surface, occurred on the wall loaded. Some mixed fractures (adhesive-cohesive) occurred, predominantly in G7. Fracture analysis showed that the presence of glass fibers was unable to significantly alter fracture propagation, which mainly ended above the CEJ.

DISCUSSION

Based on the results obtained, the null hypothesis was partially rejected, since glass fibers did not significantly increase the fracture resistance of the direct composite restorations in endodontically treated teeth. However, they did significantly reduce interfacial marginal gap progression after fatigue loading. Biomechanical analysis of endodontically treated teeth shows that coronal destruction due to caries and the loss of marginal ridge integrity decreases tooth rigidity[3,66,67] and thus fracture resistance. In the current study, MOD cavities were prepared to decrease fracture resistance as much as possible and to better evaluate the reinforcement abilities of the tested restorative techniques. MOD cavities represent the worst clinical condition to restore in endodontically treated posterior teeth. Several studies have shown that MOD preparation and endodontic treatment accentuated the concentration of stress inside the tooth, mainly due to the loss of marginal ridges[38,50,68] and the resistance to cuspal fracture.[22,58] Thus, ideal restoration of endodontically treated teeth should improve mechanical resistance, reinforcing the weakened remaining structure, to prevent fracture and to ideally restore the fracture strength to that of an intact tooth.

The literature supports the idea that non-vital posterior teeth should be treated with a cuspal coverage restoration to increase fracture resistance.[60] However, saving sound-tooth structure is crucial. Today, the good quality of adhesives and the high-performance properties of resin composite materials[40,50] have enabled minimally invasive approaches; they offer a valid option for the restoration of endodontically treated teeth which could be comparable to full-crown restorations.[16,37] It is reported that adhesive restorations better transmit and distribute functional stresses at the bonding interface to dental hard tissues, potentially reinforcing the weakened tooth structure, especially in large

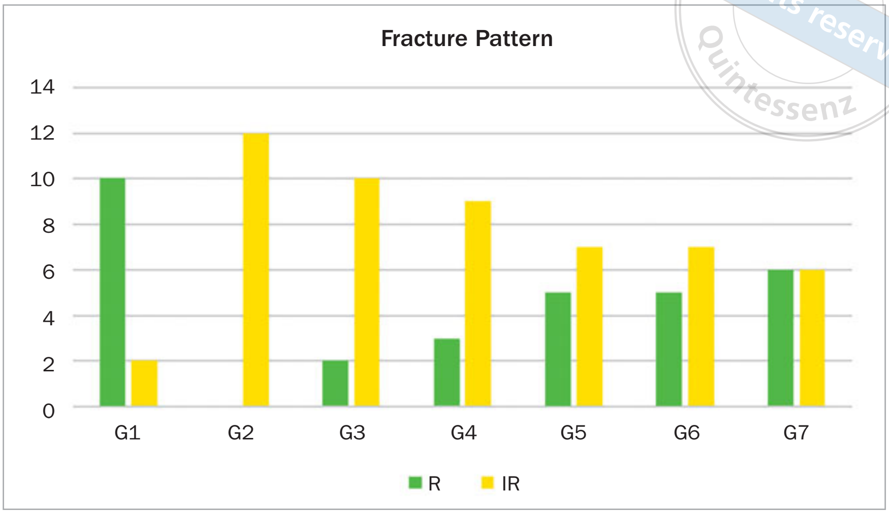

Fig 4 Number of reparable (R) or irrreparable (IR) fractures identified in the different groups.

cavities.[44] Furthermore, they decrease cusp flexion.[43] However, there is currently no consensus on the ideal final coronal restoration of endodontically treated posterior teeth.

Previous studies have demonstrated that regardless of the posterior tooth type (premolar or molar), class II resin-based composite restorations most frequently fail due to marginal leakage when the synergism of the tooth-composite interface, mediated by the adhesive bond is compromised.[17,70] Initially, a gap may originate through polymerization shrinkage and failure to obtain a good bond. Thereafter, occlusal stresses generated during mastication and especially through parafunctional habits, such as bruxism, have been shown to have a deleterious effect on the marginal adaptation of composites,[49] especially at gingival margins where occlusal forces tend to concentrate.[23] These mechanical stresses repeated over time lead to the fatigue or weakening of the adhesive interface. Once the concentrated stresses exceed the interfacial fracture toughness, a crack can form, which in turn may lead to further gap formation and microleakage.[39] In the present study, to evaluate the interfacial marginal gap of resin-based restorations, specimens were scanned before and after chewing simulation with microCT, which has proven to be an easy and accurate method to detect and evaluate 3D volumetric gaps.[41] The literature contains little on the interfacial behavior of resin-based materials examined with non-destructive techniques. However, in the oral cavity, materials are subjected to mechanical, thermal, and chemical processes; they induce fatigue damage which progresses from substructural and microscopic changes to microscopic cracks to structural instability and complete fracture.[62] Thus, interfacial analysis is crucial to better understand the kinetics of biomechanical failure. A limitation of the present study was the absence of thermal stress; intra-oral temperature changes exert an effect on the composite-tooth interface similar to mechanical stress, since composites and adhesives have a higher thermal contraction/expansion coefficients than do hard dental tissues.[25] Moreover, only marginal gaps were evaluated in the present study, not the internal adaptation of the restoration. Marginal gap formation is the result of a localized bond failure;[10] it is a concern where microgaps are found in the interface between restorative material and tooth substrate, as they may result in leakage. Nevertheless, the marginal seal may be different from internal adaptation, because localized debonding may produce microgaps that are not always associated with the outside margin and are not readily apparent.[29]

Measuring fracture strength is a static test used to predict the failure of restored teeth under compression.[63] In accordance with previous studies, no statistically significant difference was found in fracture resistance between the different direct restorative materials.[4] Short-fiber–reinforced composites are expected to enhance the longevity of medium-to-large sized composite restorations in posterior teeth,[24] because the fracture toughness of the short-fiber composite resins is generally higher than that of conventional composite resins, as shown in several studies.[18,26] This property is ascribed to the millimeter-scale short fibers, which exceed the critical fiber length,[69] enabling stress transfer from the matrix to the fibers. Furthermore, the presence of fibers results in an anisotropic property that has been suggested to relieve stress and prevent crack propagation.[69] However, a significant improvement of fracture resistance was observed between the direct techniques tested without glass-fibers insertions, which led to a slight but significant increase in load resistance independent of the composite material used. Nevertheless, it is important to highlight that none of the restoration techniques tested could re-establish the fracture resistance equivalent to that of a sound maxillary premolar.

The results of the present in vitro study showed that the insertion of glass fibers in direct composite restorations significantly influenced marginal adaptation after fatigue, but this did not statistically increase the fracture resistance of endodontically treated maxillary premolars. This result could be due to the effect of the insertion of horizontal fibers into the composites, which significantly improved their mechanical properties,[9,26,27] particularly their flexural strength.[32] This could lead to a lower cuspal deflection under cyclic loading, which is directly correlated to a reduction of marginal leakage that creates a gap at the tooth-restoration interface with consequent marginal infiltration.[1] The presence of glass fibers in the resin composite could even alter the elastic modulus of the material itself, thus modifying the stress distribution and transmission to residual cavity walls. As mentioned above, an anisotropic characteristic[69] may also play a role. However, any significant improvement of fracture resistance was observed between the direct techniques tested without glass-fibers insertions, which led to a slight but significantly increased load resistance regardless of the composite used. However, it is important to emphasize that none of the restoration techniques tested could re-establish fracture resistance equivalent to that of a sound maxillary premolar. The obtained results agreed with those of Rodrigues et al,[54] who found that fibers placed into MOD cavities did not reinforce teeth. Those authors reasoned that cusp deflection resilience occurred due to adhesive and composite resin, not due to the glass fibers insertion, which instead could have a protective effect on fracture propagation towards the pulp chamber floor. Furthermore, Cobankara et al[15] showed no difference between a resin composite restoration with or without fibers in MOD cavities in molars.

In the present study, glass fibers were inserted in a buccal-oral direction (u-shaped), similar to the method suggested by Belli et al.[6,7] Some authors reported that the form and direction of fibers, their composition, fiber:resin volume ratio and the bond strength between fibers and resin had an influence on the reinforcing effect.[8,44] Moreover, there is evidence that the mechanical properties of the composite depend on the type, extension, and length of the fibers.[56] Belli et al[7] showed that the use of polyethylene ribbon fibers under composite restorations increased the fracture resistance thanks to their ability to connect the residual walls and modify stress transmission and distribution along the restoration-dentin interface. However, that study was conducted on molars which were not subjected to cyclic loading before fracture. A similar effect was found by Karzoun et al.[34] They placed a horizontal fiber post into the post-endodontic composite restoration, joining palatal and buccal walls of a MOD cavity. This technique showed an slight, nonsignificant increase in fracture resistance, even if the horizontal post did not prevent catastrophic fractures.

Both in terms of marginal gap formation and fracture resistance, the best result was obtained with composite overlays. This can be explained by the strengthening effect of buccal and oral cusp connection provided by this therapeutic option. Other authors demonstrated the efficacy of the luted indirect techniques, based on shrinkage limited to the very thin layer of luting material.[5] Previous studies have shown that cuspal coverage with adhesive restorations is a valid option to increase the tooth fracture resistance of endodontically treated teeth.[8] However, Rocca et al, [53] who placed bi-directional E-glass fibers over the pulpal chamber area of devitalized molars restored with CAD-CAM resin composite overlays, found that such restorations did not benefit from the simultaneous use of glass fibers. Moreover, Fennis et al[21] obtained similar results: the incorporation of fiber-reinforced composite did not increase the load-bearing capacity of premolars with cusp-covering restorations. This could be related to the fact that the overlay thickness puts distance between the glass fiber and the loading impact area. In fact, Oskoee et al[47] suggested that the fracture resistance increased when fibers were placed close to the point where force was exerted, as this leds to a shorter working arm and a lower input force, according to the lever principle of Archimedes. Additionally, placing fibers on the occlusal surfaces keeps buccal and lingual cusps together, resulting in higher fracture resistance. Thus, placing glass fibers in the cervical to middle thirds did not significantly increase the fracture resistance.

CONCLUSIONS

MOD cavity preparations significantly reduced the fracture resistance of endodontically treated premolars, but none of the restorations tested were able to restore the original fracture resistance. The insertion of glass fibers into direct composite restorations could not ensure a significant increase in fracture resistance or a significant deviation of the fracture pattern; however, it was able to significantly reduce the interfacial gap opening after cycling fatigue. Further studies are necessary to confirm these results.

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Clinical relevance: The evaluation of less invasive techniques in the rehabilitation of teeth weakened by endodontic treatment is crucial. The inclusion of fibers in composite resins seems to reduce the formation of interfacial gaps, while it does not have significant effects on fracture toughness and fracture pattern.