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# The impact of postoperative intracoronal bleaching on the microtensile bond strength at the composite-dentin interface

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The study evaluated the effects of postoperative bleaching with HP and CP on microtensile bond strength (μTBS) and nanoleakage of composite restorations using total-/self-etch protocols. Sixty incisors with Black V cavities were restored using a multimode adhesive in total-/self-etch mode and resin composite. Samples were divided into five groups: control, CP×2, CP×5, HP×2, HP×5. After bleaching, 1×1×8 mm composite blocks ($n$=10) were tested for μTBS, and failure types were assessed. Two samples per group were analyzed for nanoleakage *via* scanning electron microscope (SEM). Two-way analysis of variance, Bonferroni correction, and stepwise linear regression were applied. CP×5 and HP×5 groups exhibited significantly reduced μTBS compared to control, and the self-etch protocol resulted in lower values regardless of bleaching method. Regression analysis confirmed significant effects of adhesive (total-etch) and bleaching (CP×5, HP×5). A significant relationship was found between failure modes and bleaching methods for each adhesive protocol, with adhesive failures being the most frequent. SEM revealed nanoleakage in all groups.

*Keywords*: Adhesion, Intracoronal bleaching, Microtensile bond strength, Nanoleakage

## INTRODUCTION

Tooth bleaching is a widely performed cosmetic procedure due to its technical simplicity, proven clinical efficacy, and non-invasive nature. The bleaching process is based on the oxidative potential of hydrogen peroxide, the main active component in the agents[1]. This molecule diffuses through dental hard tissues (due to its low molecular weight) and promotes the breakdown of organic pigments, transforming them into smaller molecules that reflect less light[2]. Bleaching agents can be applied to the teeth either extracoronally (vital bleaching) or intracoronally (non-vital bleaching), and they generally contain various concentrations of hydrogen peroxide, carbamide peroxide, and sodium perborate. These agents are often used in conjunction with an activation method such as heat and/or light[3].

Intracoronal bleaching is a minimally invasive procedure performed on endodontically treated teeth, first described by Dwinelle in 1850[4]. Despite their proven efficacy in intracoronal bleaching[5], the effects of bleaching agents on the structure and properties of dental hard tissues remain a subject of debate. Many studies have reported some negative effects, such as a decrease in abrasion resistance and microhardness of bleached enamel[6,7], a reduction in dentin microhardness[8,9] and diminished bond strength when restorations are performed immediately or within a week after bleaching[10,11]. The decrease in bond strength of adhesive restorations performed after bleaching has been extensively studied in the literature. This decrease in adhesion has been associated with the presence of residual peroxide on the tooth surface, which may interfere with resin infiltration and adversely affect the polymerization process[12-14].

Although studies investigating the relationship between bleaching and adhesion predominantly focus on the preoperative effects of bleaching[15-17], preserving of the existing restoration may be preferred in cases where no visible color mismatch is observed between the tooth and the restoration following bleaching, in accordance with the principle of minimally invasive dentistry[18]. Moreover, in cases where prosthetic treatments such as crowns or laminate veneers are planned after intracoronal bleaching, replacing the existing restoration may not be necessary[19]. In such scenarios, the potential indirect effects of bleaching-induced structural changes in enamel and dentin on bond strength raise questions regarding their clinical significance. However, only a limited number of studies in the literature that have addressed the effect of bleaching on the adhesion of previously placed composite restorations[20-22]. This effect has been analyzed using different methods, such as measuring bond strength[20,21], fracture toughness[23], and microleakage[24]. However, the results of these studies are inconclusive. Some authors have reported a weakening of adhesion to enamel but no issues with adhesion to dentin[20]; others have described a reduction in adhesion to dentin[23] or to both tissues[21] after bleaching.

Nowadays, the development of universal-shade composites capable of blending with a wide range of tooth shades allows restorations to adapt to color changes in the surrounding tooth structure[25,26], thereby potentially eliminating the need to replace existing restorations after bleaching[27]. This property has also laid the groundwork for a new potential indication in the context of postoperative bleaching. Although the color-matching capabilities of universal-shade composites remain a topic of ongoing investigation and debate in the literature, recent studies have reported that these

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materials can harmonize with lighter tooth shades[28], and may also adapt to the lightened shades resulting from bleaching[29]. Particularly in endodontically treated teeth with extensive structural loss, maintaining the tooth with a temporary restoration for an extended period during the walking bleach procedure may increase the risk of fracture[30]. In such cases, universal-shade composites that exhibit high color matching and better integration with bleached dental tissues may enable immediate placement of definitive restorations. Consequently, the use of temporary restorations can be limited to the extent of the bleaching cavity alone, thereby minimizing the risk of further structural weakening. In this context, evaluating the effects of bleaching agents on pre-existing composite restorations and dentin interfaces is of great importance for the long-term clinical success of restorations. Accordingly, the present study focused on the potential effects of bleaching procedures on the bond strength of restorations placed using a universal-shade composite prior to bleaching, particularly in aesthetically critical anterior teeth.

The aim of the study was to investigate the effects of postoperative bleaching with two different office-based agents (hydrogen peroxide and carbamide peroxide) applied either twice or five times on the microtensile bond strength (μTBS), failure type, and nanoleakage of universal-shade composite restorations performed using total-etch or self-etch adhesive protocols. The first null hypothesis of the study was that there would be no difference in dentin bond strength following bleaching treatment of composite restorations using different adhesive protocols. The second null hypothesis of the study was that there would be no difference in dentin bond strength following bleaching treatment of composite restorations when the same adhesive procedure was used, regardless of the bleaching procedure.

## MATERIALS AND METHODS

Based on the study conducted by Barcellos *et al.*[21], the power analysis was performed considering μTBS between dentin and restoration. An effect size of 0.52 was calculated using group means of 34.73, 35.12, 29.67, and 24.56, with a pooled standard deviation of 8.22. With a 95% confidence level (1-$\alpha$), a 95% statistical power (1-$\beta$), and this effect size, a sample size of 10 per group was required. This study was approved by the Clinical Research Ethics Committee of Çanakkale Onsekiz Mart University with the decision dated November 29, 2023, and numbered 15-04.

### *Teeth selection and preparation*

Sixty sound human maxillary and mandibular incisor teeth, extracted for periodontal reasons, were used in this study. Teeth with cracks, caries, restorations, or structural defects were excluded. Immediately after extraction, the teeth were cleaned of soft tissue debris and stored in a 0.1% thymol solution (pH 7.0) for one week for disinfection. They were then stored in distilled water at 4°C and used within six months of extraction. Standardized Black V cavities measuring 4×4 mm were then prepared on the buccal surfaces under water cooling using a fissure bur (3098, KG Sorensen, Sao José dos Campos, Brazil) and a high-speed handpiece (Kavo SMART torque, Kavo Dental, Biberach, Germany). The cavity depth was designed to ensure that, following the subsequent palatal bleaching access cavity preparation, at least 1 mm of dentin-supported composite material would remain (~1.5 mm within dentin, verified with a periodontal probe). Half of the prepared cavities were etched with 37% phosphoric acid for 10 s (K-Etchant Syringe, Kuraray Noritake Dental, Tokyo, Japan), rinsed with an air-water spray, and dried. Subsequently, a universal adhesive system (Clearfil Tri-S Bond, Kuraray Noritake Dental) was applied to the surface for 10 s, gently air-dried, and polymerized for 10 s using a 1,400 mW/cm² LED light (D-Light Pro, GC, Tokyo, Japan). For the other half of the cavities, the universal adhesive system (Clearfil Tri-S Bond, Kuraray Noritake Dental) was applied without prior etching, following the same procedure. Afterward, composite restorations were performed in both groups according to the manufacturer's instructions (Omnichroma, Tokuyama Dental, Tokyo, Japan). The composites were polymerized in 2 mm increments for 20 s using a 1,400 mW/cm² LED light-curing unit. The commercial names, materials' manufacturers, and compositions used in the study were shown in Table 1.

Intracoronal bleaching cavities were prepared from the palatal region using a diamond bur and a high-speed handpiece under water cooling. During the preparation of the access cavity, care was taken to fully expose the entire buccal restoration, including the composite–cavity interface along the gingival margin, and the cavity floor was extended up to the canal orifices. To avoid excessive material removal and accurately locate the composite, the restoration detection mode of the LCU was used during the procedure. Subsequently, the roots were sectioned 4 mm apical to the cemento-enamel junction using a diamond saw (7020, Kavo do Brasil), and the pulp tissue was removed. The canal orifices were sealed with glass ionomer cement (Ketac Molar Easymix, 3M Deutschland, Neuss, Germany). The specimen preparation procedure was based on a previously published method for intracoronal bleaching[14]. The teeth with bleaching cavities were randomly divided into 5 groups ($n$=10), and the procedures described below were followed:

The control group; no bleaching was performed. A cotton pellet soaked in distilled water was placed in the pulp chamber, and the access cavity was sealed with temporary cement (Cavit, 3M ESPE, Seefeld, Germany).

The experimental group 1 (CP×2): after placing the office-type devital bleaching agent Whiteness Super Endo (37% carbamide peroxide, FGM, Joinville, Brazil) in the pulp chamber, the access cavity was sealed with temporary cement, and the agent was left in the pulp chamber for 3 days. This procedure was repeated twice with 3-day intervals, and the bleaching process was completed after 6 days.

Table 1 Commercial names, materials' manufacturers and composition

| Commercial names | Materials' manufacturers | Generic description | Composition |
|---|---|---|---|
| Clearfil tri-S Bond | Kuraray Noritake Dental | Dental bonding agent | Bond: MDP, HEMA, Bis-GMA, photoinitiator, water, ethanol |
| K-Etchant Syringe | Kuraray Noritake Dental | Etching gel | 35% phosphoric acid, thickener |
| Omnichroma | Tokuyama Dental | Composite resin | Filler: 79 wt% uniform size supranano spheric filler ($SiO_2$-$ZrO_2$ 260 nm), 68 vol%<br>Base monomer: UDMA, TEGDMA |
| Opalescence Endo | Ultradent | Tooth bleaching gel | 35% hydrogen peroxide, potassium nitrate, fluoride |
| Whiteness Super-endo | FGM | Tooth bleaching gel | 37% carbamide peroxide, neutralized carbopol, inert filler, glycol and deionized water |

MDP: 10-methacryloyloxydecyl dihydrogen phosphate; HEMA: 2-hydroxyethyl methacrylate; Bis-GMA: bisphenol A-glycidyl methacrylate; UDMA: urethane dimethacrylate; TEGDMA: triethylene glycol dimethacrylate

The experimental group 2 (CP×5): after placing the office-type devital bleaching agent Whiteness Super Endo (37% carbamide peroxide, FGM) in the pulp chamber, the access cavity was sealed with temporary cement, and the agent was left in the pulp chamber for 3 days. This procedure was repeated five times with 3-day intervals, and the bleaching process was completed after 15 days.

The experimental group 3 (HP×2): after placing the office-type devital bleaching agent Opalescence Endo (35% hydrogen peroxide, Ultradent Products, South Jordan, UT, USA) in the pulp chamber, the access cavity was sealed with temporary cement, and the agent was left in the pulp chamber for 3 days. This procedure was repeated twice with 3-day intervals, and the bleaching process was completed after 6 days.

The experimental group 4 (HP×5): after placing the office-type devital bleaching agent Opalescence Endo (35% hydrogen peroxide, Ultradent) in the pulp chamber, the access cavity was sealed with temporary cement, and the agent was left in the pulp chamber for 3 days. This procedure was repeated five times with 3-day intervals, and the bleaching process was completed after 15 days.

Throughout the experimental procedure, the teeth were individually stored in plastic tubes containing distilled water in an incubator. At the end of every 3 days, the bleaching agents were rinsed, and fresh bleaching agent was placed in the pulp chamber[9]. The bleaching agents were applied for 2 or 5 sessions according to the manufacturer's instructions. After the bleaching sessions were completed, the pulp chamber was rinsed, and the access cavity was sealed with temporary cement.

*μTBS test*

After the bleaching procedure was completed, sections consisting of composite and dentin, measuring approximately 1×1×8 mm in size, were prepared from the inner dentin surfaces facing the access cavity of the teeth. This was done using a 0.3 mm diameter disc and a micro-cutting device (Minitom, Struers, Westlake, OH, USA). Thus, 2 or 3 composite-dentin blocks were obtained from each tooth, resulting in a total of 100 specimens from 60 teeth. This allowed for the inclusion of two different adhesive protocols and five bleaching methods (including control group), forming 10 groups with 10 specimens per group. The sections were bonded to a metal apparatus that could be mounted on a microtensile testing device (MTD-500, SD Mechatronik, Feldkirchen-Westerham, Germany) using adhesive (502 Super Glue, Evo-Bond Group, Kaohsiung, Taiwan) and subjected to tensile forces at a speed of 0.5 mm/min[31]. The bond failure values of the restorations were measured using the software program of the tensile device (MTD-500 ver. 2.0, SD Mechatronik). The shear bond strength was calculated by dividing the force at the moment of failure (N) by the base area of the samples ($mm^2$), and it was expressed in megapascals (MPa) (MPa=N/$mm^2$). Figure 1 schematically depicts the methodological procedures.

For failure type analyses, the debonded area was assessed under a stereomicroscope (Leica S8APO, Leica Microsytems, Wetzlar, Germany) at 50× magnification. The failure type was classified as adhesive (none or very little (<30%) composite residue on the dentin surface), mixed (composite residue on >30% of the dentin surface), or dentin cohesive (dentin fracture, a portion of which is attached to the resin composite part)[32].

*Nanoleakage evaluation*

Two additional samples were prepared from each group for the evaluation of nanoleakage. All tooth surfaces 1 mm away from the restoration were coated with two layers of nail varnish. The samples were immersed in distilled water for 10 min to rehydrate. Ammoniacal

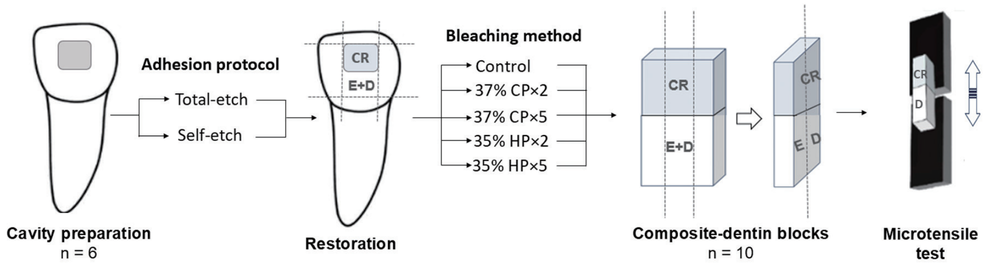


Fig. 1 Schematic representation of the methodological procedures (Total-etch: phosphoric acid on dentin; Self-etch: no phosphoric acid).
CR: composite resin; E: enamel; D: dentin.

silver nitrate solution was prepared according to the protocol previously described by Reis *et al.*[33] Twenty five grams of silver nitrate (ZAG Kimya, Istanbul, Turkey) was weighed. It was dissolved in 25 mL of distilled water. Subsequently, 25% ammonium hydroxide solution (Sigma-Aldrich, St. Louis, MO, USA) was added drop by drop. This process was continued until the black solution became clear. The samples were kept in the prepared solution in complete darkness for 24 h. The samples were then rinsed with distilled water and immersed in a photographic developing solution under fluorescent light for 8 h to reduce the silver ions to metallic silver. The samples were rinsed with distilled water after being removed from the photographic developing solution. Then, the specimens were cut along the longitudinal midline of restoration with a diamond disc, and polished with orange and yellow Soflex discs (3M ESPE Dental Products) impregnated with aluminum oxide. Scanning electron microscope (SEM) images were obtained to evaluate the nanoleakage levels at the restoration-tooth interface.

### *SEM*

Representative one specimen from each subgroup was randomly chosen and prepared for SEM (JSM-7100F, JEOL, Tokyo, Japan) analysis. The specimens were sputter-coated with a layer of gold-palladium in a vacuum evaporator to ensure electron conductivity and improve the quality of the micrographs without the existence of artifacts. SEM images at magnifications of 60×, 400×, 500×, and 2,000× were obtained, and additionally, energy-dispersive X-ray (EDX) analysis was performed on points suspected of silver nitrate nanoleakage using an X-Max 80 detector (Oxford Instruments, Abingdon, UK) with an accelerating voltage of 10 kV and 50-s counting times.

### *Statistical analysis*

The data were analyzed using the statistical software program SPSS (23.0) (SPSS, Chicago, IL, USA). A two-way analysis of variance (ANOVA) was applied to the μTBS data, which showed a normal distribution according to the Shapiro-Wilk test. Since the interaction between the main factors, 'adhesive protocol' and 'bleaching method', was not statistically significant, *post hoc* comparisons were conducted based solely on the main effects, considering the average values across the levels of the other factor. Subsequently, bonferroni correction was applied for multiple comparisons. The stepwise approach was used to apply linear regression analysis to investigate the effects of the adhesive protocol and bleaching methods on microtensile bond strength. The self-etch adhesive protocol and the control group for the bleaching method were used as references. The failure mode ratios were evaluated using Fisher's exact test. A significance level of $p<0.05$ was considered statistically significant.

## RESULTS

The mean and standard deviations of the composite groups for (μTBS) values are described in Table 2. According to the results of the two-way ANOVA, there were significant main effects of adhesive protocol ($F$=16.981, $p<0.001$) and bleaching method ($F$=4.054, $p$=0.004) on μTBS values. The interaction effect between adhesive protocol and bleaching method was not statistically significant ($F$=2.379, $p$=0.055). Bonferroni-adjusted *post hoc* comparisons revealed that the carbamide peroxide×5 and hydrogen peroxide×5 bleaching groups showed significantly lower μTBS values than the control group, independent of the adhesive protocol ($p$=0.005 and $p$=0.016, respectively). Additionally, the self-etch adhesive protocol exhibited significantly lower μTBS values compared to the total-etch protocol, regardless of the bleaching method applied ($p<0.001$).

The results of the linear regression analysis for μTBS values are presented in Table 3. ANOVA test was applied to assess the significance of the model, and the constructed regression model was found to be significant ($F$=8.833, $p<0.001$). The proportion of variance in the dependent variable explained by the independent variables in the model is 14.5%. Upon examining the VIF values of the significant variables in the model, it was found that all values were below 5, indicating that no variable contributed to multicollinearity or autocorrelation issues (Durbin Watson statistic: 1.949<2.5). The regression coefficient for the total-etch adhesive increased μTBS by 2.040 units compared to

Table 2 Mean (±standard deviation) of microtensile bond strength (μTBS) values

| Adhesive protocol | Bleaching method | | | | | |
|---|---|---|---|---|---|---|
| | Control | CP×2 | CP×5 | HP×2 | HP×5 | Average |
| Total-etch | 13.88±5.54 | 11.83±2.96 | 9.49±1.85 | 10.88±4.14 | 9.49±1.85 | 11.11±3.83 A |
| Self-etch | 9.63±1.32 | 8.34±1.70 | 8.39±2.28 | 10.03±2.66 | 8.98±2.34 | 9.07±2.16 B |
| Average | 11.76±4.51 a | 10.08±2.96 ab | 8.94±2.11 b | 10.46±3.44 ab | 9.24±2.09 b | 10.09±3.26 |

A, B: Different capital letters in the column indicate a significant difference (main effect; adhesive protocol).
a, b: Different lower letters in the row indicate a significant difference (main effect; bleaching method).

Table 3 Linear regression analysis for microtensile bond strength (μTBS) values

| Variables | | | | | | 95% C.I. | | |
|---|---|---|---|---|---|---|---|---|
| | β | S.E. | St. β | t | *p* | Lower | Upper | VIF |
| Adhesive (Total-etch) | 2.040 | 0.510 | 0.314 | 3.997 | <0.001* | 1.031 | 3.049 | 1.000 |
| Bleaching (37% CP×5) | −1.827 | 0.659 | −0.225 | −2.774 | 0.006* | −3.130 | −0.524 | 1.067 |
| Bleaching (35% HP×5) | −1.530 | 0.659 | −0.188 | −2.322 | 0.022* | −2.833 | −0.227 | 1.067 |
| F: 8.833 and *p*<0.001* | | | | R$^2$: 0.163 and Adjusted R$^2$: 0.145 | | | | |
| Excluded Variables | β | t | *p* | | | | | |
| Bleaching (37% CP×2) | −0.126 | −1.468 | 0.144 | | | | | |
| Bleaching (35% HP×2) | −0.057 | −0.664 | 0.508 | | | | | |

*$p$<0.05; S.E.: Standard error; St.: Standard; C.I.: Confidence interval
CP: Carbamide peroxide; HP: Hydrogen peroxide

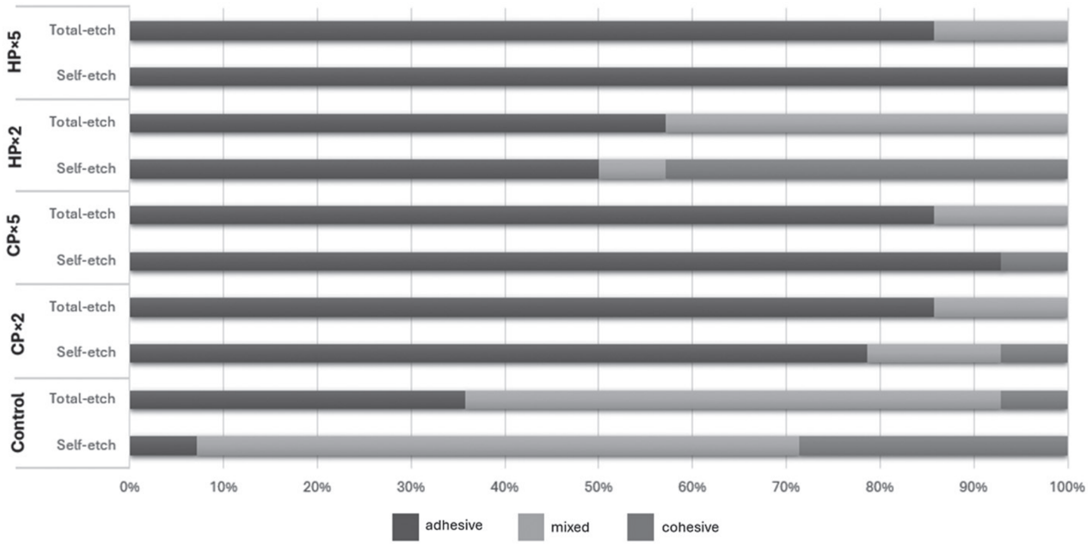


Fig. 2 Distribution of failure modes across groups in self-etch and total-etch protocols.

the self-etch protocol ($p$<0.001). Five applications of 37% carbamide peroxide showed a regression coefficient indicating a 1.827-unit reduction in μTBS compared to the control (no bleaching treatmeny) ($p$=0.006), while five applications of 35% hydrogen peroxide led to a 1.530-unit decrease ($p$=0.022).

Figure 2 shows the distribution of failure modes for each group in both the self-etch and total-etch protocols. Adhesive failure was the most common type observed across all groups. The Fisher's exact test results demonstrated a statistically significant relationship between failure modes and bleaching methods within

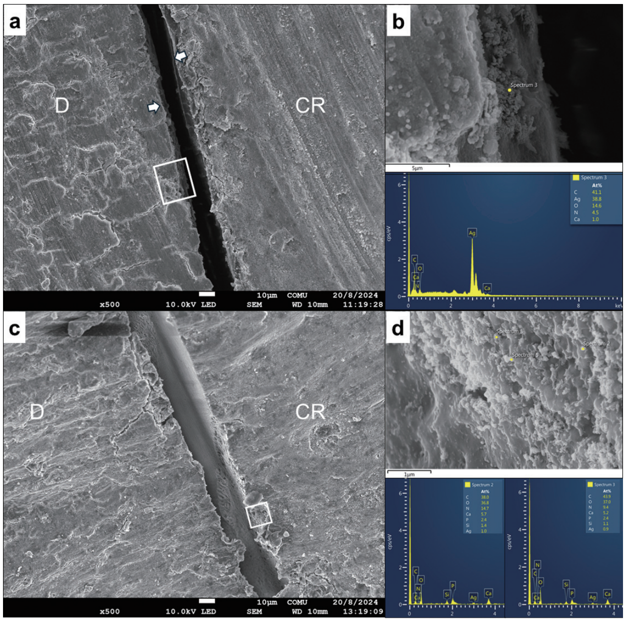


Fig. 3 Representative SEM images and EDX spectra of the dentin-restoration interface. (a, b) Total-etch control group and (c, d) self-etch control group, with no bleaching procedures. The left column show representative SEM images, while the right column present the EDX spectra obtained from the marked points on the corresponding SEM images. CR: resin composite; D: dentin.
The gap formation between the adhesive layer and the dentin at the cavity floor were observed (white arrows), which may be due to high vacuum for SEM observation (a).

each adhesive protocol (total-etch and self-etch) ($p$=0.019 and $p$<0.001, respectively). In both adhesive protocols, the control group showed a higher prevalence of mixed-type failures, while in the bleaching groups, adhesive-type failures were observed at higher rates. On the other hand, within each bleaching method, a statistically significant relationship between adhesive protocols and failure mode was detected only in the hydrogen peroxide×2 group ($p$=0.01). The cohesive-type failure was also observed at a high rate of 42.9% in the hydrogen peroxide×2 bleaching method.

Figures 3–5 represent SEM micrographs showing the accumulation of silver particles at the dentin-restoration interface, along with EDX spectra indicating the Ag peak at these points.

According to Fig. 3, the accumulation of silver particles in the total-etch control group was observed to be dispersed, while in the self-etch control group, it was detected at considerably lower levels.

For Figs. 4a–b, no silver peaks were detected at the dentin-restoration interface; however, silver deposits were observed on the external surfaces, which are presumed to have adhered during sample preparation. For Fig. 4c, no areas suspected of nanoleakage were observed; however, silver deposits were detected, particularly in images Figs. 4f, g.

The silver peaks obtained from the marked point in Fig. 5f are significantly high, while the values in images Figs. 5d, h were found to be negligible.

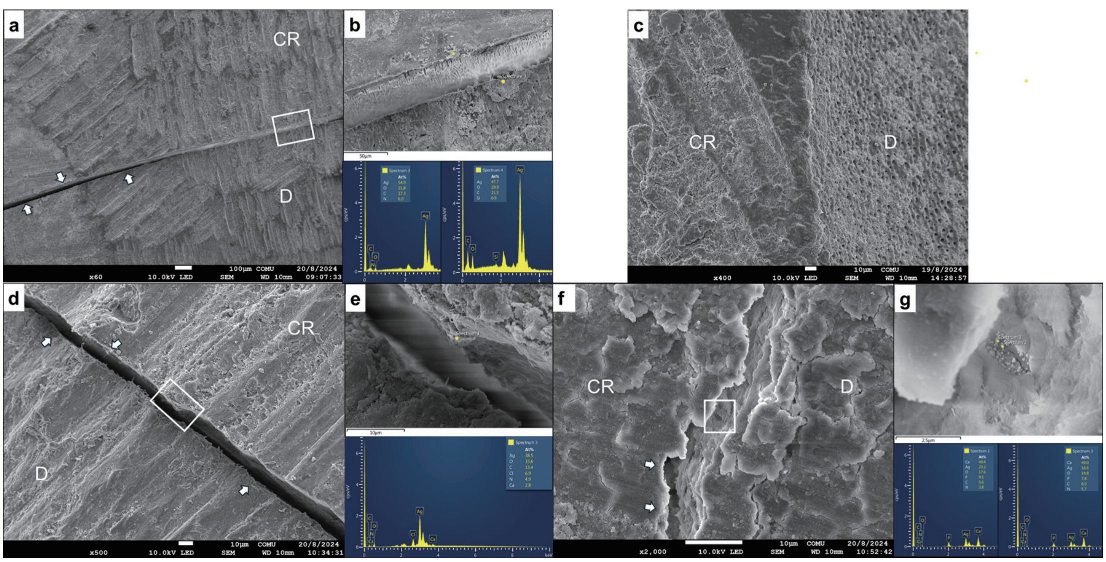


Fig. 4 Representative SEM images and EDX spectrum of the dentin-restoration interface in the total-etch group using different bleaching methods. The left column show representative SEM images, while the right column present the EDX spectra obtained from the marked points on the corresponding SEM images. CP×2 (a, b), CP×5 (c), HP×2 (d, e), HP×5 (f, g). CR: resin composite; D: dentin.
The gap formation between the adhesive layer and the dentin at the cavity floor were observed (white arrows), which may be due to high vacuum for SEM observation (a, d, f).

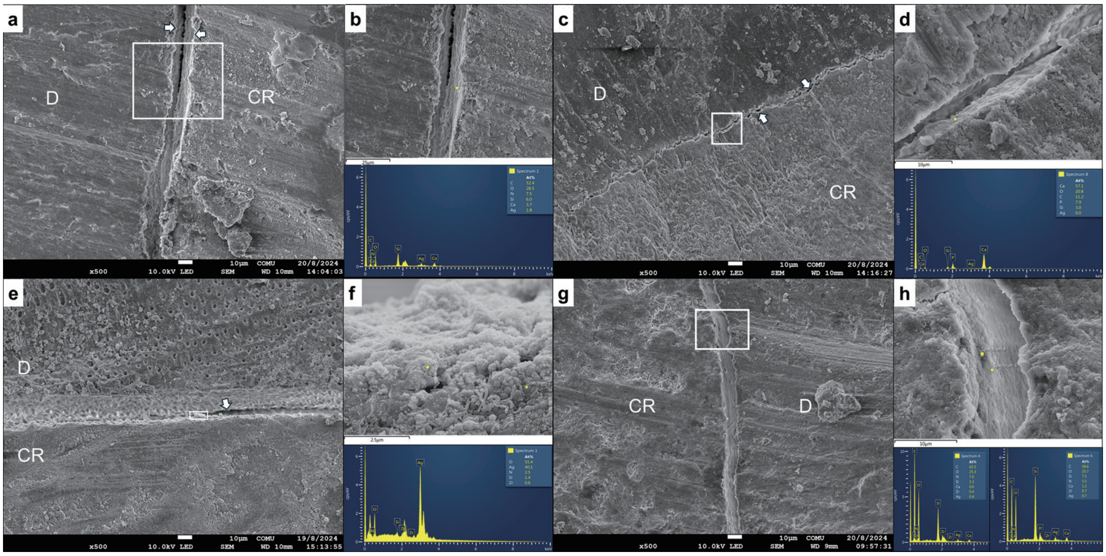


Fig. 5 Representative SEM images and EDX spectrum of the dentin-restoration interface in the self-etch group using different bleaching methods. The left column show representative SEM images, while the right column present the EDX spectra obtained from the marked points on the corresponding SEM images. CP×2 (a, b), CP×5 (c, d), HP×2 (e, f), HP×5 (g, h). CR: resin composite; D: dentin.
The gap formation between the adhesive layer and the dentin at the cavity floor were observed (white arrows), which may be due to high vacuum for SEM observation (a, c, e).

## DISCUSSION

The first null hypothesis of the study, which stated that different adhesive protocols would have no effect on the dentin bond strength in composite restorations following bleaching treatment, was rejected. This was due to the higher bond strength observed in the total-etch protocol compared to the self-etch, regardless of the bleaching method used. The second null hypothesis, which proposed that different bleaching procedures would not affect dentin bond strength, was also rejected. This is because, regardless of the adhesive protocol, lower bond strength was observed in the groups subjected to five repetitions of bleaching with both carbamide peroxide and hydrogen peroxide agents compared to the non-bleached control group.

Today, restorative treatments are based on the principle of adhesive bonding of resin-based materials to dental tissues. Oxygen radicals released from peroxide-based bleaching agents, due to their high reactivity and nonspecific structures, can lead to adverse effects on dental tissues and restorative materials. It has been shown that these radicals cause ultrastructural changes in dental tissues, such as a decrease in the Ca/P ratio, microhardness of enamel, fracture toughness, and elasticity modulus, as well as a reduction in dentin wear resistance, ultimate tensile strength, and loss of inorganic components[34-37]. Additionally, while the surface microhardness, surface properties, and marginal integrity of restorative materials can be compromised in a similar manner, the bonding interface between the dental tissue and restorative material stands out as the area most affected by these impacts[38]. Some studies have shown that postoperative bleaching can lead to a reduction in adhesive bond strength of restorations[20] and increased susceptibility to microleakage at the gingival dentin–adhesive interface of Class V restorations, thereby negatively impacting marginal seal integrity[24,39].

When the few other studies in the literature addressing the effects of postoperative bleaching on adhesion are also taken into account, it is noteworthy that Barcellos *et al.*[21] reported a reduction in μTBS with the use of carbamide peroxide, and that bond strength was more negatively affected as the concentration of carbamide peroxide increased. In contrast, in this study, bleaching procedures (for both carbamide peroxide and hydrogen peroxide), regardless of the self-etch or total-etch adhesive protocol, led to a statistically significant decrease compared to the control group when the bleaching process was repeated five times. Moreover, the μTBS values obtained in this study were considerably lower than those reported by Barcellos *et al.*[21], which were also used as a reference in the sample size calculations. A possible explanation for this difference is the variation in bleaching agent concentrations. While Barcellos *et al.*[21] used bleaching gels containing 10%–20% carbamide peroxide, the present study employed higher concentrations—37% carbamide peroxide and 35% hydrogen peroxide. It is believed that such high concentrations may have caused more pronounced structural alterations in dentin, thereby further compromising bond strength. On the other hand, consistent with the adverse effects of repeated bleaching procedures, Didier *et al.*[40] reported that postoperative hydrogen peroxide applications at different concentrations reduced the shear bond strength of existing composite–dentin interfaces depending on the clinical duration of gel application, irrespective of the concentration. Similarly, Far and Ruse[23] indicated that the fracture toughness values were negatively affected by prolonged exposure to carbamide peroxide, independent of its concentration. Supported by the findings of the present study, this suggests that cumulative exposure to bleaching agents may trigger oxidative stress–related structural and chemical changes on the dentin surface, thereby adversely affecting the bond strength of adhesive restorations.

Since the adhesive protocol is an important factor in bond strength and susceptibility to degradation, a universal adhesive system capable of adapting to different working protocols was preferred in this study. This adhesive system was applied in both the self-etch mode and, as recommended for endodontically treated teeth, in the total-etch mode[41]. The statistical analysis showed that the total-etch procedure revealed higher bond strength values, regardless of the bleaching method. Especially, the acid etching procedure showed a numerically greater difference in bond strength in the control group (without bleaching) and the 37% carbamide peroxide×2 group. At this point, the findings were consistent with those of a previous study, which reported a significant reduction in both enamel and dentin shear bond strength when composite restorations were postoperatively bleached with carbamide peroxide using single-step self-etch adhesives[22]. On the other hand, the results of another study also showed a parallel in that bleaching significantly affected the tensile bond strength of self-etching primer to enamel, while no difference was observed in dentin[20].

Preoperative bleaching procedures performed prior to composite restorations have also been investigated in the literature. In this context, Karadaş and Demirbuğa[42] reported that intracoronal bleaching with 35% hydrogen peroxide significantly decreased bond strength compared to the control group. However, unlike the present study, no significant difference was found between the 45-min and 12-day application durations. Additionally, higher bond strength values were observed in the etch-and-rinse groups compared to the self-etch groups. This finding, which aligns with the results of the present study, may have suggested that the higher bond strength values were primarily due to the initially obtained pre-bleaching values, rather than the varying sensitivity of adhesive strategies to the bleaching procedure.

SEM-EDX images were used to identify the nanoleakage areas. Accordingly, nanoleakage was either absent or minimal in most cases in the carbamide peroxide groups, while high silver peaks were observed in several areas in the hydrogen peroxide bleaching groups. This difference was considered to be potentially caused by local variations or artifacts generated during sample preparation. No significant difference was detected between the bleaching methods and adhesive protocols. Similarly, in a study examining the effect of postoperative bleaching on microleakage levels in composite restorations using two different adhesive systems, it was observed that total-etch and self-etch adhesive systems did not cause a significant difference between groups with the same bleaching system applied[39]. Another study reported that postoperative bleaching increased the microleakage scores at dentinal margins of composite restorations treated with a self-etch adhesive, while the total-etch adhesive provided superior marginal integrity at both enamel and dentin margins in bleached groups[43].

In studies evaluating bond strength, failure type analyses provide significant contributions. It has been proposed that peroxides trigger oxidative degradation of polymer chains, with unreacted double bonds representing the most vulnerable sites within the polymer structure. Furthermore, free radicals generated by peroxides are thought to impact the resin–filler interface, potentially leading to filler–matrix separation[44]. In the present study, the observation of adhesive failure as the most common type of fracture across all groups supports this assumption. For each bleaching method, a significant difference between total-etch and self-etch approaches was found only in the hydrogen peroxide×2 group, along with an increase in the frequency of cohesive failures in the self-etch protocol. Although higher values in bond strength were expected with increased cohesive failure[45], the similar frequency of adhesive failures in both types of adhesion did not reveal this difference. On the other hand, the differences in fracture types of various bleaching techniques for each adhesive system suggest that the failure patterns, especially in the control groups, may stem from a shift from adhesive to mixed-type failures. Didier *et al.*[40] reported in their study that, unlike the present findings, similar failure modes were observed in both bleached and unbleached specimens. Mixed-type failures involving the agent and the enamel/dentin interface were predominant, while cohesive fractures within enamel or dentin and adhesive failures were only rarely observed.

In current literature, most of the existing studies examine the effects of bleaching procedures on enamel or dentin prior to adhesive restorations. However, especially new-generation universal-shade composites, such as Omnichroma used in this study, have been reported to have a high compatibility with brighter tooth shades after bleaching[29]. Such developments enable whitening procedures to be performed while preserving existing leak-proof restorations, thus reducing potential negative outcomes such as tooth fractures or aesthetic dissatisfaction that may arise from temporary restorations. The limited number of studies on this topic in the literature increases the originality of this research; however, it also restricts the direct comparison of the findings with the existing literature.

This study has some limitations. Firstly, the use of teeth processed under conditions different from a clinical setting and stored in a laboratory environment may lead to an inability to fully reflect intraoral conditions. Although a universal adhesive was used in both total-etch and self-etch modes, the study involved only a single universal adhesive system. Therefore, the findings may not be generalizable to all universal adhesives, which may differ in chemical composition, pH, and interaction with dentin. Additionally, due to natural anatomical variations, it was technically not possible to achieve identical standardization of the pulp chamber during intracoronal bleaching cavity preparation. Future studies should continue to explore strategies to improve clinical relevance and methodological consistency in adhesive and bleaching research.

Considering the limitations of this study, it could be concluded that bleaching methods affected the bond strength of composite restorations; however, this effect might have varied depending on the adhesive protocol used and the number of applications. In this case, a decrease in bond strength was observed after five applications, regardless of the agent used, while an increase in bond strength was noted in groups where dentin was etched.

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## CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

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