Restoration of deep vital and root-canal treated MOD cavities using fiber-reinforced direct restorations

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Table of Contents

1. List of the publications providing the basis of, and related to the topic of the thesis

Publications providing the basis of the thesis:

Fráter M, Sáry T, Vincze-Bandi E, **Volom A**, Braunitzer G, Szabó P B, Garoushi S, Forster A. Fracture Behavior of Short fibre-Reinforced Direct Restorations in Large MOD Cavities. Polymers (Basel). 2021 Jun 23;13(13):2040. doi:10.3390/polym13132040.
(Q1)

Dr. Volom András, Dr. Fráter Márk. Transzmurális szálerősítéses merevítés a nagyméretű MOD kavitások mechanikai ellenállóképességének növelésére – technikai leírás. FOGORVOSI SZEMLE 112. évf. 3. sz. 2019. 82-86.

Jakab A, **Volom A**, Sáry T, Vincze-Bandi E, Braunitzer G, Alleman D, Garoushi S, Fráter M. Mechanical Performance of Direct Restorative Techniques Utilizing Long fibres for "Horizontal Splinting" to Reinforce Deep MOD Cavities-An Updated Literature Review. Polymers (Basel). 2022 Apr 1;14(7):1438. doi:10.3390/polym14071438.
(Q1)

Volom A, Vincze-Bandi E, Sáry T, Alleman D, Forster A, Jakab A, Braunitzer G, Garoushi S, Fráter M. Fatigue performance of endodontically treated molars reinforced with different fibre systems. Clin Oral Investig. 2023 Jun;27(6):3211-3220. doi: 10.1007/s00784-023-04934-2.
(Q1, D1)

Related publications:

Sáry T, Garoushi S, Braunitzer G, Alleman D, **Volom A**, Fráter M. Fracture behaviour of MOD restorations reinforced by various fibre-reinforced techniques - An in vitro study. J Mech Behav Biomed Mater. 2019 Oct;98:348-356. doi:10.1016/j.jmbbm.2019.07.006. Epub 2019 Jul 9. Erratum in: J Mech Behav Biomed
Mater. 2020 Feb;102:103505.
(Q1)

2. List of Abbreviations

- Bis-GMA: bisphenol-A glycidyl dimethacrylate
- CEJ: cemento-enamel junction
- FRC: fiber-reinforced composite
- MOD: mesio-occluso-distal
- RCT: root-canal treated
- SFC: short fiber-reinforced composite
- TEGDMA: triethylene glycol dimethacrylate
- UHMWPF: ultra-high molecular weight polyethylene fiber

3. Introduction

3.1. Historical background

Anthropological research shows that the teeth and periodontal tissues of early Stone Age hunter-gatherers were healthy. As the population grew, so did man's knowledge. A sedentary lifestyle and more sheltered conditions led to a more rapid increase in population numbers. Demographic pressures led to the start of farming as a supplement to fishing and hunting, which caused further population growth. This increase created conditions in which agriculture became the sole source of food, as fishing and hunting could no longer provide sufficient nutrients for the population [1]. Foods produced from agricultural crops (cultigens) are high in calories and usually cause tartar. These foods do not require significant chewing power to consume. A direct consequence of this is insufficient chewing along with reduced chewing force. The decreased chewing force caused a reduction in the size of the jawbones, resulting in malocclusion [2]. Due to the high carbohydrate diet, caries is widespread regardless of population or continent. Of course, general health also suffers from the transition, which can be demonstrated by examining fish-hunter-gatherer and agriculturist populations found in the same habitat [1]. As a result, malocclusion to a certain extent is now quite common, with the vast majority of children needing some form of orthodontic treatment [3]. Caries, together with malocclusion, presents a challenge to the practicing dentist to restore teeth with a high material deficit, as these teeth are often subjected to non-axial, i.e., lateral movement, loads due to tooth crowding. The modern diet does not really put any strain on the dentition, as the population eats highly softened foods. The early soft restorative materials such as bitumen, pewter, and beeswax were able to cover the missing tooth substance [4]. However, modern restorative materials are also expected to be able to provide a functional restoration. The early—already successful—fillers such as amalgam or gold required a unique cavity design that provided mechanical retention, as there was no chemical bond between the cavity wall and the filler. These materials were able to produce a restoration with limited ability to withstand functional loads. Gold, in particular, was outstanding in this field, but its application from a public health point of view was not significant because of its high cost. Most posterior teeth with large cavities were restored with amalgam fillings; however, both studies and everyday clinical practice have shown that the number of cracks and fractures is significantly higher next to amalgam fillings compared to other direct restorations [5,6]. Currently, with the worldwide phasedown of amalgam, restoring large cavities (e.g., mesio-occluso-distal (MOD) cavities) is an everyday problem for practitioners from a mechanical point of view [7–9]. Poisson's rule states that when elastic objects are loaded from a given direction, their dimensions will increase perpendicular to the direction of the force acting on them. Graeme Milicich adapted this concept to the coronal part of teeth. According to this, under mechanical loading, the occlusal part of teeth is in compression. The author calls this a "biodome," which in turn switches the sides of the coronal part of the tooth at the inflection points to tensile loading [10]. Following the principles of this concept, by covering the highly destructed teeth subjected to tensile loading with an occlusally placed structural element—reestablishing the biodome—it is possible to keep the sidewalls in compression, i.e., to prevent them from buckling and resulting in fracture. In the early days, the practical application of the principles described above was tantamount to making a complete full coverage crown. This was particularly justified in the case of restoring teeth with significant tooth material deficiencies, such as root-canal treated (RCT) teeth [11]. By covering the coronal surfaces and restoring teeth with crowns, using the ferrule effect, teeth can be kept in compression, i.e., protected from damage and fractures due to occlusal loading and lateral deflection [12]. However, preparing full crowns involves removing an extreme amount of tooth material. Equally good mechanical protection can be expected when the chewing surfaces are covered by indirect, but only partial restoration [13]. The material of onlays prepared for this purpose could be gold, ceramic, or composite. In the beginning, gold, which could be cast well and prepared accurately, was the most suitable material. Onlays made of gold were characterized by excellent long-term survival [14]. Gold as a material still stands out today for its excellent stress dissipation properties; however, due to aesthetic reasons, composite and ceramic restorations are more frequently used. In 1955, Buonocore discovered the chemical modification of the enamel structure by acid conditioning [15]. In 1962, Rafael Bowen created the bisphenol-A glycidyl dimethacrylate (Bis-GMA) composite matrix, which, together with conditioning, paved the way for significantly more durable restorations [16]. The introduction of composite resin materials and modern adhesive luting represents the turning point at which conservative dentistry became capable of restoring tooth material defects to a satisfactory level of functionality and morphology with direct restorative materials [17]. Currently, the placement and replacement of direct restorations belong to the most frequently performed interventions in general dentistry. Given the high patient demand for tooth-colored restorations that make a natural impression, and also due to their more convenient cost compared to indirect restorations, the use of direct posterior composite restorations has widely increased for such purposes [18]. The results and success rates that can be achieved with large posterior direct composite restorations are limited by several factors, such as polymerization shrinkage and resultant stress development [19–21], and inadequate fracture toughness [21–23]. Other factors also have a significant impact on the results achieved: properties of the bond system used [24], mechanical properties of the composite [25], cavity-related factors and dimensions [26], and the application method of the filling material [27]. One of the main problems with direct composite fillings is polymerization shrinkage, which can lead to micro-leakage and recurrent caries [28]. This can partly be addressed by the incremental layering or the decoupling-with-time concept [29]. Another problem with composite restorations is their inadequate fracture toughness. Modern composites are rigid, strong materials, but they lack fracture toughness, which is the resistance to the propagation of cracks under loading [30]. As a result of these limitations, direct composite restorations might not be the best solution for excessive MOD cavities in posterior teeth [31].

3.2. Introduction of the fiber-reinforced materials

The introduction of fibers to reinforce dental fillings in dentistry is a new opportunity/solution to make restorations more robust. The process of fiber reinforcement has been known for a long time. Fiber-reinforced materials in the true sense of the word were used in construction sites as far back as ancient Egypt. The modern construction industry has used fiber-reinforced cements to obtain new materials with improved properties [32]. Endodontic treatments, the replacement of large direct amalgam fillings, or large decays often lead to large cavities with weakened remaining walls [33]. The need for strengthening the tooth structure after excessive preparation is part of the everyday dental routine nowadays.

3.3. Fiber types

3.3.1. Ultra-high molecular weight polyethylene fiber ribbons

In the early 1990s, the first dental fiber-reinforced material, Ribbond, was introduced [34]. Ribbond is a woven (leno weave) ultra-high molecular weight polyethylene fiber (UHMWPF) tape, which is produced in several thicknesses and widths. The first is the Classic, which has a thickness of 0.36 mm, the THM 0.18 mm, and the Ultra 0.12 mm. Depending on the application, widths of 1, 2, 3, 4, and 7 mm can be used. Cold gas plasma treatment is used to ensure that the reinforcement material bonds well. Polyethylene fibers are characterized by a dense concentration of fixed nodal intersections, which aids the maintenance of the integrity of the fabric. This enables the stresses in the bulk of the material to be transferred more effectively because of the well-defined load paths from one area to another [35]. According to Rudo and

Karbhari, the favorable performance of the polyethylene fibers is due to the unique properties of the fiber, the chemical bonding between the fiber and the resin, and the effect of the leno weave with regard to crack resistance and deflection, as well as the resistance to shifting within the matrix [34]. In clinical practice, Ribbond was first used to splint periodontally weakened teeth [36]. In 2006, Belli et al. recognized the crack propagation inhibiting effect of the material, which is made by a special weaving process (leno weave), and started to use it as an internal element in restorations [17]. These features make the Ribbond fibers suitable for reinforcing direct composite bridges, splinting periodontally weakened teeth, and by placing them at the bottom or on the walls of cavities, its soft material and special weave can stop the propagation of cracks caused by polymerization stress.

3.3.2. Glass fiber ribbons

In addition to the use of UHMWPF, unidirectional and woven glass fiber reinforcing materials have also been introduced. One of the first of these is FiberSplint. Later on, Dentapreg and StickTech reinforcement fibers were introduced, which are available in unidirectional and woven types. Dentapreg fibers are based on the S2 glass system embedded in Bis-GMA and triethylene glycol dimethacrylate (TEGDMA) in a cross-linked polymer matrix. They contain 8300 unidirectional fibers coated with plasma-enhanced chemical vapor deposition [37]. In particular, according to the authors' opinion, polyethylene fibers are much easier to use for periodontal splinting due to their easier adaptability. Their disadvantage is that when exposed to the oral cavity, the material deteriorates faster than glass fibers.

3.3.3. Carbon and glass fiber posts

In 1989, Duret described the first application of intracanal fiber-reinforced pins [38]. The material of choice at that time was carbon, offering a real alternative to metal posts. Its mechanical properties, which were much more similar to those of dentin compared to those of metal, made it an attractive alternative for clinicians. However, its aesthetic appearance, as carbon posts are black, limited its use with the growing demand for aesthetic dentistry. To overcome the above-mentioned problems, quartz and glass fibers began to be used, which were white or translucent and therefore more aesthetically pleasing. In the case of these posts, the matrix incorporating the fibers is typically based on epoxy resin. The modern matrix can be bonded well with a thorough knowledge of the material, thus creating an encouraging opportunity for more effective restoration in RCT teeth.

Fiber-reinforced composite (FRC) posts have been used to restore RCT teeth in the past decades to increase the retention of the core build-up material [39]. It should be noted that the type of tooth and the amount of remaining tooth structure are significant modifiers regarding the survival of FRC posts [40,41]. Furthermore, the correct selection and proper application of the adhesive cement are also important factors when considering the success of these posts. Traditional two-component mixed or dual-cure adhesive systems are favored over light-curing cements because of the limited penetration of light [42]. A further concern is the incompatibility of dual or self-cure systems and the adhesive materials used. It should be noted that the results of studies investigating the possible tooth-strengthening effect of conventional FRC posts have been contradictory throughout the years. Several studies reported that the use of FRC posts increased the fracture resistance of RCT premolars [43,44]. In contrast, other researchers suggested that the use of FRC posts did not increase the fracture resistance of the restored teeth, and even reported the possible weakening of the root due to the post space preparation [45,46].

3.3.4. Short glass fibers

The incorporation of fibers into dental resin composites has been studied extensively and has shown superior mechanical performance compared to non-fiber-containing resin composite restorative materials [47]. In 2013, a short fiber-reinforced composite (SFC) (EverX Posterior, GC Europe, Leuven) was introduced to the market with the goal not only to change restorative indications of large class II posterior cavities towards direct restorations but also to mimic the stress-absorbing properties of the dentino-enamel junction. Bijelic-Donova et al. showed that SFC had a significantly higher fracture toughness (2.4 MPa m1/2) and fatigue limit than conventional particulate filled composite resins (range: 0.9–1.1 MPa m1/2) [48]. With its high fracture toughness and other unique features, SFC can actually function as a stress-absorbing layer within the restoration [23,49]. Furthermore, as SFC is quite transparent and short fibers can scatter the light, SFC can and should be used as a bulk-fill material with a curing depth up to 5 mm [50–52]. However, due to its high viscosity, internal adaptation and void formation remain potential challenges. In 2019, the flowable version of SFC was introduced with the promise of easy adaptability in both large cavities and limited spaces (such as root canals). So far, flowable SFC has yielded remarkably favorable results when applied either alone in the root canal (Bioblock technique) [53] or as a luting material for post luting [54].

3.4. Applications of fiber-reinforced materials

Fiber reinforcement can be used in several ways in connection with direct restorative materials: The first type of application aimed to reduce the internal stresses caused by polymerization shrinkage of the later composite filling, redistributing the generated stresses by using fiber reinforcement as a liner [55]. Secondly, fiber-reinforced materials were incorporated into the restorations as internal structural elements. By placing them in the direction of the tensional forces developed within the restoration, the stability of the fillings could be significantly improved [17,56]. The third use is a novelty of the last decade, namely the usage of fiber-reinforced materials as fillers in dental composites [57].

3.4.1. Lining with fibers

In 2005, Belli et al. published a paper describing the use of ultra-high molecular weight polyethylene fibers (Ribbond) placed at the bottom of MOD cavities, subsequently restored with composite fillings [55]. In this study, the Ribbond fibers significantly increased the fracture resistance of the tested teeth due to stress redistribution caused by polymerization shrinkage [55]. However, the results also showed that the load-bearing capacity of teeth strengthened in this way does not approach that of intact teeth. This made it clear that further research is needed to develop fracture resistance enhancement methods that perform well in clinical practice.

3.4.2. As a structural element

In 2006, Belli et al. investigated the stiffness of sub-occlusally placed polyethylene fibers in addition to the previously used sub-lining fiber placement to strengthen teeth prepared by root canal treatment and MOD cavitation to achieve the above-mentioned goals [17]. According to their theory, the bucco-lingually positioned fiber can successfully hold together the deflecting sidewalls of the MOD cavity in compression during occlusal loading on the tooth. As expected, the restored teeth exhibited higher fracture resistance compared to both unreinforced and lining-type reinforcement [17]. In 2009, Oskoee et al. [56] confirmed the findings of Belli et al. [17]. In their publication, fiber reinforcement was placed as a lining, in the middle of the cavity, and sub-occlusally. As a result of their study, occlusal fiber placement gave the highest fracture resistance among the different fiber positions within the restoration [56]. In the study by Akman and colleagues, fibers were inserted not only as liners and transversely, but also circumferentially, i.e., in the cavity in a ring-like manner from the inside [35]. In contrast to

Belli et al., they found that the insertion of fibers, although reducing the deflection of the cusps, did not change their resistance to fracture [35]. Sáry et al. compared all possible positions of Ribbond as a structural element in deep MOD cavities restored with direct fiber-reinforced restorations [31]. In this study, Ribbond was able to improve the fracture resistance of deep MOD restorations compared to composite fillings without fiber reinforcement. Interestingly, one particular application method stood out among the tested ones, namely the transcoronal fixation, developed by the author of this thesis. In this technique, on both the buccal and lingual walls of the deep MOD cavity, an artificial hole with a width of approximately 2–3 mm is prepared on the occlusal third of the wall with a diamond micropreparation bur.

Figure 1: *MOD cavity with the prepared holes on the buccal and lingual cavity walls.*

After washing and drying, the cavity receives adhesive treatment. After light-curing, the interproximal walls are built up with composite resin using the centripetal technique [58], thus transforming the MOD cavity into a class I cavity (this step could also be done after the application of the internal fiber splinting, the operator can decide, in this case it was performed later to aid visualisation of the proposed technique). After this, a piece of 1 mm wide UHMWPF ribbon reinforcement is placed through the previously prepared holes on the buccal and lingual walls into the prepared grooves on the external coronal surfaces, connecting the opposing walls like a tightrope.

Figure 2: *The polyethylene fiber is tried into the cavity to see the exact length needed for the individual cavity dimensions.*

First, the polyethylene fibers are fixed in one groove, light-cured, and covered with composite, and subsequently, the rest of the fibers on the opposing side are tightly positioned with tweezers and fixed to the opposing groove by light curing and composite coverage.

Figure 3: *The polyethylene fiber is fixec with ponding through the prepared holes.*

This produces a "transcoronal splinting" inside the cavity, inhibiting further movements of the remaining opposing cavity walls.

Figure 4: *Transcoronal fixation of the opposing cavity walls.*

After curing for 40 seconds, the cavity is restored with microhybrid composite using an oblique layering technique.

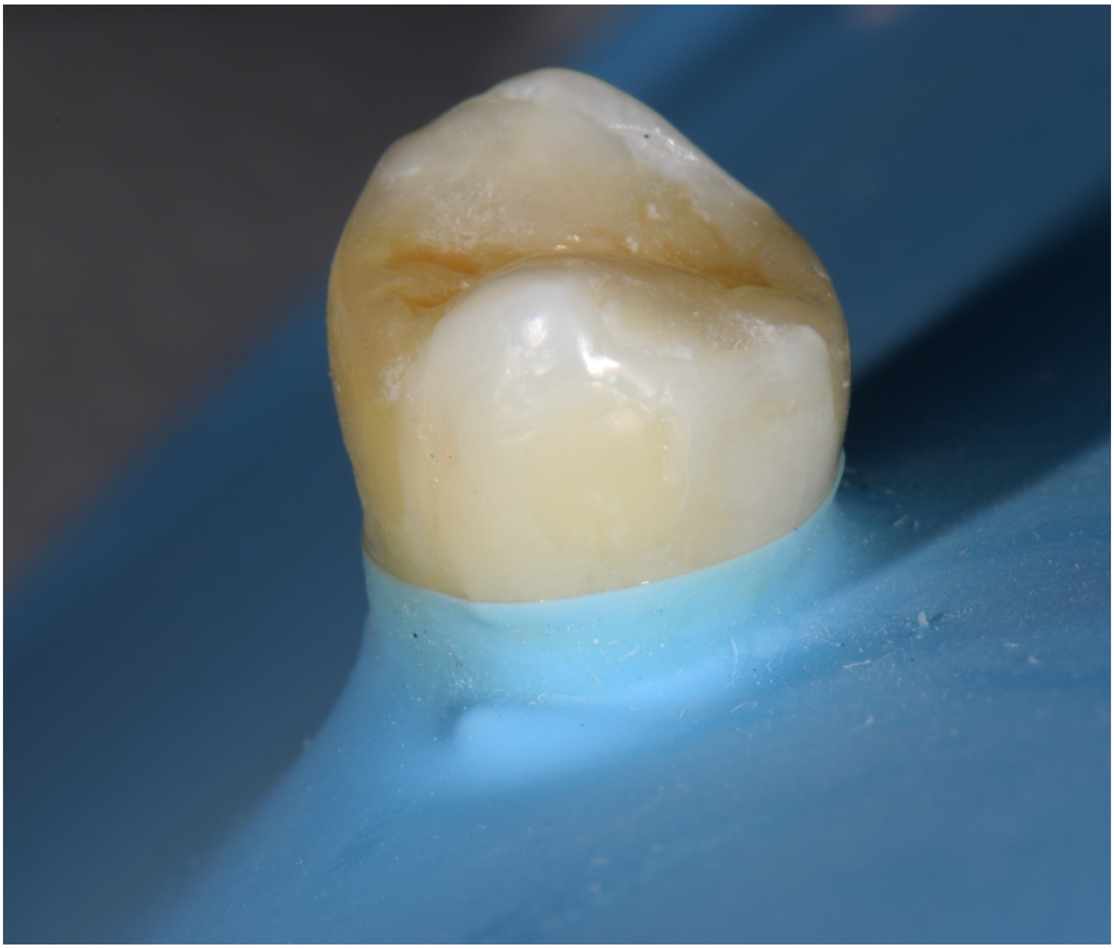

Figure 5: *Finalized direct restoration using composite filling material.*

This method played an important role in the study dealing with restoring deep RCT MOD molar cavities in this thesis. FRC posts can also be used as structural, namely rigidifying elements in deep cavities in the form of transcoronal splinting. The long fibers are placed horizontally, through a small hole prepared on the remaining buccal and lingual walls. Scotti et al. [59], Karzoun et al. [60], and Bromberg et al. [61] all managed to show significantly higher fracture resistance in the case of using horizontal FRC posts compared to composite fillings without FRC posts. One possible explanation for this could be the reduction in cusp deflection caused by anchoring the buccal and lingual walls of the cavity preparation due to the post insertion [61]. Another benefit of using FRC posts for this technique is their low elastic modulus, which is similar to dentin, leading to an even distribution of the load forces [62]. Furthermore, several studies reported that the horizontally splinted groups did not differ significantly from teeth restored with cusp-covered overlays [61,63,64]. This suggests that the horizontal application of long fibers could be an alternative treatment to cusp-coverage indirect restorations. However, more *in vitro* and preferably *in vivo* investigations are necessary to support these results. These favorable results with horizontal splinting contradict the findings of Mergulhao et al. [64], Bahari et al. [65], and Abou-Elnaga et al. [66], who did not find a significant difference when comparing the fracture resistance of MOD molar cavities restored with composite fillings with or without horizontal FRC posts. This could be caused by the extreme weakening of the posterior tooth during an MOD situation and root canal treatment. The depth of the cavity preparation, as well as the presence or absence of the marginal ridges, have been shown to be the most critical factors for generating stress in the cavity walls [67]. As already stated, cuspal deflection increases with increasing cavity dimensions [68]. This is in accordance with the findings of Forster et al. [69].

3.4.3. Fibers as filler

As early as 1993, Monett et al. explained in their study that the viscosity and mechanical strength of composite materials filled with short fibers are strongly influenced by the ratio of fiber length to diameter [70]. Shouha et al. found that when filling flowable composites with short and very short fibers, the aspect ratio of the fiber diameter and length, rather than the filling volume, played a much larger role in flexural strength [71]. The efficacy of fiber reinforcement depends on several factors, including the resins used, the length, orientation and position of the fibers, the aspect ratio, the adhesion of the fibers to the polymer matrix, and the impregnation of the fibers into the resin [50]. The aspect ratio refers to the length compared to the diameter of the fiber (l/d). The aspect ratio is of major importance in the case of advanced fiber-reinforced materials as it affects the tensile strength, flexural modulus, and the reinforcing efficiency of the material [48]. While packable SFC utilizes millimeter-long fibers, the fibers in the flowable SFC are micrometer-long. Although the fibers in the flowable material are smaller, the fiber length is equal to or greater than the critical fiber length, and the aspect ratio is within the range of 30–94 [30], thus providing reinforcement to the materials and possibly to the adhered dental tissues. It is not less noteworthy that flowable SFC contains 25 wt% of fibers, while packable SFC only contains 9 wt%.

3.5. Biomechanical considerations of tooth cavities

Due to our modern dietary habits, insufficient chewing time, and forces developing during mastication, the incidence of tooth decay is high. The greater the hard tissue deficiency, the greater the weakening of the structural stability of the tooth. According to studies by Reeh et al., the decrease in cuspal stiffness in case of MOD cavities, where both marginal ridges are sacrificed, is 63% [72]. Plotino et al. showed that with the loss of one marginal ridge, the structural weakening is 46% [28]. This clearly reflects that dental interventions that sacrifice large amounts of tooth substance significantly weaken teeth. According to several authors, not only the shape of the cavity but also its depth has a major influence on the mechanical resistance of the tooth [67,73,74]. In their article, Forster et al. analyzed in detail the influence of cavity extension, depth, and wall thickness on fracture resistance [69]. They found that wall thickness is a secondary factor to cavity depth in terms of fracture resistance of the cusps [69]. This is in accordance with other studies showing that the larger and deeper the cavity, the greater the cuspal deflection [68,75]. Hood stated that any restoration method that inhibits deflection of the cusps during loading will improve tooth survival [76]. His study managed to show that as the depth of the cavity increases, the force exerted by the tooth wall and the cusps also increases [76]. It can be concluded that any force that causes the cavity walls and consequently the opposing buccal and lingual cusps to move away from each other compromises the structural stability of the tooth, especially in deep cavities.

3.6. The objectives of our research

In our studies we aimed to clarify whether it is possible to strengthen non-RCT and also RCT deep MOD cavities with direct fiber-reinforced restorations. The questions raised were the following:

- Is flowable SFC capable of reinforcing non-RCT deep MOD cavities, irrespective of its application technique?

- Are discontinuous or continuous FRC systems better for reinforcing RCT deep MOD cavities?

The null hypotheses were the following:

(1) The deep non-RCT MOD cavities restored with the flowable SFC would show similar mechanical resistance to teeth restored with conventional composite filling.

(2) The fracture patterns in deep non-RCT MOD cavities would not depend on the applied restorative technique.

(3) The tested direct restorative options utilizing continuous fibers, with or without cuspal coverage would not differ from the control group in fatigue survival in RCT molar MOD cavities.

(4) The tested direct restorative options utilizing continuous fibers, with or without cuspal coverage would not differ from the control group in fracture pattern in RCT molar MOD cavities.

4. Materials and Methods

The performed in vitro studies were approved by the Regional Human Biomedical Research Ethics Committee at the University of Szeged, Hungary (4029-SZTE) and the study design conformed to the Declaration of Helsinki in all respects.

A total of two hundred and sixty mandibular 3rd molars extracted for periodontal or orthodontic reasons were selected for the investigations. The teeth were placed in 5.25% NaOCl for 5 min immediately upon extraction and then stored in a 0.9% saline solution at room temperature until use. All specimens were used within 2 months of extraction. The soft tissue covering the root surface was removed with hand scalers before use. The inclusion criteria were a visual absence of caries or root cracks and an absence of previous endodontic treatment, posts, crowns, or resorptions.

In the non-RCT molar study, approximately 80% of the specimens fell within the 11–11.5 mm size range (measured at the widest bucco-lingual dimension), and the rest were between 10 and 12 mm. In the RCT molar study this dimension was between 10.0-10.9 mm. Regarding the mesio-distal dimension, the deviation limit was 10% from the group mean. The height of the specimens was between 8.0 and 9.0 mm, as measured from the cemento-enamel junction (CEJ). After distributing the samples according to their dimensions, one hundred teeth were chosen for the non-RCT molar study and one hundred twenty teeth for the RCT molar study.
The teeth were evenly divided into 5 groups (n = 20).

4.1. Cavity preparation and restorative procedures for teeth in the non-RCT molar study

Teeth were evenly divided into 5 groups (n = 20). All teeth received standardized MOD cavity preparation with a depth of 4.5–5 mm and a 2.5 mm wall thickness on both vestibular and oral aspects by the same trained operator, as previously described by Forster et al. [69]. The cavity was rinsed with water and air-dried with an air/water syringe. Then, a Tofflemire (1101C 0.035, KerrHawe, Bioggio, Switzerland) matrix was applied and the enamel was acid-etched selectively with 37% phosphoric acid for 15 s, followed by rinsing with water and air-drying. For the adhesive treatment of the cavity, G-Premio Bond (GC Europe, Leuven, Belgium) was used, as per the manufacturer's instructions. The adhesive was light-cured for 40 s with a D-light Pro photopolymerization unit (GC Europe) in "HP" mode (light intensity: 1000 ± 60 mW/cm2). An approximately 0.5 mm-thin flow composite layer (G-aenial Flo A2, GC Europe) was applied on all walls of the cavity in all groups. This layer was light-cured for 40 s. After applying this flowable layer, highly filled low-viscosity flowable composite (G-aenial Injectable Flow A2, GC Europe) was injected into the approximal cavity margins, and packable composite resin (G-aenial Posterior A2, GC Europe) was placed and packed to the approximal wall of the matrix in one increment, transforming it into a class I according to the centripetal technique. This dual layer was light-cured for 40 s. The cavities were restored as follows (see Figure 6.).

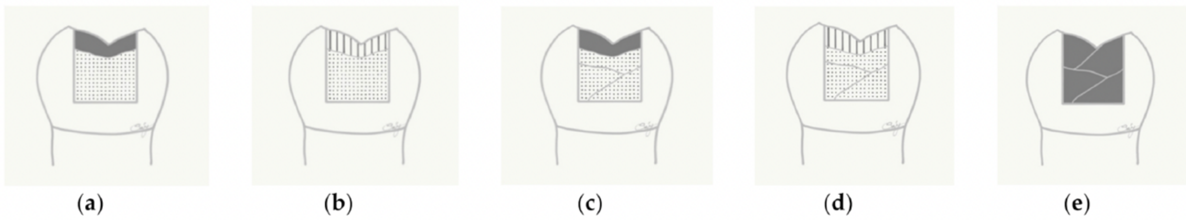

Figure 6: *Schematic figure representing the test groups (from left to right). (a) Group 1: flowable SFC bulk and conventional packable composite; (b) Group 2: flowable SFC bulk and conventional flowable composite; (c) Group 3: flowable SFC layered and conventional packable composite; (d) Group 4: flowable SFC layered and conventional flowable composite; (e) Control Group: conventional packable layered composite.*

Group 1: The cavity was restored with a bulk injection of flowable SFC (EverX Flow Bulk Shade, GC Europe), leaving 2 mm of space for the occlusal layer. The occlusal aspect was restored cusp by cusp in 2 mm-thick oblique increments of packable composite resin (G-aenial Posterior A2, GC Europe). Each increment was light-cured from the occlusal surface for 40 s and, after the removal of the Tofflemire matrix, the mesial and distal sides were also light-cured for 20 s each (total curing time: 80 s).

Group 2: The central part of the cavity was restored in the same way as described in Group 1. The occlusal aspect was restored cusp by cusp in 2 mm-thick oblique increments of highly filled low-viscosity flowable composite (G-aenial Universal Injectable Flow A2, GC Europe). The light curing of each increment and the mesial and distal sides after removing the matrix was performed in the same way as in Group 1.

Group 3: The central part of the cavity was restored with oblique increments (each maximum 2 mm thick) of SFC Flowable (EverX Flow Bulk Shade), leaving 2 mm of space for the occlusal layer. The occlusal aspect was restored cusp by cusp in 2 mm-thick oblique increments of packable composite resin (G-aenial Posterior A2). The light curing of each increment and the mesial and distal sides after removing the matrix was performed in the same way as in Group 1.

Group 4: The central part of the cavity was restored in the same way as described in Group 3. The occlusal aspect was restored cusp by cusp in 2 mm-thick oblique increments of highly filled low-viscosity flowable composite (G-aenial Universal Injectable Flow A2). The light curing of each increment and the mesial and distal sides after removing the matrix was performed in the same way as in Group 1.

Control Group: The central part of the cavity was restored with consecutive 2 mm thick oblique increments of packable composite resin (G-aenial Posterior A2). The light curing of each increment and the mesial and distal sides after removing the matrix was performed in the same way as in Group 1.

The restorations were finished with a fine granular diamond burr (FG 7406-018, Jet Diamonds, Ft. Worth, TX, USA and FG 249-F012, Horico, Berlin, Germany) and aluminum oxide polishers (OneGloss PS Midi, Shofu Dental GmbH, Ratingen, Germany). The restored specimens were stored in physiological saline solution (Isotonic Saline Solution 0.9% B.Braun, Melsungen, Germany) until the start of the experimental procedures.

4.2. Mechanical testing for teeth in the non-RCT molar study

Prior to embedding, the root surface of each tooth was coated with a layer of liquid latex separating material (Rubber-Sep, Kerr, Orange, CA, USA) to simulate the periodontal ligament. The specimens were then embedded in methacrylate resin (Technovit 4004, Heraeus Kulzer, Hanau, Germany) 2 mm from the CEJ. This was performed to simulate the bone level. Mechanical testing was carried out in two phases. In the first phase, all restored specimens were submitted to an accelerated fatigue-testing protocol [53,54,77–80] by a hydraulic testing machine (Instron ElektroPlus E3000, Norwood, MA, USA) placed parallel to the long axis of the tooth. This phase served the purpose of simulating normal biting forces. Cyclic isometric loading was applied with a round-shaped metallic tip (6 mm in diameter) to the center of the occlusal surface of the crown in the central pit, between the buccal and oral cusps. A cyclic load was applied at a frequency of 5 Hz, starting with gradually increasing the static loading till 200 N in 5 s, followed by cyclic loading in 200 N steps up to 1000 N, with 5000 cycles per step. The specimens were loaded until fracture occurred or up to 25,000 cycles. The total number of cycles survived was recorded for each specimen for the survival analyses. In the second phase, the surviving specimens underwent static load-to-fracture testing (Lloyd R1000, Lloyd Instruments Ltd., Fareham, UK) at a crosshead speed of 2 mm/min. In this phase, traumatic forces were simulated. A force vs. extension curve was dynamically plotted for each tooth. Fracture threshold—defined as the load at which the tooth–restoration complex exhibited the first fracture, resulting in a peak formation on the extension curve—was recorded in Newtons (N). Finally, each specimen was visually examined to determine the type and location of failure, as well as the direction of the failure. Fractures were classified according to Scotti and co-workers, based on optical microscopic examination, with a two-examiner agreement. A restorable fracture was defined as one above the CEJ, while a non-restorable fracture was defined as one extending below the CEJ [81].

4.3. Statistical analysis for the non-RCT molar study

Statistical analysis was performed in SPSS 23.0 (IBM Corp., Somers, NY, USA). The number of cycles survived was analyzed descriptively for each group and with the Kaplan–Meier method across the groups (with the Breslow test for the pairwise analyses). The frequency of restorable and non-restorable fractures as well as the number of surviving teeth were calculated for each group. For the comparisons between the surviving samples, ANOVA with Tukey's HSD post hoc test was used. The general limit of significance was set at $p < 0.05$.

4.4. Cavity preparation and restorative procedures for teeth in the RCT molar study

Teeth were evenly divided into 6 groups ($n = 20$). Standardized 5-millimeter-deep MOD cavities with a wall thickness of 3 mm were prepared by the same trained operator, according to the method of Forster et al. [69]. After cavity preparation, all specimens were root canal treated. Endodontic treatment was carried out exactly as described in the study of Szabó and colleagues [82]. After the endodontic treatment, the gutta-percha was cut back 2 mm below the orifices, and the access cavity was temporarily filled with Cavit W (3 M ESPE, St. Paul, MN, USA). The teeth were kept in physiological saline solution for 1 week. After this 1-week period, the temporary filling material was removed, and the MOD cavity, including the access cavity, was roughened with a diamond. After removing the temporary filling, the following preliminary modifications were made. In groups restored with cuspal coverage (SFC+CC, PFRC + CC, GFRC + CC Group, please check Table 1. for group labelling) all cusps were reduced by 2 mm. In groups restored with continuous FRC systems (PFRC, PFRC + CC, GFRC, GFRC + CC Group), on both the buccal and the lingual walls, an artificial tunnel of a diameter of approximately 3 mm was prepared in the occlusal third of each wall. For this purpose, a diamond micropreparation bur was used (MP 53, Two Striper, Airbrasive Technology Inc., USA). After covering the orifices and the floor of the pulp chamber with glass-ionomer cement (Equia Forte, GC Europe, Leuven, Belgium), all samples underwent the same adhesive protocol as described in the non-RCT molar study.

In this study the adhesive was light cured for 60 s with an Optilux 501 quartz-tungsten-halogen light-curing unit (Kerr Corp., Orange, CA, USA). The curing tip was always in close contact with the tooth surface (at a distance of not more than 1 to 2 mm). The average power density of the light source was 840 ± 26.8 mW/cm2. This was measured with a digital radiometer (Jetlite light tester, J. Morita USA Inc. Irvine, CA, USA) before the bonding procedure. After the adhesive treatment, the MOD cavity was transformed into class I according to the centripetal technique. In the SFC (control) and SFC+CC groups, the missing interproximal walls were built up with SFC (EverX Flow Dentin Shade, GC Europe,) in two subsequent increments, while in the rest of the groups, the missing interproximal walls were built up with conventional packable composite (G-aenial PA3). Each layer was light cured for 40 s.

From this point on, the cavities were restored as follows (see Figure 7. and Table 1.):

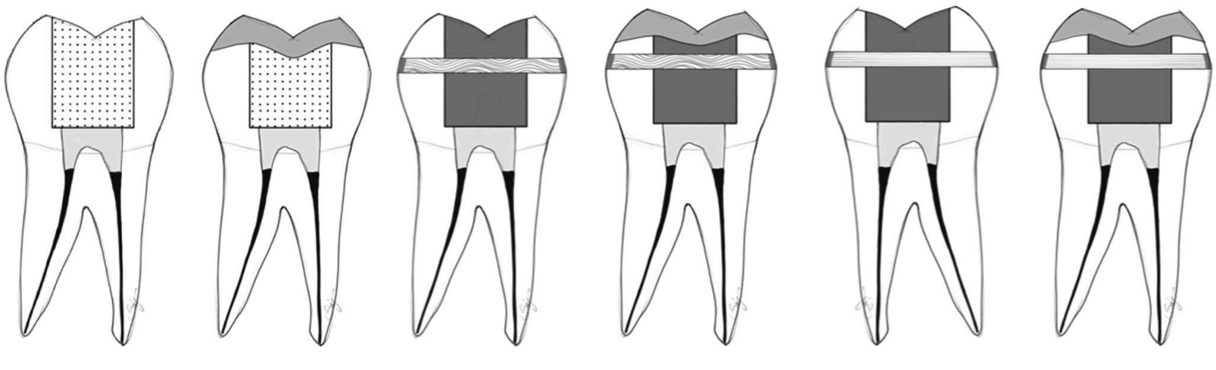

Figure 7: *Schematic figure representing the test groups (from left to right). SFC group (control): flowable SFC without cuspal coverage; SFC+CC group: flowable SFC with cuspal coverage; PFRC group: transcoronal fixation without cuspal coverage; PFRC+CC group: transcoronal fixation with cuspal coverage; GFRC group: horizontal FRC post without cuspal coverage; GFRC+CC group: horizontal FRC post with cuspal coverage*

Group	Reinforcement system	Cuspal coverage (CC)
SFC (control)	Discontinuous SFC	No
SFC+CC	Discontinuous SFC	Yes (conventional direct PFC)
PFRC	Continuous FRC in form of polyethylene ribbon	No
PFRC+CC	Continuous FRC in form of polyethylene ribbon	Yes (conventional direct PFC)
GFRC	Continuous FRC in form of glass FRC post	No
GFRC+CC	Continuous FRC in form of glass FRC post	Yes (conventional direct PFC)

Table 1: *Different fiber reinforcement systems and cuspal coverage restorations (n=20/group)*

SFC group (control group): The cavity was restored applying two 4–5-mm-thick layers of flowable SFC (EverX Flow Bulk Shade), leaving 1.5–2 mm of space for the occlusal layer of flowable SFC (EverX Flow Dentin Shade). The occlusal surface was restored cusp by cusp.

SFC+CC group: The cavity was restored with flowable SFC (EverX Flow Bulk Shade), to the level of the occlusal reduction. The previously reduced cusps were built back with a highly filled flowable composite material (G-aenial Universal Injectable A3) with the aid of a silicon index.

PFRC group: First, a 1-mm-wide piece of UHMWPF ribbon (Ribbond Ultra Orthodontic; Ribbond Inc., Seattle, WA, USA) was placed through the previously prepared tunnels in the buccal and lingual walls, connecting the opposing walls like a tightrope. Second, the polyethylene fibers were fixed in one tunnel, light cured, and covered with composite, and subsequently, the rest of the fibers on the opposing side were tightly positioned with a tweezer and fixed to the opposing groove by light curing and composite coverage. This procedure resulted in a “transcoronal splint” inside the cavity. After curing for 40s, the cavities were restored with packable composite material (G-aenial Posterior PA3) applied with an oblique incremental technique. The material was placed in consecutive 2-mm-thick increments. Each increment was light cured from the occlusal surface for 40 s.

PFRC+CC group: The cavities were restored as described in group 3, to the level of the occlusal reduction. The previously reduced cusps were built back with a highly filled flowable composite material (G-aenial Universal Injectable A3) with the aid of a silicon index.

GFRC group: One piece of FRC post (FibreKleer, Petron, Orange, CA, USA) was inserted through the artificial tunnels of the remaining cavity walls. The posts were treated with hydrofluoric acid (Porcelain Etch, Ultradent, South Jordan, UT, USA) for 30 s and silane (Silane, Ultradent) for 1 min prior to insertion. After the horizontal application of the FRC post, the cavities were restored with packable composite material (G-aenial Posterior PA3) applied in oblique increments. Two-millimeter-thick increments were placed. Each increment was light cured from the occlusal surface for 40 s. Once the cavity was filled, the excess amount of the post was cut off with a diamond bur, and the post was covered with composite material (G-aenial Posterior PA3).

GFRC+CC group: The cavities were restored as described in group 5, to the level of the occlusal reduction. The previously reduced cusps were built back with a highly filled flowable composite material (G-aenial Universal Injectable A3) with the aid of a silicon index.

In all groups, the restorations were finished as described in the non-RCT molar study.

4.5. Mechanical testing for teeth in the RCT molar study

The embedding and the simulation of the periodontal ligaments was carried out the same way as in the non-RCT molar study. The mechanical testing was performed in the form of an accelerated fatigue testing protocol by a hydraulic testing machine (Instron ElectroPuls E3000, Norwood, MA, USA). Loading direction and positioning of the loading tip was the same in both studies. Cyclic loading was applied at a frequency of 5 Hz, starting with gradually increasing the static loading up to 200 N in 5 s, followed by cyclic loading in 200 N steps up to 1600 N, with 5000 cycles per step. The teeth were loaded until fracture occurred or up to 40,000 cycles. The total number of survived cycles was recorded for each tooth for the survival analyses.

Finally, each specimen was visually examined to determine the type and location of failure, as described in the non-RCT molar study.

4.6. Statistical analysis for the RCT molar study

Statistical analysis was performed in SPSS 23.0 (IBM Corp., Somers, NY, USA). The analysis was performed by a non-dentist statistician blinded to the hypotheses of the study and the meaning of the group labels (groups SFC to GFRC-CC). The Kaplan-Meier survival analysis was conducted, followed by pairwise post hoc comparisons between the individual groups (Mantel-Cox). The level of significance was set at $p < 0.05$. The frequency of restorable and non-restorable fractures was calculated for each group. The required sample size was calculated in Stata 13.0 (StataCorp LLC, TX, USA) for the log-rank test.

5. Results

Regarding the non-RCT molar study the Kaplan–Meier survival curves are presented in Figure 8.

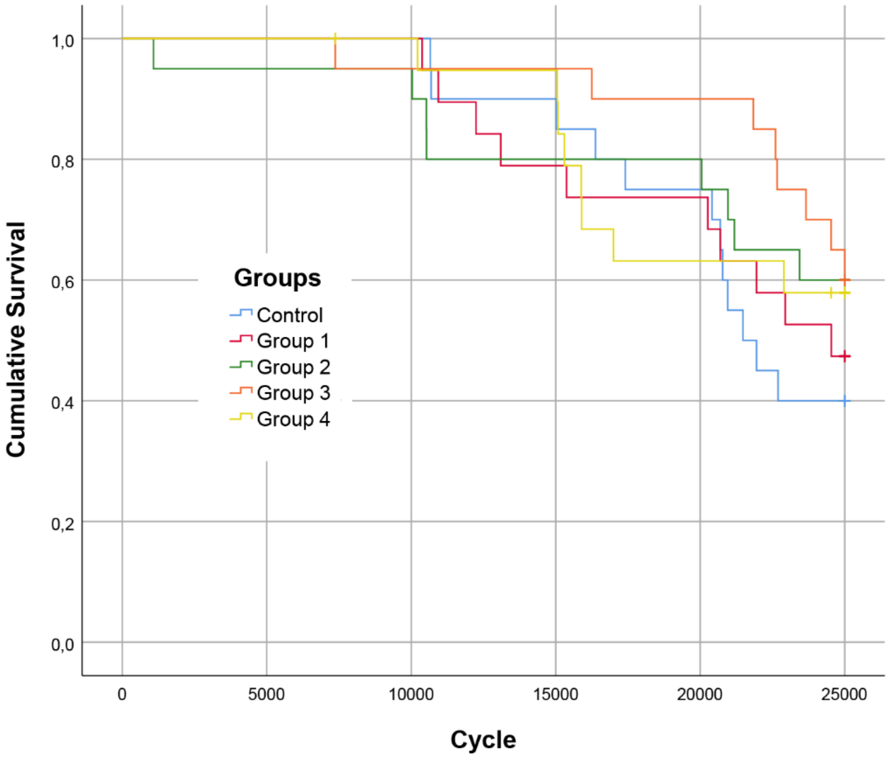

Figure 8: *Fatigue resistance survival curves (Kaplan-Meier survival estimator) for all tested groups.*

	Control		Group 1		Group 2		Group 3		Group 4	
Gr	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.
Control			.077	.781	.610	.435	3.387	.066	.257	.612
Group 1	.077	.781			.183	.669	1.512	.219	.181	.670
Group 2	.610	.435	.183	.669			.303	.582	.006	.937
Group 3	3.387	.066	1.512	.219	.303	.582			.529	.467
Group 4	.257	.612	.181	.670	.006	.937	.529	.467		

Table 2: *p values of pairwise log-rank post-hoc comparisons among tested groups (Kaplan - Meier survival estimator followed by log-rank test for cycles until failure or the end of the fatigue loading).*

	Control	Group 1	Group 2	Group 3	Group 4
No fracture	8	9	12	13	12
	40.0%	47.4%	60.0%	65.0%	60.0%
Non-restorable	8	0	0	3	1
	40.0%	0.0%	0.0%	15.0%	5.0%
Restorable	4	11	8	4	7
	20.0%	52.6%	40.0%	20.0%	35.0%

Table 3: *The distribution of fracture pattern among the tested groups (n=20).*

There was no statistically significant difference in terms of survival between the tested groups. Regarding the fracture pattern, all specimens with restorations utilizing flowable SFC showed a dominantly restorable type of fracture, while the control group presented dominantly non-restorable ones (Table 3.).

Figure 9. shows the average fracture resistance values of the previously surviving specimens under static loading. All groups using flowable SFC showed statistically significantly higher

fracture resistances compared to the control group. There was no significant difference regarding fracture resistance among the fiber-reinforced study groups.

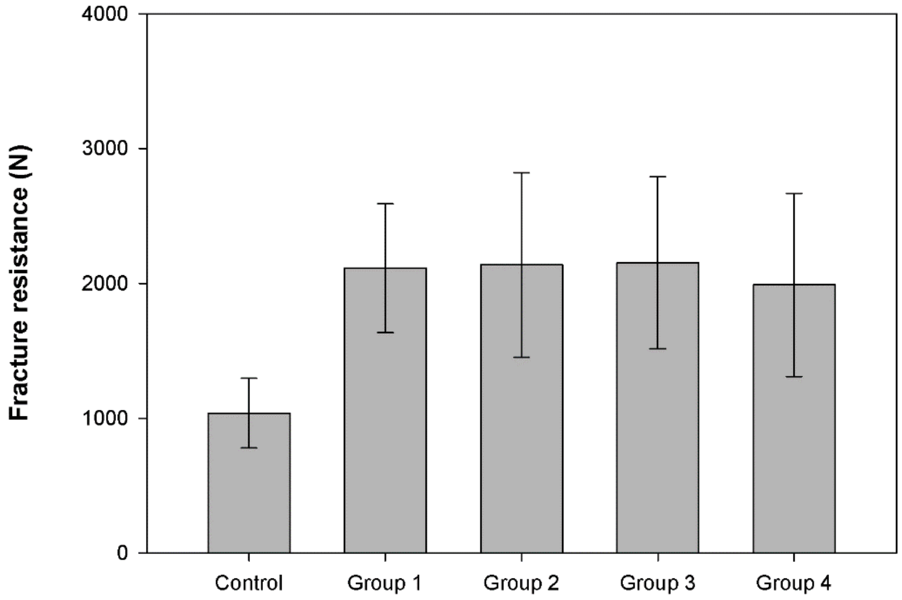

Figure 9: *Fracture resistance mean values (N) and standard deviation of survived test restorations.*

Regarding the RCT-molar study the Kaplan-Meier survival curves are presented in Figure 10. Table 4. shows the descriptive characterization of the survival as the mean and median number of survived cycles for each tested group. In Table 5., the results of the pairwise comparisons are given.

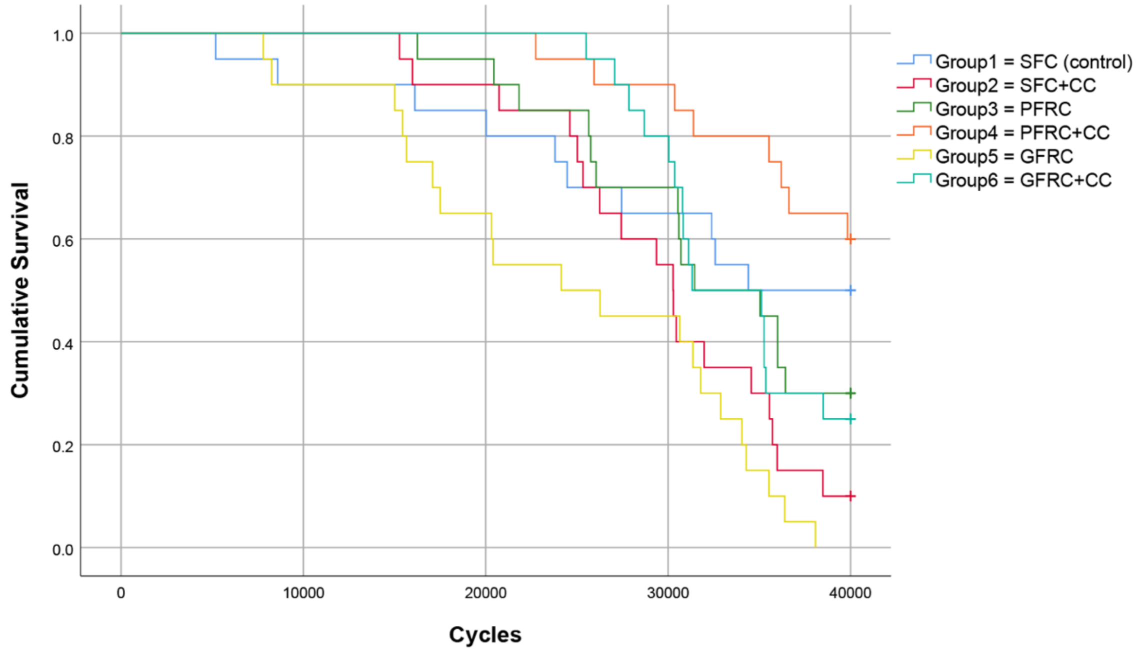

Figure 10: *Fatigue resistance survival curves (Kaplan–Meier survival estimator) for all tested groups.*

Group	Mean	SD	Median	Minimum	Maximum
SFC (control)	31250.20	11337.748	37202.0	5187	40000
SFC+CC	29661.70	7220.843	30278.0	15268	40000
PFRC	32136.65	7435.769	33246.5	16253	40000
PFRC+CC	36930.45	5232.823	40000.0	22740	40000
GFRC	24641.80	9670.161	25201.0	7799	38076
GFRC+CC	33653.65	4895.268	33214.5	25502	40000

Table 4: *Descriptive statistics of survival (cycles).*

	SFC	SFC+CC	PFRC	PFRC+CC	GFRC	GFRC+CC
SFC	-	.037	.408	.317	.001	.353
SFC+CC	.037	-	.103	.000	.118	.129
PFRC	.408	.103	-	.030	.005	.949
PFRC+CC	.317	.000	.030	-	.000	.014
GFRC	.001	.118	.005	.000	-	.006
GFRC+CC	.353	.129	.949	.014	.006	-

Table 5: *Significance matrix from the Mantel-Cox post-hoc pairwise comparisons (p-values).*

The PFRC+CC group was characterized by significantly higher survival compared to all the groups ($p = 0.000$ for SFC+CC group, $p = 0.030$ for PFRC group, $p = 0.000$ for GFRC group, and $p = 0.014$ for GFRC+CC group), except for the control group (SFC, $p = 0.317$). In contrast, the GFRC group showed significantly lower survival compared to all the groups ($p = 0.001$ for SFC group, $p = 0.005$ for PFRC group, $p = 0.000$ for PFRC+CC group, and $p = 0.006$ for GFRC+CC group), except for the SFC+CC group (SFC with coverage, $p = 0.118$). The control group showed statistically higher survival than the SFC+CC group ($p = 0.037$) and GFRC group ($p = 0.001$), but it did not differ from the rest of the groups.

Regarding the fracture patterns in the molar-RCT specimen, all specimens with restorations reinforced by horizontal FRC post (GFRC with and without CC) showed predominantly restorable fractures, while the rest of the groups presented either mostly non-restorable ones (control group and PFRC group) or an equal number of restorable and non-restorable ones (SFC+CC group and PFRC+CC group) (Table 6.).

		SFC (Control)	SFC+CC	PFRC	PFRC+CC	GFRC	GFRC+CC
non-restorable	Count	7	9	8	4	2	2
	% within Group	35%	45%	40%	20%	10%	10%
restorable	Count	3	9	6	4	18	13
	% within Group	15%	45%	30%	20%	90%	65%
did not fail	Count	10	2	6	12	0	5
	% within Group	50%	10%	30%	60%	0%	25%

Table 6: *The distribution of fracture patterns among the tested groups.*

6. Discussion

This in vitro investigation regarding non-RCT molar teeth aimed to compare the possible reinforcing effect of flowable SFC applied either in bulk or in a layered manner compared to conventional composite fillings in deep, endodontically non-treated MOD cavities. It was also assessed whether the consistency of the composite used for covering the SFC material is important in terms of fatigue failure and fracture resistance. First, cyclic loading was applied in the form of an accelerated fatigue test to all specimens. It is known that cycling fatigue loading simulates the clinical situation better than static loading, as it generates cyclic forces similar to normal masticatory forces. This protocol (accelerated fatigue) was introduced as a rational middle ground between the classic load-to-fracture test and the more sophisticated and time-consuming fatigue tests [78]. In the posterior region, forces range from 8 to 880 N during normal mastication [83]; thus, the accelerated fatigue test was only performed up to 1000 N. Some studies have used higher loads with this test [84,85], but in this specific situation it would have been unrealistic for the said reason. We thus consider the applied method to be a definite strength of this study. Regarding survival, while the control group clearly showed the lowest survival rates, there were no statistically significant differences among the tested groups. Therefore, the second null hypothesis was rejected. To the best of our knowledge, direct restorations utilizing flowable SFC in teeth have not been tested by cyclic loading so far. The results suggest that neither the use of flowable SFC nor the consistency (flowable or packable) of the occlusal conventional composite coverage could significantly improve the fatigue resistance of direct MOD restorations compared to conventional composite fillings. Thus, the first null hypothesis was partly accepted (please see later). However, SFC seems to shift the fracture pattern toward predominantly restorable. This latter finding is in line with the results of other studies in that it shows that the use of SFC, should fracture occur, allows a more favorable fracture profile than composite without fiber reinforcement [22,31,57,86,87]. This is due to the obvious difference in fracture toughness between reinforced and non-reinforced composites.

Previous studies have shown that fiber-reinforced composites have the ability to re-direct and stop crack propagation within the materials [22,30,54]. In fact, the presence of such energy-absorbing and stress-distributing fibers allows crack propagation to be deflected away from the bulk of the material and toward the peripheries (Figure 11A). On the other side, the brittleness of the conventional composites generated the bulk fracture which propagated easily through the whole thickness of the restoration (Figure 11B).

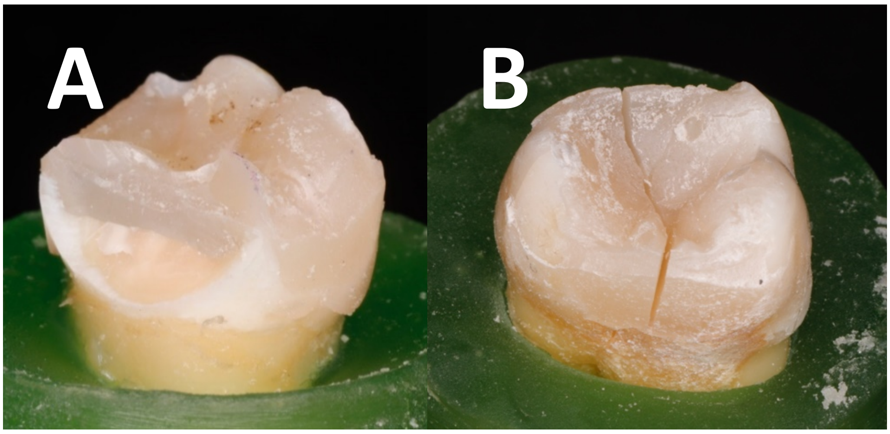

Figure 11: *Examples of failed specimen. Picture A shows a favorable repairable fracture (in case of SFC), while Picture B shown an unfavorable, irrepairable fracture going through the direct restoration (lack of SFC).*

Thus, the basic characteristics of the material do not significantly enhance the resistance of fatigue crack propagation. Upon the completion of the accelerated fatigue test, a load-to-fracture test was performed on the surviving specimens. The load-to-fracture test, given the high applied load, is similar to modelling traumatic injury to the restoration–tooth complex (e.g., biting accidentally on a seed, stone, etc.). In the static load-to-fracture test, all bi-structured restorations (SFC + conventional composite coverage), irrespective of the application mode of flowable SFC or the consistency of the occlusal composite material, showed significantly higher fracture toughness in comparison to the control group (conventional composite filling). Thus, the first null hypothesis was only partly accepted. This is in accordance with the findings of Garoushi et al., where flowable SFC covered with a minimal amount of composite showed significantly higher fracture resistance compared to conventional composite filling [88]. However, in that study the cavities were larger than those seen in this study. Furthermore, the current findings contradict the findings of Sáry et al. [31] and also our previous findings [57], where there was no statistically significant difference in terms of fracture resistance between an MOD cavity bulk-filled with SFC compared to a layered composite filling. It must be mentioned, though, that in neither of the mentioned studies was the same flowable SFC used as in this one. This contrast could be due to the unique structure and high fiber content of the flowable SFC material. While packable SFC utilizes millimeter long fibers, those in the flowable SFC are micrometer-long. Even with the smaller fibers, their aspect ratio, which refers to the length compared to the diameter of the fiber (l/d), is within the range of 30 [30]. Therefore, it holds the promise of reinforcement to the materials and also to the adhered dental tissues. Another major difference between the packable and flowable SFC is that the flowable one contains 25 wt% of fibers, while in the packable variant this ratio is only 9 wt%. So far, flowable SFC has yielded promising results when utilized in direct restorations in different clinical situations [53,54,88]. Our results show the superiority of bi-structured direct restorations over conventional composite fillings when tested with extremely high forces. This is in line with other studies [86,88]. Our results also suggest that the consistency (highly filled flowable or conventional packable) of the occlusally placed composite is not a significant factor in the fracture resistance of a direct restoration utilizing flowable SFC. This could be due to the improved mechanical properties of the flowable composite resin we used. In fact, both conventional composite resins have similar fracture toughness values of 1.1 MPa m1/2, which is much lower than the values of SFC 2.6 MPam1/2 [22]. G-aenial Universal Injectable (GC Europe) contains 69 wt% filler, making it suitable for direct restorations without any further coverage. Our results are in line with the clinical findings of Lawson et al., but it must be mentioned that they did not use bi-structured restorations for their study [89]. A known limitation of our study is that only one specific material's application (i.e., flowable SFC) was investigated and compared with the most frequently used type of direct restoration—namely, direct composite filling. In future, other composite materials should be addressed in the same study setup. The in vitro investigation regarding the RCT molar specimen aimed to compare possible direct restorative techniques utilizing discontinuous/continuous FRC systems to reinforce RCT molar teeth with MOD cavities. Using continuous fibers in the form of an FRC post for restoring RCT molar teeth has been studied by many [81,90]. Most of the studies came to the conclusion that FRC posts in RCT molar teeth do not reinforce the restoration but might shift the eventual fractures toward repairable [81,90]. However, it must be emphasized that in most of these studies, the FRC post was placed in the root canal, and the primary aim of placement was not to stabilize the remaining cavity walls [81,90]. In the present study, in the GFRC and GFRC+CC groups, an FRC post was used in a horizontal way aiming to stabilize the opposing cavity walls. The GFRC group (without cuspal coverage) showed significantly lower survival compared to all other groups including the control group ($p < 0.005$), except for the SFC with cuspal coverage group (SFC+CC). Thus, the third null hypothesis was rejected. This is contrary to the findings of Karzoun et al., which could be explained by the fact that they used premolar teeth in their study [60]. The reason behind the current inferior results of horizontal splinting with an FRC post within this study could be manifold. One of the reasons could be the poor adhesion between the FRC post and the composite material of the coronal filling. All FRC posts consist of two main components: the reinforcing fibers and the polymer matrix. Matrix polymers in FRC posts are generally epoxy resins or other thermosetting polymers with a high degree of conversion and a highly cross-linked structure [91]. These features make it very difficult to bond the conventional FRC posts to any composite resin or to the tooth structure [92]. If the bonding is poor between the post and the restorative material, stress transfer will not be possible between them under loading conditions, leading to separation and cracking. Another possible problem is that in the case of horizontal splinting with an FRC post, conventional composite resin is used to restore the coronal cavity [60,61,93]. The two main inherent problems of conventional composite resin filling materials are polymerization shrinkage and related stress, as well as the inadequate fracture toughness as compared to the dentin [22]. Modern composite resin materials are rigid; they do not lack strength, but they do lack fracture toughness [22]. Fracture toughness is a mechanical property that describes the resistance of brittle materials to the catastrophic propagation of flaws under an applied load [30]. This way, it describes damage tolerance and can be considered as a measure of fatigue resistance which predicts structural performance of the examined material [30,31]. It should be emphasized that the lack of toughness is a factor of major importance in extensive direct restorations (e.g., deep vital and RCT MOD cavities), as the volume of the restorative material increases in these cases [74]. Furthermore, as cuspal coverage was not carried out in the GFRC group, the cantilever arm developing on the existing walls was not decreased. This could also account for the inferior survival observed in this group. When direct cuspal coverage was performed together with horizontal splinting (GFRC+CC), the survival significantly increased ($p = 0.006$) compared to the same group without cuspal coverage (GFRC). With cuspal coverage, the height of the remaining walls is reduced, automatically leading to a reduction in the cantilever arm. This might be the reason for the increased survival in GFRC+CC. Furthermore, only the PFRC+CC group (transcoronal fixation with cuspal coverage) outperformed GFRC+CC in terms of survival ($p = 0.014$). Polyethylene fibers placed in different positions have been used to stabilize MOD cavities in RCT molars [31,55]. Among these, transcoronal fixation is the only one where the polyethylene fiber mesh is placed and light cured under tension inside the cavity. This way, it should allow minimal—if any—movement of the existing walls under loading. In this study, transcoronal fixation without cuspal coverage (PFRC group) allowed significantly higher survival compared to the GFRC group (horizontal FRC post without cuspal coverage) ($p = 0.005$). This could be due to the difference in the continuous fibers in these techniques. Polyethylene fibers are characterized by a dense concentration of fixed nodal intersections, which aids the maintenance of the integrity of the fabric. This enables the stresses in the bulk of the material to be transferred more effectively due to the well-defined load paths from one area to another [21]. According to Rudo and Karbhari, the unique properties of the polyethylene fiber, the chemical bonding between the fiber and the resin, and the effect of the leno weaving on crack resistance and deflection lead to the favorable performance of the fiber mesh [34]. The specimens restored with transcoronal fixation without cuspal coverage (PFRC group) did not differ significantly from the control group (SFC without cuspal coverage). This is contrary to the findings of Sáry et al. [31]. However, in their study, they tested deep MOD cavities without root canal treatment, and this major difference could easily explain the different outcomes. When cuspal coverage was performed together with transcoronal fixation (PFRC+CC), the survival increased compared to the PFRC group, so the difference exceeded the level of statistical significance ($p = 0.030$). This can be put down to the decrease in the cantilever arm in these cavities. Furthermore, the PFRC+CC group outperformed all other groups in survival, except for the control group (SFC without cuspal coverage). It should be pointed out that both with cuspal coverage (PFRC+CC group compared to GFRC+CC group) and without cuspal coverage (PFRC group compared to GFRC group) horizontally applied polyethylene fibers significantly outperformed FRC posts in terms of survival ($p = 0.014$ and $p = 0.005$, respectively). Thus, the current results suggest that polyethylene fibers are more suitable for horizontal use to reinforce RCT molars with MOD cavities than the FRC post fibers. Unfortunately, no other studies are available on this exact comparison, so these findings cannot be contrasted with the literature at the moment. In this study, specimens restored with flowable SFC without cuspal coverage were used as the control group. SFC has been recommended to be used in high stress-bearing areas to substitute the missing dentine in both direct and indirect restorations [22,31,88]. The performance of fiber reinforcement is determined by many factors, namely the used resins, the length, position, and orientation of the fibers, the fibers' aspect ratio, the adhesion between the polymer matrix and the fibers, and the fibers' impregnation into the resin [50]. While the packable version of SFC contains millimeter-long fibers, the flowable one contains micrometer-long ones [30]. While the aspect ratio is still ideal in the case of the flowable version (between 30 and 94) [30], the smaller size of the fibers allows a greater volume fraction to be used during the manufacturing of the material compared to the packable version. Due to these features, flowable SFC has a little higher fracture toughness than the packable version and has shown also slightly better results when restoring major dentinal defects compared to the packable one [53]. We would like to stress that in the case of the control group (SFC without cuspal coverage) and group 2 (SFC with cuspal coverage), not just the missing dentin but also the missing interproximal walls were restored with flowable SFC. This has been a trend in previous studies carried out by this research group, and the aim of this is to provide a tougher solution for the re-built interproximal wall compared to a conventional composite one [23,54]. Furthermore, in the case of the control group, in order to maximize the amount of fibers, the occlusal surface was also re-built from flowable SFC without any composite coverage. This is in line with other studies [86,88]. It is important to note that with the technique used in the control group, it was possible to reinforce the dental structure to the same extent as by using continuous fibers, and this technique allowed even significantly higher survival in comparison with the GFRC group ($p = 0.001$). Interestingly, the teeth of the control group were also characterized by significantly higher survival than the ones where the SFC was covered with composite during the cuspal coverage process (SFC+CC group, $p = 0.037$). This is in line with the findings of Lassila et al., who showed that restorations made purely from flowable SFC showed significantly higher fracture resistance compared to covered SFC restorations [86]. As stated by Garoushi and colleagues, if the SFC core is considered as a crack stopper, the distance from the surface of the stress initiation point to the SFC core is of importance [88]. So far, it seems that flowable SFC might not benefit from composite coverage from a mechanical (and survival) point of view. In terms of the fracture patterns of the failed specimens, restorations for which a horizontal FRC post was used (GFRC and GFRC+CC groups) showed predominantly restorable fractures (Table 6.). The current findings are in agreement with the findings of Karzoun et al. [60] but contradict the findings of Bromberg et al. [61]. The rest of the groups presented either mostly non-restorable fractures (control group and PFRC group) or an equal number of restorable and non-restorable ones (SFC+CC and PFRC+CC). Therefore, the fourth null hypothesis was also rejected. Findings on the fracture patterns associated with transcoronal fixation without cuspal coverage (PFRC+CC) are in agreement with the findings of Sáry et al. [31]. It should be noted that in the two highest-survival groups, the non-failure ratio was also high: ten teeth (50%) of the control group (SFC) and twelve teeth (60%) of the PFRC+CC group (transcoronal fixation with cuspal coverage) survived all cycles of the accelerated fatigue test. As in all the recent studies carried out by this research group, cyclic loading was used instead of static load-to-fracture testing in this study too [23,54]. When testing tooth-restoration units, cycling loading is more suitable to model the target (clinical) conditions than static testing because it generates repetitive forces, which is closer to the conditions of chewing [23]. Also, as pointed out by Le Bell-Rönnlöf, fatigue more often leads to root fracture than static forces [94]. Accelerated fatigue was introduced as a rational middle ground between the load-to-fracture test and other, more sophisticated and time consuming fatigue tests, and it has been used in several studies since its introduction [77,95,96]. Furthermore, the dynamic loading tests were not carried out in a fluid chamber, which would have modelled the intraoral environment more closely. This is a moderate limitation to this study. A minor limitation to this study is that there is no information regarding the age of the gathered teeth, which could influence the mechanical parameters of both coronal and radicular dentine of the samples.

7. Conclusion and new findigs identified based on the results of the research

Within the limitations of these ex vivo studies, it can be concluded that:

- deep non-RCT MOD cavities can be restored with both fiber-reinforced and non-fiber-reinforced direct restorations as long as the biting forces are in the normal range.
- In the case of extreme forces, direct restorations utilizing flowable SFC to restore deep non-RCT MOD cavities perform better compared to conventional composite fillings. The use of flowable SFC allows a favorable fracture profile.
- When directly restoring RCT MOD molar cavities by transcoronal fixation with polyethylene fibers, direct cuspal coverage is recommended in order to increase survival of the restored tooth.
- When directly restoring RCT MOD molar cavities by horizontal splinting with an FRC post, direct cuspal coverage is recommended in order to increase survival of the restored tooth.
- When directly restoring RCT MOD molar cavities with flowable SFC, it is advised to maximize the amount of fibers without cuspal coverage.

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