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Effects of fiber-glass-reinforced composite restorations on fracture resistance and failure mode of endodontically treated molars

Short title: Fracture resistance of fiber-reinforced restorations.

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Key words: endodontically treated, fracture resistance, glass-fiber, direct composite, fractography

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Abstract

Objectives: The study evaluated the fracture resistance and fracture patterns of endodontically treated mandibular first molars restored with glass-fiber-reinforced direct composite restorations.

Methods: In total, 60 extracted intact first molars were treated endodontically; a mesio-occluso-distal (MOD) cavity was prepared and specimens were then divided into six groups: sound teeth (G1), no restoration (G2), direct composite restoration (G3), fiber-post-supported direct composite restoration (G4), direct composite reinforced with horizontal mesio-distal glass-fibers (G5), and buccal-palatal glass-fibers (G6). Specimens were subjected to 5,000 thermocycles and 20,000 cycles of 45° oblique loading force at 1.3 Hz and 50 N; they were then loaded until fracture. The maximum fracture loads were recorded in Newtons (N) and data were analyzed with one-way ANOVA and *post-hoc* Tukey tests ($p < 0.05$). Fractured specimens were analyzed with a scanning electron microscope (SEM).

Results: The mean static loads (in Newtons) were: G1, 831.83; G2, 282.86; G3, 364.18; G4, 502.93; G5, 499.26; and G6, 582.22. Fracture resistance did not differ among G4, G5, and G6, but was significantly higher than G3 ($p=0.001$). All specimens fractured in a catastrophic way. In G6, glass fibers inducted a partial deflection of the fracture, although they were not able to stop crack propagation.

Conclusions: For the direct restoration of endodontically treated molars, reinforcement of composite resins with glass-fibers or fiber posts can enhance fracture resistance. The SEM analysis showed a low ability of horizontal glass-fibers to deviate the fracture, but this effect was not sufficient to lead to more favorable fracture patterns above the cement-enamel junction (CEJ).

Clinical significance: The fracture resistance of endodontically treated molars restored with direct composite restorations seems to be increased by reinforcement with fibers, even if it is insufficient to restore sound molar fracture resistance and cannot avoid vertical fractures.

Introduction

Providing lost resistance to occlusal load in endodontically treated posterior teeth represents one of the main goals of post-endodontic restorations, because they are generally more susceptible to fractures than vital teeth due to the loss of a large amount of tissue as a consequence of carious lesions or coronal fracture [1,2]. Recent studies have reported that the longevity of endodontically treated teeth depends directly on the amount of remaining tooth structure and the efficacy of the restorative procedures in replacing lost structural integrity [3]. These factors show the importance of highly conservative endodontic and restorative procedures preserving a sound structure as much as possible. The clinical outcomes of direct resin composite restorations, which represent a less invasive approach to restoring endodontic posterior teeth, are variable in the literature, ranging from catastrophic to acceptable [4,5,6]. More recently, the insertion of fiber posts within direct composite restorations has been tested with the intention of providing increased fracture resistance [7,8,9]. Indeed, within the radicular dentin, the fiber post serves as a distributor of stresses and loads applied to the composite restoration [10], providing reinforcement even in the presence of sufficient residual coronal dentin [11,12]. Moreover, post and core should have similar elastic moduli to root dentin to better absorb the forces concentrated along the root and, consequently, decrease the probability of fracture [13,14]. However, fiber post insertion presents some limitations: the post-space preparation tends to weaken the radicular structure, because some dentin tissue should be removed [1,2]. Moreover, several studies have reported poor bond strength in the deeper areas of the post space [15,16].

An alternative method to increase the fracture resistance of endodontically treated teeth is by the insertion of fibers, which are increasingly being used for the reinforcement of polymer-based dental materials. In particular, ultra-high-molecular-weight polyethylene fiber (PWT), which has an ultra-high elastic modulus, has been tested recently [17,18]. The woven network allows fiber wetting and the infusion of the bonding resin; this enhances the transfer of forces acting on the PWT. Previous studies showed that this network changed the stress dynamics at the enamel-composite material interface [19], but the effect on fracture resistance of endodontically treated teeth remains controversial [20,21].

Recently, UDMA-TEGDMA pre-impregnated parallel glass-fibers were introduced, but as yet there is limited knowledge about their effect on fracture resistance when used together with an extensive composite restoration on endodontically treated posterior teeth. Thus, the aim of this *in vitro* study was to evaluate the fracture resistance and failure patterns of endodontically treated mandibular first molars restored with glass-fiber reinforced composite. The null hypothesis was that glass-fibers do not increase the fracture resistance of direct composite restorations in endodontically treated teeth.

Materials and Methods

In total, 60 non-carious mandibular first molars, extracted for periodontal reasons, were selected. The inclusion criteria were as follows: sound teeth, with nearly similar crown sizes and no cracks under transillumination and magnification, extracted within 1 month. A hand scaling instrument was used for surface debridement, followed by cleaning with a rubber cup and slurry of pumice. The specimens were disinfected in 0.5% chloramine for 48 h and then stored in 4% thymol solution at room temperature until use.

Endodontic treatment was carried out in all specimens. Specimens were endodontically instrumented using Pathfiles (1-2-3) and ProTaper Next (Dentsply Maillefer, Ballaigues, Switzerland) to the working length, which was set at 1 mm short of the visible apical foramen. Irrigation was with 5% NaOCl (Niclor 5, Ogna, Muggiò, Italy) alternated with 10% EDTA (Tubuliclean, Ogna) using a 2-ml syringe and 25-gauge needle. Specimens were then obturated with gutta-percha (Gutta Percha Points, Medium, Inline; B.M. Dentale Sas Di Bertello G. & Moraes M., Torino, Italy) using the DownPack heat source (Hu-Friedy, Chicago, IL, USA) and endodontic sealer (Pulp Canal Sealer EWT; Kerr, Orange, CA, USA). Backfilling was performed with the Obtura III system (Analytic Technologies, Redmond, WA, USA).

The teeth were stored in distilled water at room temperature for at least 72 h. For the simulation of 0.3-mm-thick periodontal ligament, each root was immersed in melted wax up to the demarcation line 2 mm apical to the cement-enamel junction [18] (CEJ; checked with a digital caliper). A metal cubic mold was used to embed all the specimens in acrylic self-curing resin (StickRESIN; Stick Tech Ltd., Turku, Finland) up to 1 mm apical to the CEJ, their long axes were oriented perpendicular to the horizon using a custom-made parallelometer. Each root was removed from the resin block when primary signs of polymerization were noticed. The wax spacer was removed with hot water and then replaced by a silicone-based impression material (Light Body, Flexitime; Heraeus Kulzer, Hanau, Germany), which was injected into the acrylic resin block prior to reinsertion of the specimen.

After 48 h in distilled water, standardized class II mesio-occluso-distal (MOD) cavities were prepared by the same experienced operator in all specimens except 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 headpiece (Kavo Dental GmbH, Biberach, Germany). The residual thickness of buccal and lingual cusps at the height of the contour was 2.5 ± 0.2 mm in all specimens, with the medial and distal cervical margin located 1.5 mm coronal to the CEJ (Fig. 1). After finishing the preparation, all internal edges were smoothed and rounded.

The teeth were assigned randomly to six groups (n = 10 each) according to the post-endodontic restoration.

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 restored with a direct composite restoration. A three-step etch-and-rinse adhesive system (Optibond FL, Kerr) was applied following the manufacturer's instructions, and then cured for 60 s with an LED curing light (Valo; Ultradent Products Inc., South Jordan, UT, USA) at 1,400 mW/cm^2. The cavity floor was covered with a 1 mm layer of high viscosity flowable composite (GrandioSo Heavy Flow; Voco, Cuxhaven, Germany), and the cavity was then incrementally restored with composite resin (GrandioSo; Voco) using an oblique layering technique. Each layer, 1.5–2 mm thick, was light-cured for 20 s with an LED curing lamp (Valo) at 1,400 mW/cm^2.

Group 4 (G4): the MOD cavity was restored with a fiber post-supported direct composite restoration. A post space was prepared to a depth of 7 mm, measured from the pulpal chamber floor, using drills from the post manufacturer (Rebilda Post 15; Voco) on the distal canal of the specimen. The root canal walls were cleaned with 10% EDTA for 30 s with a continuous brushing technique, washed using a water syringe with an endodontic needle and then gently air-dried. Excess water was removed from the post space using paper points, preventing the dentin from dehydrating. The post was covered with a layer of silane (Silane Coupling Agent; 3M, St. Paul, MN, USA) and then fixed into the post space with a self-adhesive resin cement (Rely-X Unicem 2; 3M). After an initial set for 1 min, irradiation was performed with an LED curing light for 60 s (Valo). Then, a direct composite restoration was performed as described in Group 3.

Group 5 (G5): the MOD cavity was restored with a direct composite restoration reinforced with horizontally placed glass-fibers (unidirectional fibers, size 2mm x 5mm, 12 µm diameter) . After the three-step etch-and-rinse adhesive application described for Group 3, a horizontal layer of high viscosity flowable composite (GrandioSo Heavy Flow) was placed over the pulpal chamber floor until reaching the height of the mesial and distal cervical boxes. Then, pre-impregnated glass fibers (GranTEC; Voco) were horizontally placed from the mesial to the distal box, without touching the enamel margins. After light-curing for 20 s with an LED lamp (Valo), a direct composite restoration was performed as described in Group 3.

Group 6 (G6): specimens were restored with the same procedure described for Group 5 except with respect to the placement of the glass fibers, which were positioned over the flowable composite in a buccal-palatal direction, with the ends bonded to the buccal and oral walls to achieve a height of 2 mm.

All these direct restorations were performed by the same experienced operator, who aimed to obtain an intercuspidal angle of 90° to standardize cusp inclination and allow reproducible positioning of the steel sphere during the compressive tests. All the restored specimens were finished using a fine diamond bur (8379314016; Komet) and polished with fine Sof-Lex discs (3M) and silicone cups.

Loading of the specimens

After storage in distilled water at 37°C for 1 week, all specimens were subjected to 5,000 thermal cycles between 5°C and 55°C for 60 s and then exposed to 20,000 cycles of 45° oblique loading force on the center of the specimens (Mini Bionics II; MTS Systems, Eden Prairie, MN, USA), at a frequency of 1.3 Hz and 50 N, totally resting on the composite restoration.

Specimens were then 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 occlusal surface of the specimens at a constant speed of 0.5 mm/min and an angle of 45° to the long axis of the tooth. Specimens were loaded until fracture and the maximum fracture loads were recorded in Newtons (N).

Fractographic analysis

Fractured specimens were first analyzed under a stereomicroscope (SZX9; Olympus Optical Co., Ltd., Tokyo, Japan). Different magnifications (from 6.3 to 50×) and angled illumination were used to better view the fracture surface. The types of failure were determined and compared; in particular, a distinction was made between catastrophic fractures (non-reparable, below the CEJ) and non-catastrophic fractures (reparable, above the CEJ).

Subsequently a scanning electron microscope (SEM) (Digital SEM XL20; Philips, Amsterdam, Netherlands) was used for more detailed analyses of the fractured surfaces. To clean the specimens of impurities, all fragments were immersed in an ultrasonic 10% NaOCL bath for 3 min, rinsed with water, dried and then fixed on the support for the microscope. The specimens were gold-coated prior to analysis with the SEM. All recognizable features, such as compression curl, hackle, and arrest line [22,23], were photographed and documented. Magnifications up to 2,000× were used to obtain higher definition images of identified crack features in selected areas of interest.

Statistical Analysis

Data are expressed as means ± standard deviation (SD) and frequency (%). The Kolmogorov-Smirnov test for normality revealed a normal data distribution. The statistical analysis was then conducted with a one-way analysis of variance test (ANOVA) and a *post hoc* Tukey test. A p-value of < 0.05 was considered to indicate statistical significance. All statistical analyses were performed using STATA software (ver. 12.0; StataCorp, College Station, TX, USA).

Results

The mean values of fracture resistance, expressed in Newtons, obtained in the different groups are listed in Table 1. One-way ANOVA tests revealed significant differences among groups ($p<0.05$). Further *post hoc* Tukey tests showed that G1 (sound teeth) had a significantly higher fracture resistance than the other groups, while G2 (non-restored) showed significantly lower values (p=0.0001). The fracture resistance did not differ significantly among G4, G5, and G6, but was significantly higher than that of G3 (p=0.001).

In the analysis performed with the stereomicroscope, fractures were evaluated as catastrophic in all specimens, because they were all below the CEJ. In groups where a restoration was performed (i.e., G3–G6), the fractures were always adhesive. The debonding of the restoration occurred on the wall charged with the load; the debonding started from the occlusal surface and determined a deflection of the wall of the tooth that subsequently induced a lateral fracture of the same wall, leaving a "compression curl" marked on the root. Some mixed secondary fractures (adhesive-cohesive) occurred, predominantly in the internal part of the restorations or on the occlusal surface. In G6, the layer of fibers, disposed with a buccal-palatal orientation, induced a partial deflection of the fracture, although they were not able to stop the crack propagation (Fig. 2).

Discussion

The ideal rehabilitation of endodontically treated posterior teeth would improve their mechanical resistance and prevent unfavorable fractures, thereby restoring anatomy and function. This *in vitro* study aimed to evaluate the effects of glass fiber-reinforced resin composite on the fracture resistance of endodontically treated molars with MOD cavities, compared with different direct adhesive restoration techniques. It has been reported that mandibular molars are the teeth involved most frequently in endodontic treatments [24] and are often extracted because of secondary caries and cusps or radicular fractures [25]. Therefore, a restoration technique that can reinforce the weakened remaining tooth structure is fundamental to reducing the possibility of fractures. Moreover, in the selected teeth, standardized MOD cavities were prepared because this clinical condition strongly reduces resistance to cuspal fractures [2,26-29] due to the absence of mesial and distal walls, which cause a high strain on vestibular and lingual cusps [18]. Soares et al. confirmed that MOD preparation and endodontic treatment accentuated the concentration of stress inside the dental structure, mainly due to the greater removal of the dental structure [30].

To evaluate the distribution of occlusal and masticatory loads on molar crowns, forces are usually applied to the central pit and parallel [31] or oblique to the tooth axis. Nevertheless, recent studies have demonstrated that during maximum intercuspidation within the second phase of chewing, higher stresses are more concentrated along the cervical dental portion and mesiolingual radicular area of the mandibular molars. Jiang et al. [32] used a finite element model to analyze stress concentration in vital or endodontically treated mandibular molars restored with indirect adhesive restorations. Specimens received a vertical or 45° oblique occlusal load at a constant intensity of 45 N to simulate masticatory loads. In all specimens receiving lateral load application, the stress was concentrated mainly along the cervical radicular portion of the tooth and at the floor of the preparation, as well as at the loading site. Thus, in the present study, specimens were submitted to a lateral load with a 45° angle to distribute the stresses in areas of higher fracture risk.

The results of the present *in vitro* study led us to reject the null hypothesis, because the insertion of glass fibers in direct composite restorations significantly increased the fracture resistance of the endodontically treated molars. However, it is important to highlight that none of the direct restoration techniques tested in this study could restore the fracture resistance to that of a sound mandibular molar. This finding emphasizes the importance of maintaining as much sound tissue as possible during endodontic and restorative procedures, because the structural strength of a tooth strictly depends on the quantity and integrity of its anatomical form [33]. Traditionally, to prevent tooth fracture, cuspal coverage, preceded by custom cast post and cores, has commonly been used as a system to improve teeth resistance and load distribution. Aquilino & Caplan [34] showed that a tooth with crown rehabilitation had a six-fold higher rate of success than a directly restored tooth. At present, a conservative approach is preferred to preserve sound tissue, which is directly related to the fracture resistance of a tooth.

The present findings clearly showed how a direct composite restoration was able to provide a significant improvement in the fracture resistance of endodontically treated molars with MOD cavities. It has been reported that adhesive restorations are better able to transmit and distribute functional stresses through the restorative material-tooth interface, with the potential to reinforce the weakened tooth structure [35,36]. However, a significant reinforcement effect was obtained with the insertion of a glass fiber post within the direct composite restoration. Fiber post insertion within a composite restoration can improve the ability of the tooth-restoration complex to absorb the occlusal loads along the major axis of the tooth [37]; could increase the resistance of the endodontically treated tooth to occlusal loads [38,39]; and may cause less cuspal deflection, thus reducing the possibility of marginal leakage that creates a gap at the tooth-restoration interface with consequent marginal infiltration [40]. A favorable effect of a fiber post-supported composite restoration in the longevity of post-endodontic restorations has been reported in several *in vivo* studies [6,41]. Nevertheless, some *in vitro* studies have shown how endodontically treated premolars without fiber post placement had fracture toughness similar to those with a fiber post. Krejci et al. [42] confirmed that any restoration avoiding post space preparation, with less sacrifice of residual sound tissue, might result in greater resistance to fracture regardless of the degree of impairment of the dental structure. Another recent study, by Soares et al. [30], concluded that the use of glass fibers posts did not reinforce the tooth restoration complex.

These conflicting results, together with the need to find less invasive restorative solutions, prompted studies on fiber-reinforced composite restorations. In the present study, glass fibers where inserted within a direct composite restoration to better understand their effects on fracture resistance and crack propagation. Our findings showed a significant increase in fracture resistance, obtaining a strengthening effect comparable to that obtained with fiber post insertion. The presence of glass-fibers inside the resin composite could alter the elastic modulus of the material itself, thus modifying the stress distribution and transmission to residual cavity walls. In fact, the higher the elastic modulus of the restorative material at the restoration interface, the lower the deformation of dental structures [36]. These results are consistent with other studies [20,43], showing that the use of polyethylene fibers under composite restorations in root-filled teeth with large MOD preparations produced statistically greater fracture resistance than resin composite restorations. The authors suggested that the polyethylene fibers had a stress-modifying effect along the restoration-dentin interface, and the bonding ability of fibers in combination with the resin might have increased the fracture strength of the tooth by keeping both cusps together. However, Rodrigues et al. [21] concluded in a recent paper that fibers placed into MOD cavities did not reinforce teeth, but they may have a protective effect on fracture propagation towards the pulp chamber floor. These inconsistencies could be related to the different angle whereby the specimens were loaded. An irrelevant effect of fiber reinforcement was also shown in a recent study by Rocca et al. [31], in which bi-directional E-glass fibers were placed over the pulpal chamber area, as in the present study, but indirect Lava Ultimate overlays were employed to restore endodontically treated molars.

A slight, although not statistically significant, improvement in fracture resistance was found when glass fibers were placed in a buccal-palatal direction. The connection of the residual walls of the specimens through the fibers may contrast the compressive load that induced tension in the cervical area. A similar effect was tested by Karzoun et al. [44], who placed a horizontal fiber post in a post-endodontic composite restoration, joining the palatal and buccal walls of the MOD cavity. This technique showed an increase in fracture resistance, although the horizontal post did not avoid catastrophic fractures.

To evaluate the fracture pattern, a combined stereo and scanning electron microscopy technique was used [31]. The stereomicroscope showed the whole surface of the fractured specimens. SEM images gave information on fractographic markers, such as hackle lines, arrest lines, and compression curl, which are indicators of the crack propagation direction. A fractographic analysis of the pattern of a fragment provides important information when a cohesive fracture occurs. In adhesives fractures, most of the features left by the crack, such as the origin, the “mirror” and the “hackles,” are not visible. However, the end of the event was indicated by the presence of the “compression curl,” left on the cracked roots of the specimens, meaning that the origin was in an upper region. Some secondary cohesive fractures were also recognizable. In G6, the denuded ranks of fibers left a mark on the surface of the build-up after their debonding (Fig. 2). This indicates that the main front of the fracture was partially deviated once it touched the layer of fibers, following their horizontal direction. However, this effect was not sufficient to avoid a catastrophic break: the charged wall always deflected until fracture.

Conclusions

Within the limitations of this *in vitro* study, it was possible to conclude that:

- None of the direct restoration techniques tested was able to restore the fracture resistance of sound molars.

- The insertion of a fiber post or glass fibers into direct composite restoration was able to guarantee a significant increase in the fracture resistance of endodontically treated molars.

- Glass fibers with a buccal-palatal orientation showed a partial deviation of the fracture pattern, even if it did not prevent catastrophic fracture of the specimen.

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