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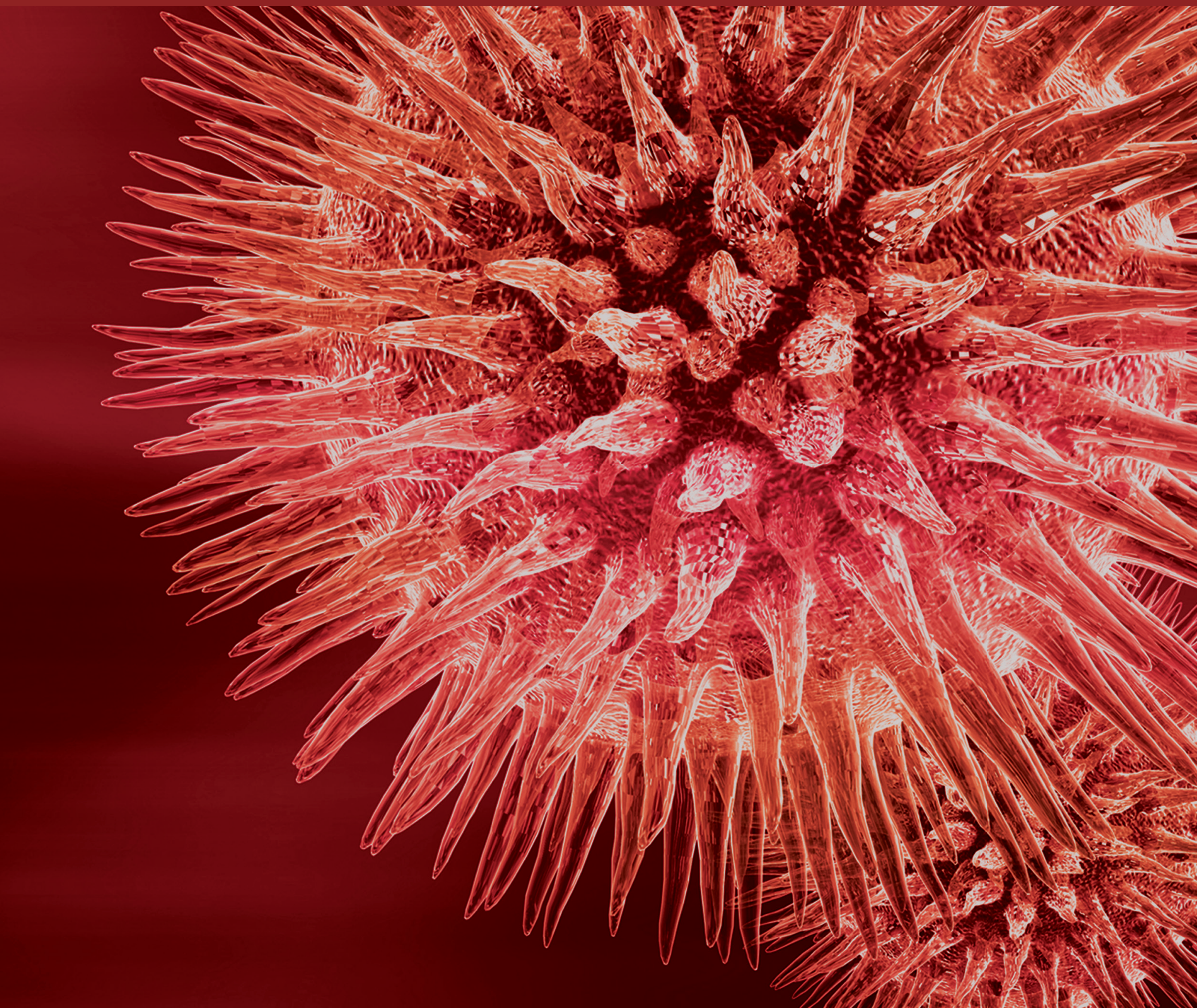
Fiber-Reinforced Composites for Dental Applications

Special Issue Editor in Chief: Andrea Scribante
Guest Editors: Pekka Vallittu and Mutlu Özcan



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Editorial

Fiber-Reinforced Composites for Dental Applications

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Fiber-reinforced composites (FRCs) are composite materials with three different components: the matrix (continuous phase), the fibers (dispersed phase), and the zone in between (interphase). FRC materials present high stiffness and strength per weight when compared with other structural materials along with adequate toughness. FRCs have been used for numerous applications in various engineering and biomedical fields for a long time. The reinforcement of dental resins with either short or long fibers on the other hand has been described in literature for more than 40 years [1]. FRCs based on carbon, polyaramid, polyethylene, and glass have been largely studied and among all, glass fibers of various compositions are more commonly applied as restorative and prosthetic materials [2, 3].

FRCs have been intensively investigated with a particular emphasis on mechanical properties such as fracture toughness, compressive strength, load-bearing capacity [4], flexural strength [5], fatigue resistance [6], fracture strength [7] or on the effect of layer thickness [8], bacterial adhesion [9], adhesion of fibers for various dental applications, such as long fibers [10], nets [11], and posts [12]. From clinical perspective, FRCs have been investigated for different clinical applications in prosthodontics, such as replacement of missing teeth by resin-bonded adhesive fixed dental prostheses of various kinds [13], reinforcement elements of dentures or pontics [14], and direct construction of posts and cores [15]. In other disciplines of dentistry, such as orthodontics FRCs have been suggested as active and passive orthodontic applications (i.e., anchorage or en-masse movement units) and postorthodontic tooth retention [16] and in periodontology for splinting mobile teeth in an attempt to prolong tooth extraction [17].

With the introduction of new technologies, nanofillers, resin matrices, fibers, adhesion protocols, and application techniques, the design principles of FRC devices need further understanding which open new fields of research both preclinically and clinically [18]. On the basis of these considerations, BioMed Research International prepared the present special issue in an attempt to explore these new variables related to FRCs.

Guest editors do hope that this special issue would be interesting for the readers of the journal and wish that the present work could help both clinicians and researchers to understand FRC applications and properties.

Conflicts of Interest

Authors Andrea Scribante and Mutlu Özcan declare that there are no conflicts of interest regarding the publication of this paper. Author Pekka K. Vallittu consults Stick Tech-GC in RD and training.

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Andrea Scribante
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Review Article

Travel beyond Clinical Uses of Fiber Reinforced Composites (FRCs) in Dentistry: A Review of Past Employments, Present Applications, and Future Perspectives

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The reinforcement of resins with short or long fibers has multiple applications in various engineering and biomedical fields. The use of fiber reinforced composites (FRCs) in dentistry has been described in the literature from more than 40 years. In vitro studies evaluated mechanical properties such as flexural strength, fatigue resistance, fracture strength, layer thickness, bacterial adhesion, bonding characteristics with long fibers, woven fibers, and FRC posts. Also, multiple clinical applications such as replacement of missing teeth by resin-bonded adhesive fixed dental prostheses of various kinds, reinforcement elements of dentures or pontics, and direct construction of posts and cores have been investigated. In orthodontics, FRCs have been used also for active and passive orthodontic applications, such as anchorage units, en-masse movement units, and postorthodontic tooth retention. FRCs have been extensively tested in the literature, but today the advances in new technologies involving the introduction of nanofillers or new fibers along with understanding the design principles of FRC devices open new fields of research for these materials both in vitro and in vivo. The present review describes past and present applications of FRCs and introduces some future perspectives on the use of these materials.

1. Introduction

Fiber-reinforced composites (FRCs) have been studied for biomedical applications for over 40 years [1] and were specifically developed in dental field over 25 years ago [2]. FRCs are composite materials with three different components: the matrix (continuous phase), the fibers (dispersed phase), and the interphase region (interphase). In general, the matrix phase is composed of polymerizable monomers that convert from a fluid to a highly crosslinked polymer upon exposure to visible light. Alternatively, linear polymers such as poly(methyl methacrylate) can be utilized in thermoplasticization process or in monomeric form [3, 4]. With cross-linkable resin systems, the light exposure catalyzes the formation of radicals that induce polymerization. The fibers are added primarily because of high stiffness/weight (specific modulus) and strength/weight (specific strength) when compared with other structural materials [5]. Essentially, fibers act as the reinforcing phases when a load is applied to the composite.

The incorporation of fibers into the organic matrix provides material-specific characteristics. Fiber bundles can

Table 1: Main clinical applications of fiber reinforced composites in dentistry.

Dentistry field	Clinical use
Prosthodontics	Provisional or definitive fixed dental prostheses, veneers, direct or indirect pontics, and repair of removable devices
Endodontics	Prefabricated or customized root canal anchoring systems
Conservative dentistry	Direct and indirect fillings, inlays, and overlays
Orthodontics	Retention splints, space maintainers, active "en-masse" units, metal-free brackets, and orthodontic wires
Periodontology	Periodontal splints and posttraumatic splints
Paediatric dentistry	Crowns in primary molars, splints, space maintainers, and direct fillings

be discontinuous or continuous, with randomly directed or directional fibers. The strongest FRC devices are typically made of continuous unidirectional fibers [6]. Fibers can be made of different materials, such as carbon, aramid, polyethylene, or glass. Glass fibers vary according to their composition and are the commonly used fibers in dentistry [7]. This is due to their transparency and beneficial surface chemistry, which allows their adhesion to resin [8]. In fact, adhesion of FRC frameworks has been reported to be reliable for long bundles [9], short bundles [10], and nets [11]. The adhesion of fibers is primarily based on the presence of hydroxyl groups on the surface of glass fibers and the reaction of the groups with resin monomers via silane coupling agents [12, 13].

Some FRCs are hand fabricated, with a polymeric matrix added to the fibers at chairside. This approach might not produce an effective composite, because coupling between the fiber and the polymer might be inadequate and leave voids. On the other hand, partial- or full- preimpregnated FRCs are partially or fully polymerized continuous long fibers, which offer superior properties, because they combine both polymer and fibers [14].

Reinforcement of polymers with long, continuous fibers is an effective mean for engineering materials for many applications. FRCs have been proposed in many fields in dentistry for different purposes, namely, prosthodontics, endodontics, conservative dentistry, orthodontics, periodontology, and paediatric dentistry (Table 1). Previous studies reported FRCs used for veneered fixed dental elements [15], root canal posts [16], filling resin composites [17], periodontal splints [18], orthodontic retainers [19, 20], and orthodontic brackets [21]. In addition, temporary fixed dental prostheses (FDP) [22], reinforcement of removable devices, [23] and repairs of conventional restorations [24] have been reported. Finally, also oral and maxillofacial surgery purposes have been described, as FRCs can be used for implants and bone substitutes for craniofacial bone reconstruction [25].

2. Literature Review and Brief Bibliometric Report

A broad search on Scopus Database has been conducted using the following MeSH terms:

> TITLE-ABS-KEY (fiber AND reinforced AND composite)

The search strategy included an initial analysis of the results in the specific Scopus sections dedicated to the different document types, thus allowing to highlight the kind of document (articles; conference papers; reviews; book chapters; articles in press; book chapters; editorial; erratum; note; and conference review). No exclusion criteria have been applied in order to provide a whole publications count.

Furthermore, the analysis has been refined with the function "search within results," with the following MeSH terms for each discipline considered in the investigation:

> (TITLE-ABS-KEY (fiber AND reinforced AND composite)) AND (dental AND materials)
>
> (TITLE-ABS-KEY (fiber AND reinforced AND composite)) AND (prosthodontics)
>
> (TITLE-ABS-KEY (fiber AND reinforced AND composite)) AND (endodontics)
>
> (TITLE-ABS-KEY (fiber AND reinforced AND composite)) AND (conservative AND dentistry)
>
> (TITLE-ABS-KEY (fiber AND reinforced AND composite)) AND (orthodontics)
>
> (TITLE-ABS-KEY (fiber AND reinforced AND composite)) AND (periodontology)
>
> (TITLE-ABS-KEY (fiber AND reinforced AND composite)) AND (paediatric AND dentistry)

The results of this research revealed that, today in the literature, more than 80.000 documents have been published on FRC materials when Scopus-indexed journals are considered. Based on the published material, it could be stated that the main subjects of investigation were engineering, materials science, physics, and chemistry. In total, 1797 studies have been reported in medical field, of which 1473 were on dental related topics. This remarkable production mainly consists of original articles (1333). Other contributions are conference papers (62), reviews (45), and book chapters (19). The main part of this type of research (1444 documents) was published in sources that require university/hospitals special access or consultation under payment, whereas only 29 documents were free access with an open access route. The research on FRC materials in dentistry seemed to start in 1975 [1] although first reports were already from the 1960s [26, 27]. However, until 1989, only 13 reports have been published on the FRCs (Figure 1). After 1990, the FRC topic started gaining increasing popularity in dental research. Starting from 2004 over 50 documents have been published each year until today, with the highest number of 121 reports in 2009. This is followed by 110 published documents in 2016 and 89 in 2017. During the first 4 months of 2018, already

Table 2: Number of studies published on FRCs in various dental fields such as prosthodontics, endodontics, conservative dentistry, orthodontics, periodontology, and paediatric dentistry. Note that the majority of the studies are multidisciplinary and present cross-matter subjects.

Document type	Number of studies	Materials properties	Prosthod	Endod	Conserv dent	Orthod	Periodontol	Paediatr dent
Articles	1333	1186	841	432	200	182	147	116
Conference papers	62	46	15	4	2	5		2
Reviews	45	40	23	8	6	6	9	7
Book chapters	19	15	10	1	5		4	6
Articles in press	4	2	4	2	1		2	1
Book chapters	3	1				1		
Editorial	2	2	2	1	1			
Erratum	2	1					1	
Note	2		2					
Conference review	1	1					1	
Total	**1473**	**1294**	**897**	**448**	**215**	**194**	**164**	**132**

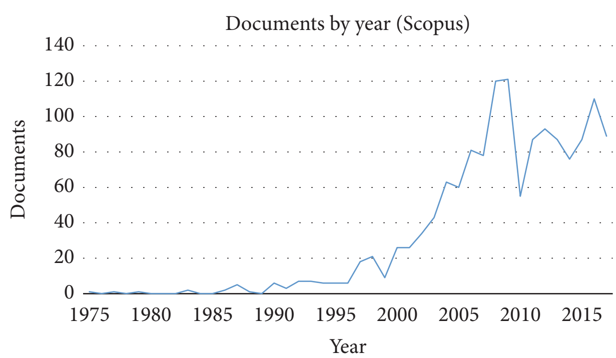

Figure 1: Number of research papers published on fiber reinforced composites by year in the field of dentistry (source: Scopus database).

35 Scopus-indexed manuscripts about the FRC in dentistry have been published, thus confirming that the interest in the FRC topic is still very high. In fact, new technologies allow continuous improvement of materials and techniques, opening new investigation and application fields of FRCs.

Among various dental fields, the main topic of published material was on material properties (1294) where 897 documents were on prosthodontics, 448 on endodontics, 215 on conservative dentistry, 194 on orthodontics, 164 on periodontology, and 132 on paediatric dentistry (Table 2). Many studies have a multidisciplinary approach and present cross-matter subjects. While most of the published research was in vitro, clinical trials were limited to 70 documents.

3. Clinical Applications in Prosthodontics

The main application of FRCs in dentistry is related to provisional or definitive prosthodontics. By using FRCs, FDPs and veneers can be realized in a minimal invasive fashion, utilizing combinations of various kinds of adhering and retentive elements [22]. A resin bonded FRC prosthesis may contain inlays/onlays, surface bonding wings, and crowns. Direct and indirect frameworks can be made also immediately after extraction of tooth [Cramer et al., 2011].

FRC FDPs could be fabricated as surface-retained, inlay-retained, or full coverage crown retained prostheses [28]. The fabrication could be realized directly in the mouth or can include prefabricated pontics, simplifying the fabrication technique and providing more predictable outcomes.

The results of mechanical [29] and adhesion [30] properties of FRC frameworks appear to be encouraging. In addition, FRCs can be used in the repair of existing conventional prosthetic devices. Repairs of veneers of porcelain-fused-to-metal restorations with resin composite veneers can be made using woven glass fiber reinforcement, thus increasing the strength of the repair [31, 32]. In addition, removable devices could be reinforced using FRCs [23]. Finally, FRCs can be used in indirect pontic fabrication, also in combination with CAD/CAM based technologies [33–35].

4. Clinical Applications in Conservative Dentistry

The applications of FRCs in conservative dentistry mainly consist of direct composite restorations. The advantages of the use of FRCs over conventional filling materials are related to their biomimetic properties. In fact, the dental restorations ideally would be as minimally invasive as possible and substitute the missing hard dental tissues resembling mechanical features and properties of natural teeth [36]. Following this principle, a bilayered approach in dental restorations has been proposed in which lost dentin is replaced by though short FRCs and enamel by surface layer of particulate filler composite resin. Several authors have shown that the FRC substructure supports the composite restoration and serves as a crack-prevention layer [37]. In fact, FRCs have been reported to have superior physical properties and fracture toughness compared to unreinforced composites [38]. In addition, polymerization shrinkage and depth of cure of FRCs have been reported to be superior to conventional resin composites [36].

Superior mechanical properties of FRCs could improve their bond durability with universal adhesives, even if there is little evidence comparing the bond durability of FRC to dentin with that of other composite resins [10]. On the other hand, bilayered biomimetic technique is recommended for direct coronal restorations of teeth with large cavities in high stress-bearing areas [24, 39, 40].

5. Clinical Applications in Endodontics

In endodontic clinical practice, the use of FRCs is mainly reported as root canal anchoring system. Studies evaluated both prefabricated and individualized FRC posts [16, 41–43]. Root canal walls restored with individually formed FRC posts displayed higher fracture resistance than those restored with only resin composite [44–46]. Bond strength to flared root canal dentin is promising also for FRC posts both used in combination with self-adhesive and glass ionomer cements and FRCs achieved better performances, even in combination with bulk fill resin composite [47]. However, after aging, mechanical behavior of posts significantly decreased when compared with values at baseline [48]. In addition, special attention should be paid to the bonding of luting cement and core-built-up composite to FRC post itself: only FRC post with interpenetrating polymer network containing polymer matrix can provide reliable bonding to resin luting cements and resin based materials in general [42, 49, 50].

Generally, FRCs present limited radio-opacity due to the low concentration of radio-opaque elements. This shortcoming of E-glass fiber would limit its application in dentistry as sufficient radio opacity is highly desirable for dental materials. The addition of synthesized iodine containing a new methacrylate monomer HMTIB has been tested to increase the radio opacity of FRCs with the results showing that FRCs present higher radiopacity than natural tooth enamel [51].

Finally, in the field of endodontics, FRCs showed excellent integration with other new technologies such as laser applications [52] and CAD/CAM [53, 54].

6. Clinical Applications in Orthodontics

The main use of FRCs in clinical orthodontics is as fixed retention [14]. After orthodontic treatment, the need for maintaining the teeth in correct position is crucial for long term stability of clinical results. These bonded retainers appear to be both relatively independent of patient cooperation and well accepted by patients [55]. Bond strength is reported to be sufficient both on enamel [56] and on dentin [10]. Clinical reliability is also reported to be successful for moderate time [57].

A great advantage of FRC splints over conventional metallic retention is aesthetics. Fibers are barely invisible and do not affect the translucency of teeth [Karaman et al., 2002]. This aspect is important, considering the higher number of adult patients who request an orthodontic therapy. Finally, FRCs are metal-free and are indicated for adult and young patients screened by Nuclear Magnetic Resonance or in subjects allergic to metals. On the other hand, FRC splints are more rigid than conventional metallic splints, thus leading to a higher ankyloses risk of teeth involved. However, the application of FRC with a spot-bonding technique has been proposed, in order to reduce framework rigidity, thus allowing physiologic tooth movement [58].

Clinical success of FRC resins has been reported also for space maintainer purpose [59]. The early loss of deciduous molars is a frequently encountered problem in dentistry and, if untreated, it could evolve in various orthodontic problems. Space maintainers are developed to prevent the loss of the space. FRC space maintainers can be prepared on plaster models of patients and fixed directly to the adjacent teeth [60].

In addition to stabilization uses, in orthodontics, FRCs have been proposed also for active tooth movement. Groups of two or more teeth can be splinted with FRCs and moved "en masse" with sectional mechanics [61].

One other application of FRCs has been proposed as innovative materials for fabrication of brackets [21] and wires [62]; yet only a few research papers have been conducted on the topic.

7. Clinical Applications in Periodontology

Periodontal or posttraumatic FRC splints have been reported in clinical periodontology. Splints are used to stabilize teeth, which have become loose as a result of supporting bone loss as a consequence of periodontal disease. The main advantage of stabilization splints is the reduction of tooth mobility. [18]. FRC periodontal or posttraumatic splints have been reported to have reliable long term stability [63]. In fact, fiber reinforced frameworks showed higher flexural forces when compared with conventional metallic wires [64]. Moreover, FRC splints showed high flexural resistance also when polymerized directly with polymerization lamp without laboratory oven postpolymerization, thus reducing the number of clinical steps and number of appointments for the patients [65]. The common failure types are debonding and fractures. In fact, the splinting with FRC materials of periodontally compromised teeth that have different mobility grade is prone to debonding, with the mobility grade as main causative factor. However, FRC splints can be easily repaired, so in many cases it is not necessary to completely debond the framework with the substitution with a new one [66].

8. Clinical Applications in Paediatric Dentistry

In paediatric dentistry FRCs can be used in almost all the fields as described above: restorations, space maintainers, splints, or other frameworks [67]. The main difference is that the enamel of primary teeth is significantly different compared to permanent enamel. The differences have been mainly detected in composition [68], mechanical characteristics [69], bond strength [70], and clinical performance [71]. However, the FRC devices used in paediatric dentistry showed acceptable clinical performance [71], durability [72], and ease of use [73].

9. Clinical Applications in Oral and Maxillofacial Surgery

The use of FRCs has been recently reported also in oral and maxillofacial surgery. These materials can be applied in oral implantology for bone replacing and bone anchoring implants. The rationale for this application is that, although metal implants have successfully been used for decades, devices made out of metals do not meet all clinical requirements. Metal objects may interfere with some medical imaging systems, while their stiffness also differs from natural bone and may cause stress shielding and overloading of bone. Glass fibers are responsible for the load-bearing capacity of the implant, while the dissolution of bioactive glass particles supports bone bonding and provides antimicrobial properties for the implant [74].

Moreover, FRCs materials can be used in maxillofacial discipline for orbital floor implants [75], cranioplasty implants [25], and craniofacial bone reconstruction [76].

10. Advantages of the Use of FRCs

The main advantages of the use of FRCs over conventional materials are mainly due to their easy manipulation and high mechanical properties especially in dynamic loading conditions. For many FRC applications, no or minimal laboratory work is needed and often frameworks can be prepared at chairside, directly in the oral cavity [77]. The other positive characteristic is the high aesthetics achieved with these materials over metal reinforced alternatives [8]. Finally, the absence of metallic parts in the FRC structure allows their use also in patients allergic to nickel or other metals. Noteworthy is that FRCs can be indicated in patients who need to undergo nuclear magnetic resonance exams [78].

11. Limitations of the Use of FRCs

The main limitations of FRC clinical use are that, even though many in vitro studies have been conducted, research is still lacking regarding long-term clinical performance. The most important weakness of FRC is the interface between the fiber and the organic matrix. Intraoral hydrolysis and degradation weaken this interface and failure can occur. Maybe this might also be a reason for missing long-term results.

Principal failure reasons of FRC devices are fracture and delamination but such events could be easily repaired with resin composite materials [66].

Finally, the higher cost than unreinforced or metallic materials is a factor that has to be considered for a global evaluation of FRC employment.

12. New Features and Future Applications

Future research on FRCs needs to focus on many aspects such as optimization of the design of the frameworks in FRC devices [79], incorporation of bioactive minerals into the reinforced resin composites, and the change to fiber binding matrix from resin base to inorganic type [80].

Another improvement is related to nanotechnology, with the production of functional structures in the range of 0.1-100 nm by various physical or chemical methods. Dental nanocomposites provided a cosmetically acceptable result with excellent mechanical properties [19, 20]. The main point involved with this new trend is the addition of nanofillers particles to resin-based dental materials [81]. The utilization of continuous [82] and discontinuous [83] nanofillers has been proposed in conjunction with FRCs.

FRC utilization has been proposed also in combination with Computer-Aided-Design/Computer-Aided-Machining (CAD/CAM) technologies. The interaction between the two technologies seems to be promising based on limited information [35].

One other field where FRCs are starting to be utilized is implantology. Implant applications could benefit from certain biomechanical properties of FRCs, and the possibility of incorporating additional bioactive components into the implant structure may open new research fields [74].

FRCs have been suggested for tissue engineering for orthopaedic scaffolds [80]. As biocompatibility results are promising, FRC biomaterials developed may constitute an optimized alternative to the other materials used for the reconstruction of craniofacial bone defects [76].

The research options with FRC materials are open and future reports about the topic are expected to widen FRC utilization in both dental and medical fields.

Data Availability

Data are available upon request at andrea.scribante@unipv.it.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. Author Pekka K. Vallittu consults Stick Tech Member of GC Group in R&D and training.

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Research Article

Effect of Load Cycling on the Fracture Strength/Mode of Teeth Restored with FRC Posts or a FRC Liner and a Resin Composite

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The aim of the study was to comparatively evaluate the fracture strength and mode of root canal treated teeth restored with resin composites with and without posts. The lingual cusps of root canal treated first upper premolars (n = 10/group) were removed down to cervical enamel and restored with the following: group A: glass-fiber post (Glassix) followed by a particulate-filled composite resin (PFC, G-aenial posterior, 3 × 2 mm layers); group B: glass-fiber reinforced composite bulk fill liner (EverX posterior, 4 mm layer) with the PFC (2 mm layer). Specimens were immersed in H_2O (1 w/37°C), then subjected to load cycling (50 N/0.2 Hz/200k cycles), and fractured under compressive loading. Failure mode was characterized by stereomicroscopy. Statistical analysis was performed by Mann-Whitney (load) and Chi-square (mode) at a = 0.05. No statistically significant differences (p = 0.273) were found in fracture load between median values of groups A (860 N) and B (1059 N). In group A, 60% of the specimens demonstrated catastrophic root fractures and 40% mixed crown fractures (tooth cusp and restoration), whereas in group B, no root fractures were found, and the failure modes were equally distributed between mixed fractures as above and fracture of the buccal cusp. These differences were statistically significant (p = 0.004). The combination of the glass-FRC bulk fill liner with the PFC diminished the catastrophic root fractures induced by FRC posts, at a similar or higher fracture load.

1. Introduction

The strength and longevity of the endodontically treated teeth (ETT) are still a controversial issue of high concern for clinicians and researchers. Long-term survival rate of ETT not only depends on the success of the endodontic treatment, since the remaining tooth structure and the definitive restoration are determinant factors, as well [1]. Restoring ETT with appropriate materials and techniques, capable of resisting fracture, is of paramount importance. With the development of new adhesive materials and techniques, these structurally compromised teeth could be reinforced.

Endodontically treated teeth often require post and core restorations for retention purposes, because of extensive loss of tooth structure due to caries or fracture. However, it has been demonstrated that cast and prefabricated metallic posts do not strengthen the tooth and do not improve ETT longevity [2–4]. As an alternative, fiber-reinforced composite (FRC) posts have been developed with a modulus of elasticity matching that of human dentin, resulting in a more even stress distribution along the root and therefore in less incidence of catastrophic failures [5–8]. Moreover, glass-FRC posts and composite resin core built-up materials demonstrate improved esthetics, when semitransparent materials are considered for the main restoration.

Although enhanced restoration retention and favorable distribution of the occlusal forces along the remaining tooth structure are the major functions of FRC posts [9–11], several disadvantages and limitations have been associated with their clinical use. Interestingly, based on a meta-analysis of clinical studies, the overall rate of catastrophic failures between metal and FRC posts was similar, with the prefabricated metal and carbon-FRC posts demonstrating a two-time higher failure incidence from cast metal and glass-FRC posts [12].

The importance of the remaining amount of coronal tooth structure and intracanal dentin wall thickness on the fracture resistance of endodontically treated teeth have been already emphasized in previous studies [13–15]. Considering that post space preparation has been shown to weaken the remaining tooth structure [16, 17], it would be tempting if post placement could be omitted, introducing new minimally invasive therapeutic options [18, 19]. Since direct composite restorations may not function optimum in ETT with extended tooth structure loss, indirect onlay, overlay, or endocrown bonded ceramic restorations have been suggested as more conservative approaches to post and core and full coverage restorations for badly broken ETT, without the need for aggressive macroretentive preparation [20–23]. However, catastrophic failures below the cementoenamel junction (CEJ) have been reported even with conservative onlays or endocrowns. As an alternative to ceramic indirect restorations, polymer composites have been proposed due to their superior stress-absorbing properties [22, 24, 25].

Recently a glass-FRC resin composite has been introduced to be used as a bulk liner for direct particulate-filled resin composite (PFC) restorations. This material is reinforced with short glass fibers (diameter 12-17 μm, length 0.3-1.9 mm, and critical fiber length 0.85-1.09 mm) randomly distributed in a conventional light-cured dimethacrylate resin matrix, along with particulate fillers [26]. The fiber reinforcing mechanism is based on the principle that a relatively soft ductile polymer matrix may transfer an applied load to the fibers via shear forces at the interface [27]. Therefore, a short glass-FRC bulk fill liner can be applied in a single-layer and serve as a reliever to polymerization stresses [28], improving the mechanical performance of the tooth-restoration structural complex [29–31].

The aim of the study was to comparatively evaluate the strength and fracture mode of root canal treated teeth restored with a resin composite, employing a root canal glass-FRC post or a glass-FRC bulk fill liner, after load cycling. The null hypothesis was that there are no differences in the fracture strength and failure mode among the two restorative modalities tested.

2. Materials and Methods

First upper premolars (#14 and 24, all intact with two fully developed roots), extracted for orthodontic reasons and kept in distilled water with 0.5% sodium azide at 8°C, were used in the study. The use of this material was approved by the Ethics Committee of the institution (#265b/30.3.2015). The teeth selected were of similar crown and root sizes and with no cracks or other defects as examined under a stereomicroscope (M80, Leica Microsystems, Wetzlar, Germany) at 4X magnification. The teeth were randomly distributed into two groups (A-B, n = 12 each) and subjected to root canal treatments. Access cavity was prepared by #330 and EndoZ burs (Dentsply-Maillefer, Ballaigues, Switzerland), and working length was determined for each canal as 1 mm short of the length of No 10 K-file (Dentsply-Maillefer), just protruding the apical foramen. For canal preparation, the Protaper Universal System (Dentsply-Maillefer) was applied up to F3 instrument. In between each file, 5 ml of 2.5% NaOCl irrigating solution was used; canal was dried with high vacuum aspiration and a small quantity of 18.6% EDTA lubricating gel (Ultradent, South Jordan, Utah, USA) was placed in the canal, proceeding the next file. Following completion of the root canal preparation, smear layer was removed by 10 ml REDTA 17% solution (Roth Int, Chicago, Ill, USA), and rinsing was completed by 10 ml sterile saline. All root canals were dried with paper points and subsequently obdurated by cold lateral condensation of gutta-percha points (Hygenic, Coltene/Whaledent Langenau, Germany) and an epoxy based sealer (AH Plus, Dentsply DeTrey GmbH, Konstanz, Germany). Excess gutta-percha was removed at the orifice of the canal with a hot instrument and the access cavity was provisionally filled with a cotton pellet and a temporary filling material (Caviton, GC International, Tokyo, Japan). All specimens were stored in 100% humidity and 37°C for a week to allow for full sealer setting. Then, the palatal cusp of each premolar was removed up to 0.5 mm length from the cervical enamel margin with a cylindrical diamond bur (Komet Dental, Lemgo, Germany) attached to an air-rotor handpiece and the teeth were restored with the materials listed in Table 1 as follows:

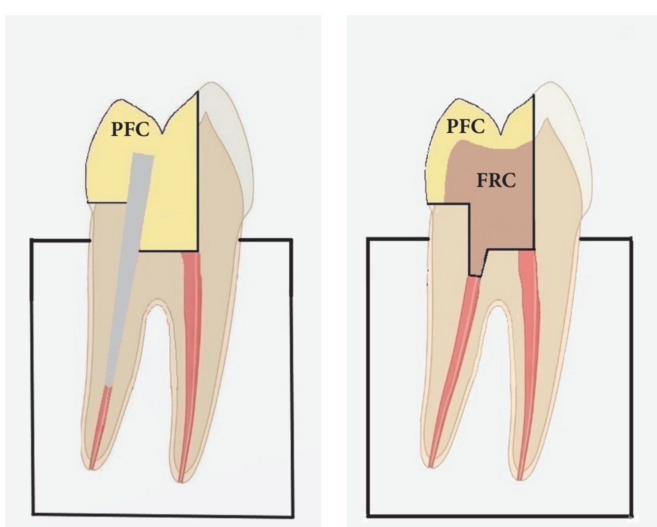
For group A (Figure 1(a)), the temporary filling material and cotton pellet were removed and a size 1 Peeso reamer (Dentsply, Maillefer, Tulsa, OK) was used to remove the filling material from the lingual root canal up to 8 mm depth from the cut cervical enamel. A glass-FRC post was silanated with the silane primer, left intact for 60 s, air-dried for 10 s, and then cemented into the prepared root canal with the self-adhesive luting agent, which was light-cured for 20 s. The post length used for retention of the restorative material was approximately 3 mm. The enamel margins were etched with the phosphoric acid gel for 10 s, rinsed with water for 5 s, and gently air-dried for 5 s, then the adhesive was applied over the prepared tooth and post surfaces exposed, left undisturbed for 10 s, air-dried for 5 s, and light-cured for 10 s. For the final restoration the PFC posterior restorative was applied (3×2 mm increments) and each increment was light-cured for 40 s. Finally, the restoration was contoured, finished, and polished with composite finishing carbide burs (Komet Dental) and alumina polishing discs (Soflex, 3 M ESPE, St. Paul, MN, USA).

For group B (Figure 1(b)), removal of the filling material from the lingual root canal was limited to a 2 mm depth from the cut cervical enamel. Acid-etching of enamel margins and adhesive application were performed as before. Then, the glass-FRC bulk fill liner was applied in a single 4 mm increment, including intracanal extension and light-cured for 40 s. A final layer of the PFC restorative (1×2 mm increment) was placed, light-cured, contoured, and finished as above. In all cases, light-curing was performed with a LED unit (G2 Bluephase, Ivoclar Vivadent) with a curing distance of 0.5 mm, operating at high mode (1200 mW/cm^2 light intensity). Specimens were inspected under the stereomicroscope for presence of marginal defects. Two specimens were discarded from each group, creating thus two groups of 10 specimens each.

To succeed proper alignment of the loading device with each occlusal tooth surface, the root apices of each specimen were cut and fixed at the bottom of empty cylindrical transparent plexiglass molds (Ø:15 mm, h: 15 mm), which

Table 1: The products used for tooth restorations in groups A and B.

PRODUCT /LOT	TYPE/COMPOSITION	MANUFACTURER
G-CEM LinkAce A2/1309241	Self adhesive luting agent. *Resin:* DUDMA, GDMA, 10-MDP Catalysts: CHP, 2-tert-butyl-4,6-dimethylphenol. *Filler:* silanated glass (50–70 wt%)	GC Corporation, Tokyo, Japan
Glassix Radiopaque S1 13930	Glass-fiber post.	H. Nordin SA, Chailly Switzerland
Monobond-Plus R85603	Prehydrolyzed silane. 10-MDP, MPTMS, Disulfide dimethacrylate, Ethanol.	Ivoclar Vivadent, Schaan, Liechtenstein
GC Promotion Etchant -	40% phosphoric acid etching gel	GC Corporation, Tokyo, Japan
G-aenial bond Lot1308181	Self-etch adhesive. 4-MET, 10-MDP, Glycerol dimethacrylate, TEGDMA, water, acetone, initiators.	GC Corporation, Tokyo, Japan
EverX Posterior 1307124	Fiber-reinforced composite (FRC) *Resin:* semi-IPN: net-PMMA inter-net-poly(BisGMA): Bis-GMA, TEGDMA, PMMA *Fillers:* E-glass fiber, barium borosilicate (57% v).	GC Corporation, Tokyo, Japan
G-aenial Posterior A2/1306112	Particle-reinforced posterior resin composite (PFC). *Resin:* UDMA, dimethacrylate co-monomers, *Fillers:* Strontium and lanthanide containing prepolymerized fillers, silanated fluoroaluminosilicate glass, silica (65% v).	GC Corporation, Tokyo, Japan



(a) (b)

Figure 1: Schematic illustration of the test specimens. PFC refers to the particulate filler composite and FRC to the short glass-fiber reinforced bulk fill liner. (a) Group A: glass-fiber-reinforced posts and PFC; (b) Group B: FRC liner and PFC.

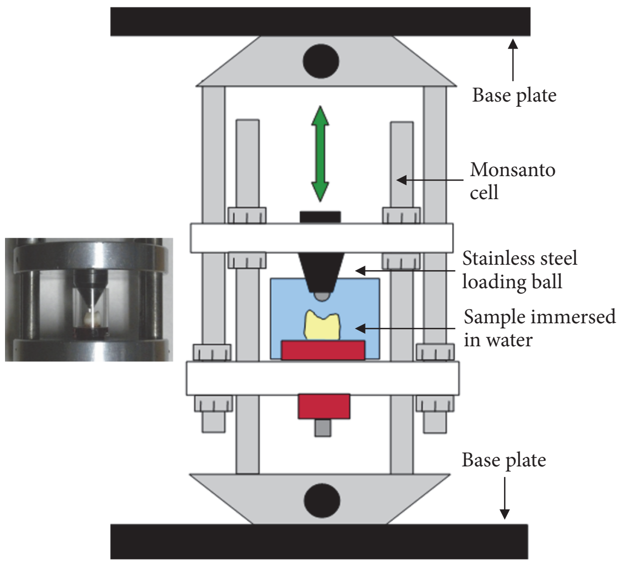


FIGURE 2: The setup used for specimen load cycling.

TABLE 2: Results of failure load values in Newtons. Same superscript letters show median values with no statistically significant differences.

GROUP	n	Median (N)	25% (N)	75% (N)
A	10	860,5[a]	698	1024
B	10	1059,2[a]	708,5	1226,7

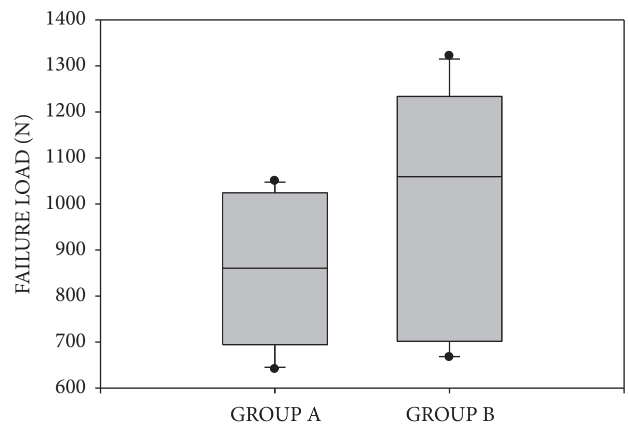


FIGURE 3: Boxplot for the results of fracture strength, including median, lower, and upper quartiles and minimum-maximum and outlier values.

were placed in-line with the stainless steel sphere (Ø: 5 mm) of the loading device. The external plexiglass surface was marked with 3 notches relative to the base of the loading device to guarantee proper repositioning of the molds. The molds were then filled with fast setting acrylic resin (Kallocryl CP GM, Dr Speier GmbH, Münster, Germany) up to a 2 mm distance apically to the dentine-enamel junction. Care was taken to avoid porosity in the embedding material, by inspection of the pouring resin through the transparent plexiglass molds. In this way individual aligned bases were produced for each specimen. All specimens were immersed in distilled water for 1 week at 37°C and then prepared for the load cycling testing.

Each specimen was placed in the loading cell (Monsanto compression cell), of a custom made load cycling unit, aligned and subjected to load cycling for 200,000 cycles at 0.2 Hz, under vertical movement of the loading head (Figure 2). A 50 N load was applied at the inclined surfaces of the premolar occlusal cusps, in contact with tooth walls and restoration surface. During load cycling the tooth crown and the loading sphere were kept in a water-cell at ambient temperature (25°C). Following load cycling, the specimens were stored again in distilled water for 1 week at 37°C and then loaded up to fracture in a universal testing machine (Model 6022, Instron, Canton, MA, USA) equipped with a similar cell at a crosshead speed of 0.5 mm/min. The fracture load was recorded in Newtons (N).

The failure mode of all the specimens was characterized by stereomicroscopy; at 7X the mode of failure was characterized as type I (failure of the buccal tooth crown wall), type II (failure of the restoration), type III (combination of type II and III failures), and type IV (root fracture).

Statistical analysis of the failure load (in N) was performed by the Mann-Whitney Rank Sum Test. For the failure mode, percentage frequencies were compared by the Chi-square test. All tests were performed with SigmaStat v 3.1 software (Jandel, S. Raphael, Ca, USA) at a 95% confidence level (a = 0.05).

3. Results

The results of the failure load and the statistical analysis are summarized in Table 2. The median value of group A (860.5 N) was lower than group B (1059.2 N). However, statistical analysis showed no statistically significant difference between the two groups in the failure load ($p = 0.273$). In group B, half of the specimens exceeded the value of 1100 N, whereas in group A, four specimens presented values between 1000 and 1100 N. In both groups the lowest recorded values were above 600 N. The box plots of the results are presented in Figure 3.

Representative photographs of failed specimens are presented in Figures 4 and 5. The results of failure mode analysis are summarized in Table 3. In group A, 40% of the specimens revealed failure in the tooth crown walls and the restoration (type III failure), while the rest of the specimens (60%) showed catastrophic root fractures (type IV failure). Catastrophic root fractures were mostly combined with type III crown failures. On the contrary, in group B, no root fractures were identified in any of the specimens. Failures were equally distributed between type I and type III involving both crown tooth structure and the restorative material. In two cases of group B, debonding and cohesive fracture of the glass-FRC bulk fill liner was observed, while in all other cases failure was located within the glass-FRC bulk fill liner. The Chi-square test revealed statistically significant difference between groups A and B in the failure mode ($p = 0.004$).

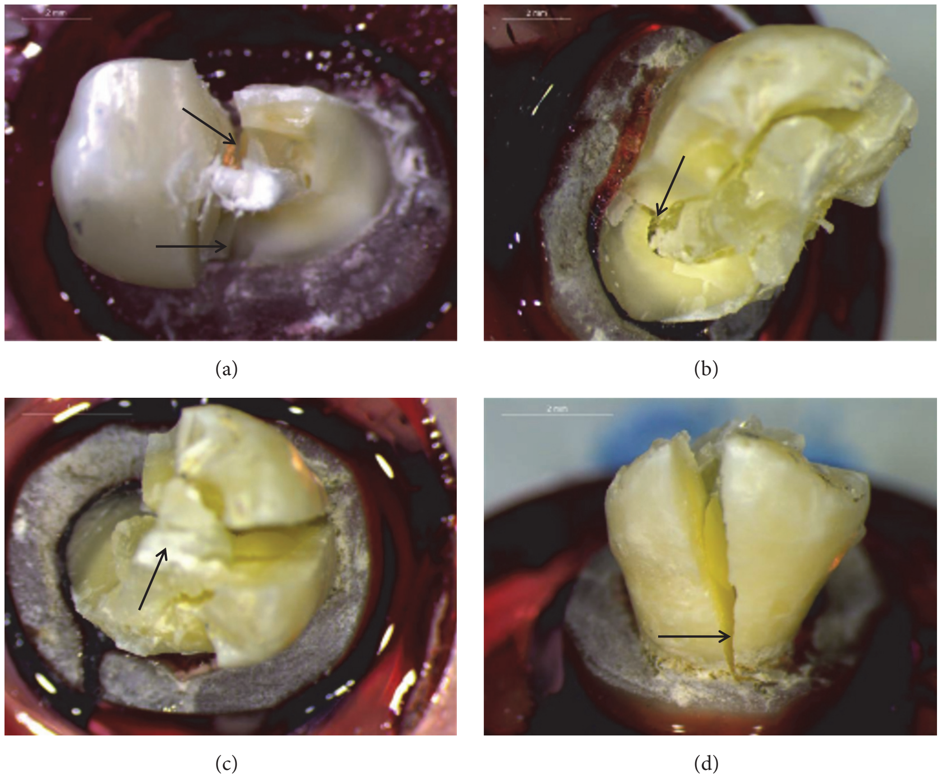


Figure 4: Fractured specimens of group A: (a) fracture of the post-retained restoration along with root fracture (arrows) and completely exposed post; (b) cleaved lingual wall (arrow) distal to the post; (c) fracture of buccal tooth wall, along with fracture and debonding of the restoration; (d) cleavage of the buccal wall through the middle level.

Table 3: The frequency of the failure modes identified. Type I: failure of remaining tooth crown walls only; Type II: failure of restoration only; Type III: mixed failure (I+II); Type IV: root fracture.

Group	Type I	Type II	Type III	Type IV
A	-	-	4 (40%)	6 (60%)*
B	5 (50%)	-	5** (50%)	-

*In all specimens this failure mode was combined with type III crown failures.
**In two specimens fracture and debonding of the FRC composite occurred.

4. Discussion

In the present study, the fracture resistance and mode of endodontically treated was evaluated in premolars restored either with glass-FRC posts and the PFC restorative or the glass-FRC bulk fill liner and the PFC restorative, after load cycling. The results of this in vitro study led to partial rejection of the null hypothesis. Although there was no significant difference in fracture strength between the groups tested, the specimens restored with the glass-FRC bulk fill liner and PFC restorative showed significantly less root fractures, considered as catastrophic failures, from restorations with the glass-FRC post and PFC restorative.

Maxillary two-rooted premolars of standardized size were selected for the study, since these teeth present an unfavorable anatomic shape, crown value, and crown/root proportion, making them more susceptible to fractures than other posterior teeth, when submitted to occlusal load application [32]. Also, a load cycling fatigue test was conducted, before final static loading up to fracture, in an attempt to mimic the actual function of mastication, even though laboratory simulations cannot accurately reflect the clinical conditions. A relatively low loading rate was used to provide time for elastic recovery and relaxation of such extended and complex restorations. Moreover, load cycling and loading up to fracture were performed along the longitudinal tooth axis, in order to concurrently load both tooth cusps. Preferential loading of the restoration, employing an inclined loading axis, was avoided to create an equivalent of simultaneous loading of the entire tooth crown. Finally, no intact teeth were used as controls, since comparison was limited only between treatments [33].

There are no similar studies available to compare the results of the present study. Hence, direct comparison of the results achieved from various laboratory studies evaluating the fracture resistance of ETT is not feasible, because of the differences in specimen type and size, tooth embedment methods, type and direction of load application, and aging conditions.

The ideal reconstruction of ETT should aim at improvement of their mechanical resistance and prevention of catastrophic failures. Traditionally, cuspal coverage along with cast post and core has been suggested as the only system to improve the ETT resistance and load distribution

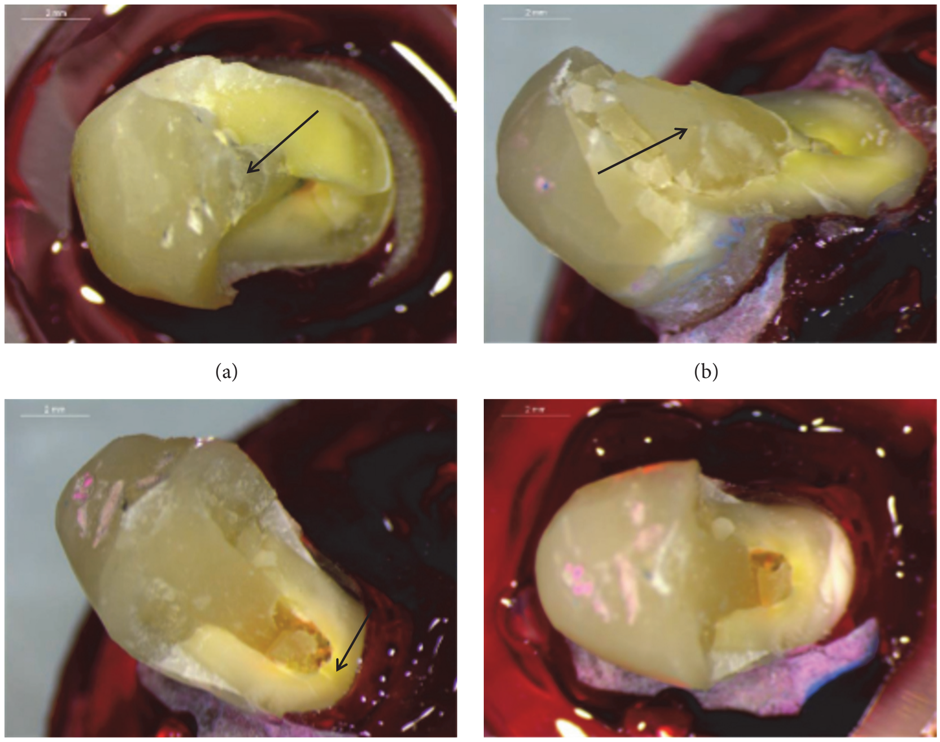


Figure 5: Fractured specimens of group B: (a) fracture of buccal, mesial, and distal walls (arrow indicates fiber-reinforced composite); (b) buccal tooth wall fracture with arrow showing the fiber-reinforced material; (c) lateral view of fracture of the buccal tooth wall, with minor secondary cracks (arrow) not extending to the margins; (d) top view of the same specimen (c) showing fracture of the buccal tooth wall extending to restoration margins.

[34]. Recent developments in adhesive dentistry and minimally invasive concepts call for less destructive restorative techniques. Several studies have shown that direct PFC restorations may provide a significant improvement in the fracture resistance of posterior teeth when two or three walls are missing [35, 36]. Tooth structure preservation is directly correlated with fracture resistance and reduction of catastrophic failures [37, 38].

The glass-FRC post extension within the PFC restoration improves the ability of tooth-restoration complex to absorb occlusal loads and increase the resistance and retention of the ETT to masticatory forces [39, 40], probably as a result of more favorable distribution of functional stresses [41]. A positive effect of FRC posts in supporting PFC restorations has been reported in several laboratory and clinical studies [42–44]. Nevertheless, the results of other studies did not confirm such an effect, especially in premolars [45–47]. The loss of moderate dental structure and the presence of glass-FRC post restoration have been shown to reduce fracture resistance and create higher stress concentrations in the tooth-restoration complex. However, in cases with large loss of dental structure, glass-FRC posts reduced the incidence of catastrophic failures, although they did not reinforce the tooth-restoration complex [45]. More specifically, for endodontically treated premolars with residual wall thickness >2 mm, an intracuspal composite restoration supported by FRC post provided sufficient fracture resistance to occlusal loads, whereas in cases with residual wall thickness <2 mm, cuspal coverage through a composite resin restoration was mandatory, with or without a FRC post [36]. This implies that the most critical factor is the remaining tooth structure and not the FRC post reinforcement.

It has been postulated that any restoration without post space preparation and less sacrifice of residual sound tissue might result in greater resistance to fracture regardless of the degree of impairment of the dental structure [44]. Studies have shown that post space preparation not only weakens the tooth structure but also might lead to cracks and defects that can concentrate stresses and increase the possibility of root fracture and tooth loss [48].

In the present study, glass-FRC post placement (group A) did not protect the tooth from root fracture. Sixty percent of the teeth restored with a glass-FRC post and PFC fractured under the CEJ with vertical catastrophic root fractures, involving the pulp chamber floor at root bifurcation. All the rest showed mixed fractures of buccal tooth cusp and restoration, with post exposure to a various extent. No fracture or debonding of the adhesively bonded post to the root canal was identified in any of the specimens. This may imply that, despite the post bonding condition, a wedge-action cannot be avoided upon loading, with detrimental effects on root integrity. In group B, where the glass-FRC bulk fill liner was used under the PFC restoration, the median fracture strength was higher compared to that achieved by the glass-FRC post supported restorations, but this increase was not statistically significant. Evaluation of the fracture mode, though, showed no cases of catastrophic root fractures. This difference, which was statistically very significant, is probably the result of a much more favorable stress distribution provided by the specific restoration complex. The differences in the statistical ranking between fracture strength and mode may be explained by the contribution of the remaining tooth cusp in the overall strength. In 50% of group B specimens, only the buccal tooth cusp was fractured, indicating that the restoration was quite effective in distributing the fatigue stresses at the tooth crown. In group A specimens the high incidence of root bifurcation fractures was mostly combined with type III failures, revealing a stressful situation.

The glass-FRC used has been introduced a few years ago, as a bulk fill liner intended to be covered with a layer of a PFC. It is a combination of a semi-interpenetrating (IPN) matrix, short E-glass fibers randomly oriented, and inorganic particulate fillers. This FRC has been reported to exhibit improved physical and static/dynamic mechanical properties compared to classical PFCs, adequate degree of C=C conversion, and low polymerization shrinkage [49–53]. Short-fiber-reinforced composites have been evaluated in direct or indirect composite restorations of anterior and posterior vital and nonvital teeth [29, 33, 54]. It has been claimed that the function of short-fiber FRC liner is based on the support provided to the superficial PFC layer and an inhibition effect to crack propagation. The reinforcing effect of the fiber fillers is attributed not only to the favorable stress transfer characteristics from the polymer matrix to fibers, but also on the behavior of individual fibers as crack inhibitors. The stress transfer from polymer matrix to the fibers is a function of the fiber length, for optimal polymer reinforcement. The short fibers, incorporated in the glass-FRC bulk fill liner tested, are within the range of the critical fiber length (0.5-1.6 mm) to enable uniform stress distribution [55]. The high fibers volume fraction inside the restoration and layer thickness of the FRC liner further contribute to crack propagation inhibition and improved load-bearing capacity of the tooth-restoration complex [29, 33].

In the present study, the glass-FRC bulk fill liner was used as a 4 mm substrate under a 2 mm layer of the PFC restorative, with a 2 mm extension into the root canal. This design provides the advantages of a single-phase custom made fiber-reinforced short post, with full adaptation to the endo preparation geometry and a more predictable adhesive bonding to the cervical root canal dentin [56, 57]. Layering of the glass-FRC liner with a PFC is considered mandatory, because the presence of the short fibers fails to meet the criteria of wear resistance, roughness, and gloss set for PFC restoratives [58].

A superior fracture resistance and favorable fracture, coronal to the CEJ of endodontically treated posterior teeth restored with the glass-FRC bulk fill liner and a PFC, has been documented in several laboratory studies [29, 59, 60]. Moreover, further improvements in fractography were registered when the glass-FRC bulk fill liner was combined with a fiber-glass under CAD/CAM resin composite overlay restorations of endodontically treated molars, even though the load-bearing capacity was not improved significantly [33].

The present study focused on the fracture resistance and fracture mode of upper endodontically treated premolars with only one cusp missing, restored with direct PFC restorations supported either by glass-FRC post or glass-FRC bulk fill liner. According to the results, the combination of a glass-FRC bulk fill liner with a PFC restorative showed a promising performance regarding the fracture mode, providing a better reinforcing effect that could serve as a less invasive and time saving approach for the rehabilitation of posterior ETT, preventing thus catastrophic failures. More investigations need to be done to resolve specific issues such as the tooth type and size, cavity design, and remaining tooth structure, along with marginal leakage assessment and long-term performance of this type of restorations.

5. Conclusions

With the limitations of the present study, the following conclusions can be reached:

(1) Median values of fracture load in N did not show any statistically significant difference between the two treatment modalities tested (group A: glass-FRC post; group B: glass-FRC bulk fill liner).

(2) The failure mode of the fractured specimens presented statistically significant differences. In group A, 60% of the specimens demonstrated catastrophic root fractures (type IV failure mode) and 40% mixed fractures of residual tooth crown and restorative material (type III failure mode). In group B, no root fractures were found, with the failure modes equally distributed between type III (50%) and type I (50%), the latter including failure of residual tooth crown.

(3) The glass-FRC bulk fill liner tested significantly modified failure mode, diminishing the catastrophic root fractures induced by FRC posts, at a similar or higher fracture load.

Data Availability

All data supporting the results reported are available in technical report that has been composed and is available from the corresponding author upon request.

Disclosure

Part of the results of this paper was presented at the 2015 IADR/CED Meeting, Antalya, Abstract no. 0100.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Multi-Fiber-Reinforced Composites for the Coronoradicular Reconstruction of Premolar Teeth: A Finite Element Analysis

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A coronoradicular reconstruction (CRR) has conventionally used a metallic inlay core (MIC) or a single-fiber-reinforced composite (sFRC) but extensive dentin removal can lead to root fracture. We propose herein a multi-fiber-reinforced composite (mFRC) based on a bundle of thin flexible fibers that can be adapted to the root anatomy without removing additional dentin. The aim of this study was to compare the mechanical behavior of the root reconstructed with mFRC, MIC, or sFRC using a finite element analysis (FEA). Models with or without a ferrule effect were created using Autodesk© software and divided into four parts: root, post, bonding composite or cement, and zirconia crown. For both models, extreme stress values (ESV), stress distribution, and risk of fracture were calculated for an oblique force (45°) of 100 N applied to the top of the buccal cusp. Results indicated that mFRC and mFRCG present a lower risk of fracture of the root and of the CRR without ferrule and thus could be valuable alternatives for premolar CRR. Further studies are necessary to evaluate the clinical success of these CRR.

1. Introduction

Coronoradicular reconstruction (CRR) is classically recommended when an endodontically treated tooth cannot be restored using coronal reconstruction [1, 2]. This strategy allows replacement of lost dentin, stabilizes the crown, and ensures resistance against cervical tooth fracture [3]. Currently, CRR are performed directly, using a single post in a fiber-reinforced composite (sFRC) or, indirectly, using the traditional metallic inlay core (MIC) [4, 5]. However, sFRC standard post placement and MIC post impression often imply extensive removal of the root dentin, which is a major drawback, since tissue preservation including the ferrule effect (FE) is strongly associated with the survival of endodontically treated teeth [6–8]. Moreover, MIC and sFRC present a greater elastic modulus than that of dentin, which also increases the risk of tooth fracture [9]. Clearly, important tissue removal and differential mechanical behavior weaken the root and lead to low tooth survival [10–14]. Furthermore, reconstructed premolars have a lower survival rate due to smaller crowns and lateral occlusal forces [15]. Alternative CRR strategies have therefore been investigated without clear consensus [16–19]. A new kind of FRC, based on a bundle of fibers bonded in the root canal, is proposed in the present study. This multi-fiber-reinforced composite (mFRC) can be adapted to the root anatomy without additional dentin removal after root canal treatment. Furthermore, adding a gutta-percha point in the center of the fiber bundle (mFRCG) is possible, which, in case of root reinfection, enables easier reintervention in the root than when a metal or single fiber post is used.

Before performing a clinical trial that will necessitate a large number of patients to deal with anatomical and clinical variations, valid comparison of these different CRR is required. Finite element analysis (FEA) has been widely used to evaluate mechanical behavior of CRR in dentistry [20–23],

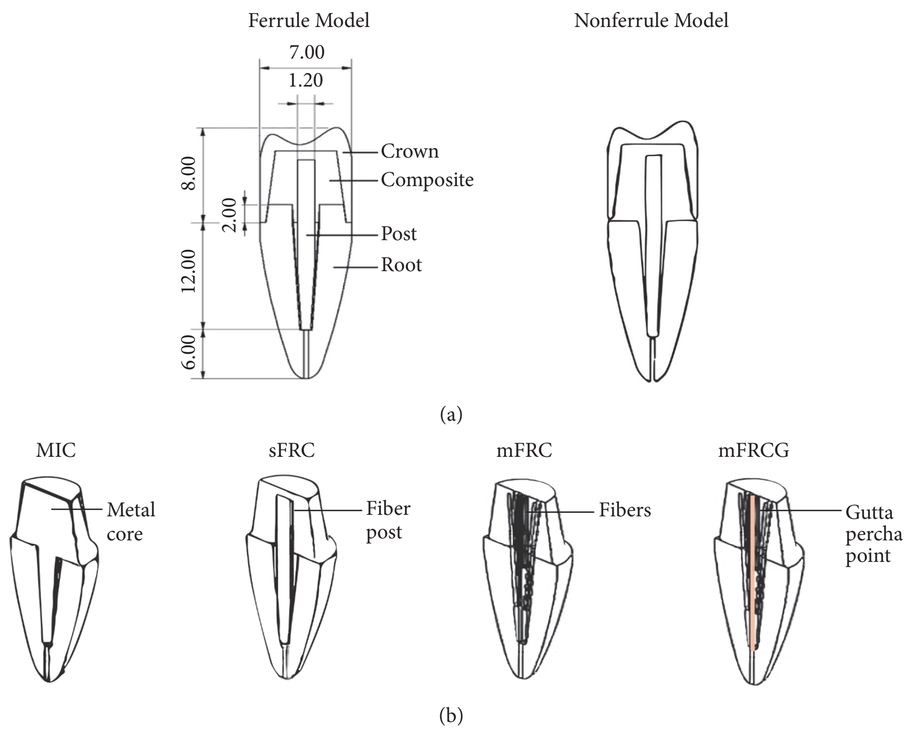

FIGURE 1: Representative figures of the models used in the study. Profile views of the ferrule and nonferrule models (a). Three-quarter view of the four different coronoradicular reconstructions (CRR): MIC (metal inlay core), single-fiber-reinforced composite (sFRC), multi-fiber-reinforced composite (mFRC), and multi-fiber-reinforced composite with gutta (mFRCG) for nonferrule models (b). Dimensions are in mm.

yet, to the best of our knowledge, there is no published study on a CRR using either mFRC or mFRCG. Our aim was therefore to compare, using FEA, the risk of root fracture of mFRC and mFRCG with that of MIC and sFRC.

2. Materials And Methods

2.1. Model Construction. The model was constructed using professional software (Autodesk Inc., Inventor, San Rafael, CA, US) to represent a premolar tooth endodontically treated and supporting a CRR and a zirconia crown. Four parts (root, post(s), bonding composite or sealing cement, and crown) were modeled independently and then matched together using the software to generate a complete 3D model.

Eight models were generated with or without a ferrule and with four different CRRs: MIC, sFRC, mFRC, and mFRCG. Dimensions of the four parts of the 3D model were chosen according to the literature [21–25]. The ferrule effect was a 2 mm high wall that was at least 1 mm thick. The 3D model measured 26 mm in length and 7 mm in width, with an 8 mm long zirconia crown and an 18 mm long root. The post occupied two-thirds of the length of the root and was 1.2 mm in diameter (Figure 1(a)). In the MIC models, inlay cores were sealed using 0.1 mm thick cement. sFRC models were created using a standard cylindrical-conical post that was 1.2 mm in diameter and 16 mm in length bonded with composite. FRC models were designed using a bonding composite that was reinforced by 14 flexible fibers bonded in the root at different levels (Figure 1(b)). The area between the post and the root was named the interface and corresponded to sealing cement or bonding composite according to the model. FRCG models included a central gutta-percha point replacing the central fiber. The gutta-percha point had the same dimensions as the central fiber.

2.2. Material Properties And Mesh. A static structural analysis was performed to calculate extreme stress values (ESV) and the stress distribution on the models. All structures were assumed to be linearly elastic, homogeneous, and isotropic [26]. Ideal adherence was assumed between structures (zirconia with cement, cement with core, core with post, post with cement, and cement with dentin interfaces). The Poisson ratio (n) and modulus of elasticity (E) of the oral tissue and crown material were determined from the literature [24–27] and are given in Table 1. All models were meshed by about 110 000 elements and 200 000 nodes according to a convergence study [28].

2.3. Load And External Conditions. All models received an oblique force of 100 N at 45 degrees at the top of the buccal cusp to simulate masticatory forces. External surfaces of the tooth were supposed to be clamped without freedom to rotate in any direction to model bone anchorage. von Mises stresses and risk of fracture (ROF) were calculated after loading on each part of the model. The stress on the buccal side represents compressive stress, whereas the stress on the palatal side corresponds to traction stress. The ROF was calculated by dividing the maximal principal stress in

Table 1: Mechanical properties of the homogeneous isotropic materials of the model.

Material	Elastic modulus (GPa)	Poisson's ratio	Tensile strength (MPa)	Reference No.
Zirconia crown	200	0.26		[19]
Composite resin	8.3	0.28	55	[19, 25]
Fiber glass post	40	0.27	99	[19, 25]
Sealing cement	0.1	0.20	3	[19, 25]
Metal post	110	0.32	145	[19, 25]
Dentin root	18.6	0.31	104	[19, 25]
Gutta-percha	0.00069	0.45		[9]

Table 2: Extreme stress values of the different parts of ferrule and nonferrule models.

	MIC (MPa)	sFRC (MPa)	mFRC (MPa)	mFRCG (MPa)
With ferrule				
CRR	55.4	5.6	14.7	13.9
Interface	26.3	8.7	12.9	12.7
Root	101.4	100.6	100.8	103.1
Without ferrule				
CRR	57.4	4.2	45.3	42.2
Interface	21.7	9.1	8.6	11.8
Root	134.5	156.2	130.0	131.2

Extreme stress values (ESV) are expressed in MPa for MIC (metal inlay core), single-fiber-reinforced composite (sFRC), multifiber-reinforced composite (mFRC), and multifiber-reinforced composite with gutta (mFRCG) for ferrule and nonferrule models.

Table 3: Risk of fracture of different parts of ferrule and nonferrule models.

	MIC	sFRC	mFRC	mFRCG
With ferrule				
CRR	0.38	0.37	0.15	0.14
Interface	8.76	0.58	0.90	0.84
Root	0.98	0.96	0.96	0.99
Without ferrule				
CRR	0.40	2.80	0.45	0.42
Interface	7.23	0.61	0.57	0.79
Root	1.29	1.50	1.25	1.26

The risk of fracture is expressed for MIC (metal inlay core), single-fiber-reinforced composite (sFRC), multifiber-reinforced composite (mFRC), and multifiber-reinforced composite with gutta (mFRCG) for ferrule and nonferrule models.

each material by its tensile strength. When the ROF value was lower than 1, it was considered low [25].

3. Results

3.1. Extreme Stress Value. ESV were lower with ferrule than without ferrule, and they were always maximal on the root irrespective of the presence of ferrule. ESV for mFRC and mFRCG were close for the model with ferrule and for the model without ferrule (Table 2).

With ferrule, the ESV on the root for all types of reconstruction were close (less than 5 MPa difference (Table 2)); there was therefore a similar ROF for the root among the types of reconstruction tested (Table 3). The ESV on the CRR and at the interface were highest for MIC, intermediate for mFRC and mFRCG, and lowest for sFRC (Table 2). The ROF of CRR was lower for mFRC and mFRCG than for MIC and sFRC (Table 3).

Without ferrule, the ESV on the root was highest for sFRC (Table 2); the ROF of the root was therefore highest for sFRC (Table 3). The ESV on the CRR was highest for MIC, intermediate for mFRC and mFRCG, and lowest for sFRC. The ESV at the interface was highest for MIC; for the other types of reconstruction it was lower and relatively close (Table 2). The ROF of the root was much higher for sFRC than for other types of reconstructions tested. The ROF of the CRR was lower for mFRC and mFRCG than for sFRC (Table 3).

3.2. Stress Distribution. Stress distribution for models with ferrule was close to that of models without ferrule (Figure 2). The stress on MIC models was maximal at the buccal side of the peripheral margin and at the middle of the post and decreased progressively between the post and the peripheral margin (Figure 3). Stress distribution of sFRC, mFRC, and mFRCG was close. For these, the stress was maximal at the peripheral side of the crown margin and decreased progressively to the center of the CRR (Figure 3).

4. Discussion

Considering both the ESV and stress distribution data, the present study indicates that the risk of root fracture in mFRC was lower than in reconstruction using sFRC and MIC in the absence of ferrule and that it was close to that of other reconstructions investigated in the presence of ferrule.

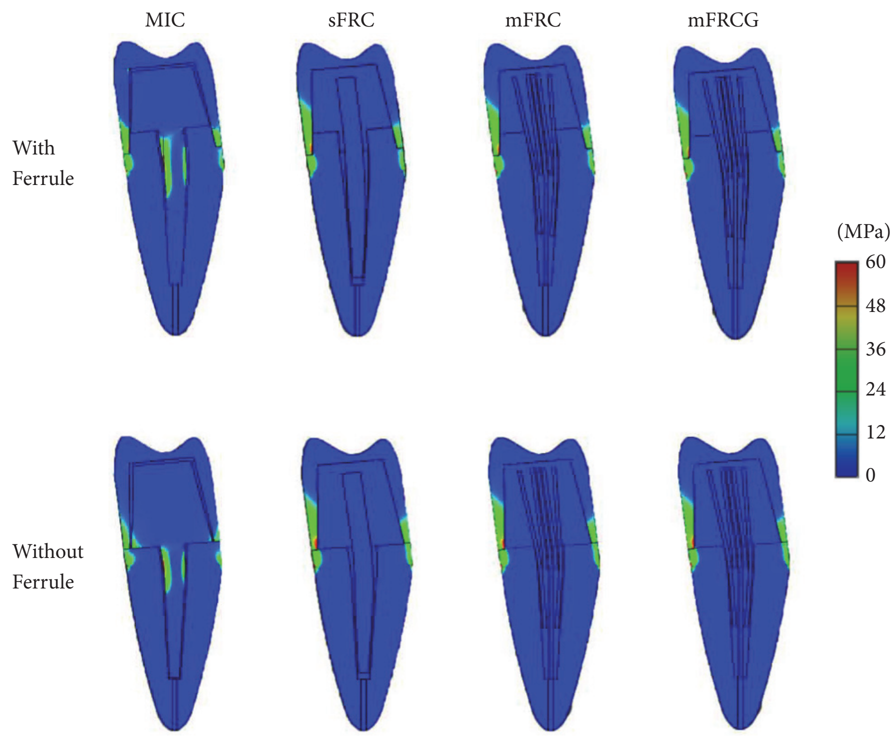

Figure 2: Distribution of von Mises stress (MPa) of each component of ferrule and nonferrule models revealing differences between MIC (metal inlay core) and other reconstructions: single-fiber-reinforced composite (sFRC), multi-fiber-reinforced composite (mFRC), and multi-fiber-reinforced composite with gutta (mFRCG).

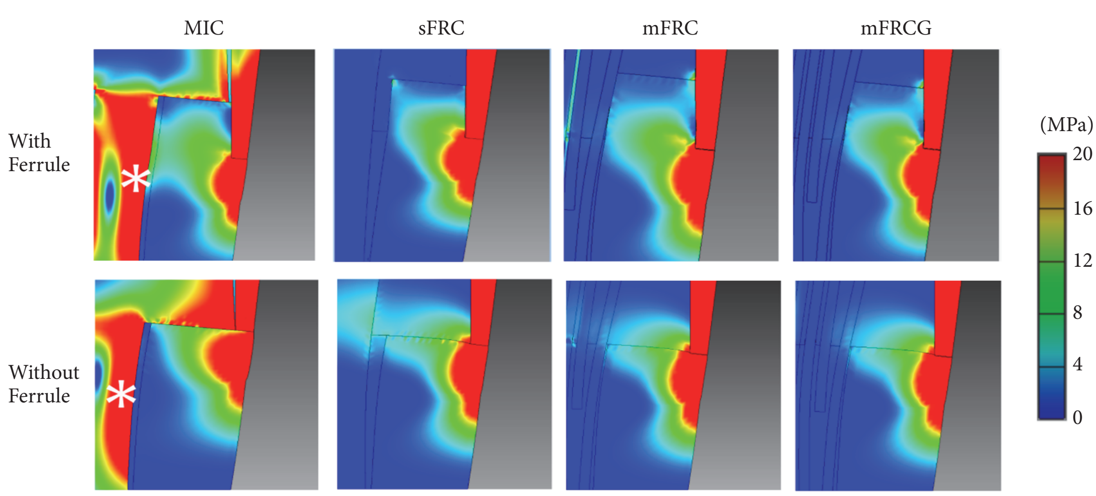

Figure 3: Enlarged view of post/root interface revealing higher stress around the post for MIC and hence a risk of severe horizontal root fracture. The asterisk indicates the zone of highest stress on the post of MIC model.

sFRC is a widely reported alternative to MIC, particularly for fragile premolars [29–31]. Herein, although the level of stress on the root and the risk of root fracture were close in the ferrule model for the different reconstructions tested, they were notably higher for sFRC in the nonferrule model. A similar finding was reported by Mahmoudi et al. who show that, without ferrule, the ESV on the root was higher for sFRC than for MIC [19]. Similarly, Santos-Filho et al. found that the mean resistance to root fracture was significantly lower for sFRC (918 N) than for MIC (1026 N) [27]. These data suggest that sFRC are not indicated for severely damaged roots in which a ferrule is not possible.

MIC does not seem to be a particularly valuable option, since it had the highest level of stress at the middle of the post and at the cervical third of the root compared to the other types of reconstruction, irrespective of the presence of ferrule. These excessive concentrations of stress have been previously reported in the literature and have been associated with an increased risk of catastrophic root fracture requiring tooth avulsion [9, 26]. Again, as previously reported, MIC was also associated with higher ESV at the interface between root and cement, which could lead to CRR debonding and increased risk of failure [19, 26].

In our FEA, mFRC and mFRCG presented the lowest ESV on the root as compared to the other types of reconstruction in nonferrule models. This suggests that, in the absence of ferrule, mFRC could be an alternative to other types of reconstruction. Moreover, mFRC was designed to reduce root canal preparation. In the current FEA, similar root canal preparations were modeled to enable a valid comparison between all models. Another FEA is now required to evaluate whether a less invasive root canal preparation for mFRC would further reduce stress and risk of root fracture. Herein, addition of a gutta point in the bundle of fibers of mFRC did not increase the risk of fracture. This gutta point was intended to facilitate reintervention but has yet to be fully evaluated *in vitro* with tests of root canal retreatment on teeth reconstructed with mFRCG.

Concerning the reconstruction itself, the ROF of the CRR in mFRC was lower than that in sFRC, particularly in the nonferrule model, suggesting that peripheral fibers enabled reinforcement of the CRR; the hypothesis is that, even if peripheral fibers were to break following excessive stress, all the fibers and the sealing composite would have to be broken to completely fracture the CRR. This has to be confirmed by a mechanical study of mFRC resistance but is in agreement with previous papers. For instance, an oval fiber post system was shown to provide better stress distribution on the CRR and the root than a circular fiber post system, suggesting that fibers should be located on more peripheral parts of the root canal and not only in its center [28]. In addition, posts having the mechanical properties of both the fibers and the composite also present a better stress distribution than a post with only the mechanical properties of the fibers, suggesting that CRR with mFRC present better mechanical behavior [26]. This is also illustrated by a recent study that found that nanofibers enhanced the mechanical performance of dental restorative composite [32], increasing the number of biomedical applications [33]. Another point to consider is then the orientation of the fibers, as Vallittu et al. reported an anisotropic behavior of fiber-reinforced composite [34]. Different mechanical properties of CRR and root may therefore be obtained according to the orientation of fibers in the mFRC [34]. This could be tested in future FEA, and it would also be interesting to explore the number of fibers composing the CRR as this does not seem to have been evaluated in the literature.

5. Conclusion

Taken together, mFRC and mFRCG appear to be valuable alternatives for CRR to be used in a premolar with ferrule but particularly in the absence of ferrule. Mechanical and clinical studies are now necessary to evaluate these two CRR.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Raphaël Richert and Maxime Ducret contributed equally to this work.

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Research Article

Effects of Fibers on Color and Translucency Changes of Bulk-Fill and Anterior Composites after Accelerated Aging

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The aim of this study was to determine the effects of glass and polyethylene fibers on the color and translucency change of bulk-fill and anterior composites before and after artificial accelerated aging (AAA). Two types of teflon molds were used to fabricate samples which were 13 mm in diameter and, respectively, 2 mm and 4 mm in height. Polyethylene fiber (PF) and glass fiber (GF) were incorporated in the middle of the composite samples. Color and translucency changes of each composite were evaluated before and after AAA with spectrophotometer. ANOVA and Tukey's HSD post hoc statistical analysis were used at a significance level of 0.05. Before AAA (for anterior composites), there were no significant differences in L^* and b^* parameters among the three groups ($p > 0.05$); there were no significant differences in L^* parameter between PF and GF groups or in TP between GF and control groups ($p > 0.05$) (for bulk-fill composites). After AAA, there were no significant differences in L^* parameter between GF and control groups, in a^* parameter between PF and control groups, in b^* parameter among all groups, or in TP parameter between GF and control groups ($p > 0.05$). Fiber reinforcement led to color and TP change in both anterior and bulk-fill resin composites.

1. Introduction

Composite resin based materials have been widely used since their introduction to meet the growing demand for esthetic dental treatments [1]. The durability of composite resins is an important factor for their success. Applying fibers, for this reason, to reinforce the composite restorations started in the early 1990s [2]. Using a fiber reinforcement currently has a wide range of dental applications as in implant superstructure, removable partial denture, periodontal splints, and orthodontic retainers and it is an alternative to metal ceramic fix partial dentures [3]. Fibers used in this study were PF and GF. Ribbond-THM is a PF consisting of ultra-high strength braided polyethylene bondable fibers and is not impregnated with resin and must be saturated with an adhesive bonding agent before using. Interlig is a preimpregnated GF.

According to a study, 3 years' survival rates range up to 82.8% for metal ceramic, 88.5% for fiber reinforced, and 72,5% for ceramic resin-bonded prosthesis [4], and also other researches reported successful results and higher patient satisfaction with resin-bonded prosthesis for single tooth replacement than conventional fix partial denture [5].

The Fiber Reinforcement Composites (FRCs) consist of two parts. The fiber part reinforces the composites and provides stiffness; the matrix component (composite) supports the fibers, stabilizes their geometric orientation, and allows workability [3]. Different composite materials can be used for FRCs. It is important to determine which composites are more successful to ensure long-lasting FRC restorations. Color stability of composites affects its clinical longevity and if the color change results in patient dissatisfaction it can be concluded for total or partial replacement [6]. Several intrinsic and extrinsic reasons may cause composites to discolor. Extrinsic factors are related to plaque accumulation, absorption and accumulation of stains and the smoking habits; intrinsic factors are related to the chemical stability of the resin matrix and the matrix/particle interface [7]. Generally, manufacturers recommend that the composites should be placed in 2 mm increments to obtain sufficient light transmission and complete the curing of composite resin but using this incremental technique increases the possibility of air bubble inclusion or moisture contamination between increments of composites and also leads to waste of time [8].

Bulk-fill resin based composites (BRBCs) are innovative class of resin composites and produced to overcome such problems. These materials can be sufficiently light to cure up to 4 mm in a single increment with regard to manufacturers and cause low polymerization shrinkage [9]; the rate of filler content has been reduced to simplify deeper light transmission and particle sizes have been increased to improve the mechanical strength [10]. Recent studies have mostly focused on the depth of cure, degree of monomer conversion, and shrinkage stress, as well as microhardness and cytotoxicity of uncured monomers for BRBCs [11–13] and mechanical properties of FRCs [3]. The differences in filler content and composition are key to the optical feature of resin composites [14]. According to manufacturer both of these composites used in this study have patented innovative initiator system called "Radical Amplified Photopolymerization Technology" (RAP), to offer reduced curing time and excellent stability to ambient light while maintaining the superior esthetic and physical properties. In addition to this feature they include Supra-Nano Spherical filler (200 nm spherical SiO2-ZrO2) with quick curing time, 10 seconds, with a halogen light (≥400 mW/cm^2) and low polymerization shrinkage different from the other brands.

Translucency is a very important optical property to consider for the color of composite resins. It can be determined with the translucency parameter (TP) and can be described as a color difference in uniform thickness of a material over a white and black background [15]. The TP value is zero when the material is absolutely opaque. The greater the TP value is the higher the actual translucency of a material is. When a material's color has optimal translucency, the restoration will highly resemble the tooth structure and meet the esthetic requirements.

Color stability and translucency are very important for the esthetic restorations but there is no study about color stability of fiber-reinforced bulk filled composites. Therefore, the samples were subjected to artificial accelerated aging (AAA) in order to predict possible alterations on color and translucency change of the composites in a short time in this study.

Recent studies mostly focused on the depth of cure, degree of monomer conversion, and shrinkage stress as well as microhardness and cytotoxicity of uncured monomers for BRBCs [16, 17]. The originality of this study was color stability and translucency is very important for the esthetic restorations but there is no study about effects of fibers on color and translucency changes of bulk-fill and anterior composites before and after AAA. Therefore, the purpose of this study was to determine the effects of fiber incorporation (glass and polyethylene fibers) and AAA on the color and translucency change of anterior composites and bulk-fill, respectively. The null hypothesis is that incorporation of fibers into the composites would not influence these composites' color and translucency.

2. Materials and Methods

In this in vitro experimental study, two types of fibers (glass and polyethylene) were incorporated into anterior and bulk-fill composites. Both composites' shades were A2. The characteristics and composition of the materials used in the study are shown in Table 1.

2.1. Sample Preparation. Two types of Teflon molds were used to fabricate samples which were 13 mm in diameter and, respectively, 2 mm and 4 mm in height. The spectrophotometer's reservoir diameter was 13 mm, so this width was chosen to allow color measurement. The first layer of the anterior composites was prepared using the shallower (2 mm) mold to enable using incremental polymerization technique and then continued with deeper mold (4 mm) to complete samples. For bulk-fill composites only deeper (4 mm) mold was used to complete samples. Filled mold surface was covered with a Mylar film and the upper and bottom surfaces of the mold were covered by glass slabs before polymerization to produce a smooth surface and finger pressure was applied to extrude excess composite [18]. The samples were polymerized for 20 seconds using a light-emitting diode (LED) curing unit (Elipar S10; 3M ESPE; St. Paul, MN, USA) at a light intensity of 1200 mW/cm^2 and a wavelength of 430–480 nm (wavelength peak 455 nm). The output of the curing light was tested with a radiometer (1,200 mW/cm^2). For fibers, both PFs (Ribbond-THM, Ribbond. Seattle, USA) (group PF) and resin impregnated GFs (glass fiber, Angelus, Sao Paulo, Brazil) (group GF) were cut with fiber scissors at 4 mm width, 10 mm length. Ten samples were prepared for each group and totally 60 samples were prepared for this test ($n = 10$).

2.1.1. For Control Groups. No fiber was added to the control groups. 2 mm Teflon mold was inserted into the 4 mm mold and the remaining 2 mm space was filled with composite and polymerized; then the remaining 2 mm composites were added for anterior composites. The residual 4 mm space of the mold was overfilled with bulk-fill composites as monoblock. The composites were cured for 20 s with using the same light curing unit.

2.1.2. For Polyethylene Fiber (PF) Groups. PF were impregnated with a bonding agent (Clearfil SE Bond) in a small plastic cup. To prepare PF-reinforced composite samples, another custom-made Teflon mold (2 mm height, 13 mm diameter) was inserted into a 4 mm thick mold. After packing a 2 mm thick layer of composite, the custom-made 2 mm Teflon mold was removed. Without curing the bonding agent, PF was placed in the middle of the 2 mm height samples (Figures 1 and 2). After the mold was slightly overfilled with more composite resin, a Mylar strip was put on it and glass slab was clamped on upper surface to throw out excess resin. The composites were cured for 20 s using the same light curing unit.

2.1.3. For Glass Fiber (GF) Groups. Since the GFs were impregnated with resin, they were not subjected to an extra

Table 1: Characteristics and composition of materials used in this study.

Material	Manufacturer	Composition
Ribbond THM	(Ribbond, Seattle, USA)	(i) Polyethylene fibers
Interlig (Resin Impregnated Glass Fiber)	(Angelus, Sao Paulo, Brazil)	(i) Glass fibers (weight), 60 ± 5% (ii) Impregnated resin (weight) 40 ± 5%: Bis-GMA, diurethane, barium glass, silicon dioxide, catalysts.
Estelite Bulk Fill Flow	(Tokuyama Dental Corporation Tokyo, Japan)	Bis-GMA, Bis-MPEPP, TEGDMA Supra-Nano Spherical filler (200 nm spherical SiO2-ZrO2) Composite filler (including 200 nm spherical SiO2-ZrO2) Filler loading: 70 wt% (56 vol%) Mean particle size: 0.2 μm
Estelite Sigma Quick	(Tokuyama Dental Corporation Tokyo, Japan)	Bisphenol A di(2-hydroxy propoxy) dimethacrylate Bis-MPEPP - 10–30% camphorquinone < 1%, dibutyl hydroxy toluene < 1%, MEQUINOL < 1%, triethylene glycol dimethacrylate 5–10%, Filler loading: 78 wt% (69 vol%) Mean particle size: 0.2 μm
Clearfil SE Bond	(Kuraray Dental, Tokyo Japan)	(i) 10-Methacryloyloxydecyl dihydrogen phosphate (MDP); (ii) 2-hydroxyethyl methacrylate (HEMA); (iii) hydrophilic aliphatic dimethacrylate; (iv) dl-camphorquinone; (v) water Bond (i) 10-methacryloyloxydecyl dihydrogen phosphate (MDP); (ii) bisphenol A diglycidylmethacrylate (Bis-GMA); (iii) 2-hydroxyethyl methacrylate (HEMA); (iv) hydrophobic aliphatic dimethacrylate; (v) dl-camphorquinone; (vi) initiators; (vii) accelerators; (viii) silanated colloidal silica

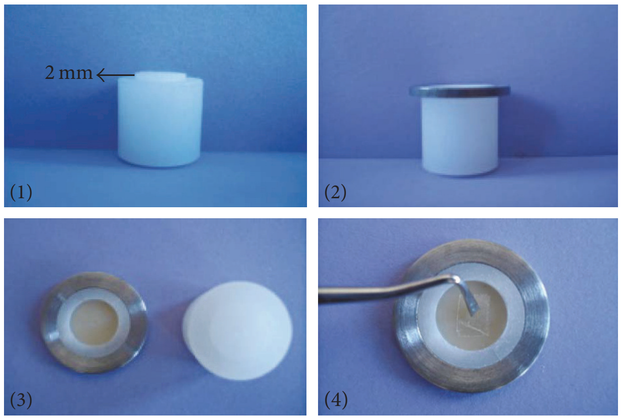

Figure 1: Preparation of samples.

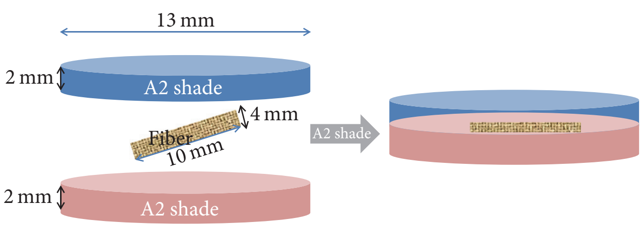

Figure 2: Final view of the samples in the mold.

bonding treatment. Composite resin filled and cured applications were performed as defined PF group.

2.2. Color and Translucency Measurement. After total 60 composite samples' polymerization, all samples were stored in distilled water at 37°C for 24 hours. Samples were stored in dark boxes until color was measured. Before placing the samples in the spectrophotometer (Lovibond® RT400 Tintometer Colour Measurement Amesbury, UK) it was calibrated according to per manufacturer's instructions and measured solely against white calibration tiles for color evaluation and against white and black calibration tiles for translucency measurements (mean calibration value study device's at D65 condition: white: $L^* = 92{,}76$, $a^* = -1{,}16$, $b^* = 0.70$; black: $L^* = 0.38$, $a^* = 0.04$, $b^* = -0.18$). The accurate positioning of samples was enabled by a way of custom jig. Three measurements were conducted at the center of each sample against a white and black background and the mean value was calculated. All samples were evaluated and measured by the same practitioner. Color alterations were determined using the Commission Internationale d'Eclairage $L^*a^*b^*$ color system (CIE $L^*a^*b^*$). Color changes were assessed using the following formula [19]:

$$\Delta E = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2},$$
$$\Delta E = \left\{\left[L_1^* - L_2^*\right]^2 + \left[a_1^* - a_2^*\right]^2 + \left[b_1^* - b_2^*\right]^2\right\}^{1/2}. \quad (1)$$

This formula was used twice in this study. First, it was used to determine the color differences between control group and fiber-reinforced composite groups at beginning measurement. After that, it was used to determine the color changes of all experimental groups after AAA.

To determine the relationship between the amount of color alteration recorded on a spectrophotometer to the clinical environment, data was converted to the National Bureau of Standards (NBS) system units as follows:

$$\text{NBS unit} = 0.92 \times (\Delta E). \quad (2)$$

(See [20].) The defined critical remarks of color change according to the quantified NBS units are given in Table 2 [15]. The TP was calculated as the difference of color coordinate values obtained from the same specimen against black and white background as follows [21]:

$$\mathrm{TP}^* = \left[(L_B^* - L_W^*)^2 + (a_B^* - a_W^*)^2 + (b_B^* - b_W^*)^2\right]^{1/2}, \quad (3)$$

where the subscript B refers to color coordinate values obtained against the black background, and the subscript W refers to the values obtained against the white background.

Table 2: National Bureau of Standards (NBS) units and the critical remarks of color change.

Colour difference	NBS unit
Trace	0–0.5
Slight	0.5–1.5
Noticeable	1.5–3.0
Appreciable	3.0–6.0
Much	6.0–12.0
Very much	>12.0

Note. This table was extracted from our other study [15].

2.3. Artificial Accelerated Aging. After baseline color measurement, all specimens were aged for 150 kJ/m^2 according to accelerated aging conditions previously described [22]. With an accelerated aging chamber (Ci35 Weather-Ometer, Atlas Electric Devices, Chicago, IL, USA), other test parameters included sample surface temperature of maximum 65°C (light) and 38°C (dark) in relative environment humidity of 65%. For rainy condition, surface temperature ranged from 18°C to 38°C. Test cycle was 108 min light plus 65% humidity, 12 min light plus water spray, 108 min dark and 65% humidity, and 12 min dark plus water spray for a total of 150 hours.

2.4. Statistical Analysis. Color difference and TP changes of anterior and bulk-fill composites were analyzed with one-way analysis of variance (ANOVA) and Tukey's HSD post hoc test according to fiber type at a significance level of 0.05. To identify the existing differences, post hoc comparisons were performed using the Tukey HSD test and Tamhane's T2 tests. As one-way ANOVA assumes homogeneity of variance, Levene's test was used for homogeneity. The Tukey HSD post hoc test was used when equal variances and specimens' sizes were assumed and the Tamhane's T2 test was used for data where equal variances were not assumed.

Table 3: Means and standard deviations of L, a, b, ΔL, Δa, Δb, TP, and ΔE values and differences between groups for anterior composites.

	Anterior PF		Anterior GF		Anterior control		p	1-2	2-3	1–3
L_1	64,25	(0,61)	63,93	(0,67)	64,31	(1,19)				
L_2	61,81	(0,67)	62,02	(0,59)	62,62	(0,98)				
ΔL	−2,43	(0,96)	−1,90	(0,87)	−1,69	(0,38)				
a_1	3,95	(0,29)	4,24	(0,21)	4,60	(0,15)	*		*	*
a_2	5,27	(0,36)	5,31	(0,20)	5,38	(0,19)				
Δa	1,32	(0,52)	1,07	(0,16)	0,78	(0,14)	*		*	*
b_1	17,76	(0,93)	18,38	(0,73)	18,42	(0,44)				
b_2	21,32	(1,67)	21,30	(0,72)	20,20	(0,62)				
Δb	3,56	(1,61)	2,92	(0,82)	1,78	(0,53)	*			*
TP_1	6,53	(0,45)	6,75	(0,32)	7,42	(0,43)	*		*	*
TP_2	5,82	(0,50)	5,71	(0,43)	6,25	(0,50)	*		*	
ΔE	4,57	(1,79)	3,68	(1,07)	2,61	(0,50)	*			*

$^* p < 0.05$; $n = 10$; anterior PF: incorporation of PF into the anterior composite (Group 1); anterior GF: incorporation of GF into the anterior composite (Group 2); anterior control: anterior composite control groups (Group 3); 1-2: statistical results between Group 1 and Group; 2-3: statistical results between Group 2 and Group 3; 1–3: statistical results between Group 1 and Group 3; L_1, a_1, b_1, and TP_1: values at baseline measurement; L_2, a_2, b_2, and TP_2: values after accelerated aging.

Table 4: Means and standard deviations of L, a, b, ΔL, Δa, Δb, and ΔE values and differences between groups for anterior composites.

	Bulk-fill PF		Bulk-fill GF		Bulk-fill control		p	4-5	5-6	4–6
L_1	67,12	(0,38)	67,22	(0,42)	68,28	(0,45)	*		*	*
L_2	65,22	(0,33)	65,97	(0,55)	65,92	(0,79)	*	*		*
ΔL	−1,91	(0,19)	−1,25	(0,49)	−2,36	(0,75)	*	*	*	
a_1	3,63	(0,13)	3,10	(0,25)	3,66	(0,19)	*	*	*	
a_2	5,37	(0,20)	5,06	(0,22)	5,33	(0,29)	*	*	*	
Δa	1,74	(0,15)	1,97	(0,27)	1,67	(0,19)	*		*	
b_1	19,34	(1,91)	20,77	(1,34)	21,76	(0,59)	*			*
b_2	20,00	(0,82)	20,08	(0,44)	20,71	(0,70)				
Δb	0,66	(1,45)	−0,70	(1,25)	−1,06	(0,54)	*	*		*
TP_1	13,38	(0,95)	14,51	(0,85)	15,09	(0,53)	*	*		*
TP_2	11,57	(0,76)	12,70	(0,53)	13,02	(0,80)	*	*		*
DE	2,98	(0,44)	2,71	(0,55)	3,17	(0,48)				

$^* p < 0.05$; $n = 10$; bulk-fill PF: incorporation of PF into the bulk-fill composite group (Group 4); bulk-fill GF: incorporation of GF into the bulk-fill composite group (Group 5); bulk-fill control: anterior composite control group (Group 6); 4-5: statistical results between Group 4 and Group 5; 5-6: statistical results between Group 5 and Group 6; 4–6: statistical results between Group 4 and Group 6; L_1, a_1, b_1, and TP_1: values at baseline measurement; L_2, a_2, b_2, and TP_2: values after accelerated aging.

3. Results

Table 3 shows the means (M) and standard deviations (SD) of L^*, a^*, b^*, ΔL^*, Δa^*, Δb^*, ΔE, TP, and p values of the anterior composites and also the differences between the experimental groups (EG). Before AAA, there were no significant differences in L^* and b^* parameters among the three EG ($p > 0.05$). However, the differences in TP and parameters between the groups were statistically significant ($p < 0.05$). After AAA, there were no significant differences in L^*, a^*, and b^* parameters in all groups ($p > 0.05$). TP chance was statistically significant between GF and control groups. Color change was statistically significant between PF and control groups ($p < 0.05$).

Table 4 shows the M and SD of L^*, a^*, b^*, ΔL, Δa, Δb, ΔE, and TP values of the bulk-fill composites and the differences among the EG. Before AAA, there were no significant differences in L^* parameter between PF and glass fiber groups, for a parameter between PF and control groups, for b parameter between PF and GF and also GF and control groups, and for TP parameter, between GF and control groups ($p > 0.05$). There were statistically significant differences observed between other groups. After AAA, there were no significant differences in L^* parameter between GF and control groups, for a parameter between PF and control groups, for b^* parameter for all groups, and for TP parameter between GF and control groups ($p > 0.05$). There were statistically significant differences observed between other groups ($p < 0.05$).

Table 5 shows the color differences between the fiber-reinforced groups and their respective control groups before AAA. As mentioned in this table, reinforcing with PF and GF to the anterior composites and reinforcing with GF fiber to the bulk-fill composites showed slight color change; on the

Table 5: Color differences between control and fiber-reinforced groups in NBS units before aging.

Material	ΔL	Δa	Δb	TP	ΔE	NBS	Color difference
Anterior PF	−2,43	1,32	3,56	6,52	0,93	0.86	Slight
Anterior GF	−1,9	1,7	2,92	6,74	0,53	0,49	Slight
Bulk-fill PF	−1,91	1,74	0,66	13,37	2,69	2,47	Noticeable
Bulk-fill GF	−1,25	1,97	−0,7	14,51	1,56	1,44	Slight

other hand, reinforcing with PF to the bulk-fill composites showed noticeable color change.

4. Discussion

On the basis of the attained data, the null hypothesis tested in the present study was partly rejected. That incorporation of fibers would not change the color of composites' color which was rejected; however, the research hypothesis was accepted with respect to the fact that TP was changed after AAA.

The CIE Lab color system that defines color with using three parameters (L^*, a^*, and b^*) was used in this study because of precise results for color parameters [23]. L^* defines lightness/darkness ranging from white (+) to black (−), a^* defines red/green ranging from red (+) to green (−), b^* defines yellow (+) and blue (−), respectively, and ΔE shows color change of the material. It is a method for evaluating color differences based on human perception. Based on the human's eye ability, values $1 < \Delta E < 3.3$ are considered appreciable by skilled operators, but clinically acceptable, $\Delta E > 3.3$ values are considered appreciable by nonskilled people and are, hence, not clinically acceptable [1]. In addition, in this study, NBS criteria were used to determine the relationship between the amount of color alteration recorded on a spectrophotometer and the clinical environment.

In this study, aging-dependent color differences are in accordance with some previous findings that accelerated aging resulting in the reduction in L^* values and increase of a^* and b^* values [24, 25]. It was surprising that in these studies aging to specimens was for 300 hours but in this study, aging time is 150 hours (150 kj/m^2), but the results are the same. Therefore it is unnecessary to age 300 hours to find these results for these materials; on the other hand, different periods and aging methods should be conducted for other materials.

The color stability of composite resins can be related to the material properties, that is, composite matrix, filler composition (size and type volume of charged particles), matrix-filler interface, and degree of polymerization (proportion of remaining unreacted carbon-carbon bonds), shade and to the restorative techniques including the finishing and polishing procedures [26, 27]. The polishing procedures were not investigated in this study; so to achieve the smoothest surface and to standardize the specimens, a Mylar strip was used during light-polymerizing and also to represent clinical situations when matrices were used [28].

Before AAA, incorporation of fibers in anterior composites changed their colors ΔE = 0,53 (anterior GF) and ΔE = 0,93 (anterior PF) and also with these color differences, they were considered clinically slight ($\Delta E < 1.5$); for bulk-fill composites ΔE = 1,56 (bulk-fill GF) and ΔE = 2,69 (bulk-fill PF) these color differences were noticeable ($\Delta E > 1.5$). As mentioned in Results, incorporation of fibers affected anterior composites clinically slightly and bulk-fill composites clinically noticeably. This discrepancy can be more translucency of bulk-fill composites.

According to a study [29], bulk-fill composites had similar color stability to hybrid composite after 40 days of AAA, which is similar to Tiba and others [30], but in this study, after accelerated aging, both of the composites showed clinically noticeable color change and also bulk-fill composites became more colorful (2,92 NBS units) than anterior composites (2,40 NBS units) without fibers. This can arise from more than one factor. Both of the composites contain silica-zirconia and composite filler but in different ratios, as showed in Table 1. Filler weight and percentage of the bulk-fill composites are lower than anterior composites. It may result in surface degradation of the material and absorbing more water, and then greater water sorption provides the composite with lower color stability, due to the increase in free volume of the formed polymer and, as a result, greater space for the water molecules emerges to diffuse into the polymeric network, contributing to degradation of the material [31]. The literature is confusing about the effects of the filler size of the composites on color [22, 31–33]. On the other hand, according to a study, monomer content and surface roughness affect discoloration of composites more than size of the filler particles does [34]. Hydrophilicity of the bulk-fill composite monomers may be more than anterior composites; for example, triethylene glycol dimethacrylate (TEGDMA) absorbs water more than a bisphenol glycidyl methacrylate does (Bis-GMA) and these proportions are also important [35]. In absence of pigments, degree of polymerization (proportion of remaining unreacted carbon-carbon bonds) and greater translucency in bulk-fill composites may be one of the other discoloration factors so discoloration is a multifactorial problem.

After AAA, the FRC and non-FRC groups of both anterior control composites and all of the bulk-fill composites showed clinically noticeable color changes in the range of 1.5–3 NBS units and also anterior PF and GF groups showed clinically appreciable color changes in the range of 3–6 NBC units in this study.

According to this study, the most color changes were observed in anterior PF composites (4.2 NBC units); the least were observed in anterior control group (2,40 NBC units). Thicknesses were chosen nearly the same in specimens (Ribbond-THM = 0,18 mm, glass fiber = 0,2 mm) in order not to affect results. Therefore, differences in their chemical structures and preparation procedures could be the reason why PF-reinforced composites exhibited greater color change than GF-reinforced composites did. PF is hand fabricated and GF is preimpregnated fibers by manufacturers. Improperly saturated fibers (PF) may cause voids in FRC and enhance water sorption, and consequently it became more colorful [18, 36]. On the other hand, this finding could be the result of superior adaptation with minimal space between the composite and the GFs. The refractive index of glass-fibers is different from that of the surrounding composite matrix along with its fillers and opacifiers and favors light penetration through composite, so it can be observed as light-colored compared to control groups. A previous study confirms this result [37].

According to our study, bulk-fill composites' TP were higher than anterior composites and adding to fibers decreased the TP values of specimens. Between the fiber groups, PF groups have less TP values than GF groups. After AAA, TP values of the all groups decreased. According to studies [22, 38] high temperature during accelerated aging could have increased the degree of conversion, leading to a change in the refractive index of the matrix. This, in turn, would make the material less translucent as our study increased scattering as a result. On the other hand, in Korkmaz Ceyhan et al. [39] study, obviously in contrast to our study, AAA did not influence the translucency of composites; it may arise from discrepancies of the shade and composites' content.

There were some limitations in this study. This was an in vitro study and influence of brushing and acids from foods and beverages effects on color stability of samples were not tested. These factors can cause major color change in composites in clinical practice. Examining all these parameters in future studies can lead to providing more precise results as well as in vivo studies.

5. Conclusions

According to present findings, the following conclusions were drawn.

(1) Fiber reinforcement led to color and TP change in both anterior and bulk-fill resin composites, but the color changes were below the visual perceptibility threshold ($\Delta E > 3.3$).

(2) PFs resulted in more colors and TP change than GFs after incorporation into the composite resins. Therefore, laboratory processed fibers would achieve better optimization of esthetics due to better processing and less voids, they can be preferred in esthetic area. PF can be used in nonesthetic area (palatal and posterior regions).

(3) After AAA, FRC and non-FRC groups of both composite materials became darker ($-L$ values), more reddish ($+a$), and more yellowish ($+b$).

(4) After AAA, anterior control and all of the bulk-fill composite groups showed clinically noticeable color changes in the range of 1.5–3 NBS units and also anterior PF and GF groups showed clinically appreciable color changes in the range of 3–6 NBC units.

(5) After AAA, the most color change was observed at anterior PF group (appreciable, 4,57 NBS units); the least was observed in anterior control groups (noticeable, 2,61 NBS units).

(6) After AAA, TP decreased in all groups; before and after AAA, bulk-fill composites were more translucent than anterior composites, and GF fibers were more translucent than PF fibers.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Bending Properties of Fiber-Reinforced Composites Retainers Bonded with Spot-Composite Coverage

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Orthodontic and periodontal splints are prepared with round or flat metallic wires. As these devices cannot be used in patients with allergy to metals or with aesthetic demands, fiber-reinforced composite (FRC) retainers have been introduced. Stiffness of FRC materials could reduce physiologic tooth movement. In order to lower rigidity of conventional FRC retainers, a modified construction technique that provided a partial (spot) composite coverage of the fiber has been tested and compared with metallic splints and full-bonded FRCs. Flat (Bond-a-Braid, Reliance Orthodontic Products) and round (Penta-one 0155, Masel Orthodontics) stainless steel splints, conventional FRC splints, and experimental spot-bonded FRC retainers (Everstick Ortho, StickTech) were investigated. The strength to bend the retainers at 0.1 mm deflection and at maximum load was measured with a modified Frasaco model. No significant differences were reported among load values of stainless steel wires and experimental spot-bonded FRC retainers at 0.1 mm deflection. Higher strength values were recoded for conventional full-bonded FRCs. At maximum load no significant differences were reported between metallic splints (flat and round) and experimental spot-bonded FRCs, and no significant differences were reported between spot- and full-bonded FRC splints. These results encourage further tests in order to evaluate clinical applications of experimental spot-bonded FRC retainers.

1. Introduction

The retention of teeth in the upper and lower jaw is often required after orthodontic treatment or for periodontal reasons [1]. Usually the stabilization is obtained with flat or round multistranded metallic wires. Splints have been introduced initially as canine-to-canine metallic round retainers [2]. Subsequently, in order to prevent incisors undesirable movements, round and then flat splints bonded to all anterior teeth were introduced [3]. Numerous types of fixed retainers have been described in literature with many sizes, diameters, and shapes [4]. These devices are very common but they cannot be used in patients that have to undergo nuclear magnetic resonance, as during the exam the metal could raise in temperature or interfere with image quality [5]. Moreover, also hypersensitivity to nickel and other metals may cause type IV allergic reactions, thus preventing the use of multistranded splints [6]. Finally, in patients with high aesthetic demands, the presence of metallic structures, even if almost or totally invisible, could slightly lower tooth translucency [7]. On the basis of these concerns, fiber-reinforced composites (FRC) retainers have been introduced for multiple clinical applications [8, 9]. In fact the reinforcement of composite with short or long fibers (Carbon, Aramid, Polyethylene, Glass) provide better mechanical and physical properties over unreinforced materials [10, 11]. FRC splints are metal-free and provide excellent aesthetical results [12].

Table 1: Materials tested.

Denomination	Flat metallic wire	Round metallic wire	Fiber reinforced composite	Fiber reinforced composite
Code	FW	RW	SF	FF
Manufacturer	Reliance	Masel	StickTech	StickTech
Name	Bond-a-Braid	Penta-one 0155	FRC Ortho	FRC Ortho
Design	Ribbon arch	Coaxial	Unidirectional fiber bundle	Unidirectional fiber bundle
Material	Stainless steel	Stainless steel	E-glass fiber 15 μm	E-glass fiber 15 μm
Dimensions	0.673 mm × 0.268 mm	Diameter: 0.394 mm	Diameter: 0.75 mm	Diameter: 0.75 mm
Unit amount	8 wires	5 wires	1000 fibers	1000 fibers
Bonding technique	Conventional spot	Conventional spot	Experimental spot	Conventional full

Clinical reliability of FRC retainers has been tested, showing conflicting results. Some reports reported similar [13–15] or higher [16] efficiency if compared with metallic splints. On the other hand some authors [1] reported less reliability if compared to conventional retainers over time. The variability of the results can be related to different fibers and techniques tested in the various investigations. Therefore it is still unclear if FRCs behavior allows better performances over metallic splints. However FRC retainers are nowadays widely used in clinical dentistry [15].

Moreover these materials showed significantly higher stiffness than conventional metallic splints and wires [17–20]. This characteristic could reduce physiologic tooth movement and this could lead to a higher ankylosis risk for the teeth involved [21].

FRC rigidity is mainly related to composite bulk that covers the entire structure once the fiber is placed onto teeth surfaces [22]. The total composite coverage of FRCs is suggested from the manufacturer [12, 13]. In fact, an experimental preparation technique that would involve composite coverage of FRCs only in correspondence of the teeth would leave the fiber exposed in the interproximal zones, thus mimicking conventional metallic splint rigidity and mechanical behavior.

To our knowledge in literature FRCs have been tested only with a full composite coverage technique, whereas no studies evaluated mechanical properties of FRC splints prepared with a spot-bonded technique. Therefore the purpose of the present report was to evaluate the load to bend FRC splints prepared with both full- and spot-bonding techniques and to compare FRCs with conventional metallic flat or round splints. The null hypothesis of the present report was that there are no significant differences among the various groups tested.

2. Materials and Methods

In the present investigation, rectangular metallic splints (Bond-a-Braid, Reliance Orthodontic Products, Bond-a-Braid, Reliance Orthodontic Products Inc., Itasca, IL, USA), round metallic splints (Penta-one 0155, Masel Orthodontics, Carlsbad, CA, USA), and FRCs (Everstick Ortho, StickTech, Turku, Finland) were tested (Table 1).

All materials were divided into coded groups of 10 specimen each (length: 28 mm), according to different bonding techniques:

(i) FW: flat metallic wire;

(ii) RW: round metallic wire;

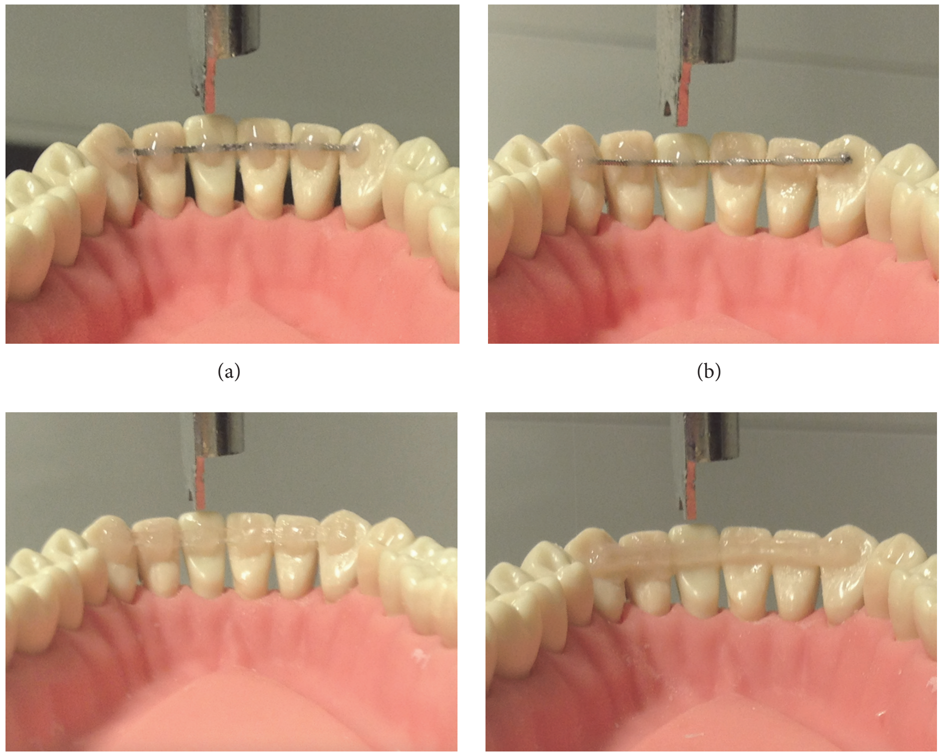
(iii) FS: FRC spot-bonded;

(iv) FF: FRC full-bonded.

All specimens were then prepared to be bonded to an acrylic Frasaco mandible model, simulating a canine-to-canine splint [23]. Element 3.1 was inserted to the correspondent hole without rigid fixation, thus allowing vertical movement of the tooth. On the other hand, other acrylic teeth were screwed to their correspondent holes. The metallic and FRC splints were bonded to each element from 3.3 to 4.3 with a one-step, self-etch 7th generation bonding agent (G-aenial Bond, GC America, Alsip, IL, USA) and fixed with flow composite (G-aenial Universal Flo, GC America, Alsip, IL, USA). As showed in Figure 1, the composite covered the retainer only in correspondence of each tooth, thus leaving the splint exposed in interproximal zones (Codes FW, RW, and FS). Conversely, composite coverage was performed also in interproximal spaces in full-bonded FRC splints (code: FF). All specimens were then light cured with ahalogen lamp (Elipar S10, 3M, Monrovia, CA, USA) with a light intensity of 1200 mW/cm^2 and a wavelength range of 430–480 nm for 40 seconds for each tooth.

Subsequently the strength to bend the retainer in correspondence of element 3.1 was measured at 0.1 mm deflection (groups 1 to 4) and at maximum load (groups 5 to 8) with a universal testing machine (Lloyd LRX; Lloyd Instruments, Fareham, United Kingdom). The crosshead speed was set at 1.0 mm per minute [18, 19]. The strength values were recorded in newton with Nexygen MT software (Lloyd Instruments).

Data were submitted to statistical analysis using computer software (R version 3.1.3, R Development Core Team, R Foundation for Statistical Computing, Wien, Austria). Descriptive statistics including mean, standard deviation, minimum, median, and maximum were calculated for the 8 groups. The normality of the data was calculated using the Kolmogorov-Smirnov test and confirmed with graphs in order to avoid



(a) (b) (c) (d)

Figure 1: Flat metallic splint (a) round metallic splint (b) experimental spot-bonded FRC (c) and conventional full-bonded FRC (d).

Table 2: Descriptive statistics (N) of load values of the 8 groups tested (each group consisted of 10 specimens).

Group	Code	Material	Shape	Bonding	Deflection	Mean	SD	Min	Mdn	Max	Post hoc
1	FW	Stainless steel	Flat wire	Spot bonded	0.1 mm	8.33	1.68	6.19	8.90	10.76	A
2	RW	Stainless steel	Round wire	Spot bonded	0.1 mm	4.24	1.16	3.23	3.84	6.66	A
3	FS	FRC	Fiber bundle	Spot bonded	0.1 mm	16.67	2.08	13.53	16.18	19.33	A
4	FF	FRC	Fiber bundle	Full bonded	0.1 mm	41.73	16.16	12.18	44.52	58.64	B, C, D
5	FW	Stainless steel	Flat wire	Spot bonded	max load	34.96	6.76	22.86	35.79	44.86	B
6	RW	Stainless steel	Round wire	Spot bonded	max load	35.62	10.26	21.22	38.19	50.74	B
7	FS	FRC	Fiber bundle	Spot bonded	max load	41.44	9.19	29.31	40.32	53.46	B, D
8	FF	FRC	Fiber bundle	Full bonded	max load	52.93	18.84	15.24	57.88	74.12	C, D

Mean with same letters is not significantly different.

misunderstanding due to sample size. An analysis of variance (ANOVA) was used and the repeated measures option was set to adjust for the fact that each specimen gave two outcomes. Tukey test was then applied to evaluate differences among the deflection values of the various groups. Statistical results were adjusted for multiple comparisons. Significance for all statistical tests was predetermined at $P < 0.05$.

3. Results

The descriptive statistics (mean, standard deviation, median, minimum, and maximum) of loads (N) recorded in the 8 groups are showed in Table 2.

The results of ANOVA indicated the presence of significant differences among the various groups ($P < 0.001$).

Post hoc test pointed out that, at 0.1 mm (Figure 2, groups 1 to 4) deflection, the lowest flexural strengths were recorded for stainless steel flat (group 1) and round (group 2) wires and for spot-bonded FRC (group 3) retainers that showed no significant differences among them ($P < 0.05$). Significantly higher force levels ($P < 0.001$) were reported for full-bonded FRC splints (group 4).

On the other hand, at maximum load (Figure 3, groups 5 to 8) no significant differences ($P > 0.05$) were reported among metallic flat, metallic round, and spot-bonded FRC splints (groups 5, 6, and 7). The highest load values were

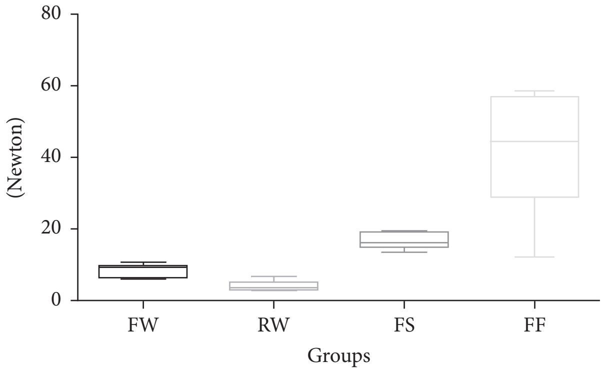


Figure 2: Box plot of strength values (N) of the various groups tested at 0.1 mm deflection.

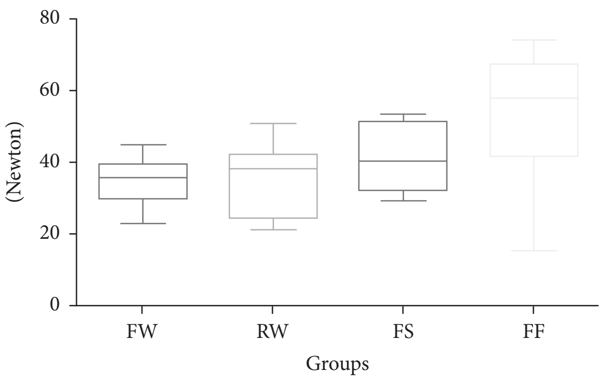


Figure 3: Box plot of strength values (N) of the various groups tested at maximum load.

reported for full-bonded FRC retainers (group 4) that showed no significant differences with spot-bonded FRC splints ($P > 0.05$).

4. Discussion

The null hypothesis of the present investigation has been rejected. No significant differences were reported among load values of flat and round stainless steel wires and experimental spot-bonded FRC retainers at 0.1 mm deflection. Significantly higher strength values were recoded for conventional full-bonded FRCs.

At maximum load no significant differences were reported between metallic splints (flat and round) and experimental spot-bonded FRC retainers. Highest strength values were reported with conventional spot-bonded FRCs; no significant differences were reported between spot- and full-bonded FRC splints.

The high bend values of conventional full-bonded FRCs reported in the present investigation is a confirmation of previous reports that showed high rigidity of FRC splints if compared with metallic splints [19, 20] and wires [17, 18]. Even if it is still controversial if the presence of an excessively rigid bonded lingual retainer has a negative effect on the periodontal tissues, ideal retention would allow physiologic tooth micromovements [21]. In fact, clinicians need to splint groups of teeth for many reasons. First of all, after orthodontic treatment the stability is considered one important goal, as the tendency of relapse has been extensively reported, mostly for lower anterior teeth [24]. Moreover, another reason for splinting is related to periodontal problems, as the teeth that have lost part of their supporting bone can be efficiently stabilized with the aid of provisional or definitive retainers connecting them in groups [16]. Finally, splints are widely used after occasional traumas, to stabilize injured teeth [25].

Multistranded wires have been showed to be a successful retention method for over 40 years [2]. They are well accepted from patients and relatively independent of patient cooperation [4], even if a certain number of patients cannot wear these devices. In fact, the release of nickel, chromium, and other metals from brackets, bars, and splints has been demonstrated [26–29]. Moreover, nuclear magnetic resonance exams require the removal of metal appliances in order to avoid heating and image artifacts risks [5]. For these reasons, FRC splints have been introduced. These retainers made of glass fibers nowadays represent the only esthetic and metal-free material, which can be processed in mouth to the desired shape and subsequently can be directly bonded to teeth surfaces [30]. The bonding technique is easy and fast, no laboratory work is needed, and procedures can be completed in a single appointment [13, 14, 18].

FRCs are constituted with continuous unidirectional glass (bundle) fibers in dimethacrylate-polymethylmethacrylate resin matrix as a substructure [30]. The FRCs used for retainer preparation are plain fibers and in prepreg form, so that the fibers were preimpregnated with polymethylmethacrylate from the manufacturer [31].

FRC retainers have been tested in literature and their biomechanical behavior is well known. Previous reports that evaluated FRCs flexural strength reported high load values already at minimum deflections [18, 19]. This is confirmed in the present study for conventional full-bonded FRCs. When comparing the results obtained at 0.1 mm deflection and at maximum load, a significant increase in strength values was reported for flat and round metallic wires and for spot-bonded FRCs. On the other hand, no significant differences were reported for conventional full-bonded FRCs. Therefore, conventional full-bonded FRCs expressed their high rigidity already with minimum deflections, whereas spot-bonded FRCs (as metallic flat and round splints) exhibited high load values only at maximum load. This could be considered an encouraging result improving FRC splints, thus allowing a behavior more similar to metallic retainers than to conventional full-bonded FRC retainers. No other studies to our knowledge evaluated bend values of spot-bonded FRCs.

Other authors evaluated the fatigue of metallic structures and FRCs. Retentive properties of cast metal clasps decrease over time because of metal fatigue. On the other hand, FRC materials showed increased fatigue resistance if compared with metals and may offer a solution to the problem of metal fatigue [31].

Moreover also shear bond strength has been measured both for FRC bundles [32] and nets [33] showing acceptable results. Most common failures in FRC reported in literature include intralaminar matrix cracking, longitudinal matrix splitting, fiber/matrix debonding, fiber pull-out, and fiber fracture, which can be often repaired in patients' mouth [30].

Finally clinical reliability of FRC splints has been reported showing many clinical applications [9, 34] and acceptable failure rates if compared with conventional multistranded metallic wires [13–15]. On the other hand FRC splints present some disadvantages, as higher costs [18], the difficulty to repair if debonded [13], and high rigidity [17]. In fact, when splinting group of teeth excessive rigidity is unwanted from the clinicians as the reduction of physiologic tooth movement could increase ankyloses risk. The low bend values recorded in the present report for experimental spot-bonded technique are promising in reducing FRCs stiffness.

In fact, the conventional FRC construction technique includes enamel etching, washing, and drying. Subsequently a thin layer of adhesive is applied and light cured, and the FRC is placed on teeth surfaces. Finally the a small account of composite paste or flow is used to cover the entire splint and light cured for 40 seconds for each teeth, as suggested from the manufacturer [12–14]. The experimental FRC preparation technique proposed in the present investigation is quite similar. The main difference is that, after FRC positioning, the composite paste or flow that covers the structure has been placed only in correspondence of each tooth, leaving the FRC free of coverage in interproximal spaces. When composites are cured in air, as in clinical practice, an oxygen inhibition layer (0.1 mm thick approximately) is formed on the surface of the freshly cured composite resin. The components of the oxygen inhibition layer present similar composition to those of the uncured resin with reduced amount of photoinitiator [35]. Therefore, also FRCs are affected by this layer, thus reducing their effective diameter of 0.1 mm approximately [36]. The reduction in diameter has been demonstrated to reduce flexural strength of both conventional [17, 18, 37] and nanofilled [38, 39]. This could explain lower bend values showed for experimental spot-bonded FRC in the present investigation. However, in literature no other reports tested spot-bonding technique for FRC retainers. Therefore, further investigation about mechanical characteristics, physical properties, and biocompatibility concerns of these partially uncovered retainers should be conducted before suggesting routinely clinical use.

5. Conclusions

The present study demonstrated that experimental spot-bonded FRC showed lower load to bend the retainer at 0.1 mm deflection if compared with conventional full-bonded FRC. Moreover no significant differences were reported among stainless steel flat and round wires and spot-bonded FRCs.

At maximum load no significant differences were reported between metallic splints (flat and round) and experimental spot-bonded FRC retainers, and no significant differences were reported between spot- and full-bonded FRC splints.

The results of the present report encourage further in vitro and in vivo tests in order to evaluate future clinical applications of experimental spot-bonded FRC retainers.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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