ARTICLE IN PRESS

DENTAL MATERIALS XXX (XXXX) XXX–XXX

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/dental

Fatigue performance of endodontically treated molars restored with different dentin replacement materials

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ARTICLE INFO

Article history:
Received 31 March 2021
Received in revised form 6 January 2022
Accepted 19 February 2022

Keywords:
Fatigue survival
Fiber-reinforced glass ionomer cement
Short fiber-reinforced composite
Root canal treated molar teeth
Occlusal cavity

ABSTRACT

Objectives: The aim was to investigate the fatigue performance of endodontically treated (ET) molars restored by various dentin-replacing materials and material configurations. Moreover, the impact of additional adhesive treatment with glass-ionomer cement (GIC) was evaluated.

Methods: 250 intact molars were collected and randomly distributed into ten groups ($n = 25$). After endodontic procedure standard Class I cavities were prepared and restored with different direct restorative techniques and dentin-replacing materials. Two-group were restored with either packable or flowable short fiber-reinforced composites (SFRCs). Two-group were restored by experimental fiber-reinforced GIC with and without adhesive treatment. Four-group were restored by conventional and resin-modified GICs with or without adhesive treatment. One-group was restored with a dual-cure composite resin and last group was restored with only conventional composite resin (control). Fatigue-survival was measured for all specimens using a cyclic-loading machine until fracture occurred or a number of 40.000 cycles were achieved. Kaplan-Meyer survival analysis was conducted, followed by pairwise log-rank post hoc comparisons. Fracture mode was then examined by means of optical microscopy and SEM.

Results: Group restored with flowable SFRC showed significantly higher survival ($p < 0.05$) compared to all of the groups, except for group restored with packable SFRC ($p > 0.05$). Group restored with fiber-reinforced GIC had significantly ($p < 0.05$) higher survival rates compared to other commercial GICs. SEM demonstrated change of the fracture line when fracture reached the SFRC layer.

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https://doi.org/10.1016/j.dental.2022.02.007

Please cite this article as: J. Molnár, M. Fráter, T. Sáry et al., Fatigue performance of endodontically treated molars restored with different dentin replacement materials, Dental Materials, https://doi.org/10.1016/j.dental.2022.02.007

Significance: Direct restoration of Class I in ET molars with the use of SFRCs as dentin-replacing materials demonstrated its ability to reinforce the dental structures and to increase the fatigue resistance in this specific clinical situation.

1. Introduction

Due to their compromised structural integrity, endodontically treated (ET) teeth require specialised restorative treatment [1]. This is mostly necessitated by extensive caries or trauma and subsequent root canal treatment, which may lead to the loss of the pulp chamber roof, the pericervical dentin or even the marginal ridges [2]. Consequently, ET teeth have a higher chance of fracture [3–7]. Reinforcing root canal treated molar teeth is therefore of key importance as molars are exposed to the highest maximum biting forces in the mouth. The stressful lifestyle and the growing incidence of temporomandibular disorders resulting to bruxism in modern Western societies further increase the stress that restorations in the molar region must withstand [8].

In ET teeth, the restorative treatment of choice largely depends on the dimensions of the cavity, namely the number of remaining cavity walls and their thickness [6,9]. While a MOD cavity causes an average of 63% loss of relative cuspal stiffness [10], a Class I occlusal cavity causes only 5–20% loss [6,11]. This significant difference can be attributed mainly to the fact that in Class I both marginal ridges are preserved. As Class I cavities are more favorable in terms of preserved tooth structure compared to MO/OD/MOD cavities, it has been often suggested that Class I occlusal cavities can be safely restored directly with fillings in ET teeth [12–14].

A variety of choices are available to substitute the missing dentin when preparing direct restorations in deep cavities. These include glass ionomer cements (GICs), resin-modified GICs (RMGICs), conventional packable composite resins, short fiber-reinforced composite resins, dual-cure core build-up composite resins, etc.

The so-called "super-closed" sandwich technique uses GIC or RMGIC as a dentin-substituting material over the adhesively treated cavity walls, covered with packable composite resin [15,16]. A number of laboratory studies have shown that using this technique decreases microleakage and increases marginal efficiency [17,18]. On the other side, from clinical point of view, it has been proposed that the use of glass ionomer cavity bases would diminish the overall strength of the composite restoration [19]. Though, long-term clinical study by van de Sande and her colleagues showed that presence of a GIC base did not affect the survival of posterior composite restorations [20].

Short fiber-reinforced composite resin (SFRC) has been recommended to reinforce composite restoration in high stress-bearing areas, including ET posterior teeth [21,22]. This SFRC was reported to exhibit improved performance in shallow and deep MOD cavities in the context of fracture resistance and/or fracture pattern [8,23]. The flowable version of SFRC was launched in 2019 with the promise of easy handling and adaptability. So far, flowable SFRC has shown promising results when utilized in direct restorations in different clinical situations [24–26].

The question arises as which material would be best to substitute the missing dentin in occlusal cavities of root canal treated molar teeth. The necessity of bonding when the "super-closed" sandwich technique is used is also an open question. Therefore, the purpose of this study was designed to analysis the fatigue performance and failure mode of Class I cavities in ET molar teeth restored by different direct restorative techniques and dentin-replacing materials.

2. Materials and methods

The University of Szeged's Ethics Committee approved all of the study's procedures, and the research was carried out in conjunction with the Helsinki Declaration. Two hundred fifty intact mandibular 3rd molars, extracted for orthodontic or periodontal causes were collected primarily for the current research. The freshly extracted teeth were kept in 5.25% NaOCl for 5 min before being preserved at room temperature in 0.9% saline solution. Within 2 months after extraction, teeth were used. Hand scalers were used to scrape the soft tissue covering the root surface during specimen preparation. The following were the inclusion criteria: no caries or root cracks, no prior endodontic procedures, no posts or other coronal restorations, and no resorptions. The coronal dimensions of the included teeth were standardized as follows: only specimen with a 10.0–10.9 mm in size, measured at the widest bucco-lingual dimension were used for this study. The specimens' mesio-distal dimension was also measured, and this parameter allowed for a maximum deviation of 10% from the calculated mean. In the end 250 teeth met the inclusion criteria and were included for restorative treatment.

These teeth were distributed at random among ten study groups (G1–10) (n = 25/group).

2.1. *Specimen preparation*

All of the groups were received a Class I cavity preparation, which was then continued into a conventional endodontic access (TEC) using the same concepts as previously stated [27,28]. The size of the occlusal cavities was standardised with the aid of periodontal probe in both buccol-lingual and mesio-distal directions (Hu-Friedy Mfg. Co., Chicago, USA). In any case when the access cavity had to be increased due to anatomical variations, leading to undermined walls or wall parts, the teeth were excluded from the study. Endodontic treatment was exactly carried out as described in one of our previous studies [29]. The access cavity was temporarily filled with Cavit W (3 M ESPE, St. Paul, MN, USA) after the guttapercha was cut back to the level of the orifice. To prevent leakage through the apex, Fuji Triage Pink was applied to the apical part of the root. The teeth were kept in water for a week (at 37 °C) in an incubator (mco-18aic, Sanyo, Japan). The temporary material was then removed, and the access cavity was refreshened with a diamond bur. The guttapercha was cut back 4 mm under the orifice with a No. 3 Gates Glidden bur (Dentsply Maillefer, Ballaigues, Switzerland). The root canal was rinsed with chlorhexidine and dried with paper points after the gutta-percha was cut back. Cavities in Group 1,2,3,5,7,9 and 10 obtained the same adhesive treatment, whereas the rest of the groups received no adhesive treatment at this stage.

During the adhesive treatment, the enamel was acid-etched selectively with 37% phosphoric acid for 15 s and rinsed with water. After drying the coronal cavity and the coronal part of the root canal 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, according to the manufacturer's instructions using a microbrush-X disposable applicator (Pentron Clinical Technologies, LLC, USA). The adhesive was light-cured for 60 s using an Optilux 501 quartz-tungsten-halogen light-curing unit (Kerr Corp., Orange, CA, USA). The average power density of the light source, measured with a digital radiometer (Jetlite light tester; J. Morita USA Inc. Irvine, CA, USA) prior to the bonding procedure, was 840 ± 26.8 mW/cm^2. The distance from the light-curing tip to the material to be cured was always 1–2 mm.

In Groups 4, 6 and 8 the dentin was conditioned with polyacrylic acid (Cavity Conditioner, GC Europe) according to the manufacturer's instructions.

Different materials and material configurations were used to substitute the missing dentin and to restore the specimens in Groups 1–10 (Fig. 1):

Group 1: The cavities including the 4 mm deep "post space" were restored with packable SFRC (everX Posterior, GC Europe) applied in a horizontal layering technique (approx. 4 mm thick each) according to the anatomy of the dentin, leaving 1.5–2 mm occlusally for the final composite layer. The first layer of SFRC was light-cured for 60 s, all other layers were cured for 40 s. The last occlusal layer was conventional composite resin (G-aenial Posterior PJ-E, GC Europe) covering the SFRC, which was light-cured for 20 s

Group 2: The cavities were restored with flowable SFRC (everX Flow, GC Europe) as described in Group 1.

Group 3: The cavities were restored with experimental fiber-reinforced RMGIC which was prepared according to our previous research [30,31]. The fiber-reinforced RMGIC was applied and light-cured according to the respective manufacturers' instructions of RMGIC material and following the anatomy of the dentin. Then the fiber-reinforced RMGIC was adhesively treated with a self-etch adhesive (G-Premio Bond, GC Europe). The excess adhesive was removed with a suction tip and was light-cured for 20 s. The last occlusal layer was reconstructed with conventional composite resin (G-aenial Posterior PJ-E) as in Group 1.

Group 4: The cavities (with no adhesive treatment) were restored with fiber-reinforced RMGIC as in Group 3. After applying and light-curing the fiber-reinforced RMGIC, the remaining cavity walls and the dentin substituting material has been adhesively treated the same way as described earlier in case of Groups 1,2,3,5,7,9,10. Once the adhesive was light-cured, the remaining 1.5–2 mm occlusally was restored with conventional composite resin (G-aenial Posterior PJ-E) as in Group 1.

Group 5: The cavities were restored with RMGIC (Fuji II LC, GC Europe) applied and light-cured according to the respective manufacturers' instructions and following the anatomy of the dentin. Then the rest of the remaining cavity was restored as described in Group 3.

Group 6: The cavities (with no adhesive treatment) were restored with RMGIC as in Group 5. Then the rest of the remaining cavity was adhesively treated and restored as described in Group 4.

Group 7: The cavities were restored with GIC (Equia Forte, GC Europe) applied in a bulk-fill technique according to the anatomy of the dentin. Then the rest of the remaining cavity was restored as described in Group 3.

Group 8: The cavities (with no adhesive treatment) were restored with GIC applied in a bulk-fill technique according to the anatomy of the dentin. Then the rest of the remaining cavity was restored as described in Group 4.

Group 9: The cavities were restored with a dual-cure composite resin (Gradia Core, GC Europe) applied and light-cured (40 s) in a bulk-fill technique according to the anatomy of the dentin. Gradia Core was inserted using its own automix cartridge with an 'elongation tip' for direct root canal application. The last occlusal layer was conventional composite resin (G-aenial Posterior PJ-E) covering the core build-up material.

Group 10: The cavities were restored with conventional (micro-hybrid) composite resin (G-aenial Posterior PJ-E) applied with an oblique incremental technique. First, the root canal was filled with 2 consecutive layers (each 2 mm thick) of flowable composite (G-aenial Flow X, GC Europe). After light-curing the flowable layers (each) for 60 s, packable conventional composite resin was placed in consecutive 2 mm thick increments to restore the whole cavity. Each increment was light-cured for 40 s. The most occlusal layer was light-cured for 20 s

Finally, for all restored specimens, glycerine gel (DeOx Gel, Ultradent Products Inc., Orange, CA, USA) was applied and final curing from the occlusal side for 40 s was performed. The restorations were finished with a fine granular diamond burs (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. Embedding of the samples was performed the same way as in our previous articles [24,26]. 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

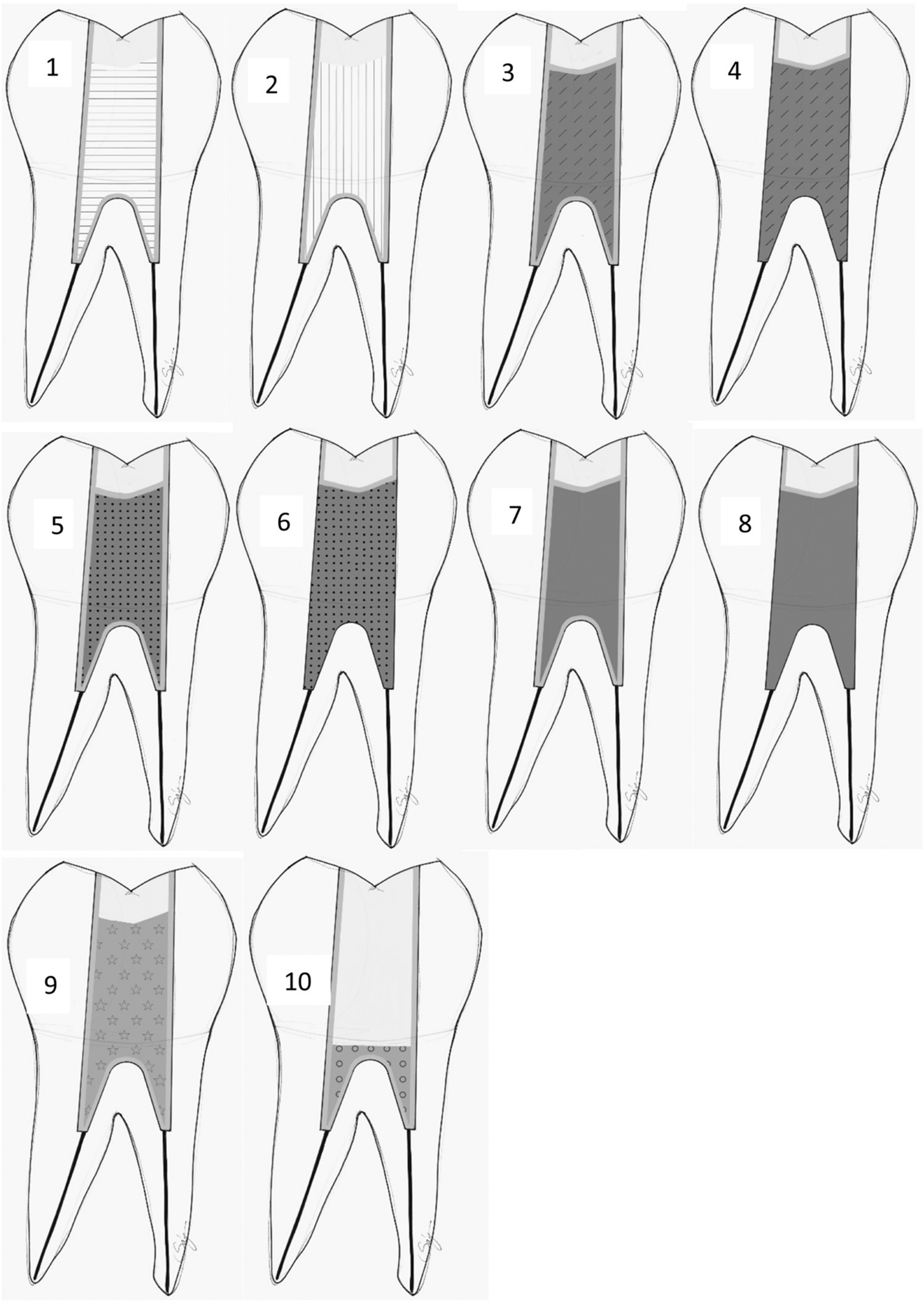

Fig. 1 – Schematic figure representing the test groups (Group 1–10) with different dentin replacing materials. Gr1: Packable SFRC; Gr2: Flowable SFRC; Gr3: Fiber-reinforced RMGIC with adhesive; Gr4: Fiber-reinforced RMGIC without adhesive; Gr5: RMGIC with adhesive; Gr6: RMGIC without adhesive; Gr7: GIC with adhesive; Gr8: GIC without adhesive; Gr9: Dual-cure composite resin; Gr10: Conventional light-cure composite resin (control).

restored specimens were submitted to an accelerated fatigue-testing protocol [15,32–34].

Cyclic isometric loading was performed by a hydraulic testing machine (Instron ElektroPlus E3000, Norwood, MA, USA) vertically, in the long axis of each tooth with a round-shaped metallic 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 stages of 200 N, 400 N, 600 N, 800 N, 1000 N, 1200 N, 1400 N, 1600 N at 5000 cycles each. The specimens were loaded until fracture occurred or a total of 40.000 cycles for the whole procedure. For the survival analyses for the simulation of forces, the amount of cycles at which the specimen failed were recorded.

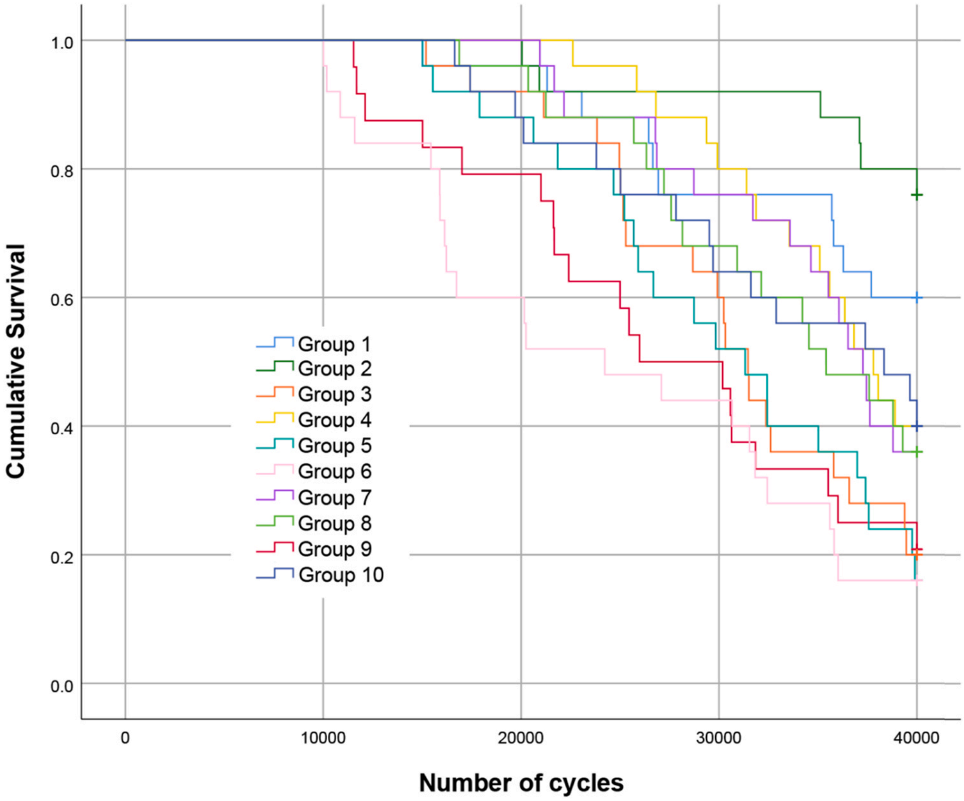

Fig. 2 – Fatigue resistance survival curves (Kaplan-Meier survival estimator) for all tested groups.

2.3. *Fracture mode analysis*

The failed specimens were examined both visually and under stereomicroscope (Heerbrugg M3Z, Heerbrugg, Switzerland) with different magnifications (6.5 and 15x) and illumination angles to detect the type and location of failure, as well as the direction of crack propagation. According to Scotti and coworkers, a distinction was made between restorable or non-restorable fractures with a two-examiner agreement. A restorable fracture is above the CEJ, meaning that in case of fracture, the tooth can be restored, while a non-restorable fracture extends below the CEJ and the tooth is likely to be extracted [35]. The representative loaded specimens were selected and examined by scanning electron microscopy (SEM, LEO, Oberkochen, Germany). Prior to observation, all sectioned specimens were cleaned by alcohol and then coated with a gold layer using a sputter coater in vacuum evaporator (BAL-TEC SCD 050 Sputter Coater, Balzers, Liechtenstein).

2.4. *Statistical analysis*

Statistical analyses were performed in SPSS 21.0 (SPSS, IBM Corp., NY, USA). 10 groups were defined according to the method of restoration. The number of survived cycles was analysed descriptively for each group and with the Kaplan-Meier method across the groups (with the Breslow test for the pairwise analyses). The frequency of restorable and non-restorable fractures was calculated for each group.

3. Results

The Kaplan–Meier survival curves for the accelerated fatigue test are presented in Fig. 2. Table 1 presents the p values for group-wise comparisons. Group 2 (flowable SFRC) revealed significantly higher survival ($p < 0.05$) compared to all of the groups, except for Group 1 (packable SFRC) ($p = 0.189$). The control group (Group 10; conventional composite resin) showed significantly higher ($p = 0.005$) survival rate compared to Group 6 (RMGIC without adhesive), and simultaniously showed significantly lower ($p = 0.008$) survival rate compared to Group 2 (flowable SFRC). The rest of the groups did not differ significantly from the control group ($p > 0.05$). The restored Group 4 (fiber-reinforced RMGIC without adhesive) had significantly ($p = 0.025$) higher survival rates compared to Group 3 (fiber-reinforced RMGIC with adhesive), Group 5 (RMGIC with adhesive) ($p = 0.013$), Group 6 (RMGIC without adhesive) ($p = 0.000$), and Group 9 (dual-cure composite resin) ($p = 0.003$). Adhesive treatment has no significant ($p > 0.05$) influence on the fatigue performance of tested commercial glass ionomer materials (Groups 5–8). Table 2 presents the maximum load value recorded for each specimen before failure.

Regarding fracture mode, all restored groups showed dominantly catastrophic non-restorable fractures (Table 3 and Fig. 3). However, in Groups 1 and 2 more than 60% of restored teeth did not fail after completion of 40.000 cycles.

Optical microscope and SEM images of tested restorations showed that the fatigue crack path propagated from loading

Table 1 – 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).

Gr.	Gr1 Chi-Square	Sig.	Gr2 Chi-Square	Sig.	Gr3 Chi-Square	Sig.	Gr4 Chi-Square	Sig.	Gr5 Chi-Square	Sig.	Gr6 Chi-Square	Sig.	Gr7 Chi-Square	Sig.	Gr8 Chi-Square	Sig.	Gr9 Chi-Square	Sig.	Gr10 Chi-Square	Sig.
Gr1			1.727	0.189	6.096	0.014	0.604	0.437	7.590	0.006	13,549	0.000	1.326	0.250	2.019	0.155	9.607	0.002	1.470	0.225
Gr2	1.727	0.189			16,383	0.000	6.346	0.012	18.207	0.000	23.617	0.000	7.394	0.007	8.401	0.004	17.371	0.000	7.142	0.008
Gr3	6.096	0.014	16.383	0.000			5.039	0.025	0.034	0.854	3.516	0.061	3.228	0.072	1.578	0.209	1.160	0.281	1.420	0.233
Gr4	0.604	0.437	6.346	0.012	5.039	0.025			6.208	0.013	12.490	0.000	0.201	0.654	0.718	0.397	8.633	0.003	0.374	0.541
Gr5	7.590	0.006	18.207	0.000	0.034	0.854	6.208	0.013			2.931	0.087	3.999	0.046	2.368	0.124	0.677	0.411	2.144	0.143
Gr6	13.549	0.000	23.617	0.000	3.516	0.061	12.490	0.000	2.931	0.087			11.257	0.001	8.445	0.004	0.812	0.368	7.977	0.005
Gr7	1.326	0.250	7.394	0.007	3.228	0.072	0.201	0.654	3.999	0.046	11.257	0.001			0.190	0.663	6.281	0.012	0.053	0.819
Gr8	2.019	0.155	8.401	0.004	1.578	0.209	0.718	0.397	2.368	0.124	8.445	0.004	0.190	0.663			4.232	0.040	0.002	0.960
Gr9	9.607	0.002	17.371	0.000	1.160	0.281	8.633	0.003	0.677	0.411	0.812	0.368	6.281	0.012	4.232	0.040			3.540	0.060
Gr10	1.470	0.225	7.142	0.008	1.420	0.233	0.374	0.541	2.144	0.143	7.977	0.005	0.053	0.819	0.002	0.960	3.540	0.060		

surface (occlusally) to the inner part at dentin-replacing materials (Fig. 4). Fig. 4d showed fracture propagation through particulate fillers of the occlusal composite resin and Fig. 4e change of the direction of the fracture when the fracture continued in the layer of SFRC. Fig. 4f showed cut fiber ends of the SFRC which suggests specific fiber orientation and that the fracture propagation was in-plane directed in the SFRC.

4. Discussion

Teeth that have been endodontically treated (ET) are more likely to crack than teeth that have not been ET treated [36–38]. Therefore, it is of high importance that the coronal restoration of these teeth should also serve as structural reinforcement. In our study, multiple direct restorative techniques and fiber-reinforced dentin-replacing materials were used to restore Class I cavities in ET molars. Of all the possible direct restorative options in this specific situation, clinicians choose composite fillings the most often. Thus, we used direct composite restoration as control (Group 10). Whether direct composite restorations would be the best option in this situation is a matter of debate. Many studies have concluded that ET molars, when root canal treated through an occlusal cavity/TEC, can be restored safely with a direct composite filling [6,12–14]. However, other studies have found significantly lower fracture resistance in such teeth as compared to intact teeth [27,39,40]. Furthermore, layering composite resin for filling in such deep cavities is time-consuming compared to any bulk-fill technique. Even more importantly, from a biomechanical perspective, in most cases when fracture occurs in deep cavities restored with only composite filling, dominantly irreparable fractures develop, leaving the tooth unrestorable [9,23]. Bilayered restorations utilizing SFRCs have shown superior fracture resistance with a favorable fracture pattern [23,41,42]. In our study, the flowable SFRC restoration (everX Flow, Group 2) showed the highest survival among the tested groups. Remarkably, it showed significantly higher survival than the control group ($p = 0.008$). To our knowledge, everX Flow has not been tested in restoring root canal treated molar teeth before. The explanation for the favorable outcome may lie in the individual characteristics especially high fiber content of the flowable SFRC. The effectiveness of fiber reinforcement is determined by a variety of factors, including the resins used, the weight, orientation, and location of the fibers, the aspect ratio, the fibers' adhesion to the polymer matrix, and the fibers' impregnation into the resin [22]. The length of the fiber in relation to its diameter (l/d) is referred to as the aspect ratio. This parameter is critical in advanced fiber-reinforced materials because it affects the material's tensile strength, flexural modulus, and reinforcing performance [43]. Though millimeter-long fibers are used in packable SFRC, micrometer-long fibers are used in flowable SFRC. Despite the fact that fibers in the flowable material are shorter than the critical fiber length. The aspect ratio is between 30 and 94 [44], which offers reinforcement to the materials and probably to the adhered dental tissues.

Although everX Flow has little higher fracture toughness value than everX Posterior [45] when the materials are tested themselves (i.e. not applied to an actual cavity), teeth restored

Table 2 – Maximum load (Newton) recorded for each failed specimen.

Gr1	Gr2	Gr3	Gr4	Gr5	Gr6	Gr7	Gr8	Gr9	Gr10
1200	1600	1400	1600	1600	800	1200	1600	1400	1000
1000	1000	1400	1400	1600	800	1200	1400	1600	800
1200	1600	1600	1000	1600	1000	1400	1000	600	1000
1600	1000	1400	1600	1000	1400	1200	1600	1400	1200
1600	1600	1200	1200	1200	1200	1000	1400	1000	800
1600	1600	1200	1600	1200	600	1000	1200	1000	1600
1600		1000	1400	1600	800	1600	1200	600	1400
1000		800	1200	800	1600	1000	1200	1200	1200
1200		800	1400	1200	1000	1600	1600	800	1600
		1600	1600	800	1400	1600	1600	1200	1400
		1400	1200	1400	800	1600	1400	1400	1200
		1200	1600	1200	600	1600	1600	600	1600
		1600	1600	1400	1000	1600	1000	1000	800
		1400	1200	1400	1400	1400	1200	800	1200
		1000	1600	1000	1400	1400	1200	1600	1600
		1200		1600	600	1600	1400	1000	
		1400		1600	600			1200	
		1600		1000	1600			1400	
		1000		1200	800			1200	
		1200		800	1600				
				1200	1200				
n = 9	n = 6	n = 20	n = 15	n = 21	n = 21	n = 16	n = 16	n = 19	n = 15

with everX Posterior (Group 1) did not differ in terms of survival from those restored with everX Flow (Group 2). This is in line with our previous findings in premolars [26]. This result may be explained by the fact that both materials contain randomly oriented short fibers, resulting in isotropic performance and multidirectional reinforcement inside the cavity [46]. Beside the already proven biomechanical advantages of SFRC materials, they are also transparent, and the fibers scatter the light, so they can be used up to 4–5 mm thick increments [47–49]. However, as the cavities used in this study were quite deep, they cannot be considered a real bulk fill option as the SFRCs were used in 3 consecutive layers.

As GIC materials are continuously improved, the question arises as to whether they could be used to restore and reinforce root canal treated molars as a dentin-replacing material. Whether a GIC core could benefit from adhesive pre-treatment (like in the “super-closed sandwich technique”) is also an intriguing question. This is the first research that we are aware of that compares various GIC materials, both with and without adhesive treatment, as dentin-replacing direct restorative materials for restoring ET molar teeth. In our study, adhesive treatment prior to the application of any of the studied GIC materials did not result in increased survival. GIC materials form a weak but real chemical bond to dentin and do not seem to remarkably benefit from prior adhesive treatment when used as dentin-replacing materials. Nevertheless, there was a clear difference in survival between the different GIC materials. The modern hybrid GIC restorative material (Equia Forte, GC Europe) outperformed the resin-modified GIC (RMGIC) restorations (Fuji II LC), both with (Group 7 was significantly better than Group 5, $p = 0.046$) and without (Group 8 was significantly better than Group 6, $p = 0.004$) adhesive pre-treatment. This is in clear contradiction to the results of Magne et al., who found that conventional GIC did not differ from the RMGIC variant [15]. However, they worked with MOD cavities, which might explain the difference. Our findings are probably best explained by the improved mechanical features to modern GIC materials. As an alternative to composite resins in the posterior region, a high-viscosity GIC restorative system (EQUIA, GC Europe) was launched in 2007 [50]. Smaller and more reactive silicate particles with higher molecular weight acrylic acid molecules are used to reinforce these modern GICs [51].

Table 3 – The distribution of fracture mode among the tested groups (n = 25).

	Gr1		Gr2		Gr3		Gr4		Gr5		Gr6		Gr7		Gr8		Gr9		Gr10	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Did not fail	16	64	19	76	5	20	10	40	4	16	4	16	9	36	9	36	6	24	10	40
Non-restorable	9	36	6	24	17	68	14	56	18	72	20	80	16	64	15	60	16	64	12	48
Restorable	0	0	0	0	3	12	1	4	3	12	1	4	0	0	1	4	3	12	3	12
Total	25	100	25	100	25	100	25	100	25	100	25	100	25	100	25	100	25	100	25	100

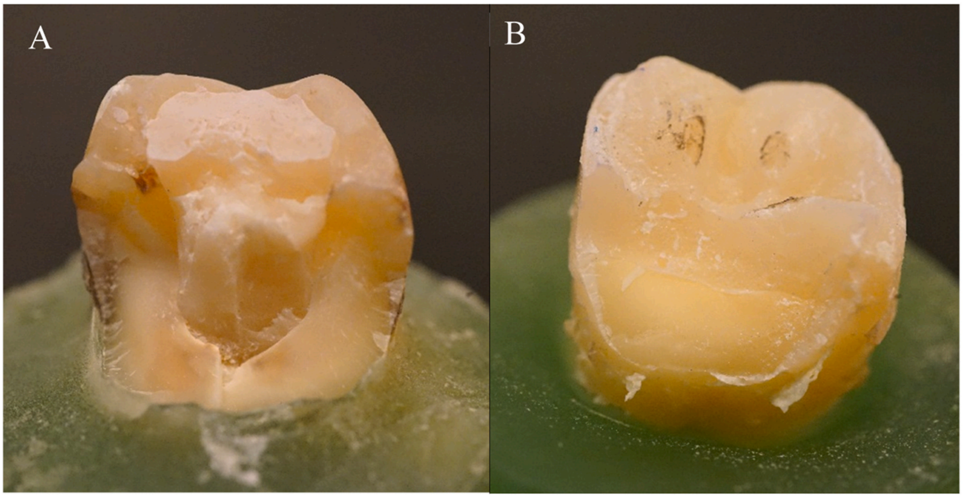

Fig. 3 – Photographs of non-restorable (A) and restorable (B) fracture mode of the tested specimens.

Furthermore, restorations utilizing GIC materials did not differ significantly in survival from the control group (Group 10), except for Group 6 ($p = 0.005$). This shows that direct restorations with GIC materials could be a good alternative to direct composite fillings in ET molar teeth in case of deep Class I cavities. In this respect, our findings are in line with those of Magne and his colleagues [15].

In Groups 3 and 4, the missing dentin was replaced with a new fiber-reinforced RMGIC material. This material developed by incorporating short glass microfiber (200–500 μm in length) to the powder of RMGIC (Fuji II LC) with 20 wt% weight ratio. Previous materials research studies revealed that combining short microfiber with RMGIC matrix improved toughening and flexural efficiency as compared to particulate RMGIC [30,31]. However, this material has not been tested in teeth restorations and loading setup. The fiber-reinforced RMGIC restorations showed significantly higher survival in cavities without prior adhesive treatment (Group 4) as compared to when the material was placed on the adhesive layer (Group 3) ($p = 0.025$). Furthermore, fiber-reinforced RMGIC without prior adhesive treatment (Group 4) did not differ in survival from either the control group (Group 10) or teeth restored with packable SFRC (Group 1). This may be attributed to the random orientation of microfibers in the RMGIC matrix (Fig. 4), which seemed to improve the material's ability to resist fatigue crack propagation as well as increase fracture energy and toughness. According to Garoushi et al., the fracture toughness of this material is 1.7 $\text{MPam}^{1/2}$, which is comparable to commercial conventional composite resins (range of 1.1–1.9 $\text{MPam}^{1/2}$) [31,52–54].

In this study, fracturegraphy was conducted on tested restorations utilizing a combination of optical stereomicroscope and SEM approach. According to this analysis, the primary crack formed on the occlusal surface of the restoration, propagated downward, and spread through the various layers of the restoration and tooth structure. This kind of fracture behavior was also observed in other loading studies [25,55,56].

Most of the failed specimen, irrespective of whether fibers were incorporated or not, demonstrated mainly catastrophic non-restorable fractures, which tends to be median-radial cracks extending into the restorative material from the loading point (Fig. 4). This again demonstrated that improved load bearing and failure mode (i.e. direction of fracture propagation) do not necessarily occur together/simultaniously (e.g. comparing Group 4 to control group). However, in case of restorations reinforced by SFRCs (Groups 1 and 2) more than 50% of the specimens withstood the accelerated testing including 40.000 loading cycles without any type of fracture, whereas no such achievement could be seen with any other tested direct restorative technique. This could again indicate that SFRC is able to both increase load bearing and also modify the pattern of fracture towards favourable types [22,47]. On the other hand, analysis of failed specimen clearly revealed that the brittleness of the conventional particle-reinforced materials generated the bulk fracture propagating easily through the whole thickness of the restoration (Fig. 4c & d). Thus, the basic characteristics of the material do not significantly enhance the resistance of fatigue crack propagation. On the other side, fiber-reinforced composites showed the ability to re-direct and stop crack propagation within the materials. As shown in Fig. 4, the presence of such energy-absorbing and stress-distributing fibers allows crack propagation to be deflected away from the bulk of the material and toward the peripheries.

Regarding this fracture behavior of SFRC restorations, Lassila et al., reported that the optimum layer thickness of the veneering conventional composite resin over the SFRC-core is between 0.5 and 1 mm [41]. Given that the SFRC-reinforcement core's function is based on a crack-stopper mechanism, the distance between the stress starting point's surface and the SFRC-core is critical. As a result, the thickness of the conventional composite resin on the surface of the restorations can play a role in crack propagation and restoration survival. This is in line with previous research that demonstrated the value of applying SFRC and conventional surface layers at different thicknesses [57,58].

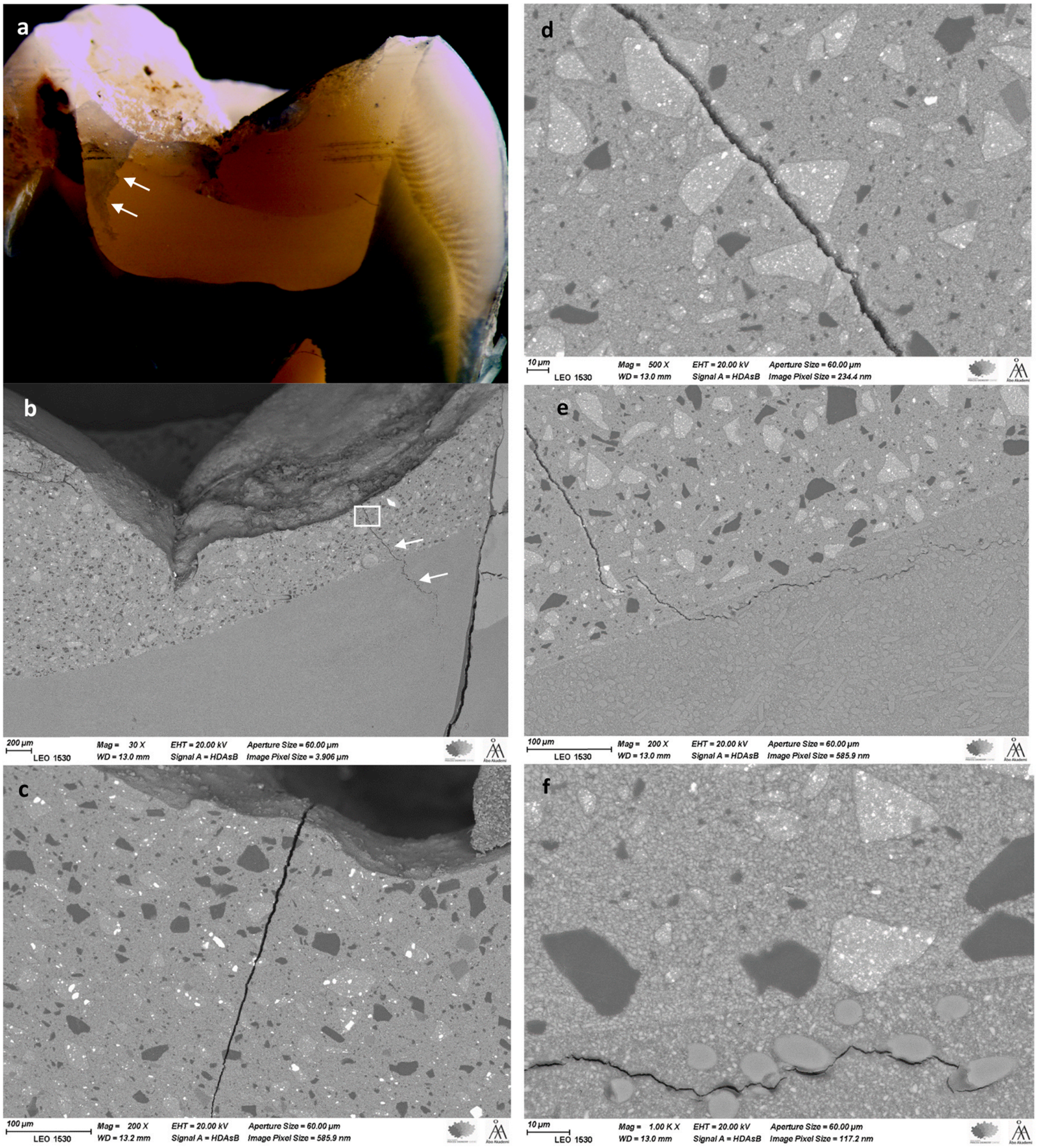

Fig. 4 – Images with different magnifications showing a fatigue crack (arrow) propagated from the load application area through composite resin to the inner part at dentin-replacing material where fibers redirect and stop the crack propagation.

5. Conclusion

For the direct restoration of Class I in ET molars, the use of short fiber-reinforced composites as dentin-replacing material demonstrated its ability to reinforce the dental structures and to increase the fatigue resistance in this specific clinical situation.

Funding

This study was supported by the Bolyai János Research Scholarship (BO/701/20/5) and by the ÚNKP-20-3-SZTE, ÚNKP-20-5-SZTE, ÚNKP-21-5-SZTE New National Excellence Program of The Ministry for Innovation and Technology from the Source of National Research, Development and Innovation Fund, Hungary.

Acknowledgments

Testing materials were provided by the manufacturing companies, which is greatly appreciated. This study belongs to the research activity of BioCity Turku Biomaterials Research Program (www.biomaterials.utu.fi).

Conflicts of interests

Author PV consults for Stick Tech - Member of GC Group in R &D and training. Other authors declare that they have no conflict of interest.

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