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Comparison of marginal adaptation and fracture resistance of contemporary composite resins in molars with extensive MOD cavities

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Abstract

Background Restoring extensively damaged posterior teeth remains challenging due to reduced fracture resistance and potential marginal deterioration over time. Contemporary composite resins, including fiber-reinforced, injectable, and conventional materials, have been developed to improve mechanical performance and marginal integrity. This in vitro study evaluated the effect of thermo-mechanical aging on marginal adaptation and fracture resistance of these composite resins materials used in extensive Class II MOD cavities.

Methods Sixty-five extracted mandibular molars were allocated to five groups ($n = 13$): intact control, G-ænial Posterior, GAP: G-ænial Universal Injectable, EXF: EverX Flow, or EXP: EverX Posterior (GC, Japan). Standardized MOD cavities were prepared, selectively etched, and restored using G-Premio Bond (GC, Japan). Aging was simulated using thermocycling and chewing simulation. Marginal adaptation was assessed by scanning electron microscopy before and after aging, and fracture resistance was tested after aging. Data were analyzed using two-way ANOVA, one-way ANOVA, Tukey's post-hoc, and Chi-square tests ($p < 0.05$).

Results Marginal adaptation differed significantly among materials both before and after aging ($p < 0.05$). Aging increased marginal gaps in all groups, with the highest values in GUI and the lowest in EXP. EXF showed higher fracture resistance than GUI ($p < 0.05$). Restorability was highest for EXP and lowest for GAP, although the difference was not significant.

Conclusion Thermomechanical aging increased marginal gaps in all materials. EXF and EXP, showed more favorable marginal adaptation and higher fracture resistance than GUI and GAP. These materials may be considered a suitable option for restoring extensively damaged posterior teeth.

Keywords Fracture resistance, Marginal adaptation, Bulkfill composite, Fiber reinforced composite, SEM

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Introduction

The primary objective of restorative dentistry is to preserve sound tooth structure and restore natural form and masticatory function while protecting the teeth and surrounding oral tissues [1]. Continuous advances in dental materials have expanded restorative options, and composite resins are now widely used, including in posterior restorations. Nevertheless, selecting materials capable of reliably withstanding masticatory forces in posterior teeth with extensive structural loss remains a major clinical challenge [2].

The fracture resistance of composite resins depends on factors such as the resin matrix composition, filler content, and filler particle size and distribution [3]. To overcome these limitations, fiber-reinforced, bulk-fill, and highly filled flowable composites have been developed, offering improved mechanical properties, reduced polymerization shrinkage, and enhanced fracture resistance [4]. Short glass fiber–reinforced composites resins, such as EverX Posterior (EXP; GC, Tokyo, Japan) which contains barium glass fillers within a polymer matrix and has been reported to provide high fracture resistance [5, 6]. More recently, flowable fiber-reinforced composites with smaller fiber dimensions have been introduced and shown to further enhance fracture resistance, improve adaptation and contribute to stress distribution [7, 8].

Highly filled flowable composites have also been developed by modifying filler size and ratios, resulting in materials with low modulus of elasticity, high wear resistance, and improved mechanical performance [9, 10]. A representative example is G-ænial Universal Injectable (GUI; GC, Tokyo, Japan). In the present study, these materials were specifically selected based on their distinct composition and microstructural characteristics. EXP represents a short fiber-reinforced composite designed to provide structural reinforcement, whereas flowable fiber-reinforced composites are expected to improve adaptation and support stress distribution. In contrast, GUI represents a highly filled flowable composite with optimized filler distribution, primarily intended to enhance adaptation and surface integrity. These differences provide a rational basis for comparing their performance in structurally compromised teeth.

Despite these developments, MOD cavity preparations significantly weaken tooth structure, reducing fracture resistance by approximately threefold compared with intact teeth [11]. Therefore, fiber-reinforced composites are frequently preferred for restoring such teeth. Garlapati et al. [12] reported superior fracture resistance with EXP, and Garoushi et al. [13] highlighted its favorable physical properties for high-stress areas. In contrast, Bertie et al. [14] found that the GUI showed lower fracture resistance than EverX Flow (EXF; GC, Tokyo, Japan). Although these materials are relatively new, only a limited number of studies have evaluated their aging-related performance under identical conditions in structurally compromised MOD cavities, despite their distinct microstructural and compositional differences [15, 16].

Marginal adaptation is essential for biological sealing, prevention of secondary caries, maintenance of pulpal and periodontal health, and long-term clinical success [17]. Proper cavity design, appropriate material and adhesive selection, and meticulous application are critical to optimize adaptation. In large MOD cavities, fiber-reinforced composites combined with a conventional capping layer or bulk-fill composites generally provide favorable marginal adaptation, whereas highly filled flowable composites should be used cautiously in high-stress areas due to potential long-term stability concerns [18]. Current evidence indicates that EXP, EXF, GUI, and G-ænial Posterior (GAP; GC, Tokyo, Japan) provide clinically acceptable marginal adaptation when applied with appropriate techniques. Using EXP or EXF as a core material with a GAP or GUI capping layer represents a biomechanically sound approach that enhances fracture resistance while maintaining marginal adaptation [19, 20].

Scanning electron microscopy (SEM) analysis for marginal adaptation assessment together with thermomechanical aging, followed by fracture resistance testing, are well-established and validated methods that have been widely used in previous studies to simulate clinical conditions and ensure reliable and reproducible outcomes [21, 22]. Accordingly, this study aimed to evaluate the pre- and post-aging marginal adaptation and post-aging fracture resistance of contemporary restorative materials with different compositions and structural characteristics used in Class II MOD cavities in structurally compromised molars. The null hypotheses were: (1) no difference in marginal adaptation among the tested composite materials, and (2) no difference in fracture resistance among the tested composite materials.

Materials and methods

The required sample size was calculated using G*Power software (version 3.1.9.6). Based on a test confidence level of 95% (1-α), a test power of 85% (1-β), and an effect size of $f = 0.49$, the minimum sample size was determined to be 65 teeth, with 13 teeth allocated to each group [4].

A total of 65 human mandibular third molars, extracted within the previous six months for orthodontic or periodontal reasons, were collected. Teeth were included if they were free of caries, restorations, and visible defects, and had similar occlusal dimensions (±1 mm). The bucco-lingual and mesio-distal widths of the teeth were measured using digital calipers. Following extraction, residual hard and soft tissues were removed with a periodontal hand instrument, and the teeth were stored in saline solution until the beginning of the study.

Preparation of teeth

The teeth were embedded in acrylic resin blocks, with the coronal border positioned 1.5 mm below the cemento-enamel junction. Standardized Class II MOD cavities were prepared with dimensions determined from the highest cusp: a cavity depth of 5 mm and a bucco-lingual wall thickness of 2.5 mm at the thickest point (Fig. 1). Preparations were performed using a high-speed, water-cooled handpiece with a diamond-coated fissure bur (ISO-806 314 112 544 014, FG Diamonds, NTI-Kahla GmbH, Germany). The cavity walls were prepared parallel to each other, and all internal line angles were standardized at 90°. Measurements were verified during preparation using a periodontal probe and digital calipers. All cavities were prepared by a single operator to minimize variability, and the bur was replaced after every five preparations.

Restorative procedure

The restorative materials used in this study and their compositions are presented in Table 1. The teeth were randomly divided into five groups according to the restorative procedure:

Control group

No cavity preparation or restoration was performed.

G-ænial posterior (GAP) group

Following MOD cavity preparation, all enamel margins were etched with 35% orthophosphoric acid (K-Etchant Syringe, Kuraray Noritake, Tokyo, Japan) for 15 s, rinsed with water for 15 s, and air-dried. G-Premio Bond (GC, Tokyo, Japan) was applied according to the manufacturer's instructions, left for 10 s, air-dried for 5 s, and light-cured for 10 s with an LED curing unit (Valo; Ultradent Products Inc., South Jordan, UT, USA). A matrix system (Super Mat Adapt Supercap, Kerr, Switzerland) was then placed. GAP composite (shade A2) was inserted in 2.5-mm increments using the incremental technique, with each layer light-cured for 20 s.

G-ænial Universal Injectable (GUI) Group

All steps were identical to the GAP group until restoration. GUI composite (shade A2) was placed into the

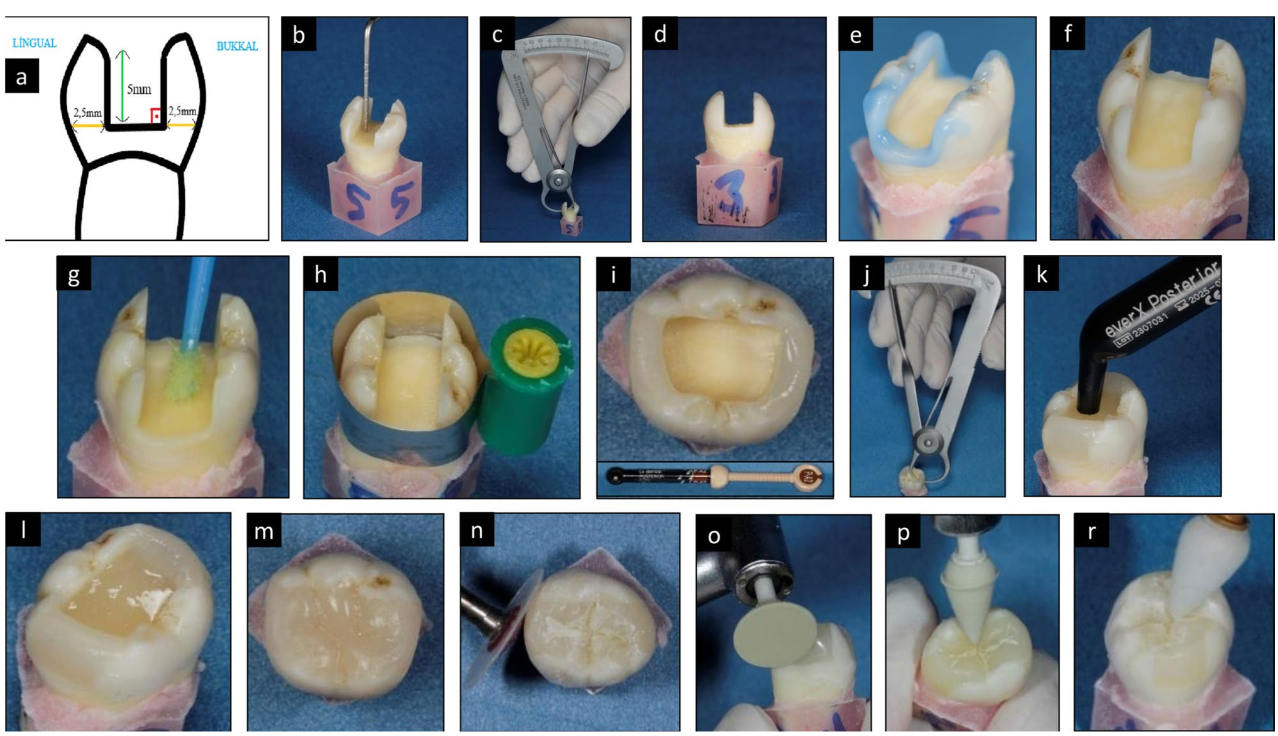

Fig. 1 **a**= Schematic representation of cavity preparation; **b**,**c**, **d**= Image of the prepared cavity; **e**,**f**, **g**,**h**=Application of adhesive system and placement of matrix system; **i**,**j**, **k**,**l**, **m**= Application procedure of the EXP composite; **n**,**o**, **p**,**r**=Step-by-step finishing and polishing of composite restorations

Table 1 Materials used in the study, their contents, and lot numbers

MATERIAL	COMPOSITION	LOT NO
G-aenial Posterior (GC, Tokyo, Japan)	UDMA, dimethacrylate co-monomer (no bis-GMA), fluoroalumina silicate, fumed silica, silica, strontium lanthanum fluoride, pre-polymerized filler (filler ratio: 77% weight, 65% volume)	220,829 A
G-aenial Universal Injectable (GC, Tokyo, Japan)	Methacrylate monomer, Silica, pigments, photoinitiator, Silane, Barium glass (filler ratio: 69% weight, 45% volume)	230,221 A
EverX Flow (GC, Tokyo, Japan)	Bis-MEPP, TEGDMA, UDMA, E-glass Fiber, Silicon Dioxide, Barium glass (filler ratio: 70% weight, 46% volume)	2,306,221
EverX Posterior (GC, Tokyo, Japan)	Bis-GMA, TEGDMA, PMMA, photoinitiator, glass fiber, silicon dioxide, barium glass (filler ratio: 76% weight, 57% volume)	2,307,031
G-Premio Bond (GC, Tokyo, Japan)	Acetone, dimethacrylate, phosphoric acid ester monomer, dimethacrylate compound, photoinitiator, butylated hydroxytoluene	2,304,171
K-Etchant Syringe (Kuraray Noritake, Tokyo, Japan)	Phosphoric acid, polyethylene glycol, colloidal silica, water, pigment	T0215

(*Bis-GMA* Bisphenol Glycidyl Methacrylate, *Bis-MEPP* Bisphenol A Ethoxylatedimethacrylate, *PMMA* Polymethyl Methacrylate, *TEG-DMA* Triethylene Glycol Dimethacrylate, *UDMA* Urethane Dimethacrylate)

cavity in 2.5-mm increments, with each increment polymerized for 20 s.

EverX flow (EXF) group

The procedures up to bonding were identical to the GAP group. The mesial and distal cavity walls were first built up with 2 mm of GAP composite. After converting the preparation into a Class I cavity shape, EXF composite was placed in a bulk increment up to 3.5 mm. The cavity was then completed with GAP composite. Each increment was polymerized for 20 s.

EverX posterior (EXP) group

All procedures up to bonding were the same as in the GAP group. The mesial and distal walls were built up with 2 mm of GAP composite, and the cavity shape was converted to Class I. EXP composite was then applied in a bulk increment up to 3.5 mm, and the restoration was completed with GAP. Each increment was light-cured for 20 s.

All restorations were finished with composite shaping discs (Sof-Lex Coarse-Medium, 3 M ESPE, USA) and polished with polishing wheels (PoGo Enhance Finishing System, Dentsply Sirona, USA).

Thermocycling was carried out between 5 °C and 55 °C, with a dwell time of 30 s, for 10,000 cycles. Subsequently, mechanical aging was performed in a chewing simulator (SD Mechatronik GmbH, Westerham, Germany) under a 50 N occlusal load, with 0.7 mm lateral movement, 240,000 cycles, and a frequency of 1.6 Hz. using a chewing simulator (SD Mechatronik GmbH, Westerham, Germany). This thermomechanical aging protocol was designed to simulate approximately one year of clinical function, based on commonly accepted correlations in the literature [23].

Marginal adaptation analysis

Marginal adaptation of the specimens were evaluated using a scanning electron microscope (FE-SEM; Tescan Mira III, Tescan, Brno, Czech Republic) before and after aging following a previously implemented protocol [24]. For SEM evaluation, all restored specimens were dried, sputter coated with a thin layer of gold prior to imaging and examined at 150× magnification. After baseline imaging, the specimens were subjected to the aging protocol. Following aging, the same specimens were re-coated and re-evaluated under SEM. Care was taken to standardize specimen positioning and to assess corresponding marginal regions before and after aging. The images were independently assessed by two calibrated researchers to perform a quantitative analysis.

For the quantitative evaluation, baseline and post-aging images were obtained from the mesial surfaces of the specimens (Fig. 2). The images were processed using a computer program, and the marginal micromorphology was classified as either "continuous margin" or "marginal gap" (for discrepancies > 250 µm) using ImageJ software (Rasband, W.S., ImageJ, U.S. National Institutes of Health, Bethesda, Maryland, USA) (Fig. 3), in accordance with the FDI World Dental Federation criteria for the evaluation of direct and indirect restorations [25].

All measurements were performed independently by two calibrated examiners who were blinded to the material type and only informed about the group allocation. In cases of any discrepancy, inter-examiner agreement was assessed by the re-evaluation and a consensus was reached. The results were expressed as the percentage (%) of marginal gap lengths relative to the total margin length.

Fracture resistance analysis

After aging, all specimens were subjected to fracture testing. A universal testing machine (Shimadzu Corp., Kyoto, Japan) equipped with a 5-mm-diameter stainless steel ball head was used to apply compressive loading at a crosshead speed of 0.5 mm/min. The load was applied parallel to the long axis of each specimen by contacting the buccal and palatal cusp ridges. The maximum force applied at failure was recorded in Newtons (N) for each specimen.

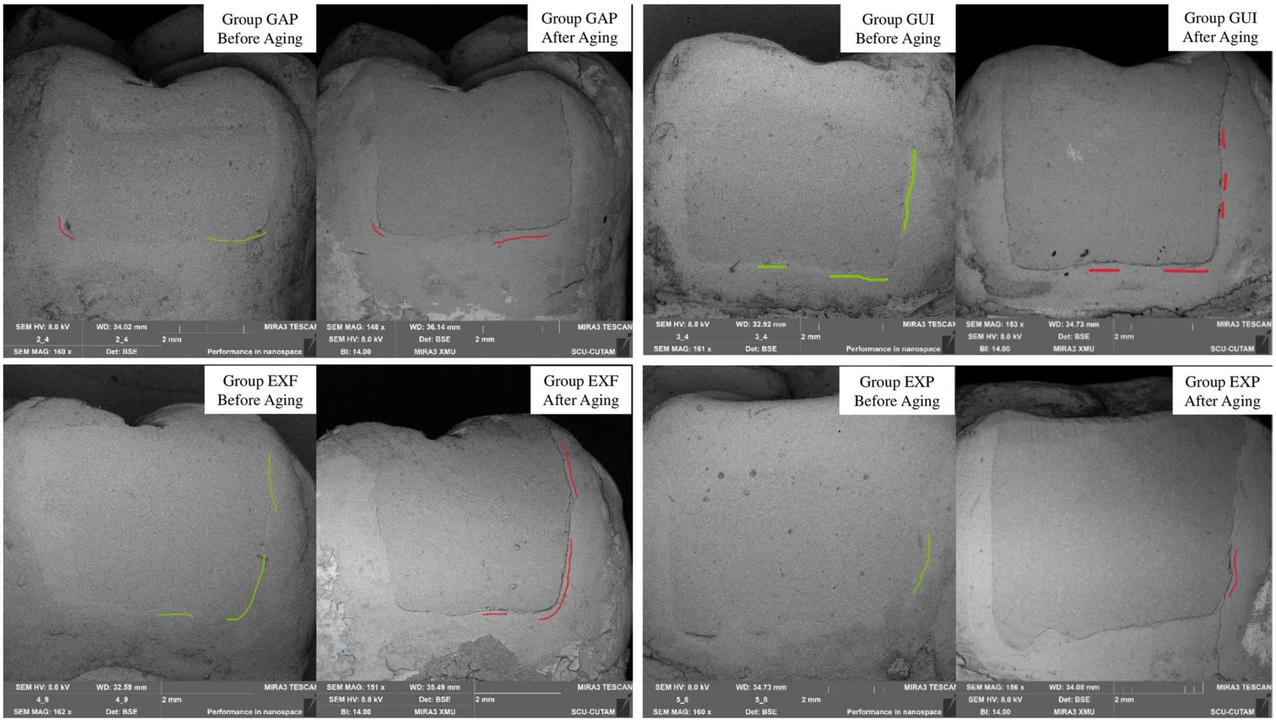

Fig. 2 SEM images of one specimen each from group GAP-GUI-EXF-EXP, before and after aging. Representative areas marked with red lines indicate regions classified as marginal gaps, whereas those marked with yellow lines indicate continuous margins

Analysis of the restorability of fractured specimens

Following fracture testing, all specimens were examined to determine fracture pattern under ×20 magnification using a stereomicroscope (Stemi2000, Axiovison4.8; Carl Zeiss, Jena, Germany). The fractures were classified as restorable or non-restorable according to previously described criteria based on the location of the fracture line relative to the cemento-enamel junction (CEJ).

Fractures extending more than 1 mm apical to the CEJ were considered non-restorable (Fig. 4), whereas those located coronal to the CEJ were considered restorable (Fig. 5) [26].

All evaluations were carried out following the same protocol described for marginal assessment. Briefly, two calibrated examiners, blinded to the material type and experimental groups, performed the evaluations independently. In cases of disagreement, a consensus was reached through joint re-evaluation.

Statistical analysis

Statistical analyses were performed using SPSS software (version 26.0; IBM Corp., Armonk, NY, USA). Data from the marginal adaptation analysis were analyzed using a two-way repeated-measures ANOVA, whereas fracture resistance data were analyzed using a one-way ANOVA. Post-hoc pairwise comparisons were conducted with Tukey's multiple comparison test. The distribution of restorable versus non-restorable fractures was analyzed using the Chi-square test. A significance level of $p < 0.05$ was considered statistically significant.

Results

Marginal adaptation evaluation

Means and standard deviations of the percentage (%) of marginal gaps relative to the total margin length are presented in Table 2. Two-way ANOVA revealed that both restorative material (F = 4.851, $p = 0.003$) and aging (F = 43.634, $p < 0.001$) had significant effects on marginal adaptation.

Before aging, no statistically significant differences were observed among the composite resin groups ($p > 0.05$). Notably, the GUI group demonstrated complete marginal continuity with no detectable gaps at baseline. Following thermomechanical aging and subsequent SEM re-evaluation, higher marginal gap values were observed in all groups ($p < 0.05$). The GUI group demonstrated the highest marginal gap values after aging, which were significantly greater than those of the other groups ($p < 0.05$). In contrast, the EXP group showed the lowest marginal gap values, and the difference among EXP, EXF and GAP was not significant ($p > 0.05$). SEM re-evaluation performed after thermomechanical aging revealed structural deformation

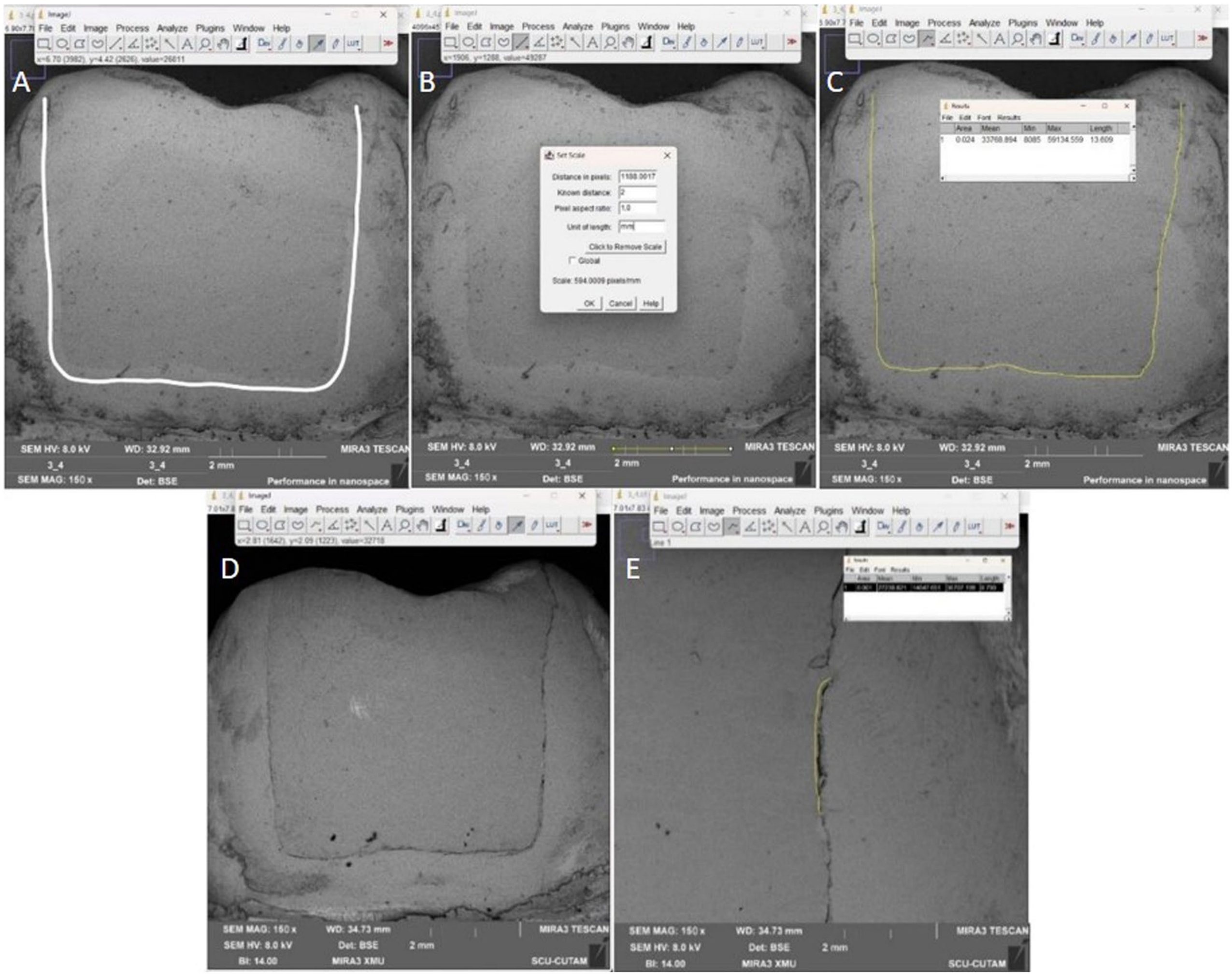

Fig. 3 Measurement of continuous and marginal gaps. **A**: Visual determination of restoration margins. **B**: Calibration for length measurement. **C**: Determining the total margin length. **D**: Determining marginal gaps. **E**: Measurement of marginal gaps

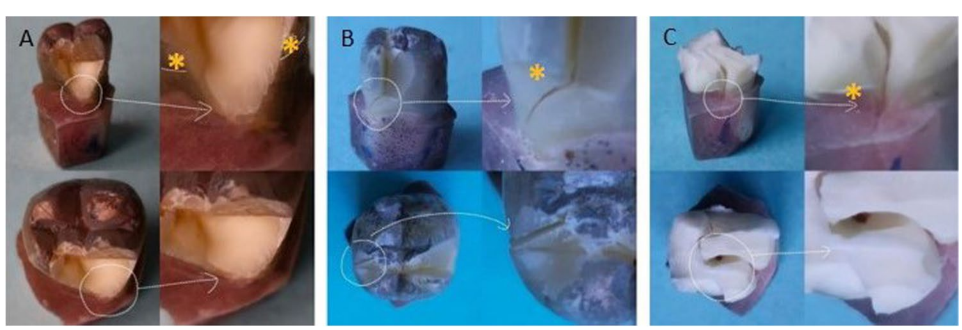

Fig. 4 Represantative images of unrestorable specimens. Occlusal and lateral photographs of three different cases. In the enlarged photographs of the areas marked with arrows, the cemento-enamel junction is indicated by an asterisk (*)

and the formation of crack lines; SEM images of these crack lines are presented in Fig. 6.

Fracture resistance evaluation

The mean fracture resistance values (Maximum load to failure, N ± standard deviation) for each group are presented in Table 3. One-way ANOVA revealed significant differences among the composite resin groups ($p < 0.05$).

The control group exhibited the highest fracture resistance, with no significant differences observed among the control, EXF, and EXP groups ($p > 0.05$). The lowest

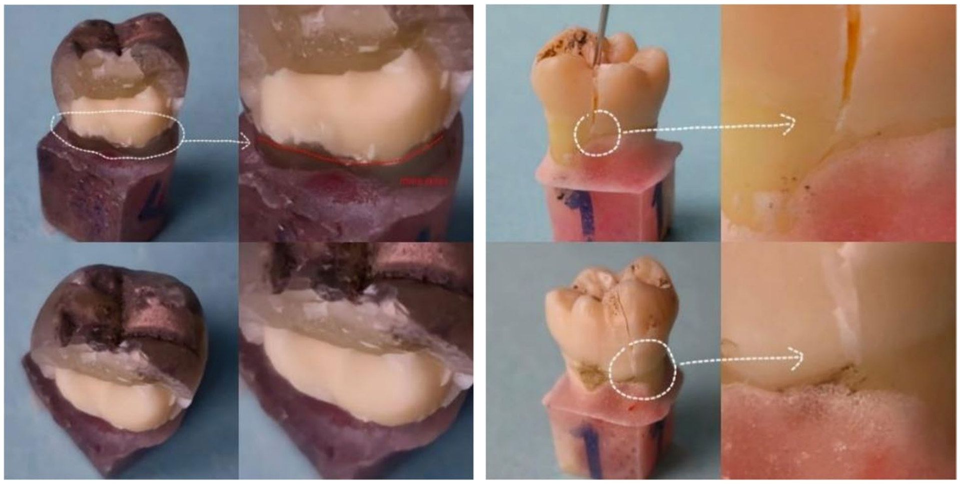

Fig. 5 Represantative images of restorable specimens. Occlusal and lateral photographs of two different cases. The fractures occurred at the cemento-enamel junction

Table 2 Means and standard deviations of the percentage (%) of marginal gaps relative to the total margin length

Mean ± Standard Deviation (%)				
	GAP	**GUI**	**EXF**	**EXP**
Before Aging	0.48 ± 1.74^{Aa}	0 ± 0^{Aa}	0.2 ± 0.7^{Aa}	0.9 ± 3.26^{Aa}
After Aging	7.22 ± 14.28^{Ba}	24.7 ± 10.67^{Bb}	10.67 ± 9.85^{Ba}	7.18 ± 16.21^{Ba}

Superscripts with uppercase letters indicate significant differences before and after aging (in column) ($p < 0.05$). Superscripts with lowercase letters indicate significant differences between groups (in row) ($p < 0.05$)

(G-aenial Posterior=*GAP*, Gaenial Universal Injectable=*GUI*, EverX Flow= *EXF*, EverX Posterior=*EXP)*

fracture resistance was recorded in the GUI group, which differed significantly from all other groups except GAP ($p < 0.05$), while no significant difference was found between the GUI and GAP groups ($p > 0.05$).

Evaluation of the restorability of the specimens after fracture resistance testing

The distribution of fracture patterns in terms of restorability is presented in Table 4. Chi-square analysis revealed no statistically significant differences among the composite resin groups ($p > 0.05$).

The highest proportion of restorable fractures was observed in the EXP group, whereas the lowest was observed in the GAP group. Both the GUI and EXP groups demonstrated a higher proportion of restorable fractures compared with the control group.

Discussion

As a result of this study, both null hypotheses stating that no differences exist in marginal adaptation or fracture resistance among composite materials used in vital teeth with extensive structural loss were rejected, as statistically significant differences were observed among the groups in both marginal adaptation and fracture resistance evaluations.

According to the SEM images obtained before aging, no marginal gap were detected in the GUI group. Although the differences among the tested composite resin groups were not statistically significant, the complete marginal adaptation observed in the GUI group represents notable finding. This may be attributed to its relatively low elastic modulus and flexibility, which can reduce stress generation during polymerization and at the adhesive interface. In addition, its flowable consistency and thixotropic behavior may further promote intimate adaptation at the tooth-restoration interface [27]. Similarly, EXF exhibits flowable characteristics and thixotropic behavior; however, because of its fiber content EXF was covered with a conventional composite resin layer (GAP) according to the manufacturer instructions, which may have masked itsdirect contribution to marginal adaptation compared with GUI.

The findings of this study should be interpreted in the context of a one-year simulated thermo-mechanical aging model rather than immediate material behavior. The aging protocol used in this study significantly increased marginal gap ormation in all groups. This finding is consistent with previous reports indicating that thermal aging induces stress accumulation at the margins and increases the risk of microleakage due to mismatches in the coefficients of thermal expansion between restorative materials and dental tissues [24, 28]. Furthermore, chemical processes such as water absorption and hydrolytic degradation of the resin matrix have been shown to adversely affect the mechanical properties and marginal adaptation of composite resins [28].

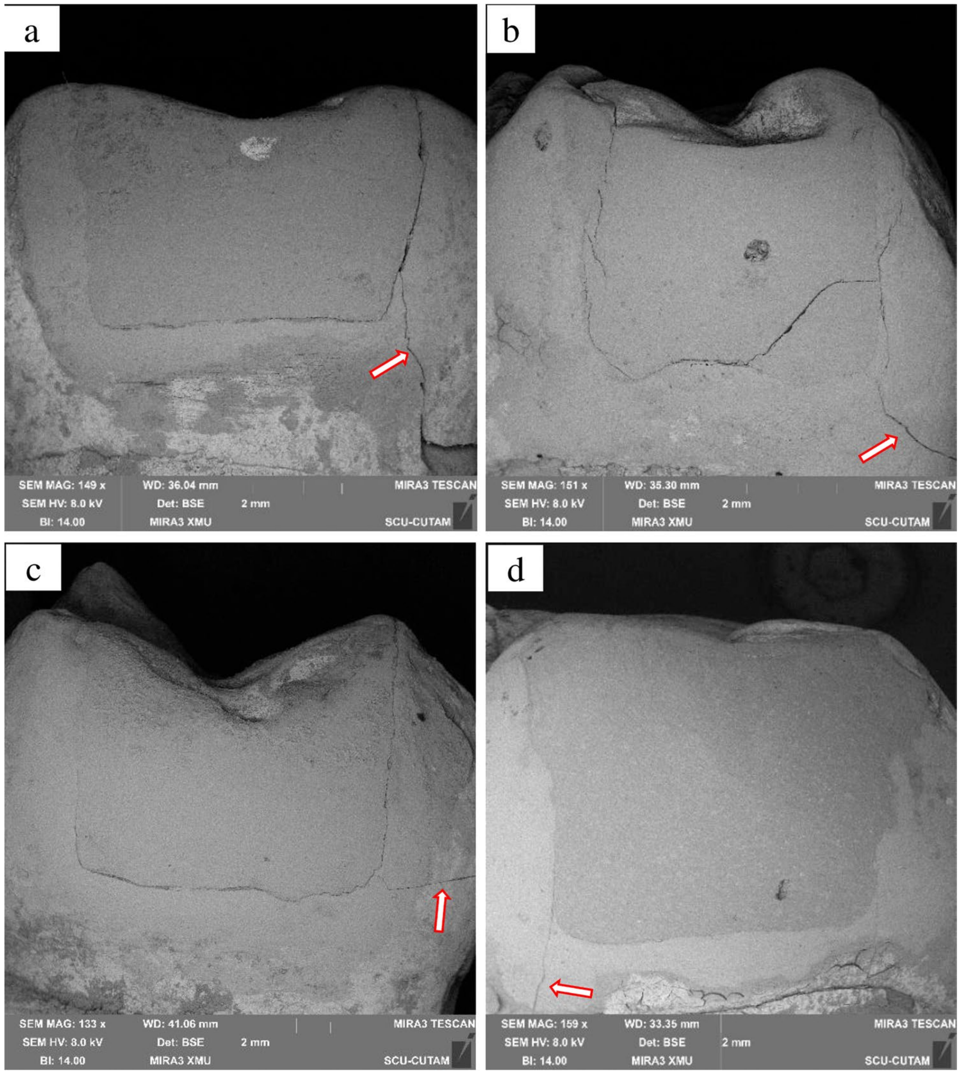

Fig. 6 Represantative SEM images of crack lines (marked with arrows) in the tooth tissues of samples after aging (a, b,c= Images of specimens from the GUI group; d= Images of specimens from the EXF group)

Table 3 Mean fracture resistance (N) and standard deviation values of groups

Mean ± Standard Deviation (*N*)							
	Control group	**GAP**	**GUI**	**EXF**	**EXP**	**Test Statistic**	***p****
Fracture resistance	2026.53 ± 339.22[a]	1409.72 ± 260.04[bc]	1124.62 ± 471.33[c]	1812.7 ± 619.54[ab]	1757.79 ± 601.95[ab]	10.092	< 0.001

Superscripts with lowercase letters indicate significant differences between groups ($p < 0.05$)

(G-aenial Posterior = *GAP*, Gaenial Universal Injectable = *GUI*, EverX Flow = *EXF*, EverX Posterior = *EXP)*

*ANOVA test

Table 4 Restorability of specimens as a result of fracture resistance test. Number of samples (percantege (%))

	Control Group	**GAP**	**GUI**	**EXF**	**EXP**	**p***
Restoreable	5 (38.5)[a]	2 (15.4)[a]	6 (46.2)[a]	4 (30.8)[a]	7 (53.8)[a]	0.298
Not Restoreable	8 (61.5)[a]	11 (84.6)[a]	7 (53.8)[a]	9 (69.2)[a]	6 (46.2)[a]	

Superscripts with lowercase letters indicate significant differences between groups ($p < 0.05$)

(G-aenial Posterior = *GAP*, Gaenial Universal Injectable = *GUI*, EverX Flow = *EXF*, EverX Posterior = *EXP*)

*Chi-square test

Interestingly, after aging, the GUI group exhibited the highest marginal gap values; however, these results should be considered within the limitations of the applied SEM methodology. Nevertheless, this observation may be associated with the relatively low elastic modulus and high flexibility of the material, which could result in greater deformation under repeated chewing loading. [29]. In addition, thermal aging may induce repeated contraction and expansion cycles, leading to stress accumulation at the tooth-restoration interface [24]. Together these factors may increase interfacial stress concentration, resulting in fatigue related degradation and progressive deterioration of marginal adaptation over time. In contrast, the EXP and EXF groups demonstrated lower measured marginal gap values following aging, which may be related to their fiber-reinforced structure. The incorporation of glass fibers may restrict crack propagation and reinforcing the resin matrix. Moreover, these fibers may reduce stress intensity by enhancing stress distribution within the restoration and improve resistance to deformation under functional loading, thereby contributing to the preservation of marginal integrity [30, 31].

In the present study, the marginal adaptation of restorative materials was evaluated using an in vitro protocol intended to approximate clinical conditions through thermomechanical aging. Based on existing literature and manufacturers' recommendations, fiber-reinforced composites such as EXF and EXP are not intended for direct exposure to the external environment [32]. Because the incorporation of fibers increases surface roughness, the outer surface of fiber-reinforced composites is recommended to be covered with a layer of light-cured conventional composite resin [33]. Accordingly, in the experimental design, EXF and EXP groups were used as substructure materials and were covered with a conventional resin composite (GAP) in order to reproduce their recommended clinical application as bilayered restorations. In this study, the restoration of the mesial and distal walls of MOD cavities with GAP in the EXF and EXP groups may have limited the ability to isolate the individual effects of these materials on marginal adaptation. As a result, no significant differences were detected among the EXP, EXF, and GAP groups.

Goteti et al. [34] reported that conventional posterior composites exhibited significantly greater marginal gaps compared with two fiber-reinforced composites. This finding was attributed to the reduced organic matrix content of fiber-reinforced composites and their ability to mitigate polymerization shrinkage. In addition, the improved performance was associated with the elastic modulus and coefficient of thermal expansion of these materials being closer to those of natural tooth structure. However, these results are not consistent with the findings of the present study. This discrepancy may be explained by methodological differences, particularly the fact that, unlike in our study, the mesial and distal walls of the cavities were not restored with conventional composite resin.

In the SEM images obtained after aging, crack lines were detected in some specimens, indicating the presence of structural changes following the aging process. Crack lines were predominantly observed in the GUI group, which may be associated with the absence of reinforcing fibers, and its relatively lower elastic modulus. These characteristics may result in greater deformation under functional loading and potentially contribute to crack initiation and propagation [27]. In contrast, fiber-reinforced composite resins exhibit mechanical properties closer to dentin and a more biomimetic behavior, which may help to inhibit crack initiation and propagation by enhancing stress distribution and providing crack-bridging effects within the resin matrix [22].

In the present study, the highest fracture toughness was observed in the EXF group, followed by the EXP group. Fracture toughness reflects a material's resistance to crack propagation. Previous studies have reported that EXP exhibits a fracture resistance of 2.6 MPa·m$^{1/2}$ and a flexural modulus of 12.6 GPa, whereas EXF demonstrates a fracture resistance of 2.8 MPa·m$^{1/2}$ and a flexural modulus of 9 GPa [22, 35]. These properties may partly explain the superior fracture resistance of EXF observed in this study. In addition, EXP contains 74.2% filler, while EXF contains 70%. The lower viscosity of EXF may have enhanced its adaptation to cavity walls, reducing gap formation and thereby improving mechanical resistance [36]. Furthermore, the dimensional characteristics of reinforcing fibers, such as length, diameter, and aspect ratio, are known to influence tensile strength, flexural modulus, and overall reinforcement behavior [37]. Fibers exceeding the critical length can effectively transfer stresses from the resin matrix and act as crack-bridging elements, thereby reducing stress concentration at the crack tip and limiting crack propagation. In addition, fiber orientation plays a crucial role in mechanical performance, as randomly oriented fibers may provide more isotropic reinforcement, whereas aligned fibers can enhance strength along specific loading directions [37, 38]. EXF, which incorporates micrometer-sized fiber particles, may have further contributed to improved fracture resistance by providing more effective reinforcement within the resin matrix and at the bonded tooth–restoration interface [7, 8, 38]. Garlapati et al. [12] and Garoushi et al. [13] similarly reported that fiber-reinforced composites possess high fracture resistance and are well-suited for high-stress areas. Bertie et al. [14] also demonstrated that EXF exhibited superior fracture resistance compared with the highly filled flowable composite GUI. These findings are consistent with the results of the present study.

In the present study, the GAP and GUI groups exhibited significantly lower fracture resistance compared with intact dental tissue. This may be explained by the limited fracture resistance of these materials, which has been reported to be approximately 1.1 $MPa \cdot m^{1/2}$, whereas intact dentin demonstrates a fracture resistance of 1.80 ± 0.10 $MPa \cdot m^{1/2}$ [39, 40]. Because these fiber-free composites cannot replicate the stress-absorbing properties of dentin, they tend to exhibit more brittle behavior than fiber-reinforced materials [40, 41]. Ideally, the fracture resistance of a restorative material should approximate that of the tissue it replaces. In this study, however, the extensive dentin loss resulting from MOD cavity preparation may not have been adequately compensated for by GAP and GUI. Accordingly, the fracture resistance values remained lower than those of intact teeth and demonstrated a statistically significant reduction. Furthermore, polymerization shrinkage stresses, which are absent in sound teeth, may contribute to adhesion failures and microleakage in resin-based restorations, further compromising fracture resistance [42, 43]. Previous studies comparing the fracture resistance of fiber-reinforced and conventional composites have reported results consistent with those of the present study [22, 44].

According to the fracture type evaluation, the highest number of restorable fractures was observed in the EXP group. This outcome may be attributed to the incorporation of long glass fibers, which are capable of guiding crack propagation [36]. By absorbing and redistributing stresses, these fibers can arrest crack progression or deflect it toward the periphery [7]. In contrast, the EXF group exhibited a higher number of unrestorable fractures than expected. Although EXF has a composition similar to EXP, it was less effective in maintaining fracture restorability. This difference may be explained by the shorter fiber length in EXF, which is below the critical threshold (0.5–1.6 mm) [45]. Such short fibers are insufficient to arrest incoming stresses or redirect them toward the periphery, potentially allowing crack lines to propagate apically toward the root tip and resulting in unrestorable fractures.

Szczesio-Wlodarczyk et al. [46] reported the modulus of elasticity of GAP as 8 GPa and that of GUI as 7.2 GPa. Because GAP exhibits lower flexural capacity, it may be more prone to transmitting stresses directly to the root tip, resulting in a greater proportion of unrestorable fractures. According to the results of this study, the lowest number of restorable fractures was observed in the GAP group. In specimens restored solely with conventional composite, crack lines may propagate directly toward the root without being absorbed by an intermediate reinforcing phase. Interestingly, the GUI group exhibited a higher number of restorable fractures than the GAP group, despite not containing fibers. This finding may be explained by differences in the modulus of elasticity between the two materials.

The present study has certain limitations. First, it was performed under in vitro conditions, which cannot fully replicate the complex biological and mechanical environment of the oral cavity. Therefore, future laboratory studies should be complemented by well-designed clinical trials to enhance the external validity and clinical relevance of the findings. Another limitation is that, according to the manufacturers' instructions, the fiber-reinforced composites were covered with a conventional posterior composite on the mesial and distal cavity walls. This restorative protocol limited the ability to compare the intrinsic marginal adaptation of the tested materials directly. In addition, marginal adaptation was evaluated using direct SEM imaging of the specimens before and after aging. Although this approach enabled comparison of the changes observed within the same specimens, the repeated sputter-coating procedures and vacuum exposure required for SEM analysis may have influenced the measured marginal gap values and should therefore be considered as a limitation of the study. Consequently, the observed differences between pre and post-aging evaluations should be interpreted in light of the potential influence of the SEM evaluation protocol on the measurements.

Conclusions

Within the limitations of this in vitro study, the findings suggest that the microstructural characteristics of composite resins, particularly fiber reinforcement and elastic properties, may influence post-aging marginal adaptation and fracture behavior. Fiber-reinforced composites exhibited more favorable fracture patterns and generally lower marginal gap values after aging, however, these findings should be interpreted within the context of the SEM evaluation methodology applied in this study. These findings support the consideration of restorative materials not only according to their composition but also according to their mechanical behavior and stress-distribution capacity. Incorporating fiber-reinforced composites may represent a promising biomimetic approach by enhancing structural support and promoting more favorable failure patterns.

Abbreviations

μTBS	Microtensile bond strength
MDP	10-methacryloxydecyl dihydrogen phosphate
SEM	Scanning electron microscopy
EDX	Energy-dispersive X-ray
EXP	EverX Posterior
GUI	G-ænial Universal Injectable
EXF	EverX Flow
GAP	G-ænial Posterior
CEJ	Cemento-enamel junction

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Informed consent
Not Applicable.

Authors' contributions
KB.: Conceptualization; methodology; supervision; data curation; visualization; writing-original draft; writing-review and editing. GT.: Conceptualization; methodology; supervision; data curation; visualization; writing-review and editing. HH.: Conceptualization; methodology; software; supervision; visualization; writing-review and editing.

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Data availability
The data that support the findings of this study are available on request from the corresponding author.

Declarations

Ethics approval and consent to participate
This study received ethical approval from the Ethics Committee of Tokat Gaziosmanpasa University, Faculty of Medicine (23-KAEK-258) and in accordance with the Declaration of Helsinki. Written informed consent with an easy Turkish language as mother language of participants was signed by the recruited participants to permit the use of the investigation data.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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