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Crack propensity of different fiber-reinforced direct restorative procedures in deep MOD cavities

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A R T I C L E I N F O

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Enamel crack
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Bulk-fill

A B S T R A C T

Objective: The aim of this study was to evaluate crack formation associated with different direct restorative procedures at various time points.

Methods: This *in vitro* study included 100 intact third molars with standardized MOD cavities, divided into five groups (n = 20). After adhesive treatment, the cavities were restored as follows: bulk-fill flowable short fiber-reinforced composite (SFRC) (Group 1); conventional flowable resin composite (RC) base and bulk-fill flowable SFRC (Group 2); polyethylene fibers embedded in flowable RC and bulk-fill flowable SFRC (Group 3); flowable SFRC combined with packable SFRC (Group 4); and layered conventional packable RC (control). The presence and orientation (vertical/horizontal) of tooth cracks after restoration were evaluated using the D-light Pro (GC Europe) in "detection mode." Cracks were examined at three distinct time points: immediately, after one week, and after five weeks of water storage. The Kruskal-Wallis and Dwass-Steel-Critchlow-Fligner tests were used for between- and within-group comparisons, respectively.

Results: No statistically significant difference in overall crack formation was observed between the groups immediately after the restorative procedure. At the one-week and five-week evaluations, the control group exhibited a significantly higher number of cracks compared to Groups 1–3 ($p < 0.01$). All groups demonstrated a significantly higher number of cracks at the five-week evaluation compared to the immediate assessment ($p < 0.05$). The SFRC groups predominantly showed horizontal cracks at all time points.

Significance: In the 5-week period of water storage following polymerization, the number of cracks appearing on the tooth gradually increased, but the flowable SFRC inserted using the bulk technique was able to moderate the phenomenon in MOD cavities.

1. Introduction

The polymerization of dental resin composites (RCs) results in a volume reduction ranging from less than 1 % to as much as 6 %, depending on the composition and curing conditions [1,2]. Polymerization shrinkage occurs as the distance between monomers decreases, when weak van der Waals forces between monomers are replaced by covalent bonds. During this reaction, the viscosity of the resin material increases, and it gradually loses its ability to flow. Following gelation and during the vitrification phase, the material undergoes a transition to a solid-like state. Prior to the vitrification process, RCs exhibit the capacity to flow and partially release tensile stresses induced by the

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contraction of the RC bonded to the tooth. However, as the material undergoes vitrification, it becomes more rigid and its elastic properties increase [1]. Consequently, the factors limiting polymerization shrinkage generate residual shrinkage stresses [1,3–8]. These stresses may manifest in various clinical symptoms, such as marginal staining, secondary caries, and pulpal inflammation, due to the penetration of saliva, bacteria, and other irritants through the debonded interface [9–14]. Postoperative hypersensitivity, resulting from fluid flow in the exposed dentinal tubules, is associated with cracks caused by cuspal deflection or gap formation at the restoration/tooth interface, often due to bending or insufficient bond strength [15,16]. Gap formation can lead to fluid movement in the dentin tubules, and the flow of dentinal fluid through the adhesive may create fluid-filled regions, contributing to the degradation of adhesives [14,17–20].

Cuspal deflection is a common biomechanical phenomenon characterized by the linear movement of the cusp tips in a restored tooth, resulting from the interaction between the polymerization shrinkage stress of the RC and the compliance of the cavity wall (determined by the continuity, thickness, as well as the length of the remaining walls) [14,21]. RC restorations have been reported to exhibit cuspal deflections ranging from approximately 10 µm to 40 µm, with variations depending on the measurement method, tooth type, and cavity size [22].

Cuspal deflection is influenced by two main categories of biomechanical factors. The first category includes geometrical and material factors, such as the volume of the cavity (primarily its width and depth), the compliance of the cavity wall, the polymerization shrinkage of the RC, and the creep and compliance of the cured RC and tooth [21,23–28]. As shown in a research on cuspal deflection, deep mesio-occluso-distal (MOD) cavities in the posterior region exhibit the greatest degree of cuspal deflection due to the absence of marginal ridges [29]. The loss of both marginal ridges creates a mechanical issue [30,31]. According to a previous study larger restorations were associated with lower stress levels at the restoration and tooth/restoration interface but increased stresses within the tooth [32]. Cavity size and configuration (C-factor) also influence the extent of cuspal deflection, with the highest deflection values observed in MOD cavities. It has been demonstrated that preparing standardized MOD cavities results in an average loss of 63 % in relative cuspal stiffness due to the loss of marginal ridge integrity [31,33], with a concomitant loss of approximately 54 % in fracture strength [34,35]. The anticipated number of fatigue fractures is proportional to the magnitude of cuspal flexure [33–35]. An in vitro study dealing with different sized of MOD cavities suggest that in such clinical situations, a depth of 5 mm is critical, as material-related disadvantages (such as suboptimal fracture toughness) begin to manifest at this point [36]. The second category includes clinical factors, such as the use of a liner, the filling technique (bulk filling versus incremental filling), the type of restorative approach (direct versus indirect), and the use of light-curing methods that influence the polymerization rate [21,28,37–42].

Numerous potential solutions can be found in the literature to decrease cuspal deflection and, consequently, reduce the formation and propagation of cracks. These methods include the incremental layering technique, whereby the RC is applied in horizontal or oblique increments with a maximum thickness of 2 mm, aimed to reduce polymerization shrinkage-induced stress [40,43]. However, Bicalho and colleagues managed to show that layering does not reduce polymerization induced cuspal flexure [6]. Furthermore, layering methods are time-consuming and complex technique, leading to the development of special bulk-fill RCs. These RCs utilize stress modulators and highly reactive photoinitiators incorporated into the material to reduce polymerization stress [40]. Further advancements resulted in the introduction of short-fiber reinforced RC (SFRC) materials. The embedded E-glass fibers help control polymerization shrinkage, as the resin exhibiting a reduced shrinkage along the fibers; thus, the horizontal dimension of the material remains largely unchanged, and only the resin matrix between the fibers undergoes shrinkage. This approach reduces volumetric shrinkage by 30–72 % compared to other non-fiber reinforced RC [44–46]. Another approach to reducing cuspal deflection is the application of a flowable RC as an intermediate layer, which serves as an alternative to the "elastic cavity wall" concept proposed for filled adhesives. According to this approach, the stress generated by the next layer of higher modulus RC is absorbed by an elastic intermediate layer, thereby reducing the stress at the tooth/restoration interface, which is clinically manifested by a reduction in cuspal deflection [28,37,47,48]. Glass-ionomer cements and resin-modified glass-ionomer cements have also been suggested as liners to provide a stress-buffering layer that aids in stress reduction [49,50]. Additionally, ultra-high molecular weight polyethylene fiber (Ribbond-Ultra THM; Ribbond Inc., Seattle WA, USA), in the form of leno weave, could alter the stress dynamics at the restoration/adhesive resin interface by creating multiple stress paths along the fibers, redistributing the load to the intact parts of the tooth and away from the bonded surfaces [51].

Water absorption of restorative materials, which subsequently undergoes hygroscopic expansion, may result in an outward force against the cavity walls. This is considered to be another possible method of relaxing polymerization stress-induced strain [52–54]. The initial phase of water uptake, which occurs within the first 4–5 weeks, is the most pronounced. However, a gradual increase in water uptake can even continue until approximately six months have elapsed [53]. Theoretically, it is possible that this expanding could compensate for the shrinking caused by polymerization [54].

The question arises as to whether using modern direct restorative approaches, such as bulk SFRC materials alone or in combination with an elastic base, with or without polyethylene fibers, would influence crack formation compared to the most frequently used layered RC direct restorations.

The null hypotheses were as follows: 1) there would be no difference in the number of cracks immediately after the restorative procedure among the tested direct restorations; 2) the same would apply for the number of cracks one week after the restoration; 3) and five weeks after the restoration within the investigated groups; 4) there would be no significant change in crack formation within the same group when comparing the three appointments over the 5-week time interval.

2. Materials and method

The study was approved by the Ethics Committee of the University of Szeged and the Medical Research Council of Hungary (BM/23566–1/2023) and adhered to the principles outlined in the Declaration of Helsinki. A total of 100 mandibular third molars, extracted for orthodontic purposes, were included in the study. The selected teeth exhibited consistent coronal dimensions, with orovestibular diameters ranging from 9 to 10 mm, mesiodistal diameters from 10 to 11 mm, and crown heights (measured from the cemento-enamel junction, CEJ) ranging from 6 to 8 mm. Throughout the study, the samples were preserved in 0.9 % saline solution at room temperature. All teeth were used within 6 months of extraction.

2.1. Specimen preparation

Class II MOD cavities were prepared in all teeth included in the study. In alignment with our previous research, the cavity dimensions were standardized to a depth of 5 mm and a wall thickness of 2.5 mm for both the oral and vestibular walls [36,55,56]. The preparation protocol [57] was executed in the following manner: a round end parallel diamond bur (881.31.014 FG – Brasseler USA Dental, Savannah, GA, USA) was used, initially positioned at the midpoint of the occlusal surface, calculated by dividing the distance between the buccal and lingual cusp tips. During the preparation, the wall thickness at the cavity base was continuously monitored with a digital caliper (Mitutoyo Corp., Kawasaki, Japan) to ensure a uniform 2.5 mm thickness. The cavity walls were aligned parallel to the tooth axis. The depth of the cavity was assessed using a 15 UNC periodontal probe (Hu-Friedy Mfg. Co., Chicago, USA), measuring from the corresponding cusp tip while ensuring full contact with the cavity wall. The final cavity was a single, continuous structure, with the proximal box having identical width and depth to the occlusal portion. Cavosurface margins were prepared perpendicular to the tooth surface upon completion of the cavity preparation.

Following cavity preparation, all teeth were thoroughly examined for cracks using D-Light Pro (GC Europe, Leuven, Belgium) in "detection mode," at 4.3x magnification. Any teeth exhibiting pre-existing enamel cracks were excluded from the sample set and replaced with crack-free specimens following the MOD cavity preparation. Ultimately, 100 third molars with prepared MOD cavities were included in the study and randomly allocated into five groups (n = 20/group).

2.2. Restorative procedures

All teeth received the same adhesive treatment as follows. A Tofflemire matrix (1101 C 0.035, KerrHawe, Bioggio, Switzerland) was applied, and the enamel surrounding the cavity was etched with 37 % phosphoric acid for 15 s, followed by rinsing with water. After drying the cavity, a one-step self-etch adhesive system (G-Premio Bond, GC Europe, Leuven, Belgium) was applied in accordance with the manufacturer's instructions. 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 radiant exitance of the curing unit, measured with a digital radiometer (Bluephase Meter II, Ivoclar Vivadent, Solna, Sweden), was 820 ± 40 mW/cm^2. Following the restoration of each fifth tooth, the radiant exitance was evaluated with a radiometer to guarantee that all RCs were subjected to an identical irradiation. The class II cavities were first converted to class I using the centripetal technique by building up the proximal walls. In the control group (Group 5), a conventional packable RC material (G-aenial A′CHORD, GC Europe, Leuven, Belgium) was used, while in the remaining groups (Groups 1–4), SFRC material (EverX Flow Dentin Shade, GC Europe, Leuven, Belgium) was employed for this purpose. The cavities were then restored in one of the below listed ways. The handling of the packable materials (G-aenial A′CHORD and EverX Posterior) was facilitated by the use of an Optrasculpt Pad (Ivoclar, Schaan, Liechtenstein) compaction tool, which was thinly coated with modelling resin (Modeling Liquid, GC Europe, Leuven, Belgium).

Group 1 (n = 20): The cavities were restored using a single 4 mm thick bulk layer of flowable SFRC (EverX Flow Bulk Shade, GC Europe), shaped according to the dentin anatomy, leaving a 1 mm space for the occlusal covering. The bulk SFRC layer was light-cured for 40 s and subsequently covered with a flowable SFRC layer (EverX Flow Dentin Shade). The occlusal layer was then light-cured for 20 s.

Group 2 (n = 20): Initially, a thin layer (maximum 0.5 mm) of conventional flowable RC (G-aenial Hiflo, GC Europe, Leuven, Belgium) was applied to cover the occlusopulpal cavity wall and light-cured for 40 s. From this point, the cavities were restored in the same manner as described for Group 1.

Group 3 (n = 20): Similar to Group 2, a thin layer (maximum 0.5 mm) of conventional flowable RC (G-aenial Hiflo) was used to cover the occlusopulpal cavity wall. Before polymerization, additionally, a piece of ultra-high molecular weight polyethylene fiber (Ribbond-Ultra THM; Ribbond Inc., Seattle, WA, USA) was placed over the occlusopulpal surface and embedded in the flowable RC, which was then light-cured for 40 s. The cavities were subsequently restored as described in Group 1.

Group 4 (hybrid SFRC restoration, n = 20): The cavity was partially filled with flowable SFRC (EverX Flow Bulk Shade), up to half of its depth. Next, packable SFRC (EverX Posterior, GC Europe) was placed and condensed into the center of the flowable SFRC (using snow plaw technique), ensuring that the flowable material covered all areas of the axial walls, leaving 1 mm for the occlusal coverage. This hybrid SFRC layer was light-cured for 40 s, followed by the application of a flowable SFRC layer (EverX Flow Dentin Shade) to cover the surface. The occlusal layer was light-cured for 20 s.

Group 5 (control group, n = 20): The cavities were restored using conventional RC (G-aenial A′CHORD) with an oblique layering technique. Each layer was approximately 2 mm thick, with the deeper layers light-cured for 40 s, and the superficial layers for 20 s.

The study groups, application methods, materials investigated, and their compositions are summarized in Table 1 and Table 2. The restorations were finished using a fine-grit diamond bur (FG 7406–018, Jet Diamonds, Ft. Worth, TX, USA, and FG 249-F012, Horico, Berlin, Germany) and polished with aluminum oxide polishers (OneGloss PS Midi, Shofu Dental GmbH, Ratingen, Germany). The restored teeth were stored in physiological saline solution until the experimental procedures began.

2.3. Screening for cracks in the restored teeth

Crack screening was performed using D-Light Pro (GC Europe, Belgium, Leuven) at 4.3x magnification under transillumination in "detection mode", following a protocol requiring agreement between two examiners, as outlined in our previous research [57]. The light source was applied in multiple positions over the external tooth surface for 1–2 min to ensure no cracks were overlooked. In this study, only cracks measuring 2 mm or longer were classified as shrinkage-induced cracks (Fig. 1). Crack lengths were measured using a 15 UNC periodontal probe (Hu-Friedy Mfg. Co., Chicago, USA) positioned parallel to the remaining coronal surface of the tooth adjacent to the crack. Both the presence and the orientation (vertical or horizontal) of the cracks were recorded. The teeth were examined for cracks at three time points: first, immediately after the final polymerization phase, then one week later, and finally five weeks after completing the direct restoration. Between the sessions, the teeth were stored in physiological saline solution.

2.4. Statistical analysis

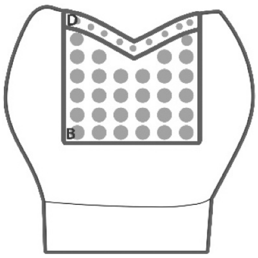
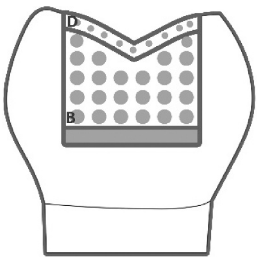
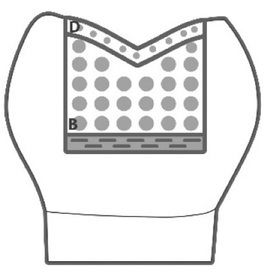
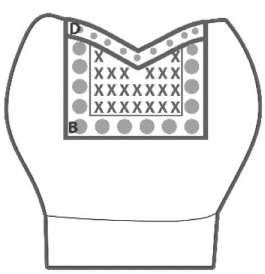
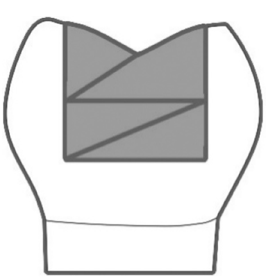
For the statistical analyses, Jamovi 2.3.28 was used. Descriptive statistics were calculated to summarize the distribution of crack counts (total, vertical, and horizontal) for each group at each time point following the restorative procedure. For each crack type, the mean, median, standard deviation, minimum, and maximum values were calculated.

For all hypothesis tests involving the five groups, a significance level of $p < 0{,}01$ was applied, as adjusted by the Bonferroni correction to control for multiple comparisons. The assumption of normality was not met in all cases, thus non-parametric tests (Kruskal-Wallis and Friedman ANOVA) were applied to analyze differences between and within groups.

The primary analysis assessed differences in crack counts between groups at specific time points: immediately after the restorative procedures, and then one week and five weeks later. The Kruskal-Wallis test was used to determine significant differences in total, vertical, and horizontal crack counts across groups at each time point. For significant Kruskal-Wallis results, Dwass-Steel-Critchlow-Fligner (DSCF) post-hoc pairwise comparisons were conducted to identify specific group differences (level of significance: $p < 0.05$). For the post-hoc power analyses, G*Power 3.1 (Universität Düsseldorf, Germany) was used.

The secondary analysis examined changes in crack counts over time within each group. Friedman's ANOVA was used to evaluate temporal changes in total, vertical, and horizontal crack counts within each group. Where significant differences were observed, Durbin-Conover post-hoc pairwise comparisons were conducted to detect differences between specific time points within each group (level of significance: $p < 0.05$).

Table 1
Study groups, materials and application methods.

Group	Application method	Used materials
Group 1 	SFRC flow (bulk shade) used with bulk-fill method. Coronally 1 mm thick layer of SFRC flow (dentin shade)	EverX Flow, bulk and dentin shade
Group 2 	Flowable conventional resin composite base (U shade) + bulk-fill SFRC flow bulk shade + coronally 1 mm SFRC flow (dentin shade)	Essentia HiFlo as flowable base, then EverX Flow bulk and dentin shade
Group 3 	Polyethylene fibers embedded in the flowable composite base + bulk-fill SFRC flow (bulk shade) + coronally 1 mm SFRC flow (dentin shade)	Ribbond fibers + Essentia HiFlo as flowable base, then EverX Flow bulk and dentin shade
Group 4 	SFRC flow (bulk shade) and packable SFRC using snow plaw technique. Coronally 1 mm SFRC flow dentin shade.	EverX Flow (bulk and dentin shade) + EverX Posterior (bulk shade)
Group 5 (control) 	2 mm thick oblique layers of conventional packable resin composite	G-ænial A'chord (A2 shade)

SFRC: short fiber-reinforced composite

3. Results

Immediately following the restorative procedure, there was no significant difference in the total crack counts (horizontal + vertical) across the tested groups ($\chi^2 = 7.43$, $p = 0.115$). Likewise, no statistically significant differences were found across the groups when horizontal ($\chi^2 = 1.99$, $p = 0.737$) and vertical ($\chi^2 = 12.74$, $p = 0.013$) crack counts were analyzed separately (Figs. 2–4). One week after the restorative procedure, the total crack counts varied across the five groups significantly ($\chi^2 = 24.60$, $p < 0.001$). Group 5 had the highest mean number of, while Group 1 exhibited the lowest mean number of cracks.

The DSCF post-hoc pairwise comparisons revealed significant differences between several groups. Specifically, Group 5 (control group) had a significantly higher number of cracks than Group 1 ($p < 0.001$), Group 2 ($p = 0.023$), and Group 3 ($p = 0.003$). Additionally, Group 4 had significantly more cracks than Group 1 ($p = 0.024$). These results suggest that Group 5 (control group) suffered the most cracking at one week, while Group 1 consistently showed fewer cracks. The presence of statistically significant differences highlights the variability in crack formation among the different groups shortly after the restorative

Table 2
Composition of the investigated resin based composites (GC Europe, Belgium, Leuven).

Used material	Organic matrix	Type of fillers	Filler ratio (wt%)
EverX Flow	Bis-MEPP, TEGDMA, UDMA	barium glass + short E-glass fibers (140 ×6 μm)	70 % (fibers: 25 %)
EverX Posterior	Bis-GMA, TEGDMA, PMMA	barium glass + short E-glass fibers (1–2 mm×17 μm)	74,2 % (fibers: 9 %)
Essentia HiFlo	UDMA, Bis-EMA, Bis-GMA, TEGDMA	barium-glass	69 %
G-ænial A'chord	TEGDMA, UDMA, Bis-MEPP, TCDDDMA, Neopentyl glycol dimethacrylate	barium glass, fumed silica	82 %

Bis-MEPP: Bis(2-methylpropenoicacid)(1-methylethylidene)bis(4,1-phenyleneoxy-2,1-ethanediyl)ester; TEGDMA: Triethylene glycol dimethacrylate; UDMA: Urethane acrylate methacrylate; Bis-GMA: bisphenol A-glycidyl methacrylate; PMMA: polymethyl metachrylate; Bis-EMA: Bisphenol A ethoxylate dimethacrylate; TCDDDMA: Tricyclodecanedimethanol dimethacrylate

Fig. 1. The images illustrate the detection of vertical and horizontal crack formation (indicated by arrows) observed during the polymerization process. A 15 UNC periodontal probe was used under transillumination to measure the length of the detected cracks. Both the orientation and length of cracks were documented.

procedure. The descriptive statistics are shown in Table 3.

As for the vertical crack counts, these also varied significantly among the five groups one week after the restorative procedures ($\chi^2 = 22.20$, $p < 0.001$). Again, Group 5 (control group) exhibited the highest number of cracks, with a mean of 2.90, a median of 3.00, and a standard deviation of 0.91, ranging from 1 to 5 cracks. The lowest number of cracks was observed in Group 3, with a mean of 1.15 (median = 1.00, SD = 1.23).

The DSCF post-hoc pairwise comparisons, revealed significant differences in vertical crack counts between several groups. Group 5 (control group) demonstrated a significantly higher number of vertical cracks compared to Group 1 ($p < 0.001$), Group 3 ($p < 0.001$), and Group 4 ($p = 0.004$) (Table 3).

Regarding the horizontal crack counts, these also varied significantly among the five groups one week after the restorative procedures ($\chi^2 = 16.01$, $p = 0.003$). Groups 4 and 5 (control group) exhibited the highest

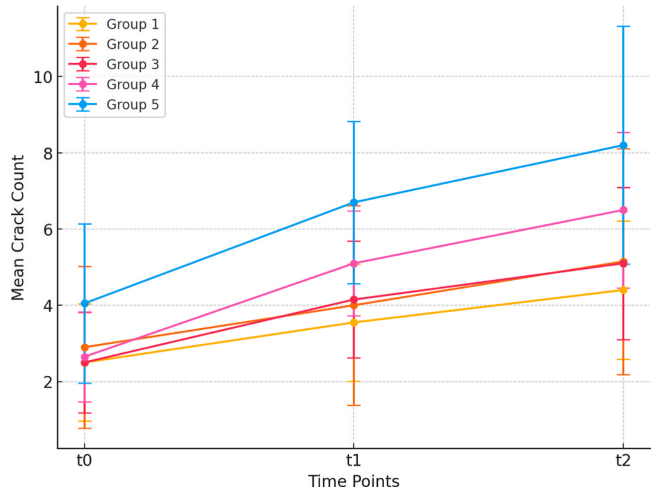


Fig. 2. Mean total crack counts across time (t0, immediately after photopolymerization; t1, after soaking in water for one week; t2, after soaking in water for five weeks) by group. Values are shown as mean±SD.

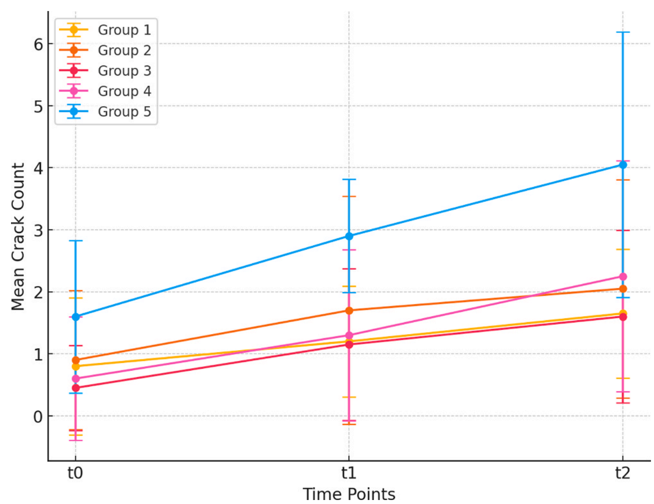


Fig. 3. Mean vertical crack counts across time (t0, immediately after photopolymerization; t1, after soaking in water for one week; t2, after soaking in water for five weeks) by group. Values are shown as mean±SD.

number of cracks. In contrast, the lowest number of cracks was observed in Group 2.

The DSCF post-hoc pairwise comparisons revealed significant differences in horizontal crack counts between several groups. Group 4 had a significantly higher number of horizontal cracks compared to Group 1 ($p = 0.029$) and Group 2 ($p = 0.016$) (Table 3).

When examining the total crack counts 5 weeks after the restorative procedure, the observed pattern was quite similar to what had been seen at the 1-week examination. There was a significant variability across the groups ($\chi^2 = 20.45$, $p < 0.001$).

The DSCF post-hoc pairwise comparisons revealed significant differences in total crack counts between several groups. Group 5 (control group) demonstrated a significantly higher number of total cracks compared to Group 1 ($p = 0.001$) and Group 3 ($p = 0.016$). Additionally, Group 1 showed a significantly lower number of cracks than Group 4 ($p = 0.014$). The difference between Group 5 (control group) and Group 2 approached significance ($p = 0.055$). The descriptive statistics are shown in Table 4.

Vertical crack counts continued to vary across the five groups at 5 weeks ($\chi^2 = 18.91$, $p < 0.001$). Group 5 (control group) exhibited the highest mean number of vertical cracks. In contrast, Group 3 displayed the lowest mean number of cracks.

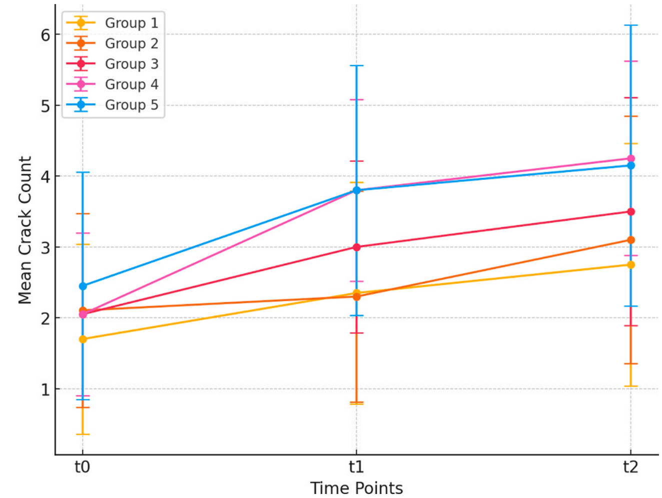


Fig. 4. Mean horizontal crack counts across time (t0, immediately after photopolymerization; t1, after soaking in water for one week; t2, after soaking in water for five weeks) by group. Values are shown as mean±SD.

The DSCF post-hoc pairwise comparisons revealed significant differences in vertical crack counts between several groups. Group 5 (control group) demonstrated a significantly higher number of vertical cracks compared to Group 1 ($p < 0.001$), Group 2 ($p = 0.023$), and Group 3 ($p = 0.002$) (Table 4).

As for the horizontal crack counts at 5 weeks, these showed some variation across the five groups, but this did not reach the level of statistical significance ($\chi^2 = 10.33$, $p = 0.035$). Group 4 exhibited the highest mean number of horizontal cracks, and Group 1 showed the lowest mean number of cracks (Table 4). Due to the lack of significant variance among groups, no post-hoc comparisons were performed.

The significant differences from all the above analyses, along with significance levels, effect sizes and estimated statistical power are summarized in Table 5.

As for the analysis of crack counts within individual groups over time, we conducted a Friedman's ANOVA for the total crack count, as well as for the vertical and horizontal cracks. In every case, the analysis showed significant variance, indicating that crack counts in each group changed significantly over time (Figs. 2–4). According to the Durbin-Conover post-hoc pairwise comparisons, this also meant that, with one exception, there was a significant change between each time point in every group. The sole exception was the horizontal crack count in Group 2, which did not change significantly during the first week.

The summarized results of the Friedman ANOVA for each group are presented in Table 6. For reasons of space, we do not report the results of the post-hoc pairwise comparisons here; instead, they are provided as supplementary material.

4. Discussion

Polymerization shrinkage-induced stress in RC direct restorations remains a clinically relevant problem in dentistry due to its multiple adverse consequences, such as decreased bond strength, gap formation at the margins or between the cavity walls and the filling material, cuspal deformation, and enamel crack development [1,58–60]. From the tooth's perspective, cuspal deflection and subsequent enamel crack formation are closely associated with cavity dimensions, particularly the volume factor and the compliance of the cavity walls [23,57,61]. Deep MOD cavities, characterized by the absence of two marginal ridges and a high volume factor, present a unique yet common challenge, both in terms of crack formation [57] and structural reinforcement [55,56,62].

Table 3
Total, vertical, and horizontal crack counts across the groups 1 week after restoration.

	Group	Mean	Median	SD	Minimum	Maximum
Total crack counts	Group 1	3.55	4.00	1.54	1	6
	Group 2	4.00	4.00	2.62	0	8
	Group 3	4.15	4.00	1.53	1	7
	Group 4	5.10	5.00	1.37	2	7
	Group 5 (control)	6.70	6.50	2.13	3	11
Vertical crack counts	Group 1	1.20	1.00	0.89	0	3
	Group 2	1.70	1.00	1.84	0	6
	Group 3	1.15	1.00	1.23	0	4
	Group 4	1.30	1.00	1.38	0	4
	Group 5 (control)	2.90	3.00	0.91	1	5
Horizontal crack counts	Group 1	2.35	2.50	1.57	0	5
	Group 2	2.30	2.50	1.49	0	5
	Group 3	3.00	3.00	1.21	0	5
	Group 4	3.80	4.00	1.28	1	7
	Group 5 (control)	3.80	3.50	1.77	1	6

Table 4
Total, vertical, and horizontal crack counts across the groups 5 week after restoration.

	Group	Mean	Median	SD	Minimum	Maximum
Total crack counts	Group 1	4.40	5.00	1.82	1	8
	Group 2	5.15	5.50	2.96	0	10
	Group 3	5.10	5.50	2.00	1	8
	Group 4	6.50	6.00	2.04	3	11
	Group 5 (control)	8.20	8.00	3.12	3	14
Vertical crack counts	Group 1	1.65	1.00	1.04	0	3
	Group 2	2.05	2.00	1.76	0	6
	Group 3	1.60	1.50	1.39	0	4
	Group 4	2.25	2.00	1.86	0	6
	Group 5 (control)	4.05	3.50	2.14	1	9
Horizontal crack counts	Group 1	2.75	3.00	1.71	0	5
	Group 2	3.10	3.50	1.74	0	6
	Group 3	3.50	3.50	1.61	0	7
	Group 4	4.25	4.00	1.37	1	7
	Group 5 (control)	4.15	4.50	1.98	1	7

For these reasons, deep MOD cavities with standardized dimensions were selected in this study to analyze crack development during direct restorative techniques performed with different RC materials.

In our study, when analyzing the total crack formation immediately after the restorative procedure, there was no statistically significant difference in the number of cracks among the differently restored groups. Therefore, the first null hypothesis was accepted. This finding is contrary to our previous results, where SFRC-containing direct restorations produced significantly fewer cracks compared to the control group (layered conventional RC filling) [57]. Although Soares and colleagues found only a few cracks of less than 3 mm, the tendency to crack was significantly higher for the direct group of SFRCs after one week of storage in water compared to the indirect and semi-direct groups [63]. However, in the current study, a flowable SFRC was used either alone or in combination with packable SFRC material, whereas only packable SFRC was utilized in the previous study [63].

In addition, this study used flowable SFRC without a conventional RC coverage. Usually, neither flowable, nor fiber-reinforced RC materials were recommended for restoring extensive occlusal hard tissue deficiencies. However, highly filled flowable RC materials, due to their improved mechanical properties, have been shown to be capable of fabricating both direct [55] and indirect occlusal restorations [62,64]. Earlier fiber-reinforced materials were not optimal for occlusal restorations as they are prone to excessive wear, resulting in a rough, biofilm-retentive surface [65,66]. However, modern flowable SFRCs have shown significant improvements in this regard, meeting the American Dental Association's wear criteria [67,68]. Rawda and colleagues in their in vitro study reported satisfactory clinical outcomes under clinical conditions where flowable SFRC was used without coverage following an 18-month observation period [69]. Interestingly, neither the conventional flowable RC base (Group 2) nor the polyethylene fiber mesh combined with the flowable base (Group 3) effectively reduced the number of cracks. This outcome is likely influenced partly by the dimensions of the cavity, and consequently the amount of missing dentin, and partly by the unique characteristics of the flowable SFRC material placed over the aforementioned adhesive bases. The flowable SFRC used in this study (EverX Flow) contains 25 wt% of discontinuous, micrometer-sized fibers with an aspect ratio exceeding 30 [67]. For reinforcement to occur, a fiber's length must meet or exceed the critical fiber length, and its aspect ratio should fall within the range of 30–94 [70]. Additionally, this material demonstrates significantly higher fracture toughness (2.8 $MPa{\cdot}m^{1}/^{2}$) compared to conventional RC restorative materials [67,71].

To increase the toughness of resin composites and thus improve their durability and resistance to damage, polyethylene fibers can be used in addition to short glass fibers [72]. Sadr and colleagues demonstrated that using polyethylene fiber in combination with a conventional flowable RC as a base resulted in zero polymerization shrinkage-related gap formation in deep cavities [59]. In contrast, our results showed that polyethylene fibers were unable to mitigate cracking to a greater extent than the Flow SFRC. Furthermore, in our case, the polyethylene fiber has been used in combination with SFRC Flow.

When analyzing the total number of cracks one week after the restorative procedure, the control group exhibited a significantly higher number of cracks compared to Group 1 ($p < 0.001$), Group 2 ($p = 0.023$), and Group 3 ($p = 0.003$). Therefore, the second null hypothesis was rejected. These findings align with our previous work on samples examined after one week [57]. Interestingly, samples restored solely with flowable SFRC (Group 1) exhibited significantly fewer cracks at this time point compared to the mixed use of flowable and paste

Table 5
Significant intergroup differences 1 week (T1) and 5 weeks (T2) after the restorative procedures. Pairwise comparisons. Level of significance: $p < 0.05$.

Time point	Crack count	Comparison	p	Cohen's d	Power
T1	Total	Group 5 vs Group 1	< 0.001	1.69	1.00
		Group 5 vs Group 2	0.023	1.13	0.94
		Group 5 vs Group 3	0.003	1.38	0.99
		Group 4 vs Group 1	0.024	1.06	0.91
	Vertical	Group 5 vs Group 1	< 0.001	1.89	1.00
		Group 5 vs Group 3	< 0.001	1.62	1.00
		Group 5 vs Group 4	0.004	1.37	0.99
	Horizontal	Group 4 vs Group 1	0.029	1.01	0.88
		Group 4 vs Group 2	0.016	1.08	0.91
T2	Total	Group 5 vs Group 1	0.001	1.49	0.99
		Group 5 vs Group 3	0.016	1.18	0.95
		Group 4 vs Group 1	0.014	1.09	0.92
	Vertical	Group 5 vs Group 1	< 0.001	1.43	0.99
		Group 5 vs Group 2	0.023	1.02	0.88
		Group 5 vs Group 3	0.002	1.36	0.99
	Horizontal	No post-hoc comparisons were made due to the lack of significant variance among groups.			

Table 6
Results of the Friedman ANOVA. Level of significance: $p < 0.01$.

Group 1			
	χ^2	df	p
Vertical	15.6	2	< 0.001
Horizontal	23.3	2	< 0.001
Total	29.5	2	< 0.001
Group 2			
Vertical	17.2	2	< 0.001
Horizontal	19.0	2	< 0.001
Total	29.5	2	< 0.001
Group 3			
Vertical	20.6	2	< 0.001
Horizontal	26.1	2	< 0.001
Total	35.4	2	< 0.001
Group 4			
Vertical	21.5	2	< 0.001
Horizontal	31.6	2	< 0.001
Total	34.8	2	< 0.001
Group 5			
Vertical	30.1	2	< 0.001
Horizontal	28.0	2	< 0.001
Total	34.6	2	< 0.001

SFRCs (Group 4) ($p = 0.024$). This difference can likely be attributed to the distinct properties of paste and flowable SFRC materials. While everX Flow contains a lesser quantity of inorganic fillers in general (70 wt%) which consequently elevates the polymerization shrinkage (3.37 % for bulk shade and 3.65 % for dentin shade opposed to 2.87 % of everX Posterior) [67,73], the proportion of glass fibers is markedly higher (25 wt%) than that observed in everX Posterior, which incorporates a greater number of inorganic fillers (74,5 wt%) but a relatively smaller amount of glass fibers (9 wt%). Furthermore, the paste comprises SFRC fibers of a millimetre size [71], in contrast to the micrometre size of the flowable variant [46]. The fine fibers, which have undergone a full-coverage silane coating process, demonstrate enhanced stress absorption and a local transfer of load from the matrix to the more robust fibers. In addition to its reduced filler content, the Bis-MEPP monomer is a significant contributing factor to the flexibility of everX Flow. In conjunction with UDMA and TEGDMA, it provides fluidity, good handling and stress relief [74].

In order to identify the potential causes of the substantial disparities observed in comparison to the control group, it is imperative to consider the impact of the employed application techniques. In Group 1–3, the bulk-fill technique was implemented using flowable RC, while in Group 4, the bulk-fill technique was employed in conjunction with the snowplow method, utilizing a packable SFRC with a flow SFRC lining. As a control (Group 5), layered conventional RC was applied. Looking for correlations between internal adaptation, degree of conversion, filling technique and consistency, a previous study demonstrated that both the utilization of bulk technique resulted in preferable internal adaptation after polymerization in comparison to the application of layered packable RC [75]. Thus, to a certain extent, the application technique in case of non-fiber-reinforced RC could account for the increased number of cracks detected in this study.

When analyzing the total number of cracks five weeks after the restorative procedure, the same pattern of significant differences among the tested groups was observed as at the one-week time point. Consequently, the third null hypothesis was rejected.

Furthermore, when analyzing the total number of cracks within the same group across different time points (immediately after, one week after, and five weeks after the restorative procedure), a significant increase in crack number was observed at each subsequent time point ($p < 0.05$). Therefore, the fourth null hypothesis was also rejected.

It is well recognized that the post-polymerization of RC materials continues for more than 24 h after light curing [76] and has even been detected up to one month after the curing of such restorative materials [77]. Post-polymerization is resulted in an increase of DC [78], while DC correlates with polymerization shrinkage [73]. Polymerization shrinkage stress causes the walls of the cavity to deflect in the direction of the restoration [58]. Debonding phenomenon, as the failure of the bond between the RC and the tooth may result in the removal of the restraints on the RC [52]. This, in turn, may lead to the elimination of the residual shrinkage stresses that were caused by the restraining cavity. This process may consequently result in the relaxation of the deformed tooth cusps.

Since the occurrence of enamel cracks is linked to a certain extent to the polymerization shrinkage of RC materials [79], post-cure polymerization presumably plays a role in the increase in the number of cracks observed after restorative treatment [57]. Our results demonstrate a significant increase in the total number of cracks in all groups at both test times. However, the increase in the number of cracks after 5 weeks of soaking most likely should not be attributed to post-polymerization and the associated shrinkage stress. As demonstrated in previous research, cuspal flexure has been observed to decrease or even cease over time in storage conditions involving water [80]. This process could serve to neutralize shrinkage-related stresses and thereby close or reduce contraction gaps [52,54,81]. However, it has been expressed that there is a concern that the coefficient of hygroscopic expansion of certain restorative materials may exceed that of polymerization shrinkage, which could potentially have undesirable consequences for the remaining tooth structure or the restoration [82,83]. There is a possibility that internal stresses formed by the expansion of the RC could potentially result in strain at the interface and it could possibly exceed the critical strain of the dental enamel or that of an overlying restoration leading to the formation of microcracks and subsequent fracture [53,82]. The water uptake of a RC is predominantly contingent on the chemical nature of the matrix monomers. On the contrary, however, it has been shown that the water uptake of the RC decreases with an increasing volume fraction of glass fibers [84]. Additionally, the water sorption of barium glass-filled RCs is relatively high, yet the water durability of barium glass is low, resulting in damage to the surface of the barium glass filler. This, in turn, has a detrimental effect on the flexural strength of the material, thereby reducing its resistance to deformation [85]. In the present study, all RCs were filled with barium glass in a high volume fraction, with the exception of everX Flow, in which the barium glass was partially replaced with a relatively high (25 %) weight fraction of glass fibers, thus contributing to a reduction in water absorption. This is in line with novelle findings showing reduced water uptake in case of flowable SFRC applied in a bulk-manner compared to layered CR restoration (Tarjányi et al., DOI lesz).

When categorizing the total number of cracks into vertical and horizontal ones, both vertical and horizontal crack counts showed a significant increase five weeks after the restorative procedure compared to the baseline numbers (immediately after the procedure) in all study groups ($p < 0.05$). When analyzing horizontal and vertical crack counts independently within each study group, horizontal cracks consistently dominated over vertical cracks in all SFRC-containing groups (Groups 1–4) at all time points (immediately, one week, and five weeks after the restorative procedure) (Figs. 3 and 4). This aligns with the findings of Oliveira et al., who also reported a dominance of horizontal post-cure cracks in restored deep MOD cavities [23].

In the control group (layered conventional RC filling), horizontal crack counts predominated immediately after and one week after the restorative procedure. However, by five weeks after the intervention, horizontal and vertical crack counts were nearly equal (Figs. 3 and 4). This observation could have future implications regarding crack propagation and potential fracture occurrence.

In our study, direct restorations utilizing flowable SFRC without conventional RC coverage were evaluated for crack formation. The body of literature on flowable SFRC restorations without conventional RC coverage is rapidly growing and demonstrates remarkable results in terms of mechanical performance [62,69,86–88]. Consequently, it is essential to investigate all associated issues, such as polymerization stress-induced crack formation, related to this restorative option. Although enamel cracking is not a direct or reliable phenomenon in terms of measuring shrinkage stress, it can be correlated. However, further research is needed to clarify what, beyond hypotheses, may cause an increase in the number of cracks after longer storage times.

In light of these findings and given the limitations, future research could benefit from employing a similar study design but incorporating micro-CT analysis to evaluate gap formation internal adaptation and water sorption in conjunction with crack development in greater detail. This approach could provide a more comprehensive understanding of the material behavior and enhance the accuracy of the results. Further limitation of our study is that transillumination does not provide information on the depth-wise extension of the developed cracks, which is of significant importance in clinical practice. In addition, tracking crack propensity requires shorter time intervals to provide more accurate information about the change in their number. For example, although we counted after 5 weeks, cracks may only have continued to increase for up to 10 days, and no longer. Last but not least, crack formation should be evaluated later on also in case of samples restored with RC in a bulk-fill manner.

5. Conclusions

Within the limitations of this study, it was demonstrated that the bulk application of flowable SFRCs reduces crack formation more effectively than conventional packable RCs and other tested techniques. These findings suggest that SFRCs may improve the durability of deep MOD cavity restorations. However, further investigation including the measurement of hygroscopic expansion and its consequences is necessary to understand the cause of the cracking tendency, particularly over time.

Declaration of Competing Interest

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dental.2025.06.010.

References

[1] Soares CJ, Faria-E-Silva AL, Rodrigues MDP, Vilela ABF, Pfeifer CS, Tantbirojn D, et al. Polymerization shrinkage stress of composite resins and resin cements – what do we need to know? Braz Oral Res 2017;31:e62. https://doi.org/10.1590/1807-3107bor-2017.vol31.0062.
[2] Soares CJ, Bicalho AA, Tantbirojn D, Versluis A. Polymerization shrinkage stresses in a premolar restored with different composite resins and different incremental techniques. J Adhes Dent 2013;15:341–50. https://doi.org/10.3290/j.jad.a29012.
[3] Versluis A., Tantbirojn D. Relationship between shrinkage and stress, in Dental Computing and Applications: Advanced Techniques for Clinical Dentistry 2009.
[4] Pereira R, Valdívia A, Bicalho A, Franco S, Tantbirojn D, Versluis A, et al. Effect of photoactivation timing on the mechanical properties of resin cements and bond strength of fiberglass post to root dentin. Oper Dent 2015;40:E206–21. https://doi.org/10.2341/14-115-L.
[5] Bicalho A, Pereira R, Zanatta R, Franco S, Tantbirojn D, Versluis A, et al. Incremental filling technique and composite material—part I: cuspal deformation, bond strength, and physical properties. Oper Dent 2014;39:e71–82. https://doi.org/10.2341/12-441-L.
[6] Bicalho A, Valdívia A, Barreto B, Tantbirojn D, Versluis A, Soares C. Incremental filling technique and composite material—part II: shrinkage and shrinkage stresses. Oper Dent 2014;39:e83–92. https://doi.org/10.2341/12-442-L.
[7] Park J, Chang J, Ferracane J, Lee IB. How should composite be layered to reduce shrinkage stress: incremental or bulk filling? Dent Mater 2008;24:1501–5. https://doi.org/10.1016/j.dental.2008.03.013.
[8] Kim RJ-Y, Kim Y-J, Choi N-S, Lee I-B. Polymerization shrinkage, modulus, and shrinkage stress related to tooth-restoration interfacial debonding in bulk-fill composites. J Dent 2015;43:430–9. https://doi.org/10.1016/j.jdent.2015.02.002.
[9] Braga R, Ballester R, Ferracane J. Factors involved in the development of polymerization shrinkage stress in resin-composites: a systematic review. Dent Mater 2005;21:962–70. https://doi.org/10.1016/j.dental.2005.04.018.
[10] Ellakwa A, Cho N, Lee I. The effect of resin matrix composition on the polymerization shrinkage and rheological properties of experimental dental composites. Dent Mater 2007;23:1229–35. https://doi.org/10.1016/j.dental.2006.11.004.
[11] Kleverlaan CJ, Feilzer AJ. Polymerization shrinkage and contraction stress of dental resin composites. Dent Mater 2005;21:1150–7. https://doi.org/10.1016/j.dental.2005.02.004.
[12] Lee IB, Cho BH, Son HH, Um CM. A new method to measure the polymerization shrinkage kinetics of light cured composites. J Oral Rehabil 2005;32:304–14. https://doi.org/10.1111/j.1365-2842.2004.01414.x.
[13] Ferracane J. Developing a more complete understanding of stresses produced in dental composites during polymerization. Dent Mater 2005;21:36–42. https://doi.org/10.1016/j.dental.2004.10.004.
[14] Tantbirojn D, Versluis A, Pintado MR, DeLong R, Douglas WH. Tooth deformation patterns in molars after composite restoration. Dent Mater 2004;20:535–42. https://doi.org/10.1016/j.dental.2003.05.008.
[15] Tay FR, Pashley DH. Water treeing - a potential mechanism for degradation of dentin adhesives. Am J Dent 2003;16:6–12.
[16] Souza-Junior E, Souza-Régis M, Alonso R, Freitas A, Sinhoreti M, Cunha L. Effect of the curing method and composite volume on marginal and internal adaptation of composite restoratives. Oper Dent 2011;36:231–8. https://doi.org/10.2341/10-107-L.
[17] Brännström M. The hydrodynamic theory of dentinal pain: sensation in preparations, caries, and the dentinal crack syndrome. J Endod 1986;12:453–7. https://doi.org/10.1016/S0099-2399(86)80198-4.
[18] Marzouk MA, Ross JA. Cervical enamel crazings associated with occluso-proximal composite restorations in posterior teeth. Am J Dent 1989;2:333–7.
[19] Eick JD, Welch FH. Polymerization shrinkage of posterior composite resins and its possible influence on postoperative sensitivity. Quintessence Int 1986;17:103–11.
[20] Lutz F, Krejci I, Barbakow F. Quality and durability of marginal adaptation in bonded composite restorations. Dent Mater 1991;7:107–13. https://doi.org/10.1016/0109-5641(91)90055-4.

[21] Lee M-R, Cho B-H, Son H-H, Um C-M, Lee I-B. Influence of cavity dimension and restoration methods on the cusp deflection of premolars in composite restoration. Dent Mater 2007;23:288–95. https://doi.org/10.1016/j.dental.2006.01.025.

[22] Jafarpour S, El-Badrawy W, Jazi H, McComb D. Effect of composite insertion technique on cuspal deflection using an in vitro simulation model. Oper Dent 2012; 37:299–305. https://doi.org/10.2341/11-086-L.

[23] Oliveira LRS, Braga SSL, Bicalho AA, Ribeiro MTH, Price RB, Soares CJ. Molar cusp deformation evaluated by micro-CT and enamel crack formation to compare incremental and bulk-filling techniques. J Dent 2018;74:71–8. https://doi.org/10.1016/j.jdent.2018.04.015.

[24] van Heumen CCM, Tanner J, van Dijken JWV, Pikaar R, Lassila LVJ, Creugers NHJ, et al. Five-year survival of 3-unit fiber-reinforced composite fixed partial dentures in the posterior area. Dent Mater 2010;26:954–60. https://doi.org/10.1016/j.dental.2010.05.010.

[25] Hood JA. Biomechanics of the intact, prepared and restored tooth: some clinical implications. Int Dent J 1991;41:25–32.

[26] Meredith N, Setchell DJ. In vitro measurement of cuspal strain and displacement in composite restored teeth. J Dent 1997;25:331–7. https://doi.org/10.1016/S0300-5712(96)00047-4.

[27] Suliman AA, Boyer DB, Lakes RS. Interferometric measurements of cusp deformation of teeth restored with composites. J Dent Res 1993;72:1532–6. https://doi.org/10.1177/00220345930720111201.

[28] Alomari QD, Reinhardt JW, Boyer DB. Effect of liners on cusp deflection and gap formation in composite restorations. Oper Dent 2001;26:406–11.

[29] Magne P, Oganesyan T. Premolar cuspal flexure as a function of restorative material and occlusal contact location. Quintessence Int 2009;40:363–70.

[30] Reeh ES, Messer HH, Douglas WH. Reduction in tooth stiffness as a result of endodontic and restorative procedures. J Endod 1989;15:512–6. https://doi.org/10.1016/S0099-2399(89)80191-8.

[31] Wu Y, Cathro P, Marino V. Fracture resistance and pattern of the upper premolars with obturated canals and restored endodontic occlusal access cavities. J Biomed Res 2010;24:474–8. https://doi.org/10.1016/S1674-8301(10)60063-2.

[32] Versluis A, Tantbirojn D, Pintado MR, DeLong R, Douglas WH. Residual shrinkage stress distributions in molars after composite restoration. Dent Mater 2004;20: 554–64. https://doi.org/10.1016/j.dental.2003.05.007.

[33] El-Helali R, Dowling AH, McGinley EL, Duncan HF, Fleming GJP. Influence of resin-based composite restoration technique and endodontic access on cuspal deflection and cervical microleakage scores. J Dent 2013;41:216–22. https://doi.org/10.1016/j.jdent.2012.11.002.

[34] Hannig C, Westphal C, Becker K, Attin T. Fracture resistance of endodontically treated maxillary premolars restored with CAD/CAM ceramic inlays. J Prosthet Dent 2005;94:342–9. https://doi.org/10.1016/j.prosdent.2005.08.004.

[35] Seo D-G, Yi Y-A, Shin S-J, Park J-W. Analysis of factors associated with cracked teeth. J Endod 2012;38:288–92. https://doi.org/10.1016/j.joen.2011.11.017.

[36] Forster A, Braunitzer G, Tóth M, Szabó BP, Fráter M. In vitro fracture resistance of adhesively restored molar teeth with different MOD cavity dimensions. J Prosthodont 2019;28:e325–31. https://doi.org/10.1111/jopr.12777.

[37] Unterbrink GL, Liebenberg WH. Flowable resin composites as “filled adhesives”: literature review and clinical recommendations. Quintessence Int 1999;30:249–57.

[38] Abbas G, Fleming GJP, Harrington E, Shortall ACC, Burke FJT. Cuspal movement and microleakage in premolar teeth restored with a packable composite cured in bulk or in increments. J Dent 2003;31:437–44. https://doi.org/10.1016/S0300-5712(02)00121-5.

[39] Versluis A, Douglas WH, Cross M, Sakaguchi RL. Does an incremental filling technique reduce polymerization shrinkage stresses? J Dent Res 1996;75:871–8. https://doi.org/10.1177/00220345960750030301.

[40] Sengupta A, Naka O, Mehta SB, Banerji S. The clinical performance of bulk-fill versus the incremental layered application of direct resin composite restorations: a systematic review. :143–143 Evid Based Dent 2023;24. https://doi.org/10.1038/s41432-023-00905-4.

[41] Rees JS, Jacobsen PH. Stresses generated by luting resins during cementation of composite and ceramic inlays. J Oral Rehab 1992;19:115–22. https://doi.org/10.1111/j.1365-2842.1992.tb01088.x.

[42] Davidson CL, de Gee AJ. Light-curing units, polymerization, and clinical implications. J Adhes Dent 2000;2:167–73.

[43] Fronza BM, Rueggeberg FA, Braga RR, Mogilevych B, Soares LES, Martin AA, et al. Monomer conversion, microhardness, internal marginal adaptation, and shrinkage stress of bulk-fill resin composites. Dent Mater 2015;31:1542–51. https://doi.org/10.1016/j.dental.2015.10.001.

[44] Garoushi S, Säilynoja E, Vallittu PK, Lassila L. Physical properties and depth of cure of a new short fiber reinforced composite. Dent Mater 2013;29:835–41. https://doi.org/10.1016/j.dental.2013.04.016.

[45] Bocalon ACE, Mita D, Narumyia I, Shouha P, Xavier TA, Braga RR. Replacement of glass particles by multidirectional short glass fibers in experimental composites: effects on degree of conversion, mechanical properties and polymerization shrinkage. Dent Mater 2016;32:e204–10. https://doi.org/10.1016/j.dental.2016.06.008.

[46] Garoushi S, Gargoum A, Vallittu PK, Lassila L. Short fiber-reinforced composite restorations: a review of the current literature. J Invest Clin Dent 2018;9:e12330. https://doi.org/10.1111/jicd.12330.

[47] Cara RR, Fleming GJP, Palin WM, Walmsley AD, Burke FJT. Cuspal deflection and microleakage in premolar teeth restored with resin-based composites with and without an intermediary flowable layer. J Dent 2007;35:482–9. https://doi.org/10.1016/j.jdent.2007.01.005.

[48] Alhadainy HA, Abdalla AI. 2-year clinical evaluation of dentin bonding systems. Am J Dent 1996;9:77–9.

[49] Sampaio P, De Almeida Júnior A, Francisconi L, Casas-Apayco L, Pereira J, Wang L, et al. Effect of conventional and resin-modified glass-ionomer liner on dentin adhesive interface of class I cavity walls after thermocycling. Oper Dent 2011;36: 403–13. https://doi.org/10.2341/09-240-L.

[50] Azevedo LM, Casas-Apayco LC, Villavicencio Espinoza CA, Wang L, Navarro MFDL, Atta MT. Effect of resin-modified glass-ionomer cement lining and composite layering technique on the adhesive interface of lateral wall. J Appl Oral Sci 2015; 23:315–20. https://doi.org/10.1590/1678-775720140463.

[51] Belli S, Cobankara FK, Eraslan O, Eskitascioglu G, Karbhari V. The effect of fiber insertion on fracture resistance of endodontically treated molars with MOD cavity and reattached fractured lingual cusps. J Biomed Mater Res 2006;79B:35–41. https://doi.org/10.1002/jbm.b.30508.

[52] Meriwether LA, Blen BJ, Benson JH, Hatch RH, Tantbirojn D, Versluis A. Shrinkage stress compensation in composite-restored teeth: relaxation or hygroscopic expansion? Dent Mater 2013;29:573–9. https://doi.org/10.1016/j.dental.2013.03.006.

[53] Momoi Y, McCabe JF. Hygroscopic expansion of resin based composites during 6 months of water storage. Br Dent J 1994;176:91–6. https://doi.org/10.1038/sj.bdj.4808379.

[54] Suiter EA, Watson LE, Tantbirojn D, Lou JSB, Versluis A. Effective expansion: balance between shrinkage and hygroscopic expansion. J Dent Res 2016;95:543–9. https://doi.org/10.1177/0022034516633450.

[55] Fráter M, Sáry T, Vincze-Bandi E, Volom A, Braunitzer G, Szabó PB, et al. Fracture behavior of short fiber-reinforced direct restorations in large MOD cavities. Polymers 2021;13:2040. https://doi.org/10.3390/polym13132040.

[56] Sáry T, Garoushi S, Braunitzer G, Alleman D, Volom A, Fráter M. Fracture behaviour of MOD restorations reinforced by various fibre-reinforced techniques – an in vitro study. J Mech Behav Biomed Mater 2019;98:348–56. https://doi.org/10.1016/j.jmbbm.2019.07.006.

[57] Néma V, Sáry T, Szántó FL, Szabó B, Braunitzer G, Lassila L, et al. Crack propensity of different direct restorative procedures in deep MOD cavities. Clin Oral Invest 2023;27:2003–11. https://doi.org/10.1007/s00784-023-04927-1.

[58] Rosatto CMP, Bicalho AA, Veríssimo C, Bragança GF, Rodrigues MP, Tantbirojn D, et al. Mechanical properties, shrinkage stress, cuspal strain and fracture resistance of molars restored with bulk-fill composites and incremental filling technique. J Dent 2015;43:1519–28. https://doi.org/10.1016/j.jdent.2015.09.007.

[59] Sadr A, Bakhtiari B, Hayashi J, Luong MN, Chen Y-W, Chyz G, et al. Effects of fiber reinforcement on adaptation and bond strength of a bulk-fill composite in deep preparations. Dent Mater 2020;36:527–34. https://doi.org/10.1016/j.dental.2020.01.007.

[60] Ferracane JL, Hilton TJ. Polymerization stress – is it clinically meaningful? Dent Mater 2016;32:1–10. https://doi.org/10.1016/j.dental.2015.06.020.

[61] Van Dijken JWV, Pallesen U. Clinical performance of a hybrid resin composite with and without an intermediate layer of flowable resin composite: a 7-year evaluation. Dent Mater 2011;27:150–6. https://doi.org/10.1016/j.dental.2010.09.010.

[62] Volom A, Vincze-Bandi E, Sáry T, Alleman D, Forster A, Jakab A, et al. Fatigue performance of endodontically treated molars reinforced with different fiber systems. Clin Oral Invest 2023;27:3211–20. https://doi.org/10.1007/s00784-023-04934-2.

[63] Soares LM, Razaghy M, Magne P. Optimization of large MOD restorations: composite resin inlays vs. Short fiber-reinforced direct restorations. Dent Mater 2018;34:587–97. https://doi.org/10.1016/j.dental.2018.01.004.

[64] Molnár J, Fráter M, Sáry T, Braunitzer G, Vallittu PK, Lassila L, et al. Fatigue performance of endodontically treated molars restored with different dentin replacement materials. Dent Mater 2022;38:e83–93. https://doi.org/10.1016/j.dental.2022.02.007.

[65] Fagundes TC, Barata TJE, Carvalho CAR, Franco EB, Van Dijken JWV, Navarro MFL. Clinical evaluation of two packable posterior composites. JADA 2009;140:447–54. https://doi.org/10.14219/jada.archive.2009.0194.

[66] Van Dijken JWV, Sunnegårdh-Grönberg K. Fiber-reinforced packable resin composites in class II cavities. J Dent 2006;34:763–9. https://doi.org/10.1016/j.jdent.2006.02.003.

[67] Lassila L, Säilynoja E, Prinssi R, Vallittu P, Garoushi S. Characterization of a new fiber-reinforced flowable composite. Odontology 2019;107:342–52. https://doi.org/10.1007/s10266-018-0405-y.

[68] Wang L, Garcia FCP, De Araújo PA, Franco EB, Mondelli RFL. Wear resistance of packable resin composites after simulated toothbrushing test. J Esthet Restor Dent 2004;16:303–14. https://doi.org/10.1111/j.1708-8240.2004.tb00058.x.

[69] Elaziz RHA, ElAziz SAA, ElAziz PMA, Frater M, Vallittu PK, Lassila L, et al. Clinical evaluation of posterior flowable short fiber-reinforced composite restorations without proximal surface coverage. Odontology 2024;112:1274–83. https://doi.org/10.1007/s10266-024-00905-5.

[70] Vallittu PK. High-aspect ratio fillers: Fiber-reinforced composites and their anisotropic properties. Dent Mater 2015;31:1–7. https://doi.org/10.1016/j.dental.2014.07.009.

[71] Garoushi S, Vallittu P, Lassila L. Mechanical properties and radiopacity of flowable fiber-reinforced composite. Dent Mater J 2019;38:196–202. https://doi.org/10.4012/dmj.2018-102.

[72] Metwaly AA, Elzoghby AF, Abd ElAziz RH. Clinical performance of polyethylenefiber reinforced resin composite restorations in endodontically treated teeth: (a randomized controlled clinical trial). BMC Oral Health 2024;24:1285. https://doi.org/10.1186/s12903-024-05009-8.

[73] Szczesio-Wlodarczyk A, Garoushi S, Vallittu P, Bociong K, Lassila L. Polymerization shrinkage of contemporary dental resin composites: comparison of three measurement methods with correlation analysis. J Mech Behav Biomed Mater 2024;152:106450. https://doi.org/10.1016/j.jmbbm.2024.106450.

[74] Szczesio-Wlodarczyk A, Polikowski A, Krasowski M, Fronczek M, Sokolowski J, Bociong K. The influence of low-molecular-weight monomers (TEGDMA, HDDMA, HEMA) on the properties of selected matrices and composites based on Bis-GMA and UDMA. Materials 2022;15:2649. https://doi.org/10.3390/ma15072649.

[75] Néma V, Kunsági-Máté S, Őri Z, Kiss T, Szabó P, Szalma J, et al. Relation between internal adaptation and degree of conversion of short-fiber reinforced resin composites applied in bulk or layered technique in deep MOD cavities. Dent Mater 2024;40:581–92. https://doi.org/10.1016/j.dental.2024.02.013.

[76] Par M, Gamulin O, Marovic D, Klaric E, Tarle Z. Effect of temperature on post-cure polymerization of bulk-fill composites. J Dent 2014;42:1255–60. https://doi.org/10.1016/j.jdent.2014.08.004.

[77] Schneider LFJ, Consani S, Ogliari F, Correr AB, Sobrinho LC, Sinhoreti MAC. Effect of time and polymerization cycle on the degree of conversion of a resin composite. Oper Dent 2006;31:489–95. https://doi.org/10.2341/05-81.

[78] Carek A, Dukaric K, Miler H, Marovic D, Tarle Z, Par M. Post-cure development of the degree of conversion and mechanical properties of dual-curing resin cements. Polymers 2022;14:3649. https://doi.org/10.3390/polym14173649.

[79] Han L, Okamoto A, Fukushima M, Okiji T. Enamel micro-cracks produced around restorations with flowable composites. Dent Mater J 2005;24:83–91. https://doi.org/10.4012/dmj.24.83.

[80] Versluis A, Tantbirojn D, Lee MS, Tu LS, DeLong R. Can hygroscopic expansion compensate polymerization shrinkage? Part I. Deformation of restored teeth. Dent Mater 2011;27:126–33. https://doi.org/10.1016/j.dental.2010.09.007.

[81] Huang C, Kei L, Wei SHY, Cheung GSP, Tay FR, Pashley DH. The influence of hygroscopic expansion of resin-based restorative materials on artificial gap reduction. J Adhes Dent 2002;4:61–71.

[82] Sindel J, Frankenberger R, Krämer N, Petschelt A. Crack formation of all-ceramic crowns dependent on different core build-up and luting materials. J Dent 1999;27:175–81. https://doi.org/10.1016/S0300-5712(98)00049-9.

[83] Kirsten M, Matta RE, Belli R, Lohbauer U, Wichmann M, Petschelt A, et al. Hygroscopic expansion of self-adhesive resin cements and the integrity of all-ceramic crowns. Dent Mater 2018;34:1102–11. https://doi.org/10.1016/j.dental.2018.04.008.

[84] Lassila LVJ, Nohrström T, Vallittu PK. The influence of short-term water storage on the flexural properties of unidirectional glass fiber-reinforced composites. Biomaterials 2002;23:2221–9. https://doi.org/10.1016/s0142-9612(01)00355-6.

[85] Tarumi H, Torii M, Tsuchitani Y. Relationship between particle size of barium glass filler and water sorption of light-cured composite resin. Dent Mater J 1995;14:37–44,102. https://doi.org/10.4012/dmj.14.37.

[86] Lassila L, Säilynoja E, Prinssi R, Vallittu PK, Garoushi S. Fracture behavior of Bi-structure fiber-reinforced composite restorations. J Mech Behav Biomed Mater 2020;101:103444. https://doi.org/10.1016/j.jmbbm.2019.103444.

[87] Jakab A, Palkovics D, T. Szabó V, Szabó B, Vincze-Bandi E, Braunitzer G, et al. Mechanical performance of extensive restorations made with short fiber-reinforced composites without coverage: a systematic review of in vitro studies. Polymers 2024;16:590. https://doi.org/10.3390/polym16050590.

[88] Lassila L, Säilynoja E, Prinssi R, Vallittu PK, Garoushi S. Bilayered composite restoration: the effect of layer thickness on fracture behavior. Biomater Invest Dent 2020;7:80–5. https://doi.org/10.1080/26415275.2020.1770094.