journal of the mechanical behavior of biomedical materials 118 (2021) 104440

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: http://www.elsevier.com/locate/jmbbm

Fatigue failure of anterior teeth without ferrule restored with individualized fiber-reinforced post-core foundations

Márk Fráter[a,1,*], Tekla Sáry[a,1], Gábor Braunitzer[b], Balázs Szabó P.[c], Lippo Lassila[d], Pekka K. Vallittu[d,e], Sufyan Garoushi[d]

[a] Department of Operative and Esthetic Dentistry, Faculty of Dentistry, University of Szeged, Szeged, Hungary
[b] DicomLAB Dental Ltd., Szeged, Hungary
[c] Department of Food Engineering, Faculty of Engineering, University of Szeged, Szeged, Hungary
[d] Department of Biomaterials Science and Turku Clinical Biomaterials Center -TCBC Institute of Dentistry, University of Turku, Turku, Finland
[e] City of Turku Welfare Division, Oral Health Care, Turku, Finland

ARTICLE INFO

Keywords:
Fatigue survival
Post-core foundation
Short fiber-reinforced composite
Individualized post

ABSTRACT

Objectives: The aim was to explore the survival of extensively damaged anterior teeth without ferrule restored with different fiber-reinforced composite (FRC) post-core foundations and composite crowns.

Materials and methods: Sixty extracted upper central incisors were decoronated and randomly divided into four groups (n = 15). After endodontic treatment, the specimens were restored with different individualized fiber-reinforced post-core foundations as follows: control group (CTRL): multiple unidirectional FRC-post + dual-cure composite-core, PFC: multiple unidirectional FRC-post + packable short fiber-reinforced composite (SFRC), BPFC: Bioblock technique with only packable SFRC, BFFC: Bioblock technique with only flowable SFRC. After core build-up, the teeth were finalized with adhesively luted CAD/CAM composite crowns. Cyclic isometric loading (5 Hz) was applied at 100 N for 5000 cycles, and then 200 N and 300 N for 15,000 cycles each in a fluid chamber. The specimens were loaded until fracture occurred or when a total of 35,000 cycles were reached. Kaplan-Meyer survival analysis was conducted, followed by pairwise log-rank post hoc comparisons (Mantel-Cox).

Results: The survival rates of the control (8279 cycles) and PFC (6161 cycles) were significantly higher compared to BPFC (3223 cycles) and BFFC (2271 cycles) ($p < 0.05$). Regarding fracture pattern, nearly all specimens fractured in a restorable manner.

Conclusions: For restoring extensively damaged anterior teeth, multiple unidirectional FRC posts are recommended.

Clinical relevance: Although different FRC post/core systems are available for the restoration of damaged root canal treated anterior teeth, multiple unidirectional FRC posts tend to be a good option when the ferrule is missing.

1. Introduction

Root canal treated (RCT) teeth usually need significant build-up with various post-core materials to help the retention of the full crown restoration (Lassila et al., 2019). Post usage is determined by the amount of residual coronal structure and the internal root structure. The primary purpose of a post is to provide retention when the residual coronal structure is inadequate to retain the core material (Santos Pantaleón et al., 2018). Post placement is advised in anterior teeth when less than 50% of the crown remains (Zarow et al., 2018; Meyenberg, 2013a). One of the key elements influencing the success of post-restorations is the presence or absence of a 1.5–2 mm high coronal dentin after preparation, known as the “ferrule”.

The purpose of the ferrule is to redistribute the occurring stress on the outer coronal third of the root, therefore possibly shifting the fracture pattern to a restorable one (Fragou et al., 2012).

* Corresponding author. Chair of the department Department of Operative and Esthetic Dentistry Faculty of Dentistry University of Szeged Tisza Lajos Krt. 64 H-6720, Szeged, Hungary.
E-mail address: meddentist.fm@gmail.com (M. Fráter).
[1] Márk Fráter and Tekla Sáry contributed equally to this work.

https://doi.org/10.1016/j.jmbbm.2021.104440
Received 22 December 2020; Received in revised form 6 February 2021; Accepted 26 February 2021
Available online 3 March 2021

Studies have shown that the presence of a ferrule is of high importance (Santos Pantaleón et al., 2018; Lazari et al., 2018; Magne et al., 2016). However, restoring RCT anterior teeth can be a challenge when there is no ferrule (Saker and Özcan, 2015). Possible approaches to such a situation involve surgical crown lengthening and orthodontic extrusion. However, many times patients are unwilling to undergo these interventions and only allow restorative procedures.

In such situations, choosing the adequate type of post is a key element of success. Of the different post materials, glass fiber-reinforced composite (FRC) posts stand out with their favourable biomechanical characteristics and ability to enhance light transmission through the root canal space (Saker and Özcan, 2015). FRC posts contain long unidirectional fibers encapsulated with resin matrix of epoxy or mono/di-methacrylate. Depending on the resin system, there are two main type of FRC posts: regular FRC posts with a predefined shape containing fully-polymerized and highly cross-linked polymer matrix, and individually-made FRC posts which contain nonpolymerized resin matrix which forms a semi-IPN matrix after curing (Vallittu and Özcan, 2017). Some studies have shown that FRC posts decrease the incidence of catastrophic fractures (Mohammadi et al., 2009), however, other studies found no difference (Figueiredo et al., 2015) or even the opposite (Magne et al., 2017) regarding the fracture pattern.

It should be emphasized that anterior teeth restored with a post have a fracture rate that is 3 times higher compared to posterior teeth (Garcia et al., 2019). This could partly be attributed to the higher horizontal forces that these teeth are exposed to because of their position in the arch. Once greater horizontal forces are present, the post-root canal interface is challenged, and any potential flaw can later progress into failure. In case of FRC posts, loss of retention or post fracture are the most frequent types of failure (Zicari et al., 2012). The reasons are manifold, including the assumed weakening of the root during post space preparation, the inaccurate fit of the post due to the irregular geometry and cross section of the root canal, or the inability of the post material to adequately bond to the luting or core build-up material. This later one could be solved by the usage of individually-made FRC posts (everStick Post, GC Europe) containing polymethyl methacrylate (PMMA) resin, which insures proper and durable bonding to the luting/and or core build-up resin material (Bell-Rönnlöf et al., 2019). Vallittu concluded that the amount and adaptation of fibers in the critical cervical part of the tooth could determine the success of restorative procedures involving post insertion (Vallittu, 2016). Should the post fail to fit well, particularly at the coronal level, the resin cement film will be too thick; this favours bubble formation, which may result in post de-bonding. A way to overcome this problem is to fabricate individualized posts that aim to maximize the amount of fibers and minimize the amount of luting material in the root canal, thus providing an ideal fitting of the post irrespective to the unique cross-section of the root canal. One clinically relevant option is to make an individualized FRC post from multiple unidirectional FRC posts (Hatta et al., 2011; Fráter et al., 2017). Another possibility is to fabricate the post and core build-up directly from short fiber-reinforced composites (SFRC) inside the root canal (Garoushi et al., 2009; Forster et al., 2016; Fráter et al., 2020a). In the Bioblock technique, both the root canal space and the coronal cavity are filled with conventional or packable SFRC in 4–5 mm thick horizontal increments (Fráter et al., 2020a, 2020b). In 2019, the flowable form of SFRC was introduced with the promise of easy adaptability in limited spaces (such as root canals).

The question arises whether one may use just any version of SFRC for post and core to restore RCT anterior teeth in the absence of ferrule or unidirectional long fibers (in the form of FRC posts) are preferable. To the authors' best knowledge, this is not well documented in literature. Thus, unlike previously published research, the purpose of this *in vitro* study was to investigate the fatigue resistance and failure patterns of RCT anterior teeth without a ferrule restored with different FRC materials and crowns. The null hypotheses were that (1) the tested individualized FRC post and core techniques would not differ from the control group in fatigue resistance, or (2) in their fracture pattern.

2. Materials and methods

The Ethics Committee at the University of Szeged approved this study as it was planned in according to the declaration of Helsinki. All materials adapted in this study are made by the same manufacturer and used according to the instructions of use.

Intact maxillary central incisors extracted for periodontal causes were collected for this research. The newly extracted maxillary central incisors were directly inserted for only 5 min in sodium hypochlorite (5.25%) and then kept in solution of saline (0.9%) for a maximum 8 weeks at room temperature before use. After extraction, with the aid of hand scalers, the root surface was cleaned from the covered soft tissue. Sixty upper central incisors having equal mesiodistal and buccolingual dimensions and root length of 13 mm were chosen. On the basis of the measurements, only teeth with a maximum deviation of 10% from the determined mean were included in this study.

Before performing root canal treatment, diamond disc with water cooling was used to section all crowns horizontally at the level of the cementoenamel junction (CEJ). ProTaper Universal files (S1, S2, F1, F2) (Dentsply Maillefer, Ballaigues, Switzerland) were used for cleaning and shaping of the root canals. Irrigation with sodium hypochlorite (2.5%) was applied during instrumentation. After the instrumentation phase, alcohol (96%) and paper points were used for drying the root canals. Single cone obturation technique was performed for root canal filling using a master cone (F2 gutta-percha, Dentsply Maillefer) and sealer (AH plus, Dentsply Maillefer). Fuji Triage Pink (GC Europe, Leuven, Belgium) was used as temporary filling and also applied on the root tip with the purpose of preventing apical leakage. The filled roots were kept in an incubator (mco-18aic, Sanyo, Japan) for 7 days (100% relative humidity, 37 °C). Before the post space preparation the decoronated flat surface of the root was roughened with a diamond bur. All roots obtained a post space preparation (minimal invasive) with a 7 mm depth measured from the orifice, but no post preparation drills were used so that the individual anatomy of the root canal can be maintained. ISO standard Hedstrom files (Dentsply Maillefer) and Number 3 Gates Glidden burs (Dentsply Maillefer) were used to remove only the gutta-percha and leaving a minimum apical seal of 5–6 mm in the canal. Once the post space was ready, the root canal was washed with chlorhexidine and dried with paper points.

In the control (CTRL) and PFC groups, an individualized FRC post was directly created in the canal as described by Hatta et al. (2011). The root canal received as many fiber bundles (0.9-mm-sized) of uncured FRC posts (everStick POST, GC Europe) as possible, to exactly fit the individual cross-section of the root canal. These posts were gently removed from the root canal as one unit with a needle-nose plier and then light cured for 40 s.

Same adhesive treatment was used for all teeth. According to the manufacturer's instructions a dual-cure one-step self-etch adhesive system (Gradia Core Self-Etching Bond, GC Europe) was applied. Suction tip and paper point were used to remove the excess adhesive. An Optilux 501 quartz-tungsten-halogen light-curing unit (Kerr Corp., Orange, CA, USA) was used to light cure (60 s) the adhesive. The average power density of the light-curing unit, which was justified with a digital radiometer (Jetlite light tester; J. Morita USA Inc. Irvine, CA, USA) was 900 mW/cm^2. After light curing the adhesive, the specimen were distributed among 4 groups according to the different individualized fiber reinforced post-and-core techniques. The teeth were restored as follows (Fig. 1):

CTRL: The teeth received an individualized FRC post fabricated from 2 to 3 pieces of FRC posts as previously described. Following the manufacturer's instructions the surface of the individualized post was activated with pure resin (Stick Resin, GC Europe). Luting of the individualized posts and the core build-up was performed with a dual-cure resin composite core material (Gradia Core, GC Europe). After

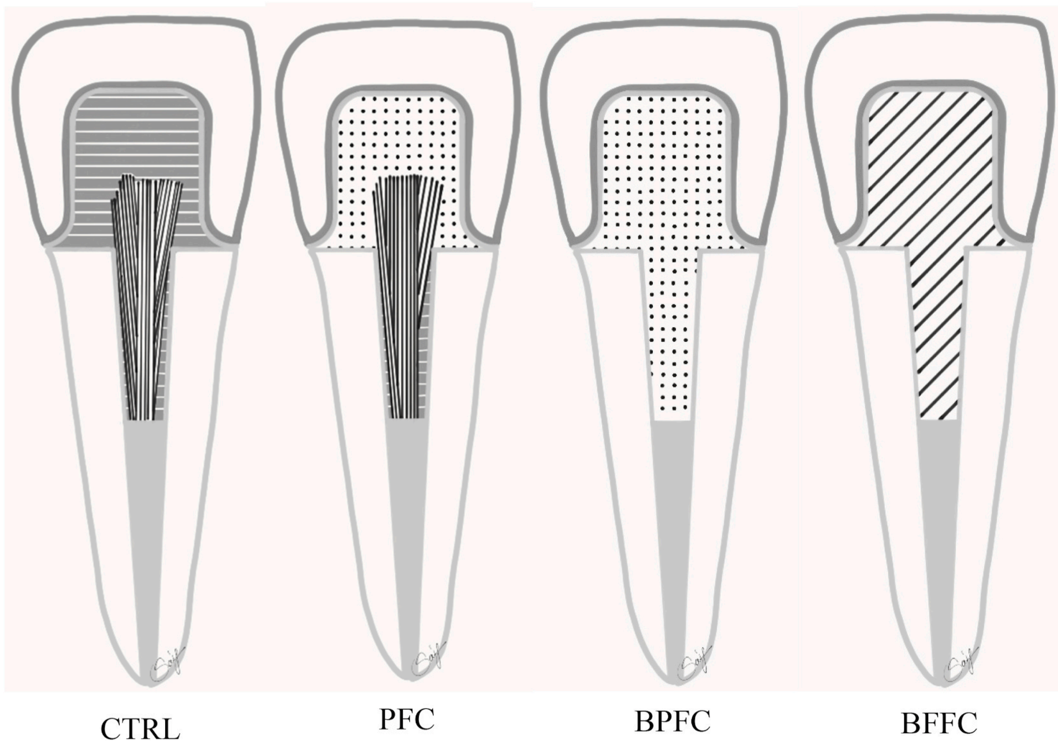

Fig. 1. Schematic figure representing the test groups. CTRL: Individually-made unidirectional FRC post + Gradia Core; PFC: Individually-made unidirectional FRC post + packable SFRC core; BPFC: Bioblock technique with packable SFRC; BFFC: Bioblock technique with flowable SFRC.

the insertion of the post, 5 min of autopolymerization time was given to decrease polymerization stress. Subsequently the build-up was light cured for 40 s from each side (a total of 160 s/tooth).

PFC: The teeth received an individualized FRC post, fabricated in the same way as in the control group. Luting of the individualized posts was performed the same way as in the control group, but the core build-up around the post was performed with SFRC (everX Posterior, GC Europe) packed around the post using approximately 3-mm-thick horizontal increments. Each increment was light cured from the side for 40 s (a total of 160 s/tooth).

BPFC: The teeth were restored with the Bioblock technique described by Fráter et al. (2020a), building a direct layered post and core from packable SFRC (everX Posterior). An approximately 4 mm thick increment of SFRC was packed into the apical portion of the post space using a microbrush-X disposable applicator (Pentron Clinical Technologies, LLC, USA). A short piece of light-transmitting FRC post (1.2 mm GC Fiber post, GC Europe) was inserted into the post space with the aim of aiding the transmission of the light to the apically placed layers. As described in the Bioblock technique (Fráter et al., 2020a) the light-transmitting post was positioned 0.5–1 mm coronally from the surface of the uncured SFRC layer. After each layer, 80 s of light curing through the fiber post followed. After incrementally filling the root canal to the level of the CEJ, SFRC was layered to form the core build-up. Each coronally placed increment was light cured from the occlusal direction for 40 s.

BFFC: The teeth were restored with flowable SFRC (everX Flow, GC Europe) as described in BPFC.

After the post and core build-ups all cores were finalized according to the protocol of Maroulakos et al. (2015). All cores were prepared 3 mm incisal to the finish line lingually and 6 mm incisal to the finish line buccally. This simulated a central incisor preparation having no remaining tooth structure above the prepared finish line. The finish line was a 1 mm wide circumferential shoulder prepared with a flat-end, medium grit, tapered diamond (847/018; Brasseler). After finalizing the preparation, polyether impression (Permadyne, 3M ESPE, Germany) was taken of each prepared specimen. The impressions were molded and the models underwent digital scanning using the Cerec CAD/CAM system (Sirona Dental Systems GmbH, Bensheim, Germany) and restorations were designed using the 4.4 Cerec software. Nanofilled composite resin anterior crowns (Cerasmart, GC Europe) with standardized dimensions and thickness were milled and carefully adjusted to the prepared specimen under optical microscopy (Carl Zeiss Technical Stereomicroscope, Germany), and polished.

At the luting phase, the fitting surface of the composite crowns was sandblasted, rinsed and ultrasonically cleaned (Emag, Valkenswaard, Netherlands) in distilled water for 5 min. After drying the surface, the fitting surface was treated with a special silane (G-Multi Primer, GC Europe). The prepared core was sandblasted and adhesively treated with a self-etch universal adhesive (G-Premio Bond, GC Europe). The adhesive was thinned out and photopolymerized for 60 s. The crowns were adhesively luted with a dual-cure adhesive resin cement (G-CEM Link-Force, GC Europe). The luting agent was applied into the fitting surface of the restoration and the crowns were positioned on the prepared cores under finger pressure until they reached their final position. After ensuring that all excess material had been removed, glycerine gel (DeOx Gel, Ultradent Products Inc., Orange, CA, USA) was applied and photopolymerization was performed from each side for 40 s with Optilux 501. All teeth after luting of the crown had a standardized coronal cervical-incisal length between 8 and 8.5 mm.

The restored specimens were kept wet (Isotonic Saline Solution 0.9%; B. Braun, Melsungen, Germany) in an incubator (37 °C). The root surface of each specimen was coated with two layers of liquid latex separating material (Rubber-Sep, Kerr, Orange, CA, USA) prior to embedding for mimicking the periodontal ligament. To simulate the bone level, the restored teeth were embedded in methacrylate resin (Technovit 4004, Heraeus-Kulzer, Germany) at 2 mm from the cementoenamel junction (CEJ). For mechanical testing, the restoration-tooth units were submitted to an accelerated fatigue-testing protocol, described by Lazari et al. (2018), performed with a hydraulic testing machine (Instron ElektroPlus E3000, Norwood, MA, USA). The specimens were tested at an angle of 135° to the long axis of each tooth in a fluid chamber filled with saline in order to simulate oral conditions as much as possible. Cyclic isometric loading was applied on the incisal edge of the tooth using a 1 cm wide, flat ended metallic tip. Cyclic load was applied at 5 Hz, starting with gradually increasing static loading until 100 N in 5 s, followed by cyclic loading at 100 N for 5000 cycles, and then at 200 N and 300 N, for 15,000 cycles each. The specimens were loaded until fracture occurred or when a total of 35,000 cycles were reached. For the survival analyses, the total number of pre-failure cycles was recorded. After the loading test all specimens were inspected under optical microscope and the failure mode was evaluated. Distinction was made between restorable or nonrestorable fractures with a two-examiner agreement. A restorable fracture was defined as a fracture that ends above the CEJ, whereas a nonrestorable fracture extends below the CEJ. This means that the fractured tooth can be restored and kept in the mouth in case of a restorable fracture, while in case of a nonrestorable one the tooth is likely to be extracted.

Statistical analysis was performed in SPSS 23.0 (IBM Corp., Somers, NY, USA). Kaplan-Meyer survival analysis was conducted, followed by pairwise log-rank post hoc comparisons (Mantel-Cox).

3. Results

The Kaplan–Meier survival curves are presented in Fig. 2. Table 1 shows the descriptive characterization of the survival as the mean and median number of survived cycles for each tested group. Table 2 displays the p values for group-wise comparisons. There was no statistically significant ($p > 0.05$) difference in terms of survival between CTRL and PFC groups, and also between BPFC and BFFC groups. Regarding the fracture pattern, all specimens showed a restorable type of fracture except PFC group that had one specimen presenting a nonrestorable fracture type (Fig. 3).

4. Discussion

Endodontically treated teeth without adequate ferrule pose considerable therapeutic challenge, and the selection of the correct post type could be a key element in the success of the treatment (Maroulakos et al., 2015). In this study, different individualized FRC post-and-cores were used with the purpose of reinforcing anterior teeth without ferrule. Our hypotheses are partially rejected, as there was a significant difference found in fatigue resistance performance among the restorative techniques used (Fig. 2). However, there were no differences in fracture pattern between the groups.

During the mechanical testing, cyclic loading was applied according to an accelerated fatigue testing protocol (Lazari et al., 2018; Magne et al., 2016). Cycling fatigue loading simulates the clinical situation better than static loading, as it generates cyclic forces similar to normal masticatory forces. Moreover, frequently acting cyclic forces induce root fracture more often than static forces. This protocol (accelerated fatigue) was introduced as a rational middle ground between the load to fracture test and the more sophisticated and time-consuming fatigue tests. By convention, the specimens were loaded at 135° to mimic the chewing forces applied on the palatal surface of an upper anterior tooth.

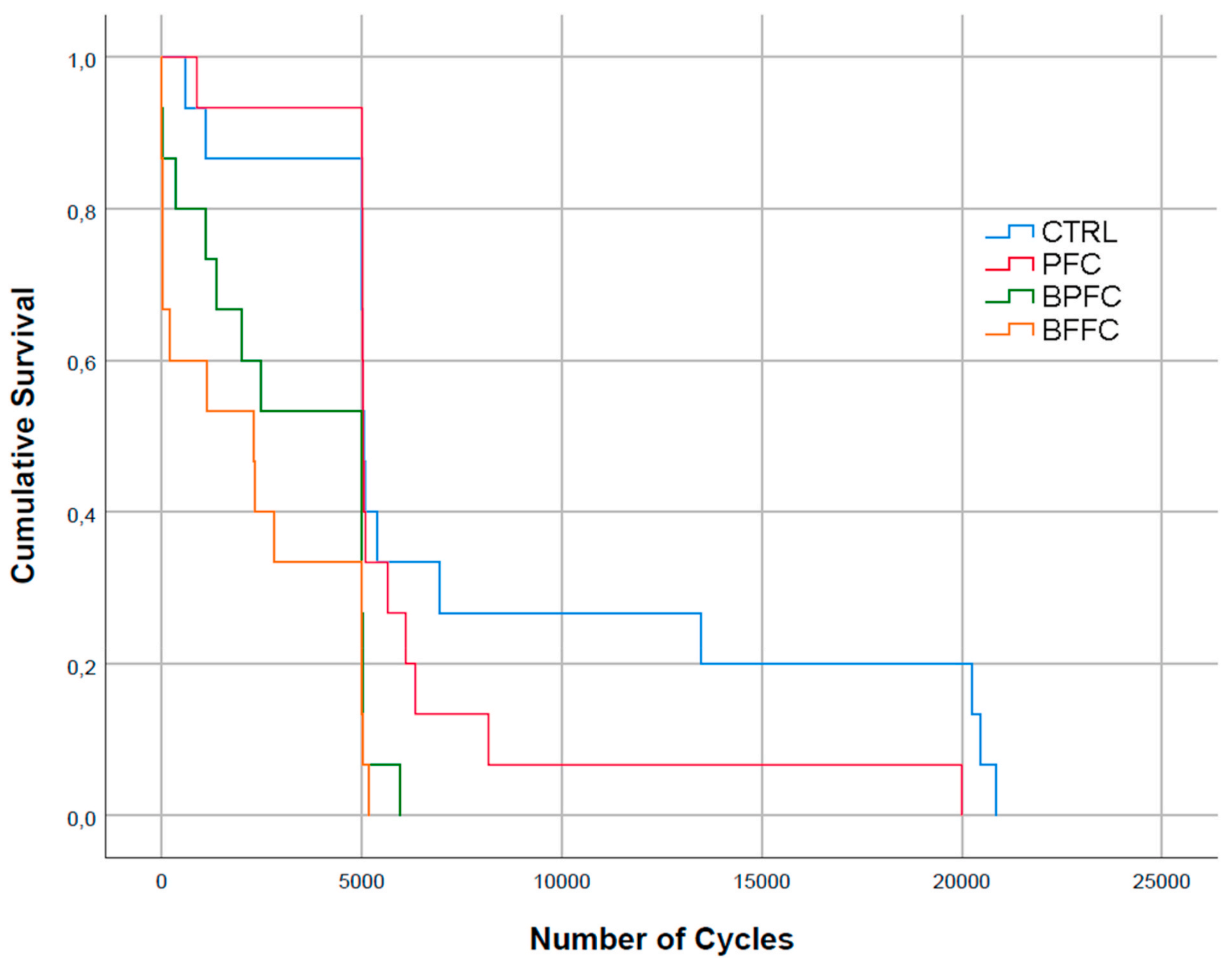

Fig. 2. Fatigue resistance survival curves (Kaplan-Meier survival estimator) for all four groups. Individually-made unidirectional FRC post + Gradia Core (CTRL); individually-made unidirectional FRC post + packable SFRC core (PFC); Bioblock technique with packable SFRC (BPFC); Bioblock technique with flowable SFRC (BFFC).

Table 1
The mean and median number of survived cycles for each tested group.

Groups	Mean[a]				Median			
	Mean cycles	Std. Error	95% Confidence Interval		Median cycles	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound			Lower Bound	Upper Bound
CTRL	8279,73	1788,27	4774,73	11,784,74	5045,00	39,93	4966,73	5123,27
PFC	6161,60	1057,79	4088,34	8234,86	5031,00	19,32	4993,13	5068,87
BPFC	3223,47	572,68	2101,01	4345,93	4999,00	1941,20	1194,25	8803,75
BFFC	2271,33	576,69	1141,02	3401,64	2296,00	1359,61	,00	4960,84

[a] Estimation is limited to the largest survival time if it is censored.

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

Groups	CTRL		PFC		BPFC		BFFC	
	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.
CTRL			0.770	0.380	9.598	0.002	13.213	0.000
PFC	0.770	0.380			10.383	0.001	13.889	0.000
BPFC	9.598	0.002	10.383	0.001			0.911	0.340
BFFC	13.213	0.000	13.889	0.000	0.911	0.340		

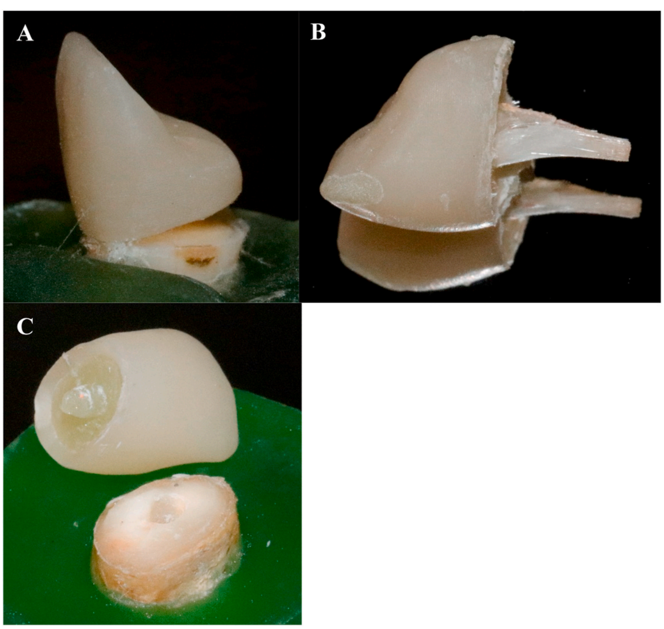

Fig. 3. Photographs of various restorable fracture patterns (no tooth fracture) of crown specimens. (A & B) adhesive failure at interfaces presented in CTRL and PFC groups. (C) adhesive failure with post fracture presented in BPFC and BFFC groups.

In our study, the control (CTRL) and PFC groups were restored with long fibers in the form of individualized unidirectional FRC posts, while BPFC and BFFC were restored with short fibers in the form of packable or flowable SFRC. The benefits of using multiple posts compared to single ones have been demonstrated by many (Hatta et al., 2011; Fráter et al., 2017; Garoushi et al., 2020; Maceri et al., 2007). Maceri et al., have shown that a multipost technique will potentially enhance resistance to long-term cyclic loading and decrease pull-out risk (Maceri et al., 2007). In the study of Hatta et al. (2011), and also in one of our previous studies (Fráter et al., 2017), applying multiple unidirectional FRC posts to form an individualized FRC post in a root canal resulted in higher fracture resistance in comparison to a single FRC post. As individualized posts perform better than single ones *in vitro*, they also show promising results clinically (Garoushi et al., 2020). In this investigation, specimens restored with individualized unidirectional FRC posts (CTRL and PFC groups) showed significantly higher survival than the ones restored with the Bioblock technique (BPFC and BFFC) ($p < 0.05$).

In the Bioblock technique, SFRC is directly and tightly adapted to the walls of the root canal, excluding the drawbacks of using luting cement. In addition, the fibers are correctly placed from a biomechanical point of view, thereby reducing all damaging tensile stresses when the restoration is loaded (Fráter et al., 2020a). Our current results contradict the previous findings of Garoushi et al. (2009), who found no difference in fracture resistance when anterior decoronated teeth were restored with FRC post or with SFRC post and core (an early version of the Bioblock technique). It must be noted that in the latter study, the post was a conventional FRC post which was not individualized in any way. Our findings also seem to contradict the results of Bijelic et al. (2013), but in their study the tested anterior teeth had an adequate ferrule.

Furthermore, our present findings contradict our previous results where the Bioblock technique outperformed the individualized unidirectional FRC posts (Fráter et al., 2020a). The difference may be due to the different clinical situations (anterior no ferrule vs. premolar MOD cavity), implying different amounts of dentin in the coronal aspect. In the case of anterior teeth without a ferrule, teeth restored with the Bioblock technique showed similar survival, regardless of whether packable or flowable SFRC was used. This is in line with our earlier results (Fráter et al., 2020b). Flowable SFRC has at least as favourable mechanical properties (e.g. fracture toughness, flexural strength, degree of conversion, etc.) as packable SFRC (Lassila et al., 2018) with the benefit of easier adaptation. Also, flowable SFRC could be used to lute posts inside the root canal, which is an aspect not tested in the present study.

Comparing the two groups restored with unidirectional multiple FRC posts, SFRC as a core build-up (PFC) did not turn out to be superior to using the non-fiber-reinforced core build-up material (CTRL). This is contrary to the findings of Lassila et al., where the usage of SFRC as core build-up beside an FRC post resulted in superior fracture resistance (Lassila et al., 2019). Our findings are in accordance with those of Lazari et al., who did not manage to demonstrate difference in survival rates when comparing different core build-up materials next to FRC posts in anterior teeth without ferrule (Lazari et al., 2018). The same was found by da Silva et al. (da Silva et al., 2010). Our findings can be explained from multiple different perspectives. First, the amount of SFRC used in PFC was minimal as multiple unidirectional FRC posts were used not leaving much space for the SFRC. Second, the use of long unidirectional fibers seems to be of key importance in the given clinical situation. Continuous unidirectional fibers in the form of FRC posts provide an anisotropic effect with high strength in one direction and are suitable for applications where the highest stress is known to occur (Başaran et al., 2013). SFRC contains randomly oriented short fibers, which leads to an isotropic behavior and multidirectional reinforcement, but at the cost of decreased strength in any one direction compared to unidirectional fibers (Başaran et al., 2013). Based on this preliminary investigation, placement of an individualized unidirectional FRC posts significantly improve the fatigue resistance of damaged anterior teeth without ferrule, despite the type of core material.

In this study, all individualized FRC posts were placed 7 mm deep into the root canal. According to Meyerberg clinically it could be enough to have 7 mm of FRC post inserted intraradicularly with an approx. 4 mm of the post providing coronal retention to the core build-up (Meyenberg, 2013b). Some studies have shown that the length of the FRC post did not influence the fracture resistance of anterior root canal treated teeth restored with a crown (Ramírez-Sebastià et al., 2014; Chuang et al., 2010). Also the post length in case of FRC posts did not influence the generated mvM stresses in anterior teeth upon loading (Dejak and Młotkowski, 2013). This was further justified by Santos-Filho and colleagues (Santos-Filho et al., 2014). Individualized posts have better fitting in the critical cervical part of the canal and a better fiber/luting cement ratio compared to prefabricated FRC posts. Thus, the increased width of individualized FRC posts can potentially compensate the reduced post insertion depth used in this study. It has been emphasized by many that the effect of post diameter is more important compared to post length from a biomechanical point of view (Okamoto et al., 2008; Wang et al., 2016). The reason behind is that post diameter weighs more in resisting bending forces than the length of the post in the root canal (Wang et al., 2016).

Regarding the fracture pattern, nearly all specimens presented a restorable type of fracture with no tooth fracture (only one non-restorable fracture in PFC group), which contradicts the findings of Lazari et al. (2018). All of the fractures happened in the form of the core build-up together with the crown detached from the tooth surface, which suggests adhesive failure. When long unidirectional fibers were used (CTRL and PFC) failures presented as a wide gap lingually at the interface between the tooth and the restoration without post fracture (Fig. 3 A&B). This kind of failure has been reported in previous studies by Lazari et al. (2018), and Magne et al. (2017). Such a failure was also observed in other studies on endodontically treated molars restored with fiber posts (Magne et al., 2016). From a clinical point of view, this type of failure is extremely critical because it is difficult to detect, can initiate bacterial contamination of the root-canal system, and can be a potential cause of periodontic and endodontic failure (Saunders and Saunders, 1994). This could be attributed to the flexibility of the FRC post, suggesting that a flexible post allows too much movement of the core, resulting in increased microleakage under the crown. On the other hand, when SFRC was used to fabricate the post and core build-up (BPFC and BFFC), failures presented as restoration detached from the tooth surface with post fracture (Fig. 3C). Most likely, the generated stresses at the interface (cervical) were exceeding the toughening capability of SFRC.

Within this study setup, the tested specimens fractured at relatively low levels of loading, in the 100–200 N range. This could be traced back to multiple factors. One of these is that the specimens were loaded at the incisal edge, which is admittedly a shortcoming of our setup. More importantly, this low resistance (also reflected in the low number of survived cycles) could be attributed to the total absence of ferrule in our specimens, which has been shown to cause great reduction in fracture resistance or survival (Santos Pantaleón et al., 2018; Magne et al., 2016; Saker and Özcan, 2015). According to Laurell et al., the mean maximum occlusal force is 200–228 N in the anterior region (Laurell and Lundgren, 1984). Regalo et al., reported the mean maximum incisor occlusal force to vary between 93 and 206 N (Regalo et al., 2008). Irrespective of the lower number of survived cycles compared to other studies, our results regarding the withstood maximal forces fit well into the range of forces developing in the anterior region during actual chewing (Figueiredo et al., 2019).

Another shortcoming could be the accelerated fatigue test used within this study. While this test could be positioned in terms of its clinical relevance between the lower value static load-to-fracture test and the most valid fatigue test, many studies have used this method to gather important information on restoration survival both in vital and root canal treated teeth (Lazari et al., 2018; Magne et al., 2017; Goldberg et al., 2016). Non-accelerated fatigue testing would be beneficial with the same study setup in the future.

5. Conclusions

For the restoration of extensively damaged anterior teeth without ferrule, the use of multiple long unidirectional FRC posts demonstrated better performance than SFRC in reference to fracture-behavior. Once multiple unidirectional fibers are used the core build-up material does make a difference.

Author contributions

Márk Fráter – Conceptualization, preparation of samples
Tekla Sáry - Conceptualization, preparation of samples
Gábor Braunitzer – statistical analysis, data curation
Balázs Szabó P. – validation, software
Lippo Lassila – methodology
Pekka Vallittu – review and editing
Sufyan Garoushi – methodology, writing and editing, supervision
Márk Fráter and Tekla Sáry contrebuted equally to this work.

Funding

This study was supported by the research activity of BioCity Turku Biomaterials Research Program in Turku, Finland and by the ÚNKP-20-3-SZTE, ÚNKP-20-5-SZTE New National Excellence Program of The Ministry for Innovation and Technology from the Source of National Research, Development and Innovation Fund, Hungary.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent

For this type of study, formal consent is not required.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Author Márk Fráter declares to have no conflict of interests. Author Tekla Sáry declares to have no conflict of interests. Author Gábor Braunitzer declares to have no conflict of interests Author Balázs Szabó P. declares to have no conflict of interests. Author Lippo Lassila declares to have no conflict of interests. Author Pekka Vallittu consults for Stick Tech - Member of GC Group in R&D and training. Author Sufyan Garoushi declares to have no conflict of interests.

Acknowledgment

we would like to thank the valuable help of Árpád Schindler.

References

Başaran, E.G., Ayna, E., Vallittu, P.K., Lassila, L.V., 2013 Feb. Load bearing capacity of fiber-reinforced and unreinforced composite resin CAD/CAM-fabricated fixed dental prostheses. J. Prosthet. Dent 109 (2), 88–94. https://doi.org/10.1016/S0022-3913(13)60022-0.

Bell-Rönnlöf, A.L., Jaatinen, J., Lassila, L., Närhi, T., Vallittu, P., 2019 Dec 1. Transmission of light through fiber-reinforced composite posts. Dent. Mater. J. 38 (6), 928–933. https://doi.org/10.4012/dmj.2018-217.

Bijelic, J., Garoushi, S., Vallittu, P.K., Lassila, L.V., 2013 Sep. Short fiber reinforced composite in restoring severely damaged incisors. Acta Odontol. Scand. 71 (5), 1221–1231. https://doi.org/10.3109/00016357.2012.757640.

Chuang, S.F., Yaman, P., Herrero, A., Dennison, J.B., Chang, C.H., 2010 Dec. Influence of post material and length on endodontically treated incisors: an in vitro and finite element study. J. Prosthet. Dent 104 (6), 379–388. https://doi.org/10.1016/S0022-3913(10)60171-0.

da Silva, N.R., Raposo, L.H., Versluis, A., Fernandes-Neto, A.J., Soares, C.J., 2010 Nov. The effect of post, core, crown type, and ferrule presence on the biomechanical behavior of endodontically treated bovine anterior teeth. J. Prosthet. Dent 104 (5), 306–317. https://doi.org/10.1016/S0022-3913(10)60146-1.

Dejak, B., Młotkowski, A., 2013 Sep. The influence of ferrule effect and length of cast and FRC posts on the stresses in anterior teeth. Dent. Mater. 29 (9), e227–e237. https://doi.org/10.1016/j.dental.2013.06.002.

Figueiredo, F.E., Martins-Filho, P.R., Faria-E-Silva, A.L., 2015 Mar. Do metal post-retained restorations result in more root fractures than fiber post-retained restorations? A systematic review and meta-analysis. J. Endod. 41 (3), 309–316.

Figueiredo, F.E., Santos, R.C., Silva, A.S., et al., 2019. Ferrule design does not affect the biomechanical behavior of anterior teeth under mechanical fatigue: an in vitro evaluation. Operat. Dent. 44 (3), 273-280. https://doi.org/10.2341/17-296-L.

Forster, A., Sáry, T., Braunitzer, G., Fráter, M., 2016. In vitro fracture resistance of endodontically treated premolar teeth restored with a direct layered fiber-reinforced composite post and core. J. Adhes. Sci. Technol. 31, 1454–1466. https://doi.org/10.1080/01694243.2016.1259758.

Fragou, T., Tortopidis, D., Kontonasaki, E., Evangelinaki, E., Ioannidis, K., Petridis, H., Koidis, P., 2012 Apr. The effect of ferrule on the fracture mode of endodontically treated canines restored with fibre posts and metal-ceramic or all-ceramic crowns. J. Dent. 40 (4), 276–285. https://doi.org/10.1016/j.jdent.2012.01.002.

Fráter, M., Forster, A., Jantyik, Á., Braunitzer, G., Nagy, K., Grandini, S., 2017 Apr. In vitro fracture resistance of premolar teeth restored with fibre-reinforced composite posts using a single or a multi-post technique. Aust. Endod. J. 43 (1), 16–22. https://doi.org/10.1111/aej.12150.

Fráter, M., Lassila, L., Braunitzer, G., Vallittu, P.K., Garoushi, S., 2020 Jan. Fracture resistance and marginal gap formation of post-core restorations: influence of different fiber-reinforced composites. Clin. Oral Invest. 24 (1), 265–276. https://doi.org/10.1007/s00784-019-02902-3.

Fráter, M., Sáry, T., Néma, V., et al., 2020b. Fatigue failure load of immature anterior teeth: influence of different fiber post-core systems. Odontology. https://doi.org/10.1007/s10266-020-00522-y.

Garcia, P.P., Wambier, L.M., de Geus, J.L., da Cunha, L.F., Correr, G.M., Gonzaga, C.C., 2019 Jun. Do anterior and posterior teeth treated with post-and-core restorations have similar failure rates? A systematic review and meta-analysis. J. Prosthet. Dent 121 (6), 887–894. https://doi.org/10.1016/j.prosdent.2018.08.004 e4.

Garoushi, S., Vallittu, P.K., Lassila, L.V., 2009 Mar 18. Continuous and short fiber reinforced composite in root post-core system of severely damaged incisors. Open Dent. J. 3, 36–41. https://doi.org/10.2174/1874210600903010036.

Garoushi, S., Tanner, J., Keulemans, F., Le Bell-Rönnlöf, A.M., Lassila, L., Vallittu, P.K., 2020 May 7. Fiber reinforcement of endodontically treated teeth: what options do we have? Literature review. Eur. J. Prosthodont. Restor. Dent. https://doi.org/10.1922/EJPRD_2002Garoushi10.

Goldberg, J., Güth, J.F., Magne, P., 2016. Accelerated fatigue resistance of thick CAD/CAM composite resin overlays bonded with light- and dual-polymerizing luting resins. J. Adhesive Dent. 18 (4), 341–348. https://doi.org/10.3290/j.jad.a36515.

Hatta, M., Shinya, A., Vallittu, P.K., Shinya, A., Lassila, L.V., 2011 Jan. High volume individual fibre post versus low volume fibre post: the fracture load of the restored tooth. J. Dent. 39 (1), 65–71. https://doi.org/10.1016/j.jdent.2010.10.004.

Lassila, L., Keulemans, F., Säilynoja, E., Vallittu, P.K., Garoushi, S., 2018 Apr. Mechanical properties and fracture behavior of flowable fiber reinforced composite restorations. Dent. Mater. 34 (4), 598–606. https://doi.org/10.1016/j.dental.2018.01.002.

Lassila, L., Oksanen, V., Fráter, M., Vallittu, P.K., Garoushi, S., 2019 Dec 18. The influence of resin composite with high fiber aspect ratio on fracture resistance of severely damaged bovine incisors. Dent. Mater. J. https://doi.org/10.4012/dmj.2019-051.

Laurell, L., Lundgren, D., 1984 Jan. A standardized programme for studying the occlusal force pattern during chewing and biting in prosthetically restored dentitions. J. Oral Rehabil. 11 (1), 39–44. https://doi.org/10.1111/j.1365-2842.1984.tb00550.x.

Lazari, P.C., de Carvalho, M.A., Del Bel Cury, A.A., Magne, P., 2018 May. Survival of extensively damaged endodontically treated incisors restored with different types of posts-and-core foundation restoration material. J. Prosthet. Dent 119 (5), 769–776. https://doi.org/10.1016/j.prosdent.2017.05.012.

Maceri, F., Martignoni, M., Vairo, G., 2007. Mechanical behaviour of endodontic restorations with multiple prefabricated posts: a finite-element approach. J. Biomech. 40 (11), 2386–2398. https://doi.org/10.1016/j.jbiomech.2006.11.018.

Magne, P., Goldberg, J., Edelhoff, D., Güth, J.F., 2016 Jan-Feb. Composite resin core buildups with and without post for the restoration of endodontically treated molars without ferrule. Operat. Dent. 41 (1), 64–75.

Magne, P., Lazari, P.C., Carvalho, M.A., Johnson, T., Del Bel Cury, A.A., 2017 Jul/Aug. Ferrule-effect dominates over use of a fiber post when restoring endodontically treated incisors: an in vitro study. Operat. Dent. 42 (4), 396–406. https://doi.org/10.2341/16-243-L.

Maroulakos, G., Nagy, W.W., Kontogiorgos, E.D., 2015 Sep. Fracture resistance of compromised endodontically treated teeth restored with bonded post and cores: an in vitro study. J. Prosthet. Dent 114 (3), 390–397. https://doi.org/10.1016/j.prosdent.2015.03.017.

Meyenberg, K., 2013 Summer. The ideal restoration of endodontically treated teeth - structural and esthetic considerations: a review of the literature and clinical guidelines for the restorative clinician. Eur. J. Esthetic Dent. 8 (2), 238–268. Review. PubMed PMID: 23712344.

Meyenberg, K., 2013 Summer. The ideal restoration of endodontically treated teeth - structural and esthetic considerations: a review of the literature and clinical guidelines for the restorative clinician. Eur. J. Esthetic Dent. 8 (2), 238–268.

Mohammadi, N., Kahnamoii, M.A., Yeganeh, P.K., Navimipour, E.J., 2009 Oct. Effect of fiber post and cusp coverage on fracture resistance of endodontically treated maxillary premolars directly restored with composite resin. J. Endod. 35 (10), 1428–1432. https://doi.org/10.1016/j.joen.2009.07.010.

Okamoto, K., Ino, T., Iwase, N., Shimizu, E., Suzuki, M., Satoh, G., Ohkawa, S., Fujisawa, M., 2008 Jan. Three-dimensional finite element analysis of stress distribution in composite resin cores with fiber posts of varying diameters. Dent. Mater. J. 27 (1), 49–55. https://doi.org/10.4012/dmj.27.49.

Ramírez-Sebastià, A., Bortolotto, T., Cattani-Lorente, M., Giner, L., Roig, M., Krejci, I., 2014. Adhesive restoration of anterior endodontically treated teeth: influence of post length on fracture strength. Clin. Oral Invest. 18 (2), 545–554. https://doi.org/10.1007/s00784-013-0978-3.

Regalo, S.C., Santos, C.M., Vitti, M., Regalo, C.A., de Vasconcelos, P.B., Mestriner Jr., W., Semprini, M., Dias, F.J., Hallak, J.E., Siéssere, S., 2008 Mar. Evaluation of molar and incisor bite force in indigenous compared with white population in Brazil. Arch. Oral Biol. 53 (3), 282–286. https://doi.org/10.1016/j.archoralbio.2007.10.003.

Saker, S., Özcan, M., 2015 Dec. Retentive strength of fiber-reinforced composite posts with composite resin cores: effect of remaining coronal structure and root canal dentin conditioning protocols. J. Prosthet. Dent 114 (6), 856–861. https://doi.org/10.1016/j.prosdent.2015.06.015.

Santos Pantaleón, D., Morrow, B.R., Cagna, D.R., Pameijer, C.H., Garcia-Godoy, F., 2018 Mar. Influence of remaining coronal tooth structure on fracture resistance and failure mode of restored endodontically treated maxillary incisors. J. Prosthet. Dent 119 (3), 390–396. https://doi.org/10.1016/j.prosdent.2017.05.007.

Santos-Filho, P.C., Veríssimo, C., Soares, P.V., Saltarelo, R.C., Soares, C.J., Marcondes Martins, L.R., 2014 Jan. Influence of ferrule, post system, and length on biomechanical behavior of endodontically treated anterior teeth. J. Endod. 40 (1), 119–123. https://doi.org/10.1016/j.joen.2013.09.034.

Saunders, W.P., Saunders, E.M., 1994 Jun. Coronal leakage as a cause of failure in root-canal therapy: a review. Endod. Dent. Traumatol. 10 (3), 105–108.

Vallittu, P.K., 2016 Feb. Are we misusing fiber posts? Guest editorial. Dent. Mater. 32 (2), 125–126. https://doi.org/10.1016/j.dental.2015.11.001. Epub 2015 Nov 30. PubMed PMID: 26652233.

Vallittu, P.K., Özcan, M., 2017. A Clinical Guide to Principles of Fibre Reinforced Composites (FRCs) in Dentistry. Woodhead Publishing.

Wang, C.H., Du, J.K., Li, H.Y., Chang, H.C., Chen, K.K., 2016 Jul. Factorial analysis of variables influencing mechanical characteristics of a post used to restore a root filled premolar using the finite element stress analysis combined with the Taguchi method. Int. Endod. J. 49 (7), 690–699. https://doi.org/10.1111/iej.12499.

Zarow, M., Ramírez-Sebastià, A., Paolone, G., de Ribot Porta, J., Mora, J., Espona, J., Durán-Sindreu, F., Roig, M., 2018 Mar. A new classification system for the restoration of root filled teeth. Int. Endod. J. 51 (3), 318–334. https://doi.org/10.1111/iej.12847.

Zicari, F., De Munck, J., Scotti, R., Naert, I., Van Meerbeek, B., 2012 Mar. Factors affecting the cement-post interface. Dent. Mater. 28 (3), 287–297. https://doi.org/10.1016/j.dental.2011.11.003.