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Fatigue behavior of endodontically treated premolars restored with different fiber-reinforced designs

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ABSTRACT

Objectives. The aim was to investigate the fatigue survival and marginal-gap inside the root-canal of endodontically treated (ET) premolars reinforced by various fiber-reinforced post-core composites (FRCs). Moreover, composite-curing at different depths in the canal was evaluated.

Methods. 170 intact upper-premolars were collected and randomly divided into ten groups (n = 15). One group served as control (intact-teeth). After endodontic procedure standard MO cavities were prepared and restored with different post-core fiber-reinforced materials and designs. Three-group (A1-A3) were restored with either packable and flowable short fiber-reinforced composite (SFRC) core or conventional composite-core. Two-group (B1-B2) were restored with SFRCs as short post (3 mm) and core. Four-group (C1-C4) were restored with SFRCs as post (6 mm) and core with or without unidirectional FRC posts (individually-made or conventional). After completing the restorations, teeth from Group C1-C4 (n = 5/group) were sectioned and stained. Specimens were viewed under a stereo-microscope and the percentage of microgaps within the root-canal was calculated. Fatigue-survival was measured using a cyclic-loading machine in the rest of the specimens.

Results. Application of flowable SFRC as luting-core material with individually-made FRC post (Group C3) did not differ from intact-teeth regarding fatigue-survival ($p > 0.05$). The rest of the groups produced significantly lower survival ($p < 0.05$) compared to intact-teeth. Post/core restorations made from packable SFRC (Group C1) had a lower microgap (19.1%) at the examined interphase in the root-canal than other groups.

Significance. The restoration of ET premolars with the use of individually-made FRC post and SFRC as luting-core material showed promising achievement regarding fatigue-resistance and survival.

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1. Introduction

Caries, trauma and cavity preparation may cause too much loss of coronal tooth structure, which is a major challenge to the clinicians during the restoration of root canal treated (RCT) teeth [1]. As a result of lost structural integrity, RCT teeth are weak and reveal limited resistance to fracture [2,3]. This is mostly critical in the instance of RCT premolars, as several investigations reporting a high fracture incidence for these teeth, especially in the upper arch [4–6]. Upper premolars are subjected to a combination of compressive and shearing forces, which drives them particularly prone to fracture [7]. The marginal ridges loss leads this even more noticeable. Reeh et al., clearly showed that the loss of marginal ridge integrity resulted in considerable loss of stiffness [3,8]. While a standardized MOD (mesio-occlusal-distal) cavity preparation in upper premolars was proved to lead in mean loss of 63% in relative cuspal stiffness [9], the loss of only one marginal ridge resulted in a loss of only 46% in elative cuspal stiffness [10]. Therefore, intracoronal reinforcement of RCT premolars is essential to defend them against fracture [7,11]. Since the 1990s, fiber-reinforced composite (FRC) posts have been used with increasing frequency to restore RCT teeth with excessive loss of coronal tooth structure [12]. The sole aim of this approach is to inhance the retention of the core build-up material. Many researchers reported that using a post into RCT premolars considerably improved their fracture resistance [13–16], though, other researchers just managed to confirm the beneficial effect of placing a post on the fracture mode of such premolar teeth [17–19]. This was also approved by Trope et al. [20], and Zicari et al. [21], who assumed that placement of FRC post does not really enhance or reinforce the given tooth. This could be caused by multiple reasons, namely the possible weakening of the root during the post space preparation [21–23], the inaccurate fit of the post due to the irregular geometry and cross section of the root canal [24,25], or the inability of the post material to adequately bond to the luting or core build-up material [26,27].

Applying short fiber-reinforced composites (SFRC) inside the root canal has been suggested by many authors [28–30]. In the Bioblock technique, both the coronal cavity and the root canal are filled by packable SFRC in 4–5 mm thick horizontal increments [30,31]. From our previous research, premolar teeth restored with the Bioblock technique showed significantly higher fracture resistance compared to the ones restored with an FRC post [31]. In 2019, the flowable version of SFRC was released with the promise of easy versatility or adaptability in limited spaces (e.g. root canals). In our latest study, apexified anterior teeth restored with the Bioblock technique using the flowable SFRC did not differ significantly from the intact teeth (control group) in terms of survival, whereas the rest of the tested groups had significantly lower survival rates compared to the control group [31].

The question arises whether one may use just any version of SFRC to restore RCT premolar teeth with mesio-occlusal (MO) cavities or long fibers (in the form of FRC posts) are preferable. The purpose of this laboratory investigation was to evaluate the fatigue resistance and failure mode of RCT premolar with MO cavities restored by different direct techniques with FRC materials. Furthermore, adaptation within the root canal and curing quality at different depths were studies for each technique.

2. Materials and methods

The study was approved by the Ethics Committee of the University of Szeged, and was designed in accordance with the declaration of Helsinki.

One hundred seventy upper premolar teeth, extracted for periodontal or orthodontic causes were used for this research. The newly extracted premolars were directly inserted in 5.25% NaOCl for 5 min and stored in 0.9% saline solution at room temperature. Teeth were used during 8 weeks after extraction. At time of specimen preparation hand scaler was used to remove the soft tissue covering the root surface. The teeth selection criteria were absence of caries, cracks, previous endodontic treatments, posts or crowns, root resorptions and obvious accessory canals. Radiographs from different directions for all teeth were taken and examined to evaluate the number of existing canals and the root integrity. In order to standardize the test set-up, all premolars used in this reasearch had one root canal with a curvature of less than 5°, evaluated by Schneider's technique [32], and premolars with a root length of 15 ± 1 mm and equal mesiodistal and bucco-lingual dimensions (±10%) were selected. 90% of the premolars ranged 9–10 mm in size, assessed at the widest bucco-lingual dimension, and the rest measured teeth were 6.5–8 mm. From the mesio-distal dimension, 90% of the teeth ranged 7–7.5 mm, and the rest were 6.5–8 mm.

Teeth were randomly divided over ten test groups, where four groups (Group C1-C4) contained of 20 specimens each, and the rest of the groups only containing 15 specimen. One group containing 15 teeth was left intact to serve as control. Class II. MO cavity preparation and later on root canal treatment was conducted by the same trained dental practitioner in the rest of the groups (Group A1-A3,B1-B2 and C1-C4).

2.1. *Specimen preparation*

A standardized MO cavity was prepared on teeth using a round end paralel diamond bur (883H.146.016 F G - Brasseler USA Dental, Savannah, GA) with water coolant so that the buccopalatal width of the occlusal isthmus was one third, and the proximal box width was two thirds of the buccopalatal width of the crown. The gingival floor was prepared 1 mm above the cemento-enamel junction (CEJ). All internal angles were rounded and the cavosurface margins were at 90°. After finalizing the MO cavity preparation, access cavity preparation was perfromed with a round-end diamond bur (850–014 M SSWhite, Lakewood, NJ, USA) with water cooling and root canal treatment was made in the prepared teeth. The working length was created with the direct method by subtracting 1 mm from the real root length defined by introducing a number 10 K-file (Maillefer-Dentsply, Ballaigues, Switzerland) until it was visible through the apical foramen. The root canals were prepared using rotary ProTaper Universal files (Dentsply, Maillefer, Ballaigues, Switzerland). The ProTaper sequence (S1, S2, F1, F2) was used for the preparation at the working length. Irrigation was done after every instrument with 2 ml of 2.5% NaOCl solution and the canal space was saturated with irrigant during the instrumentation phase. After root canal cleaning and shaping, the roots were dried using 96% alcohol and paper points. Root canal obturation was made by matched single-cone obturation with a master cone (F2 gutta-percha, Maillefer-Dentsply, Ballaigues, Switzerland) and sealer (AH plus; Dentsply De Trey GmbH, Konstanz, Germany). The guttapercha was cut back to the level of the orifice and the access cavity was temporarily filled with Fuji Triage Pink (GC Europe, Leuven, Belgium). Fuji Triage Pink was applied to the apical part of the root in order to prevent leakage through the apex. The teeth were stored wet in an incubator (mco-18aic, Sanyo, Japan) for one week (at 37 °C, 100% relative humidity). After this the temporary material was removed and the MO cavity, including the access cavity was refreshened with a diamond bur.

In Group A1-A3 the root canal was no longer invaded by any preparation and teeth were restored with MO filling without any radicular reinforcement. In Group B1-B2 a very shallow post space preparation was carried out by a 1.2 GC Fiber Post drill to a depth of 3 mm apical from the root canal orifice. In Group C1-C4 post space preparation was carried out by a 1.2 GC Fiber Post drill to a depth of 6 mm apical from the root canal orifice. After cutting back the gutta-percha, the root canal was washed with chlorhexidine and dried with paper points.

All specimen had the same adhesive treatment. Tofflemire (1101C 0.035, Hawe-Neos, Italy) matrix band was applied prior to the adhesive treatment of the cavity and the root canal, the enamel was selectively acid-etched with 37% phosphoric acid for 15 s and washed with water. The coronal cavity and the root canal were rinsed with 2 ml of water and dried with paper points and air. A dual-cure one-step self-etch adhesive system (G-Premio Bond and DCA, GC Europe, Leuven, Belgium) was used for bonding procedure according to the manufacturer's instructions using a microbrush-X disposable applicator (Pentron Clinical Technologies, LLC, USA). Extra adhesive was eliminated by suction drying (Evacuation Tip – Starryshine, Anaheim, CA, USA) within 0.5 cm from the occlusal cavity (without contact). The excess adhesive resin at the bottom of the canal was eliminated using a paper point. The adhesive was light-cured for 60 s using an Optilux 501 quartz-tungsten-halogen light-curing unit (Kerr Corp., Orange, CA, USA). The light-curing tip was always located in close contact (1−2 mm) with the tooth surface. The average power density of the light source, measured with a digital radiometer (Jetlite light tester; J. Morita USA Inc. Irvine, CA, USA) before the bonding procedure, was 840 ± 26.8 mW/cm^2. After light-curing the adhesive, the missing interproximal walls were build-up with conventional composite (G-aenial Posterior PJ-E, GC Europe, Leuven, Belgium) using the centripetal technique, thus transforming the MO cavity into a class I. cavity. This interproximal wall was light cured for 40 s.

Nine different techniques were used to restore the specimens in Group A1-C4. (Fig. 1):

Group A1: The cavities were restored with packable SFRC (everX Posterior, GC Europe, Leuven, Belgium) applied in a bulk-fill technique. The material was placed in single increment according to the anatomy of the dentine, leaving 1.5-2 mm occlusally for the final composite layers as prescribed by the manufacturer. The SFRC increment was light cured from the occlusal surface for 40 s. The last occlusal layer was conventional composite material (G-aenial Posterior PJ-E) covering the SFRC.

Group A2: The cavities were restored with flowable SFRC (everX Flow, GC Europe, Leuven, Belgium) applied in a bulk-fill technique. The material was placed in single increment according to the anatomy of the dentine, leaving 1.5-2 mm occlusally for the final composite layers as prescribed by the manufacturer. The SFRC increment was light cured from the occlusal surface for 40 s. The last occlusal layer was conventional composite material covering the SFRC.

Group A3: The cavities were restored with conventional composite material (G-aenial Posterior) applied with an oblique incremental technique. The material was placed in consecutive 2 mm thick increments. Each increment was light cured from the occlusal surface for 40 s.

Group B1: The cavities including the 3 mm deep post space were restored with packable SFRC applied in a horizontal layering technique. The material was placed in 2 increments (approx. 4 mm thick each) according to the anatomy of the dentine. The light curing of the layers and covering with a final occlusal layer of composite material was performed as in Group A1.

Group B2: The cavities including the 3 mm deep post space were restored with flowable SFRC the same way as described in Group B1.

Group C1: The cavities and the 6 mm deep post space were reconstructed with the Bioblock technique described by Fráter et al., [30] building a direct layered post and core from packable SFRC. An approx. 4 mm thick increment of using a microbrush-X disposable applicator (Pentron Clinical Technologies, LLC, USA). A light transmitting FRC post (1.2 mm GC Fiber post, GC Europe, Leuven, Belgium) was inserted into the post space to aid the transmission of the light to the apically positioned layers. The 'light transmitting' post was withdrawn with 0.5–1 mm from the surface of the uncured SFRC layer not to have direct contact with it. This apical layer was light cured through the fiber post for 80 s. The rest of the cavity was restored as described in Group A1.

Group C2: The cavities and the 6 mm deep post space were restored with the Bioblock technique with the use of flowable SFRC. The coronal portion of the cavity was restored as described in Group A2

Group C3: The teeth received an individually-made unidirectional FRC post (everStick Post, GC Europe, Leuven, Belgium). Before the adhesive treatment, the posts of 1.2 mm diameter was tried in and cut to a length 2 mm below the level of the occlusal cavity margins with a sterile scrissors. Luting of the posts and the core build-up was performed with flowable SFRC. Flowable SFRC was applied in an approx. 4 mm thick layer into the post space. After insertion of the post, light curing was performed for 60 s. The coronal portion of the cavity was restored as described in Group A2.

Group C4: The teeth received a conventional unidirectional FRC post (GC Fiber post, GC Europe, Leuven, Belgium). Before the adhesive treatment, the conventional translucent FRC posts of 1.2 mm diameter was tried in and cut to a length 2 mm below the level of the occlusal cavity margins with a water-cooled diamond disc (Isomet 2000; Buehler Ltd., Lake Bluff, IL,

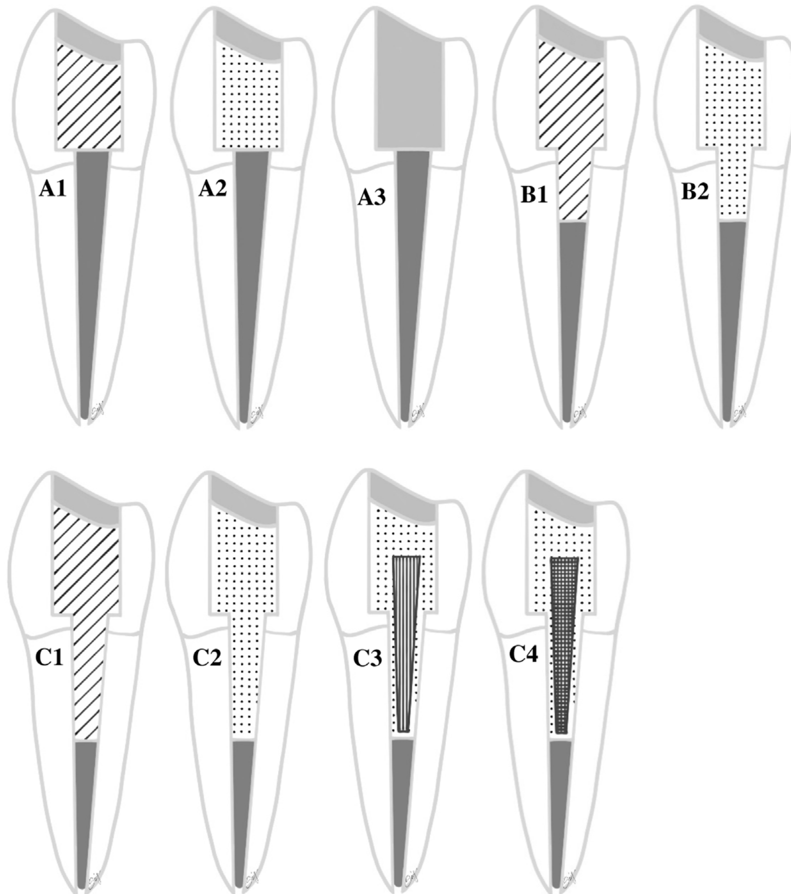

Fig. 1 – Shematic figure representing the test groups (Group A1-C4). Gr. A1: Packable SFRC core; Gr. A2: Flowable SFRC core; Gr. A3: Conventional composite core; Gr. B1: Packable SFRC directly layered as post (3 mm) and core; Gr. B2: Flowable SFRC directly layered as post (3 mm) and core; Gr. C1: Packable SFRC directly layered as post (6 mm) and core; Gr. C2: Flowable SFRC directly layered as post (6 mm) and core; Gr. C3: Individually-made unidirectional FRC post luted by flowable SFRC; Gr. C4: Conventional unidirectional FRC post luted by flowable SFRC.

USA) and cleaned with alcohol after try in. The posts received silanization of the surface (Ceramic Primer, GC Europe, Leuven, Belgium) following the manufacturer's recommendation. After silanization, the post surface was bonded with the same bonding agent used for the cavity. Luting of the posts and the core build-up was performed with flowable SFRC. Flowable SFRC was applied in an approx. 4 mm thick layer into the post space. After insertion of the post, light curing was performed for 60 s. The coronal portion of the cavity was restored as described in Group A2.

Finally, for all restored specimens, glycerine gel (DeOx Gel, Ultradent Products Inc., Orange, CA, USA) was applied and final polymerization from each side for 40 s was performed. The restorations were finished with a fine granular diamond burr (FG 7406-018, Jet Diamonds, USA and FG 249-F012, Horico, Germany) and aluminum oxide polishers (OneGloss PS Midi, Shofu Dental GmbH, Ratingen, Germany).

2.2. *Mechanical loading of the specimen*

The restored specimens were stored in distilled water at 37 °C for a week. To simulate the periodontal ligament, the root surface of each tooth was coated with a layer of liquid latex separating material (Rubber-Sep, Kerr, Orange, CA) prior to embedding. Specimens were embedded in methacrylate resin (Technovit 4004, Heraeus-Kulzer) at 2 mm from the cementoenamel junction (CEJ) to simulate the bone level. For mechanical testing, the restored specimens were submitted to an accelerated fatigue-testing protocol [31] by a hydraulic testing machine (Instron ElektroPlus E3000, Norwood, MA, USA) at an angle of 135 degrees to the long axis of each tooth. Testing was carried out in two parts. During the first part of testing (simulation of normal forces) cyclic isometric loading was applied on the triangular ridge of the buccal cusp of the tooth using a round-shaped metallic tip (with a diameter of 5 mm). The palatal cusp was slightly reduced to aid the propoer positioning of the testing tip. A cyclic load was applied at a frequency of 5 Hz, starting with gradually increasing static loading till 100 N in 5 s, followed by cyclic loading in 100 N steps, up to 500 N, 5000 cycles per step. The specimens were loaded until fracture occurred or 25,000 cycles were reached. The total number of survived cycles were recorded for each specimen for the survival analyses.

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The specimens that survived 25,000 cycles were then loaded with extremely high forces simulating parafunction (clenching or bruxism). During this part of the testing, cyclic isometric loading was continued. Cyclic load was applied at a frequency of 5 Hz, continuing with gradually increasing static loading up to 600 N in 5 s, followed by cyclic loading in 100 N steps, up to 1000 N, 5000 cycles per step. The specimens were loaded until fracture occurred or 30,000 cycles were reached (within this second phase). The total number of survived cycles were recorded for each specimen for the survival analyses.

The failed specimens were visually examined under an optical microscope for the type, location and direction of failure, with two-examiner agreement. According to Scotti and co-workers, a distinction was made between repairable and irrepairable fractures, where a repairable fracture is above the CEJ, meaning that in case of fracture, the tooth can be restored, while an irrepairable fracture extends below the CEJ and the tooth is likely to be extracted [33].

2.3. Microgap detremination test

Four groups (C1-4), each consisting of 5 endodontically treated and restored teeth, were investigated in the microgap detremination test. The teeth (n = 20) were restored in the same way as mentioned earlier. Teeth were sectioned mid-sagitally in the mesio-distal plane using a ceramic cutting disc operating at a speed of 100 rpm (Struers, Glasgow, Scotland) under water cooling. In each group, one of the sectioned restoration that contains the post was further grind and polish using #4000-grit silicon carbide papers at 300 rpm under water cooling using an automatic grinding machine (Rotopol-1; Struers, Copenhagen, Denmark). Then, sectioned teeth were painted with permanent marker, and polish gently for few seconds. The dye penetration along post/core margins of each section was evaluated independently using a stereo-microscope (Heerbrugg M3Z, Heerbrugg, Switzerland) at a magnification of 6.5x and the extent of dye penetration was recorded in mm as a percentage of the total margin length [34].

2.4. Microhardness test

Microhardness of luting composite inside the canal was measured using a Struers Duramin hardness microscope (Struers, Copenhagen, Denmark) with a 40 objective lens and a load of 1.96 N applied for 10 s. Each sectioned restoration was subjected to 5 indentations on the top (coronal part) and the bottom (apical part) of the canal for indication of polymerization [35,36]. The diagonal length impressions were measured and Vickers values were converted into microhardness values by the machine. Microhardness was obtained using the following equation:

$$H = \frac{1854.4 \times P}{d^2}$$

where H is Vickers hardness in kg/mm^2, P is the load in grams and d is the length of the diagonals in μm.

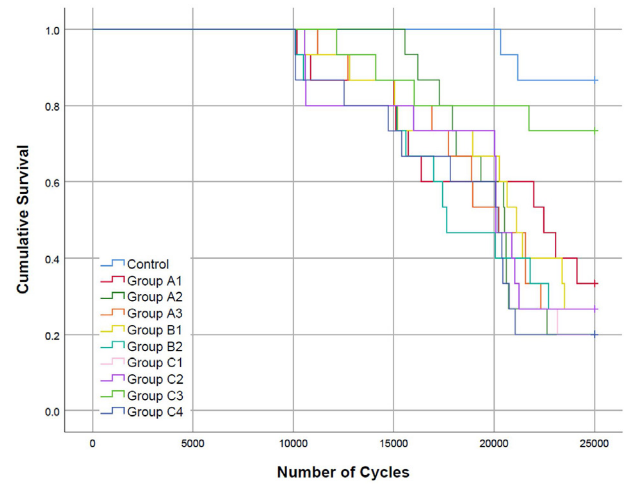

Fig. 2 – Fatigue resistance survival curves (Kaplan-Meier survival estimator) for all tested group loaded with a force of magnitude 100-500 N.

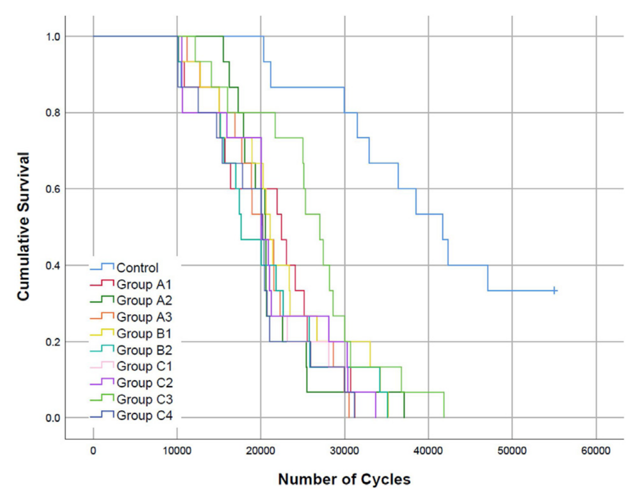

Fig. 3 – Fatigue resistance survival curves (Kaplan-Meier survival estimator) for all tested groups loaded with a force of magnitude 600-1000 N.

2.5. Statistical analysis

Statistical analyses were performed in SPSS 21.0 (IBM, USA). Groups were defined according to the method of restoration (or the lack thereof for the control group). The number of survived cycles was analyzed descriptively for each group and with the Kaplan-Meier method across the groups (with the Breslow test for the pairwise analyses). The frequency of restorable and non-restorabe fractures was calculated for each group.

3. Results

The Kaplan–Meier survival curves for the test simulating normal (100–500 N) and parafunctional (600–1000 N) forces are displayed in Figs. 2 and 3 respectively. Table 1 presents the p values for group-wise comparisons in the test simulating nor-

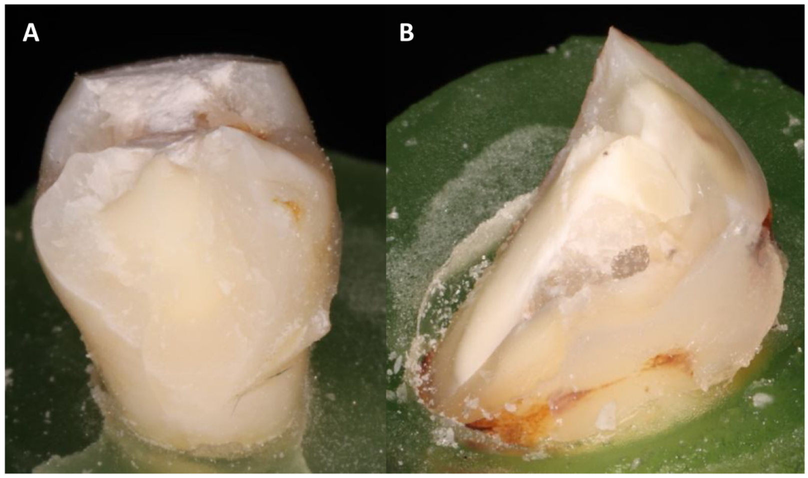

Fig. 4 – Photographs of repairable (A) and irrepairable (B) fracture pattern of the tested specimens.

mal forces, while Table 2 presents the p values for group-wise comparisons in the test simulating parafunctional forces.

In the test simulating normal forces the survival rate of Group C3 was not showing significant difference ($p > 0.05$) from Group A1 or the control group (intact teeth). The rest of the groups had significantly lower survival rates compared to both Group C3 and the control group.

In the test simulating parafunctional forces for the specimens survived the first phase of mechanical testing ($n = 54$), the survival rate of the control group showed significantly higher survival ($p < 0.05$) compared to the rest of the tested groups. The restored groups present in the second phase of the test did not differ significantly ($p > 0.05$) from each other in terms of survival.

All restored groups showed dominantly irrepairable fractures, whereas only the control group presented almost exclusively repairable fractures (Table 3 and Fig. 4).

The average values with SD of microgap percentage at post/core–tooth interface of four groups (C1-C4) are illustrated in Fig. 5. Values revealed that post/core restorations made of directly layered packable SFRC (Group C1) had a less microgap (19.1%) than other tested groups. While, Group C3 exhibited the highest number of microgap (55.9%) at the studied interphase within the root canal (Fig. 5).

Concerning the microhardness values for the packable and flowable SFRCs at the bottom (apical) of the root canal, flowable SFRC (C2-C4) showed higher microhardness values (56.9 VH) as well as lower difference among the microhardness values at the coronal and at the apical part of the root canal (Fig. 6).

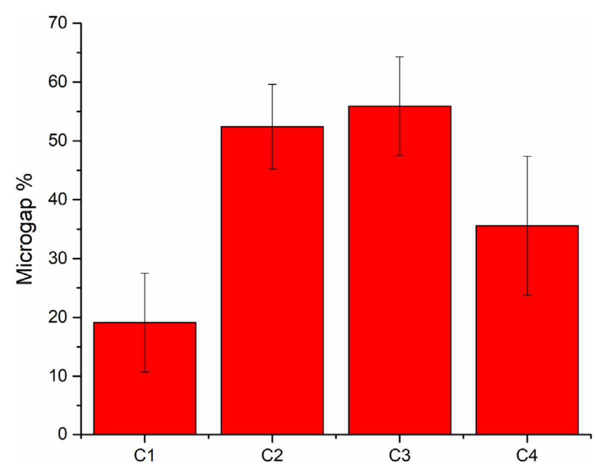

Fig. 5 – Mean percentage of microgap observed in different groups from total post/core-tooth interface length after staining. Vertical lines represent standard deviation.

4. Discussion

One of the main goals of post-endodontic restoration of RCT teeth is restoring lost resistance to masticatory load [37]. In this investigation, upper RCT premolars with MO cavities were selected as they present an unfavorable anatomy in crown to root ratio and crown volume, which makes them at greater risk to cusp fractures compared to other posterior teeth when subjected to occlusal load [13]. Furthermore, premolars are exposed to more detrimental lateral forces than molars during mastication, namely a combination of compressive and shear forces that raises the possibility of cusp fracture [38]. The tested specimens loaded with an angle (45 degree to the long axis of the tooth), which seems to be the worst-case scenario in regards to the fracture resistance of RCT teeth as described by Wandscher and his colleagues [39].

According to Ferrario et al., the normal biting force that develops during a single tooth bite is approximately 250–290 N for the first and second premolars in healthy young male adults [40]. This is in accordance with the findings of Jantarah et al., who reported the normal biting force for maxillary premolars to be in the range between 100–300 N [41]. However, higher biting forces have to be predicted in individuals with functional disturbances, such as clenching or bruxism where biting force can be as high as 520–800 N [42,43]. It was on the basis of these published values that we divided our test protocol into 2 phases, where the first phase simulated normal biting forces (up to 500 N) and the second phase simulated extremely high forces (up to 1000 N). The

Table 1 – p values of pairwise log-rank post-hoc comparisons among tested groups loaded with a force of magnitude 100-500 N (Kaplan-Meier survival estimator followed by log-rank test for cycles until failure or the end of the fatigue loading).

	A1		A2		A3		B1		B2		C1		C2		C3		C4		control	
Gr.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.
A1			0.028	0.866	0.074	0.785	0.053	0.818	0.370	0.543	0.448	0.503	0.276	0.600	3.252	0.071	1.099	0.294	8.658	0.003
A2	0.028	0.866			0.035	0.852	0.126	0.723	0.736	0.391	0.007	0.934	0.000	0.983	4.509	0.034	0.918	0.338	13.778	0.000
A3	0.074	0.785	0.035	0.852			0.085	0.770	0.367	0.545	0.097	0.755	0.053	0.819	4.305	0.038	0.471	0.493	11.571	0.001
B1	0.053	0.818	0.126	0.723	0.085	0.770			0.419	0.517	0.416	0.519	0.230	0.631	4.294	0.038	1.134	0.287	10.864	0.001
B2	0.370	0.543	0.736	0.391	0.000	0.545	0.419	0.517			0.229	0.632	0.318	0.573	5.080	0.024	0.004	0.950	12.320	0.000
C1	0.448	0.503	0.007	0.934	0.471	0.755	0.416	0.519	0.229	0.632			0.007	0.934	6.367	0.012	0.247	0.619	14.155	0.000
C2	0.276	0.600	0.000	0.983	0.735	0.819	0.230	0.631	0.318	0.573	0.007	0.934			5.312	0.021	0.315	0.575	12.320	0.000
C3	3.252	0.071	4.509	0.034	0.140	0.038	4.294	0.038	5.080	0.024	6.367	0.012	5.312	0.021			6.619	0.010	1.019	0.313
C4	1.099	0.294	0.918	0.338	0.121	0.493	1.134	0.287	0.004	0.950	0.247	0.619	0.315	0.575	6.619	0.010			15.017	0.000
Con.	8.658	0.003	13.778	0.000	15.059	0.001	10.864	0.001	12.320	0.000	14.155	0.000	12.320	0.000	1.019	0.313	15.017	0.000		

Table 2 – p values of pairwise log-rank post-hoc comparisons among tested groups loaded with a force of magnitude 600-1000 N (Kaplan-Meier survival estimator followed by log-rank test for cycles until failure or the end of the fatigue loading).

	A1		A2		A3		B1		B2		C1		C2		C3		C4		control	
Gr.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.	Chi-Square	Sig.
A1			0.022	0.881	0.235	0.628	3.938	0.047	0.928	0.336	1.000	0.317	0.928	0.336	0.029	0.866	0.184	0.668	0.022	0.000
A2	0.022	0.881			0.533	0.465	0.533	0.465	0.533	0.465	0.429	0.513	0.533	0.465	0.006	0.938	0.429	0.513	8.008	0.000
A3	0.235	0.628	0.533	0.465			1.391	0.238	0.000	1.000	0.471	0.493	0.735	0.391	0.140	0.708	0.121	0.728	15.059	0.000
B1	3.938	0.047	0.533	0.465	1.391	0.238			0.735	0.391	0.500	0.480	0.750	0.386	0.973	0.324	2.207	0.137	5.255	0.000
B2	0.928	0.336	0.533	0.465	0.000	1.000	0.735	0.391			0.000	1.000	0.000	1.000	0.065	0.799	0.000	1.000	8.290	0.004
C1	1.000	0.317	0.429	0.513	0.471	0.493	0.500	0.480	0.000	1.000			0.032	0.858	0.624	0.430	0.409	0.522	7.877	0.005
C2	0.928	0.336	0.533	0.465	0.735	0.391	0.750	0.386	0.000	1.000	0.032	0.858			0.952	0.329	0.500	0.480	9.587	0.002
C3	0.029	0.866	0.006	0.938	0.140	0.708	0.973	0.324	0.065	0.799	0.624	0.430	0.952	0.329			0.137	0.712	14.569	0.000
C4	0.184	0.668	0.429	0.513	0.121	0.728	2.207	0.137	0.000	1.000	0.409	0.522	0.500	0.480	0.137	0.712			12.129	0.000
Con.	17.069	0.000	8.008	0.005	15.059	0.000	5.255	0.022	8.290	0.004	7.877	0.005	9.587	0.002	14.569	0.000	12.129	0.000		

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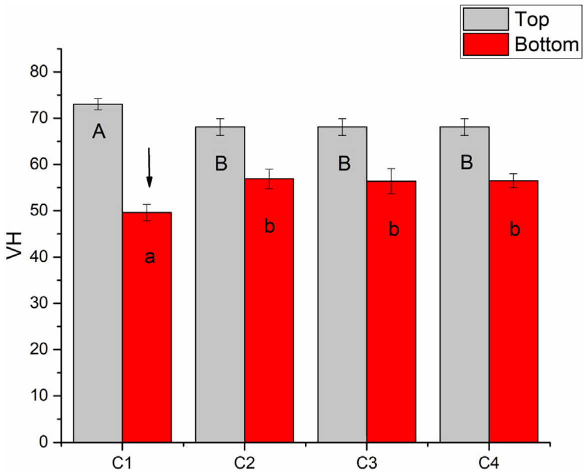

Fig. 6 – Microhardness (VH) mean values for packable and flowable SFRCs at the top (coronal) and bottom (apical) part of the root canal. Arrows above the columns indicate VH of this group dropped below 80 % of the coronal part value. Vertical lines represent standard deviation.

latter aspect requires to be taken into consideration because temporomandibular disorders are highly prevalent in Western societies [44]. Occlusal load is a key factor in the successful treatment of root-filled teeth and it is crucial for the clinician to know if the patient has parafunctional movements [45].

In our study, only specimens restored with an individually-made unidirectional FRC post luted with flowable SFRC (Group C3) showed significantly higher survival compared to the rest of the restored groups when exposed to normal biting forces. The only exception was the Group A1, which did not differ significantly from the C3 group in terms of survival. The individually-made post used in Group C3 is made of unidirectional fibers (E-glass) impregnated with a combination of bisphenol A-glycidyl methacrylate as the cross-linked phase and polymethyl methacrylate as a linear phase, which together form a semi-interpenetrating polymer network (semi-IPN) [46]. As the semi-IPN structure contains both cross-linked and linear polymer phases, it ensures a stable adhesion to resin materials used for luting. Logically, this could possibly influence the fracture resistance of the restoration. In the study of Doshi et al., teeth restored with the individually-made FRC post presented higher fracture resistance compared to the ones restored with a conventional FRC post [47]. On the contrary, in our previous study the individually-made FRC post did not make a significant difference in regards to fracture resistance compared to a conventional FRC post [48]. It must be noted that in the mentioned study the teeth were decoronated premolar teeth (not MO cavities), and also the luting and core build-up material was a conventional particulate filled dual-cure resin, not a fiber-reinforced one. The same was found in our latest study where apexified anterior teeth were used [31]. In this present study, the superior resistance of the specimens restored with the individually-made FRC post might be attributed to the flowable SFRC used for post luting and subsequent core build-up. The flowable SFRC forms a unit with the individually-made post due to the semi-IPN polymer matrix of this post. Studies have demonstrated increased bond strength between the individually-made FRC post and composite resin materials compared to conventional FRC post [26]. To our knowledge, flowable SFRC has not been used to lute posts into root canals. This indication could be important from a biomimetic point a view. FRC posts usually do not have a perfect fit inside the root due to the irregular anatomy and individual cross section of the root canal. As a result, it is usually the mechanically inferior luting material that fills out the gaps between the root canal walls and the post, acting as the interfacial medium between them. As detrimental tensile stresses occur on the surfaces of the root canal walls, the restorative material placed with the intention of stress-bearing should be luted directly to them with close contact [49]. As highlighted by Le Bell-Rönnlöf et al., if the conventional FRC post is inserted in the most central part of the post position (i.e. the neutral axis of the tooth), the post is not ideally placed with respect to biomechanics if reinforcement is the intended results [49]. Beside their superior resistance in the normal force range (100−500 N), specimens restored with the individually-made FRC post combined with flowable SFRC did not show statistically significant difference compared to controls (Table 1). Fiber-reinforced materials are increasingly used for crack-arresting and reinforcement in high stress-bearing areas. In the Bioblock technique, SFRC is directly and tightly fitted to the wall of root canal, excluding the shortcomings of the usage of luting cement or the biomechanically improper positioning of the FRC post, thus theoretically eliminating all damaging tensile stresses created when the restoration is loaded [30]. This enables the clinician to fill and restore any root canal with irregular cross section deemed not ideal for FRC post insertion. With the Bioblock technique, the amount of fibers can be maximized also in the critical cervical area of the tooth, which seems to be important regarding future stress accumulation [50]. Not less importantly, the Bioblock technique minimizes the number of interfaces within the restoration-tooth complex, which has been shown to be beneficial as interfaces increases the amount of stress within this unit [51]. Interestingly, in this study neither the normal Bioblock technique (Group C1), nor its modification (extending only 3 mm into the canal; Group B1) achieved survival comparable to Group C3 or intact teeth. In one of our previous studies, the Bioblock technique yielded higher fracture resistance compared to teeth restored with a conventional FRC post. However, in that study we tested the restoration of MOD cavities in premolars and static loading was applied [30]. Our current findings are in accordance with previous studies showing that restorations prepared with the Bioblock technique failed to reach fracture resistance or survival comparable to intact teeth, in MOD RCT premolars [30] and apexified anterior teeth [31], respectively. The performance of fiber reinforcement relies on many factors, namely the used resins, the thickness, length, position and the orientation of fibers, the fibers aspect ratio, the adhesion of the polymer matrix and fibers, and the impregnation of the fibers into the resin [52]. The fiber aspect ratio refers to the length of the fiber compared to the diameter of the fiber (l/d). The fiber aspect ratio is of major importance in the case of modern fiber-reinforced materials since it affects flexural modulus, tensile strength, and the reinforcing

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Table 3 – The distribution of fracture pattern among the tested groups (n = 15).

Fracture pattern	A1	A2	A3	B1	B2	C1	C2	C3	C4	Control
repairable	1	3	2	1	0	1	0	0	0	12
irrepairable	14	12	13	14	15	14	15	15	15	3

efficiency of the material [53,54]. While packable SFRC contains millimeter-long fibers, the fibers in the flowable SFRC are micrometer-long. Even with the shorter fibers incorporated in the flowable SFRC, the fiber aspect ratio is within the range of 30–94 [55], thus offering reinforcement to the materials and likely to the adhered dental tissues. Curiously, the Bioblock technique did not allow superior survival compared to the other groups and was significantly weaker compared to intact teeth, even with the flowable SFRC. This is against our previous findings in anterior apexified teeth where the Bioblock technique with flowable SFRC was the only tested restorative technique yielded survival comparable to intact teeth [31].

Regarding the fracture behavior and load-bearing capacity of SFRC restorations, Lassila et al., stated that the optimal thickness of the surface conventional composite over the SFRC-core is between 0.5–1 mm [56]. Assuming that reinforcement role of the SFRC-core is built upon the mechanism of a crack-stopper, the length from the surface of the stress starting point to the SFRC-core is of importance. Thus, the veneered conventional composite thickness might contribute to the crack propagation and the survival rate of the restorations. This is consistent with earlier investigations which showed the importance of how thick SFRC and conventional surface layers should be applied [57,58].

Most dental practitioners regularly restore RCT upper premolars with conventional fiber posts, but this approach is a matter of debate [4]. There are studies to indicate that RCT upper premolars without a fiber post show similar fracture resistance to those restored with a post [59–61], while other studies showed superior results when a conventional FRC post was used compared to a composite filling alone [62,63]. In our present setup, there was no difference between teeth restored with a conventional composite filling alone (Group A3) or with a conventional FRC post and flowable SFRC (Group C4). The survival of the groups restored with the latter two techniques was also significantly lower compared to intact teeth. Our current findings are also in accordance with those of Shah et al. [37], and Nothdurft et al. [16], showing that RCT premolars with MO cavities cannot be reinforced with a composite filling only, as these teeth do not have the same fracture resistance as intact teeth. As for testing in the extreme force range, none of the tested techniques allowed survival comparable to intact teeth. This is important to consider when treating patients who could possibly overload the restoration due to clenching or bruxism. Regarding the fracture patterns, all specimens in all groups showed predominantly irreparable fractures, except for the control group, where the fractures were predominantly reparable.

Considering the adaptation of the used materials within the root canal appeares to be very important, gap formation was also evaluated with a microgap determing test for the packable and flowable SFRCs (Fig. 5). The packable SFRC (Group C1) had notably good adaptation to the canal walls than other tested groups (C2-C4), which was in agreement with our previous findings [30,31]. Though the adaptation of the packable SFRC to the canal walls was ideal, voids were seen within the material itself. These voids could be due to poor condensation of the material inside the tighten space, or entrapment of air when applying the thick material into the canal. The authors' opinion is that these voids could contribute in reducing the shrinkage stress during the polymerization and this might decrease the microgaps at interfaces. Infact, this has been suggested also earlier when the influence of FRC in regular filling application was studied [64].

In line with previous findings and due to the higher volumetric shrinkage of the flowable SFRC, the microgap formation at the examined interphase in the root canal with flowable SFRC (Group C2-C4), was not so perfect.

Microhardness test was carried out in order to assess the curing of SFRCs inside the root canal. The data revealed that SFRCs used in the coronal part of the canal had superior microhardness compared to the apical part of the same canal, demonstrating enhance curing due to higher intensity of light polymerization. In the crucial apical part of the canal, flowable SFRC (C2-C4) showed higher microhardness values and also lower difference between the microhardness measured at the apical and at the coronal parts of the root canal (Fig. 6). This is in line with previous results showing that SFRC can be light-cured inside the canal [29–31]. This is resulting from both the translucency of the material and the fact that the randomly oriented fibers within it may conduct and scatter the light over longer distances [65]. It has been shown that refraction index of glass fibers and dimatehacrylate resin matrix during its curing phase benefits light scattering and improves photopolymerization [66].

To mimic more clinical environment and to have perfect view of restorative material/design behavior under clinical conditions, fatigue survival after long-term water storage and thermal aging should also be taken into consideration.

5. Conclusion

The restoration of ET premolars with the use of individually-made FRC post and SFRC as luting-core material showed promising achievement regarding fatigue-resistance and survival.

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