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Short Communication

Evaluation of microhardness of short fiber-reinforced composites inside the root canal after different light curing methods – an in vitro study

Márk Fráter[1*], János Grosz[2], András Jakab[1], Gábor Braunitzer[3], Tamás Tarjányi[4,5], Gábor Gulyás[5], Krisztián Bali[5], Paula Andrea Villa-Machado[6], Sufyan Garoushi[7] and András Forster[2]

[1]Department of Operative and Esthetic Dentistry, Faculty of Dentistry, University of Szeged, Szeged, Hungary

[2]Urban Regeneration Institute, Budapest, Hungary

[3]dicomLAB Dental Ltd., Szeged, Hungary

[4]SEMILAB Semiconductor Physics Laboratory Co. Ltd., Budapest, Hungary

[5]Department of Medical Physics and Informatics, University of Szeged, Szeged, Hungary

[6]Graduate Endodontics Programme, Faculty of Dentistry, University of Antioquia, Medellín, Colombia

[7]Department of Biomaterials Science and Turku Clinical Biomaterials Center - TCBC
Institute of Dentistry, University of Turku, Turku, Finland

Márk Fráter and János Grosz contributed equally to this work.

*Corresponding author:
Dr. habil. Márk Fráter, DMD, PhD, M.Sc., assistant professor
Department of Operative and Esthetic Dentistry
Faculty of Dentistry
University of Szeged
Tisza Lajos Krt. 64

H-6720
Szeged, HUNGARY
+36303192937
E-mail address: meddentist.fm@gmail.com

Abstract

Objectives: Short fiber-reinforced composite (SFRC) materials make it possible to reinforce root canal treated teeth with individualized, directly layered intraradicular posts (the Bioblock technique). The question arises, however, as to whether the photopolymerization of the material is sufficient deep within the root canal space and if it can be improved through different light-conducting options. Our study aimed to investigate the hardness of intraradicular SFRC material applied using the Bioblock technique and cured with various illumination methods, as measured through nanoindentation.

Materials and methods: For this investigation, thirty plastic artificial teeth that had undergone root canal treatment were selected. These teeth were randomly divided into six study groups (Group 1-6; each group consisting of 5 teeth). The restoration procedures involved the use of SFRC or conventional composite materials, placed 6 mm apically from the root canal orifice. In Group 1 and 2, a conventional composite was used, whereas in Group 3-6, SFRC was employed for interradicular reinforcement (with a layered technique in Group 3 and 4 and a bulk-fill technique in Group 5 and 6). A modified light source was utilized for photopolymerization in Group 2, 4, and 6, whereas in Group 3 and 5, the polymerization light was directed through a prefabricated glass fiber posts. The control group (Group 1) utilized conventional composite material with a standard light-curing method. Following embedding and sectioning, the hardness of the composite materials was measured at 2 mm intervals within the root canal (1st, 2nd, 3rd measurements, in the coronal to apical direction).

Results: During the 1st measurement, light curing conducted through the glass fiber posts (Group 3 and 5) led to markedly higher hardness levels compared to the groups restored with conventional composite (control group with p=0.002, p=0.001, and Group 2 with p=0.043, p=0.034, respectively). In the 2nd measurement, only Group 5 demonstrated significantly greater hardness in comparison to the control group (p=0.003) and Group 2 (p=0.015). However, in the 3rd measurement, no statistically significant differences were observed among the groups.

Conclusion: light curing through the glass fiber post provides outstanding hardness for the SFRC material in the apical layer in the root canal.

Key words: short fiber-reinforced composite, Bioblock technique, fiber post, light transmission, photopolymerization, microhardness, Young-modulus, root canal

Introduction

Endodontically treated teeth (ETT) face an elevated risk of fracture-related failure [1, 2], necessitating specialized restorative interventions to reinforce the existing tooth structure [3, 4]. According to research by Dietschi et al., this increased risk primarily stems from the depletion of dental coronal hard tissue, such as marginal ridges, pericervical dentine, and the arched roof of the pulp chamber, caused by factors such as caries, trauma, or subsequent endodontic procedures [5]. The most common approach for reinforcing these teeth has been the utilization of fiber-reinforced composite (FRC) posts since the 1990s, particularly in cases where there is substantial loss of coronal tooth structure [6]. Nevertheless, the efficacy of FRC posts in reinforcement remains a subject of debate in the literature. Some studies suggest a positive impact of FRC posts on strengthening ETT [7–9], while others fail to provide conclusive evidence to support this assertion [10, 11]. Several factors contribute to the inconsistent performance of FRC posts in reinforcement. These include improper fitting of the post in the cervical region of the root canal, leading to an excess of luting cement [12, 13], suboptimal bonding between the post and luting cement [14, 15], and the biomechanically unsuitable positioning of fibers within the root canal [16, 17]. These limitations can potentially be addressed by employing customized FRC posts designed to snugly fit each individual canal. Currently, two prominent direct methods for crafting personalized FRC posts are FRC post relining [12, 18–21] and the Bioblock technique [22–26].

FRC post relining seeks to address the challenges associated with conventional FRC posts, including misfitting, bonding between the FRC post and the relining composite material, and the distribution of fibers in the critical cervical region. With the emergence of flowable short fiber-reinforced composite (SFRC) in the market, it is now possible to incorporate short fibers into this method [27, 28]. It is therefore reasonable to assert that the future success of FRC post relining largely hinges on the choice of FRC post (conventional or elastic) and the type of material (fiber or non-fiber-reinforced) used for relining. In the Bioblock technique, the intraradicular post, along with the coronal core build-up and dentin substitution, is directly created from flowable SFRC material [26, 29]. This flowable SFRC contains micrometer-sized fibers that can disperse light during the light-curing process [30–33]. Furthermore, this material is available in a translucent version (EverX Flow Bulk Shade, GC Europe), allowing the flowable SFRC to be light-cured in layers up to a maximum of 5 mm in thickness, a dimension that aligns with the approximately 4-5 mm thick layers used in the Bioblock technique.

Throughout this technique, these layers are subjected to light curing through a conventional FRC post, aimed at transmitting light into the deepest regions of the root canal. So far, the Bioblock technique has demonstrated an enhanced in-vitro capability in reinforcing root canal-treated teeth in various scenarios [24–26] as compared to traditional endo-restorative methods. Nevertheless, a question arises regarding whether the use of an FRC post or other light-conducting option to transmit light is necessary, or if conventional light curing alone could yield the necessary conversion and physical properties to yield such reinforcing capability.
The objective of this investigation is to asses if the studied light transmitting aids are beneficial in light curing different composite resins in the root canal.
The null hypothesis is that the studied materials can be light cured equally as effectively with or without the investigated light transmitting instruments.

Materials and Methods

Thirty identical artificial resin teeth (P-Occlusal Flex – Manequim Odontológico, tooth 09D1103, Sao Paulo, Brasil) were utilized and divided into six distinct groups (n=5). The dimensions of the resin teeth, as depicted in Figure 1, remained unaltered throughout the specimen preparation process. The groups underwent restoration using resin-based restorative materials employing various light curing strategies. A high-power wide spectrum four LED light curing unit (D-Light Pro, GC Europe, Leuven, Belgium) was employed for all procedures. The full depth of the root canal space, measured from the buccal margin of the orifice, was 12.5 mm. The apical 4.5 mm of the root canal was filled with a packable microhybrid restorative composite (Gradia Posterior A2, GC Europe) and light cured for a minimum of 80 seconds, at least 24 hours prior to the specimen preparation.

Figure 1. Resin tooth mimicking a root canal treated situation for potential intracanal reinforcement.

The specimen preparation was performed under 4.3x magnification surgical loupes by a skilled operator (Zeiss, Oberkochen, Germany). The root canal space underwent sandblasting with 27-micron aluminum oxide powder (Aquacare, Velopex International, Florida, USA) for a duration of 30 seconds. Subsequently, it was rinsed with water utilizing a universal endodontic irrigation syringe (Ultradent, South Jordan, UT) and an irrigation needle of ISO 30 diameter. The root canal was meticulously dried using ISO 30 paper points and oil-free airflow.

A dual-cure one-step self-etch adhesive system (G-Premio Bond and DCA, GC Europe) was applied to the root canal space using a microbrush-X disposable applicator (Petron Clinical Technologies, LLC, USA) following the manufacturer's instructions. The application was agitated for 30 seconds. Excess pooling was removed with paper points, and the solvent was evaporated with a combination of air flow and high-power suction with a point tip end (Surgitip, Coltene Group, Altstatten, Switzerland) until visible movement of the adhesive. The adhesive was light cured for 60 seconds with the original fiber optics of the light curing unit and the best-performing battery that provided an intensity of 1540 mW/mm². The optics were placed centrally to the orifice of the root canal, with the optics surface perpendicular to the canal orientation. The depth of each layer in all groups was measured in relation to the buccal orifice margin, placing a UNC 15 periodontal probe (Hu-Friedy, Frankfurt am Main, Germany) flat on the buccal root canal wall. Two batteries that provided an intensity of 1210 mW/mm² were used throughout the specimen preparation phase. The two batteries were interchanged after every specimen to ensure optimal output. The samples were restored as follows:

Group 1 (control group): Three consecutive layers of conventional packable composite (Gradia Posterior A2) each measuring 2 mm in thickness were applied. Layer one and two, numbered from the deepest layer, were individually applied and subsequently light-cured for 60 seconds using the original fiber optics of the light curing unit. The optics were positioned centrally to the root canal orifice, ensuring the optics surface was perpendicular to the canal orientation. Layer 3 was light-cured for 20 seconds using the same procedure as the previous layers.

Group 2: Similarly, three 2 mm thick layers of conventional packable composite (Gradia Posterior A2) were applied consecutively. Layers one and two were applied and then light-cured for 60 seconds using a modified fiber optic device that could directly enter the root canal space. This modified device comprised the body of the D-light pro unit without the original fiber optic tip, along with the fiber optic from a Microlux 2 device (Endo light insert, Addent Inc., Danbury, CT). These elements were connected using a 3D printed, individually designed grey plastic scaffold, compensating for the diameter difference of the two elements and centering the fiber optic to the light source. The optics were placed centrally in the root canal, parallel to the canal orientation. Layer 3 was light-cured for 20 seconds using the same protocol as the previous layers.

Group 3: Three consecutive 2 mm thick layers of flowable SFRC (EverX Flow Bulk, GC Europe) were applied. Layers one and two were individually applied and subsequently light-cured for 60 seconds using the original fiber optics of the light curing unit, with the light directed through a 15 mm long FRC post (GC Fiber Post 0.8 mm, GC Europe), following the method described by Forster et al. [29]. The FRC post was centrally placed in the root canal, with its surface perpendicular to the canal orientation, facilitating light transfer into the canal. Layer 3 was light-cured for 20 seconds during the procedure, following the same protocol as the previous layers.

Group 4: Similarly, three consecutive 2 mm thick layers of flowable SFRC (EverX Flow Bulk) were applied. Layers one and two were individually applied and then light-cured for 60 seconds using a modified fiber optic device (Figure 2). The optics were centrally positioned in the root canal, parallel to the canal orientation. Layer 3 was light-cured for 20 seconds during the procedure, following the same protocol as the previous layers.

Figure 2. Fiber optic transillumination tip connected to a high power wide spectrum polymerisation unit with an individually designed 3D printed connector element.

Group 5: Two consecutive 4 mm thick layers of flowable SFRC (EverX Flow Bulk) were applied. Layer one was applied and light-cured for 60 seconds using the original fiber optics of the light curing unit, with the light directed through a 15 mm long light-transmitting fiber post (GC Fiber Post 0.8 mm). The post was centrally placed in the root canal, with its surface perpendicular to the canal orientation, aiding light transfer. The final layer was light-cured for 20 seconds during the procedure, following the same protocol as the previous layers.
Group 6: Two consecutive layers of flowable SFRC (EverX Flow Bulk) each measuring 4 mm in thickness were applied. Layer one was applied and subsequently light-cured for 60 seconds using a modified fiber optic device. The optics were centrally positioned in the root canal, parallel to the canal orientation. The second final layer was light-cured for 20 seconds during

the procedure, following the same protocol as the previous layers. Table 1. summarizes the apllied techniques and study groups.

Group	Application tech.	Curing tech.
1 (Gradia)	3 layers, 2 mm each	original curing unit (control)
2 (Gradia)	3 layers, 2 mm each	modified fiber optic device
3 (everX)	3 layers, 2 mm each	light directed through a FRC post
4 (everX)	3 layers, 2 mm each	modified fiber optic device
5 (everX)	2 layers, 4 mm each	light directed through a FRC post
6 (everX)	2 layers, 4 mm each	modified fiber optic device

Table 1. Description of groups used in this study

After the restorative procedures, glycerine gel (DeOx Gel, Ultradent Products Inc., Orange, CA, USA) was applied to all samples, and a final polymerization step of 10 seconds was performed. Subsequently, the samples were stored in physiological saline solution (Isotonic Saline Solution 0.9% B. Braun, Melsungen, Germany) before the testing process.

To assess the mechanical properties of the six different filling materials, nanoindentation tests were conducted. The main results of the nanoindentation measurements include quantifying the mechanical properties such as microhardness and material stiffness, represented as the elastic modulus (Young's modulus). Elastic modulus quantifies the resistance of a material to (reversible) deformation, while the ratio of hardness to elastic modulus is important in both tribology and fracture mechanics. True hardness (theoretical hardness) is a measure of plasticity and Young's modulus is a measure of elasticity [34]. The hardness of a material tends to increase with an increase in the elastic modulus [35]. These two measurement types are applied to gain more valuable data of the physical properties of the studied materials in this simulated clinical setting and to justify the measured values obtained.

Embedding and sample preparation

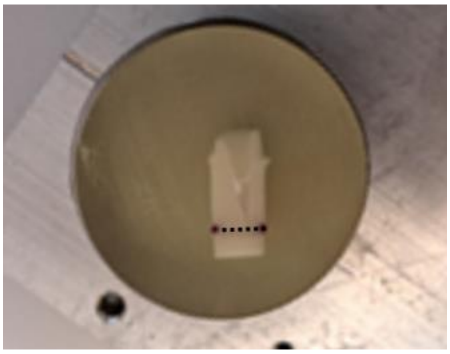
The artificial teeth, each reinforced differently inside the root canal, were placed in a 30 mm diameter plastic holder. The samples were embedded using the Buehler two-component epoxy resin system (EpoxiCure 2 hardener and EpoxiCure 2 resin) at the recommended mixture value specified by the manufacturer (Figure 3).

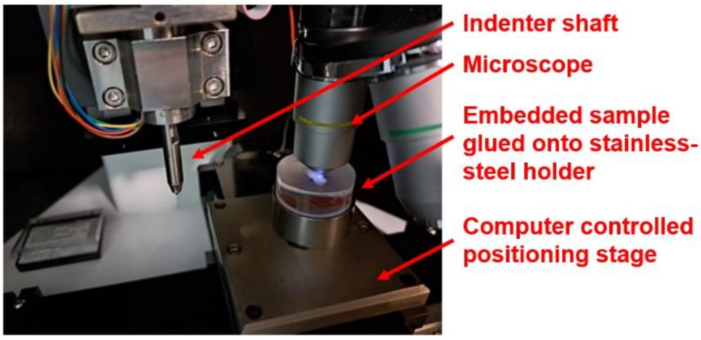
Figure 3. The embedded composite-filled samples in epoxy.

The resin was given 2 days to set and embed the samples. Once the embedding resin had cured, the samples were precisely cut at the same cross-section where the internal dental filling was placed. This cutting process was executed using the Buehler IsoMet 1000 precision saw at 650 rpm, and a 400 g weight was employed to pull the samples uniformly through the blade. The cut samples underwent additional grinding steps to achieve the desired dental filling cross-section, making it optically visible (using various grits of sandpaper, from P320 to P2000, under water cooling). Finally, the prepared samples were affixed to a stainless-steel holder using heat-softening resin at 90 °C. The thick embedding layer ensured that there was no heat transfer to the teeth sample and dental composite filling.

Nanoindentation measurements

A total of 1800 nanoindentation measurements were conducted using the IND-1500 nanoindenter (Semilab, Budapest, Hungary). Each sample underwent measurements at three different layers, with 20 points measured at 20 µm intervals within the composite filling material section. The layers were measured relative to the bottom reference layer, positioned at 1 mm (1st measurement), 3 mm (2nd measurement), and 5 mm (3rd measurement). The microscope integrated into the nanoindentation system was utilized to accurately select the distances from the reference layer. The samples were precisely moved under the indenter by the built-in computer-controlled motorized translation stage, as shown in Figure 4.





a) b)

Figure 4. (a) The cross-section of the composite filled embedded sample, marked at the bottom reference layer; (b) the glued sample under microscope in the indenter machine.

For the nanoindentation measurements, a general-purpose diamond Berkovich indenter tip was employed. The maximum force was set to 10 mN, and a Poisson's ratio of 0.24 was adopted for the composite fillings. During the loading and unloading phases of the measurement, 20 data points were recorded, as illustrated in Figure 5, which provides an example curve. As the compressive force escalates, the nanoindenter tip penetrates more deeply into the material.

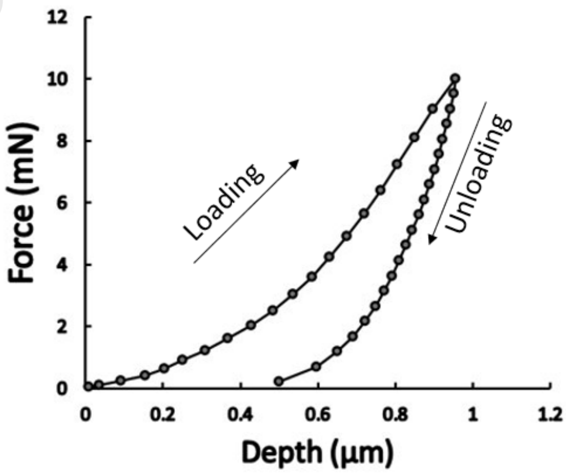


Figure 5. An example measurement curve (Group 1, sample 1, 1st measurement).

The material's microhardness is determined by the maximum force and the contact area, calculated from the measured depth during nanoindentation. The elastic modulus was derived from the slope of the unloading curve. The frame compliance, which is specific and unique to each testing machine, was set to 0.000252 μm/mN. To correct for the initial penetration, an 8-point logarithmic fit was applied.

Statistical analysis

The statistical analysis was conducted using SPSS 23 (IBM Corp., Armonk, NY). The assessment of the homogeneity assumption preceding the ANOVA was performed using the Levene test, specifically examining variance equality across groups, while the normality assumption was evaluated using the Shapiro-Wilk test. Mean values of microhardness and elastic modulus among the six groups were compared using analysis of variance (ANOVA) test, followed by Tukey HSD post hoc test. A significance level of 0.05 was set for all the statistical tests.

Results

The bar chart in Figure 6 illustrates the microhardness values obtained from nanoindentation, while Table 2 provides the corresponding p values for group-wise comparisons. In the comparison of microhardness among various materials and techniques at the same depth, SFRC light cured through the FRC post (Groups 3 and 5) exhibited significantly higher microhardness than the control group at the deepest layer (1st measurement) ($p=0.002$, $p=0.001$, respectively). No significant differences in microhardness were observed among the SFRC-containing groups (Groups 3-6) during the 1st measurement. In the middle layer (2nd measurement), Group 5 demonstrated significantly higher microhardness compared to all other groups, except for group 3. However, in the coronal layer (3rd measurement), there were no discernible differences in microhardness among the tested groups. When comparing different layers within the same group, significant differences in microhardness were only noted in the control group and Group 2 (Table 3).

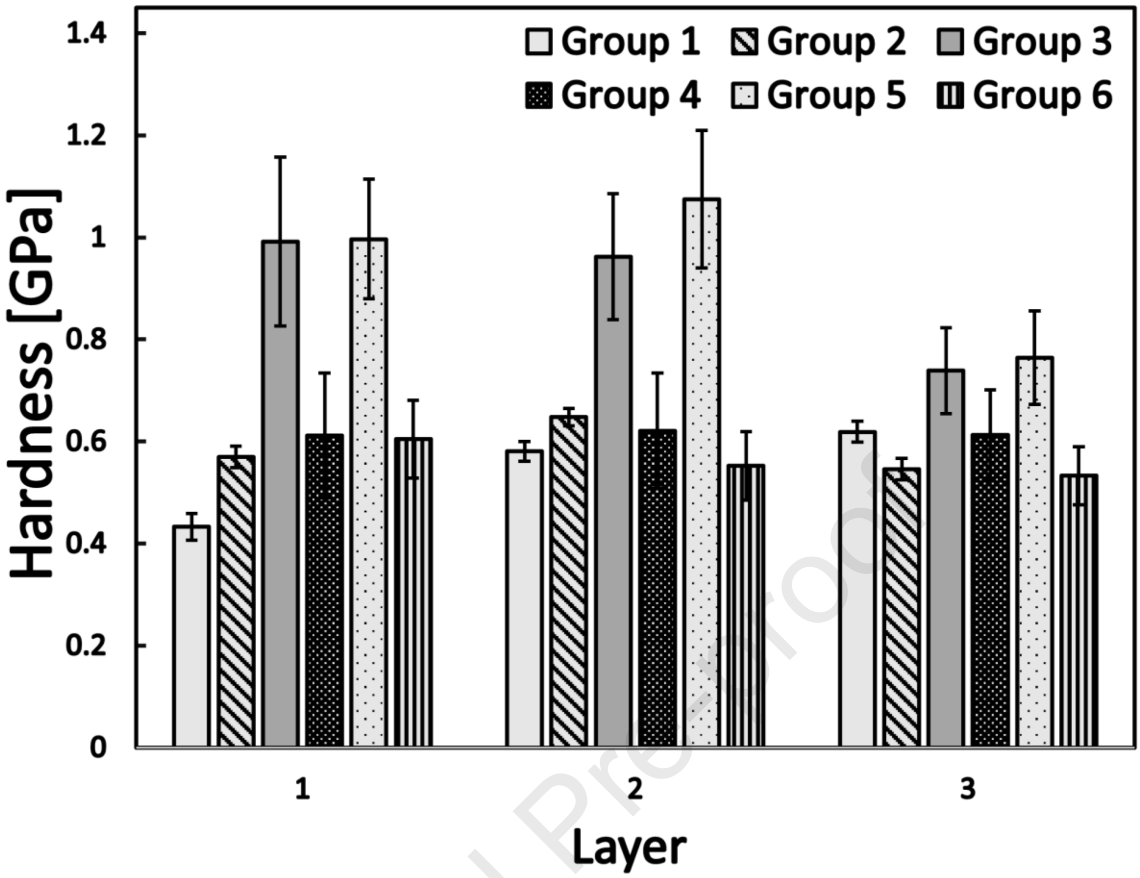


Figure 6. Mean microhardness values and standard error represented in a bar chart for Group 1-6 in each of the 3 layers (1st, 2nd and 3rd measurement).

	Mes.	Group 1			Group 2			Group 3			Group 4			Group 5			Group 6		
		1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Group 1	1st	-			0.935			0.002*			0.828			0.001*			0.839		
	2nd		-			0.996			0.056			1.000			0.003*			1.000	
	3rd			-			0.923			0.811			1.000			0.657			0.953
Group 2	1st	0.935			-			0.043*			1.000			0.034*			1.000		
	2nd		0.996			-			0.166			1.000			0.015*			0.979	
	3rd			0.923			-			0.232			0.941			0.135			1.000
Group 3	1st	0.002*			0.043*			-			0.103			1.000			0.078		
	2nd		0.056			0.166			-			0.106			0.958			0.026*	
	3rd			0.811			0.232			-			0.774			1.000			0.292
Group 4	1st	0.828			1.000			0.103			-			0.085			1.000		
	2nd		1.000			1.000			0.106			-			0.008*			0.995	
	3rd			1.000			0.941			0.774			-			0.611			0.965
Group 5	1st	0.001*			0.034*			1.000			0.085			-			0.063		
	2nd		0.003*			0.015*			0.958			0.008*			-			0.001*	
	3rd			0.657			0.135			1.000			0.611			-			0.178
Group 6	1st	0.839			1.000			0.078			1.000			0.063			-		
	2nd		1.000			0.979			0.026*			0.995			0.001*			-	
	3rd			0.953			1.000			0.292			0.965			0.172			-

* significant difference at $p<0.05$.

Table 2. Tukey HSD post hoc table showing the mean differences in microhardness between the groups in the 1st, 2nd and 3rd measurement.

Group 1

Micro hardness	Layer 1	Layer 2	Layer 3
Layer 1	-	<0.001*	<0.001*
Layer 2		-	0.443
Layer 3			-

Group 2

Micro hardness	Layer 1	Layer 2	Layer 3
Layer 1	-	0.012*	0.238
Layer 2		-	<0.001*
Layer 3			-

* significant difference at p<0.05.

Table 3. Tukey HSD post hoc table showing the mean differences in microhardness between the layers (within the same group).

Regarding the elastic modulus , the bar chart in Figure 7 illustrates the elastic modulus values obtained from nanoindentation for each group, while Table 4 provides the corresponding p values for group-wise comparisons. The results appear to align with the microhardness values, although variations in significance are noticeable. At the deepest layer (1^{st} measurement), elastic modulus was significantly higher in Group 3 and 5 compared to the control group. Group 5 also exhibited statistically superior elastic modulus values than Group 2 ($p=0.004$) and Group 4 ($p<0.001$). In the middle layer (2^{nd} measurement), Group 5 demonstrated significantly elevated elastic modulus values in comparison to the control group ($p<0.001$) as well as Groups 2 ($p<0.001$), 4 ($p<0.001$), and 6 ($p<0.001$). Group 3 showed significantly higher elastic modulus figures compared to Group 2 ($p=0.045$) and 4 ($p=0.001$). At the coronal layer (3^{rd} measurement), Group 5 displayed significantly higher elastic modulus values than all other groups, with no notable difference in measured elastic modulus among the remaining groups.

Notably, when comparing the three measurement points (1st, 2nd, and 3rd measurements) within each group, a significant disparity was only observed in the control group, where the deepest layer (1st measurement) differed significantly from both the 2nd and 3rd measurements ($p<0.001$) (Table 5).

According to the results the null hypothesis was rejected as there were significant differences between the examined groups.

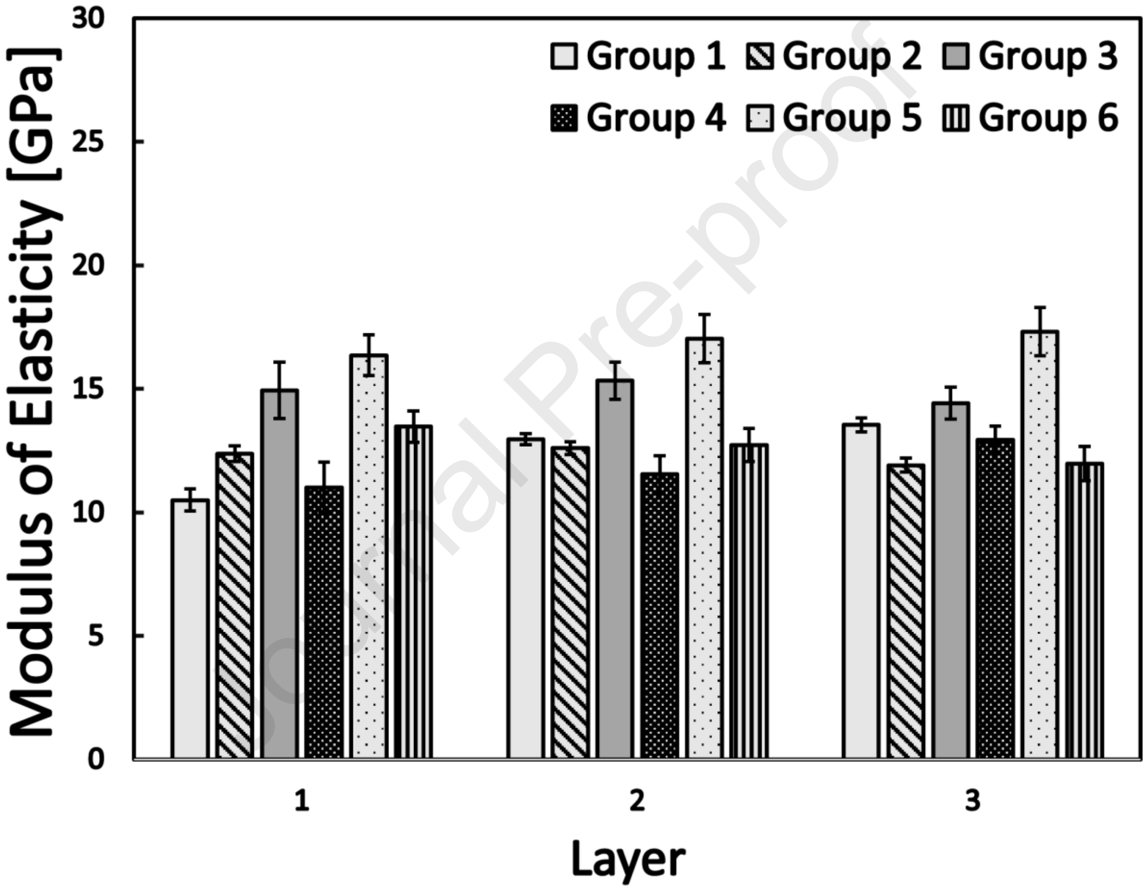


Figure 7. Mean elastic modulus values and standard error represented in a bar chart for Group 1-6 in each of the 3 layers (1st, 2nd and 3rd measurement).

		Group 1			Group 2			Group 3			Group 4			Group 5			Group 6		
	Mes.	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Group 1	1st	-			0.531			0.001*			0.998			<0.001*			0.075		
	2nd		-			0.999			0.140			0.686			<0.001*			1.000	
	3rd			-			0.450			0.920			0.984			<0.001*			0.505
Group 2	1st	0.531			-			0.193			0.824			0.004*			0.918		
	2nd		0.999			-			0.045			0.876			<0.001*			1.000	
	3rd			0.450			-			0.058			0.857			<0.001*			1.000
Group 3	1st	0.001*			0.193			-			0.007*			0.787			0.768		
	2nd		0.140			0.045*			-			0.001*			0.464			0.069	
	3rd			0.920			0.058			-			0.545			0.013*			0.075
Group 4	1st	0.998			0.824			0.007*			-			<0.001*			0.23		
	2nd		0.686			0.876			0.001*			-			<0.001*			0.813	
	3rd			0.984			0.857			0.545			-			<0.001*			0.890
Group 5	1st	<0.001*			0.004*			0.787			<0.001*			-			0.085		
	2nd		<0.001*			<0.001*			0.464			<0.001*			-			<0.001*	
	3rd			<0.001*			<0.001*			0.013*			<0.001*			-			<0.001*
Group 6	1st	0.075			0.918			0.768			0.23			0.085			-		
	2nd		1.000			1.000			0.069			0.813			<0.001*			-	
	3rd			0.505			1.000			0.075			0.890			<0.001*			-

* significant difference at $p<0.05$.

Table 4. Tukey HSD post hoc table showing the mean differences in elastic modulus between the groups in the 1^{st}, 2^{nd} and 3^{rd} measurement.

	Group 1		
Elastic modulus	Layer 1	Layer 2	Layer 3
Layer 1	-	<0.001 *	<0.001 *
Layer 2		-	0.439
Layer 3			-

* significant difference at p<0.05.

Table 5. Tukey HSD post hoc table showing the mean differences in elastic modulus between the layers (in the same group).

Discussion

A root canal treated, partially decoronated maxillary central incisor typodont was selected for this investigation in order to standardize cavity size and depth in all specimens. The typodont is fabricated from an A2 shade material which is one of the most common shades for human teeth [36]. According to the manufacturer optical properties are similar to natural teeth. These teeth serve as a standardized scaffold for such a measurement as natural teeth sizes, shades and refractive indices may vary on a large scale [36, 37]. Therefore such level of standardization could not have been carried out using natural teeth. This kind of methodology can only be carried out in an in-vitro setting therefore it is not possible to emulate the exact effect of the surrounding tissues. This could be a minor limitation to this study.

SFRC materials, when applied in the root canal, present a promising option for the fabrication of individual intraradicular reinforcement of ETT [24, 25, 38–41]. These materials, when used with specific techniques, enhance the physical properties of ETT more effectively than conventional FRC post solutions [25, 26]. One of the primary challenges in applying SFRC within the root canal, either in bulk (Bioblock technique) [22, 26, 27] or in a layered manner [29], is ensuring adequate light curing of these materials intraradicularly, occasionally at a depth of 6-8 mm apical to the CEJ. In previous publications, an FRC post (GC Fiber Post 0.8 mm, GC Europe, Leuven) was employed to transmit light from the curing unit [25, 26, 29, 38]. In these studies, light curing of SFRC applied in bulk through an FRC post resulted in similar microhardness compared to dual-cure composite cements [25, 26, 38]. However, in the mentioned studies, no statistical analysis was conducted due to the small sample size. Also, only bulk-fill application of SFRC was tested in the previous studies. Current results seem to correlate with previous findings, as light curing through the FRC post exhibited good values both in microhardness and elastic modulus in the case of SFRC, irrespective of the application method of the material.

From a practical standpoint, it is crucial to highlight that using a conventional FRC post for light transmission in a clinical setting is not ergonomic, and the light curing durations employed in prior studies are excessively long in comparison to industry standards [25, 26, 38]. Therefore, it would be advantageous to develop a light curing unit capable of efficiently delivering high-intensity curing light to the depth of the root canal, designed in a single ergonomic piece. Such a setup is likely to reduce curing times and assist clinicians in effectively employing these novel endo-restorative techniques. In the present study, a modified light curing device (utilized in Groups 4 and 6) incorporated the light-transmitting fiber optics from a transillumination device (Figure 6).

The diameter of the LEDs in the curing light is approximately twice that of the light source side of the fiber optic element connecting to the curing light LED in this configuration. Consequently, the optics had to be stabilized and centered using a 3D printed component, which also blocked the light emitted from the periphery of the LEDs. Due to this unique modification, some of the energy emitted from the light source might have been lost. This potential loss could explain the lack of significant results when light curing the SFRC material (Groups 4 and 6) in comparison to the control group at various depths within the root canal (1st, 2nd, and 3rd measurements). Additionally, the modified light curing device was unable to achieve higher microhardness or elastic modulus values when used to cure conventional composite (Group 2) in comparison to the control group. When examining the microhardness results of the SFRC-containing groups (Groups 3-6), a significant difference favoring light curing through the FRC post was observed only in the middle layer (2nd measurement). Therefore, the hypothesis was rejected. Specifically, Group 3 exhibited significantly higher microhardness compared to Group

6 (p=0.026), while Group 5 demonstrated significantly higher microhardness compared to both Group 4 (p=0.008) and Group 6 (p=0.001).

The observed differences in results can be attributed to variations in light transmission among different FRC posts or fiber optic devices. Transmitted light radiant exposure [42] has been recognized as a phenomenon in light transmission through fiber optics and is considered crucial for effective light-induced polymerization through a fiber post [43]. Numerous studies have demonstrated disparities in light transmission among different fiber posts [43–46]. Alkhallagi et al. reported that the diameter, length, and type of FRC post can influence the amount of light transferred into the root canal [43]. Similarly, Goracci et al. found significant differences in light transmission among various types of FRC posts [44]. FRC posts typically consist of multiple unidirectional long fibers embedded in a resin matrix, running along the post's length [47]. The optical behavior of longitudinal glass fibers within the FRC, when exposed to light, resembles that of a multimode fiber optic. In a multimode fiber, light beams are guided along the fiber core through total internal reflection [44]. Intriguingly, in Goracci et al.'s study, the GC Fiber Post, which was also used in our study for light transmission (Groups 3 and 5) [44], exhibited the highest light energy passing through the tested FRC post's tip. It is well-documented that the transmitted light gradually diminishes as it travels apically along the length of the fiber post and decreases further as it penetrates deeper inside the root canal [44, 48, 49]. In our study (Groups 3-6), there was no statistically significant difference in microhardness or elastic modulus values between the layers (1^{st}, 2^{nd}, and 3^{rd} measurements) within the same group for the SFRC material. This absence of variation could be attributed to the consistent distance between the light source and the cured layer. Regardless of which layer was light-cured, the length of the FRC post or the fiber optics remained constant. This uniformity in curing distance likely contributed to the consistent results across different layers within the SFRC groups. In contrast, when examining the different layers in the conventional composite groups (Group 2 and the control group), deeper layers exhibited reduced microhardness and elastic modulus values. Specifically, in the control group, the deepest layer (1st measurement) displayed statistically significantly lower microhardness (p<0.001, p<0.001) and elastic modulus values (p<0.001, p<0.001) compared to the middle (2^{nd} measurement) and the coronal (3rd measurement) layers. Similar patterns were observed in Group 2, where a significant difference in microhardness was noted between the 1st and 2nd measurements (p=0.012), as well as between the 2nd and 3rd measurements (p<0.001). Given these findings, it is logical to conclude that the lack of variation within the SFRC-containing groups (Groups 3-6) between each layer is, at least in part, due to the SFRC material itself. The transparency of the used

SFRC (EverX Flow Bulk Shade, GC Europe) and the scattering capability of the short fibers incorporated in the material likely contributed to a higher depth of cure [50–53].

When analyzing the various application and light curing methods of SFRC within the root canal (Groups 3-6), it became apparent that the light curing technique exerted a more significant impact on the investigated mechanical parameters compared to the application method. In the deepest layer (1st measurement), this difference was observable primarily in the elastic modulus values. Both groups using FRC posts for light curing the SFRC (Group 3 and 5) exhibited higher elastic modulus compared to Group 4 ($p=0.007$, $p<0.001$, respectively). However, SFRC-containing groups (Groups 3-6) did not show variation in microhardness values in the deepest layer. In the middle layer (2nd measurement), both Group 3 and 5 demonstrated higher microhardness compared to Group 6 ($p=0.026$, $p=0.001$, respectively), and Group 5 exhibited higher microhardness compared to Group 4 ($p=0.008$). Additionally, Group 3 and 5 displayed higher elastic modulus values compared to Group 4 and 6 in this middle layer ($p<0.005$). In the most coronal layer, Group 5 stood out among the outer groups regarding elastic modulus values ($p<0.005$). This underscores the significance of the method employed for light transfer. Notably, within the same light transferring method – namely, light transfer through the FRC post (Groups 3 and 5) and the modified fiber optics (Groups 4 and 6) – no differences were observed in either of the tested parameters. This clearly indicates that when selecting a method for light transmission into the root canal, the microhardness or elastic modulus does not seem to be influenced significantly by a specific application method, whether it is layering or bulk-filling. Our present findings do not demonstrate any advantage in applying SFRC in a layered manner within the root canal compared to bulk-fill application. These results align with other studies that also failed to find any benefits of layering SFRC over the bulk-fill method, be it in terms of fracture resistance, failure patterns [54] or the development of polymerization-induced cracks [53]. According to research conducted by Néma, Fráter, and their colleagues, layering SFRC provided no advantage over bulk placement concerning internal material adaptation or even the degree of conversion *(under publication)*.

Regarding the main objective of this investigation the deepest layers in the root canal are the most important as they reflect how effective the proposed methods are in such a demanding situation that was mostly the domain of dual cured restorative materials in the past [55]. The microhardness data gathered in this layer (1st measurement) seem to suggest that the light transmitting fiber post may be a more effective tool compared to the modified light source in its current experimental form as both Group 3 and 5 produced statistically higher values compared to the control group (p=0.002, p=0.001, respectively) or to Group 2 (p=0.043, p=0.034, respectively), whereas this was not the case for Group 4 or 6. The authors suspect that if all of the light intensity could be guided into the fiber optics light transmitting tip the possibility of better curing results would be higher also in case of the modified fiber optic device. These results highlight the need for a novel light transmitting device, which could be beneficial compared to performing light curing with a conventional light source directly at the orifice without an extra light transferring aid.

According to the biomimetic concept, using dental restorative materials with mechanical properties similar to the tissues they replace can be advantageous for preserving and reinforcing the masticatory system [56]. The application of SFRC restorative materials is considered beneficial due to their elastic modulus, which closely matches dentine at 11-19 GPa [57–60]. Another advantage of SFRC is its higher fracture toughness compared to conventional non-fiber-reinforced composites [51, 61], therefore this material was chosen for fabricating the direct post and core build-up in the Bioblock technique. All the experimental SFRC-containing groups displayed elastic modulus values ranging from 11-17 GPa, indicating that, based on these measurements, SFRC material is suitable for dentine substitution. Slightly more favorable values were obtained using the light-transmitting post, with Group 3 and 5 values ranging between 14-17 GPa. SFRC material is composed of a resin matrix, randomly oriented E-glass fibers, and inorganic particulate fillers.

It is worth noting that the elastic modulus of E-glass fibers is approximately 73.5 GPa [62]. The substantial standard deviation observed in elastic modulus values for Groups 3-6 can be explained by the measuring tip sometimes touching the E-fiber on the cut surface, resulting in higher elastic modulus values, while at other times, it contacts the surrounding resin with considerably lower elastic modulus values [57]. The elastic modulus results align with the microhardness measurements, indicating superior physical properties when higher conversion rates are achieved.

A recognized limitation of this study is that the samples were not subjected to thermocycling, which could potentially impact the obtained results. Furthermore, it may be considered as a limitation of this investigation that the teeth used for the measurements are not in physiological environment and that rubber-dam, the gingiva and the alveolar process are not covering the root as in an in vivo scenario.

Conclusions

Within the limitations of this in vitro investigation the following conclusions can be drawn:

- Utilizing a light transmitting fiber reinforced composite post is an effective method to aid the light curing of SFRC in the root canal.
- Bulk SFRC material is more suitable compared to conventional composites for light curing applications in the root canal.
- The elastic modulus of the SFRC material light cured with a curing aid in the root canal is similar to that of dentine, therefore in this perspective the material can be deemed a biomimetic restorative material.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author András Jakab declares that they have no conflict of interest.
Author András Forster declares that they have no conflict of interest.
Author Tamás Tarjányi declares that they have no conflict of interest.
Author Gábor Gulyás declares that they have no conflict of interest.
Author Krisztián Bali declares that they have no conflict of interest.
Author Paula Andrea Villa-Machado declares that they have no conflict of interest.
Author János Grosz declares that they have no conflict of interest.
Author Gábor Braunitzer declares that they have no conflict of interest.
Author Sufyan Garoushi declares that they have no conflict of interest.
Author Márk Fráter declares that they have no conflict of interest.