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Therapeutic and protective effects of light-cured varnishes on erosive lesions: an *in vitro* study

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Abstract

Background This study aimed to investigate the efficacy of light-cured fluoride varnishes on artificial erosive lesions.

Methods Thirty extracted third molars were subjected to a 5-day erosive cycle, involving exposure to citric acid (pH 3.6, 4 × 1 min) and artificial saliva (pH 7, 4 × 2 h). The samples were then divided into five groups: light-cured glass ionomer varnish (CXT; Clinpro XT, 3 M™ ESPE, USA), light-cured giomer varnish (PRG; PRG Barrier Coat, SHOFU™, USA), casein phosphopeptide-amorphous calcium fluoride phosphate (MIV; MI Varnish, GC Corp., Tokyo, Japan), 5% sodium fluoride (VPF; Voco Profluorid Varnish, VOCO GmbH, Germany), and distilled water (DW, negative control) groups. After initial erosion, the samples were treated with varnishes and subjected to a second 7-day erosive cycle. The Vickers microhardness and surface roughness were measured at each stage. The therapeutic (rehardening) effects were expressed as the surface microhardness recovery percentage (SMHR%) and roughness progression (RP1%), whereas the protective effects were indicated by relative erosion resistance percentage (RER%) and roughness progression (RP2%).

Results The VPF group showed significantly higher SMHR% compared to the control group ($p < 0.05$). After the second demineralization, the CXT and PRG groups demonstrated significantly higher RER% than the negative control group ($p < 0.05$). Surface roughness measurements revealed no significant differences among the groups ($p > 0.05$). Qualitative analysis of profilometric images showed that surface irregularities present after the initial demineralization (t1) were reduced following varnish application at t2. However, after the second erosive cycle at t3, new irregularities were observed, particularly in the DW and VPF groups.

Conclusion This study revealed that conventional fluoride varnish exhibited greater therapeutic effects, as evidenced by improved surface microhardness recovery, whereas light-cured varnishes were more effective at providing protection against erosion. These findings highlight the potential of light-cured fluoride varnishes in providing extended surface protection.

Keywords Dental erosion, Light-cured varnish, Giomer, Fluoride varnish

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Introduction

Dental erosion is the loss of tooth hard tissues caused by acid dissolution from nonbacterial sources, including intrinsic factors (e.g., gastric acids) and extrinsic factors (e.g., dietary or environmental acids) [1]. The term "dental erosion" has been widely used to describe the process of tooth wear, which includes surface softening and mechanical wear. However, it specifically refers to the demineralization and surface loss that occur due to prolonged acid exposure. In contrast, "erosive tooth wear" (ETW) describes a process that begins with the chemical softening of enamel due to acid exposure, followed by the removal of this softened layer through mechanical forces [2].

The frequent consumption of acidic beverages and foods is a significant etiological factor in the development of dental erosion. The extent of the erosive effect has been determined by various factors, including the frequency of acid intake, the duration of acid exposure to the tooth surfaces, and atypical consumption patterns [3]. Early diagnosis of erosive tooth lesions and the implementation of appropriate preventive and therapeutic measures are crucial for promoting and sustaining oral health. The primary strategy should focus on addressing patient-specific etiological factors, particularly dietary habits. In addition to eliminating the underlying cause, the application of specific products to lesions can further aid in both prevention and treatment [4].

A recent study on erosive tooth wear demonstrated that enamel softening can occur within a short period of acid exposure (less than 5 min), with the softened layer extending to a depth of approximately 0.2 µm to 2 µm. This softening is attributed to the partial demineralization of the enamel surface, leading to increased surface roughness and reduced microhardness [5]. Clinically, the introduction of attritive or abrasive forces can significantly exacerbate the irreversible loss of tooth structure, particularly when combined with prolonged acid exposure [6].

A recent meta-analysis by Zanatta et al., which included 32 studies, concluded that fluoride agents are effective in controlling enamel erosive wear [7]. Conventional fluorides, such as sodium fluoride (NaF) and amine fluoride (AmF), help prevent erosive demineralization primarily by forming a calcium fluoride (CaF_2) layer that reduces or delays acid contact with the underlying enamel [8]. Professionally applied fluoride gels and varnishes offer higher fluoride concentrations and longer adherence, resulting in more substantial CaF_2 deposition compared to at-home products such as toothpastes and rinses [9]. However, some studies suggest that while CaF_2 deposits increase with higher fluoride concentrations, the primary protective effect against erosive wear is due to the temporary mechanical barrier formed by residual varnish, rather than the CaF_2 itself, which may only last a few hours [10, 11]. However, light-cured fluoride varnishes may serve as a more long-lasting protective effect for ETW. These varnishes chemically bond to the tooth surface, thereby extending the duration of the varnish layer and prolonging fluoride activity, which may help prevent detachment during abrasive processes [12].

Clinpro™ XT varnish (3 M ESPE, St Paul, MN, USA) is a light-cured resin-modified glass ionomer that releases fluoride, calcium, and phosphates. A previous study demonstrated that Clinpro XT Varnish released more fluoride than other traditional fluoride varnishes over a period of 6 months [13]. Clinpro XT varnish was primarily developed for the treatment of dentin hypersensitivity but can also serve as a surface-protective and remineralizing/rehardening agent against dental caries and erosion. The glass ionomer composition of Clinpro XT varnish enhances its adhesion to the tooth surface, while the silanized fluoroaluminosilicate glass particles facilitate the release of calcium, phosphate, and fluoride [14].

Another light-cured fluoride varnish is the Giomer-based PRG Barrier Coat (Shofu, Kyoto, Japan), which contains surface pre-reacted glass ionomer (S-PRG) fillers, synthesized through the reaction of fluoro-boro-aluminosilicate glass with a polyacrylic acid solution [15]. The S-PRG filler has bioactive properties and releases fluoride, aluminum, borate, strontium, sodium, and silicate ions, which act both individually and synergistically [16]. These ions have been shown to buffer lactic acid, thereby protecting against enamel demineralization and promoting enamel remineralization in carious lesions [17–19]. However, no studies have yet evaluated the protective or therapeutic effects of S-PRG varnishes on enamel erosive lesions.

Light-curing varnishes, primarily used for treating dentin hypersensitivity, have been proposed as suitable for managing enamel erosive lesions [12]. While previous studies have investigated the effects of light-curing varnishes on carious demineralization [19–22], there is a lack of studies assessing the efficacy of light-curing varnishes on enamel erosive lesions. Therefore, the present study aimed to assess both the therapeutic and protective effects of two light-curing varnishes on enamel erosion via microhardness and surface roughness analysis. Specifically, the study aimed to:

1. Compare the therapeutic effect of light-cured fluoride varnishes to that of sodium fluoride (NaF) and casein phosphopeptide-amorphous calcium fluoride phosphate (CPP-ACFP) varnishes using surface microhardness recovery percentage (SMHR%) and roughness progression 1 (RP1) measurements.

2. Assess the ability of these varnishes to protect enamel against further erosion (protective effect) through relative erosion resistance percentage (RER%) and roughness progression 2 (RP2) measurements.

In this study, the 'therapeutic effect' refers to enamel rehardening achieved through the deposition of minerals on partially demineralized eroded enamel following varnish application. The 'protective effect' relates to erosion resistance, defined as the ability of varnish-treated enamel surfaces to resist subsequent demineralization. The two null hypotheses tested were: (I) light-curing fluoride varnishes would show no significant difference in therapeutic effect (rehardening potential), and (II) no significant difference in protective effect (erosion resistance), when compared to NaF CPP-ACFP varnishes.

Materials and methods

This in vitro investigation received approval from the Ethics Committee of Istanbul University Faculty of Dentistry (Reference No: 2022/35-REV/1). Thirty human third molars, extracted from individuals aged 18–40 years and free of caries, restorations, or enamel defects, were collected and stored in 0.1% thymol solution at 4 °C for a maximum duration of one month. All patients gave written informed consent for the utilization of their extracted teeth for research purposes.

Sample size estimation was performed using G*Power version 3.1.9.6. For the SMH analysis, the sample size was calculated as five specimens per group (effect size: 1.1135) based on parameters reported by Ustun and Guven [23]. For the roughness analysis, it was determined as six specimens per group (effect size: 0.9615) using parameters from Alexandria et al. [24]. Both analyses used an alpha level (α) of 0.05, a beta level (β) of 0.05, and a statistical power of 95%. To ensure consistency, the final sample size was set at six specimens per group for both analyses.

Specimen preparation

The teeth were sectioned 2 mm below the cementoenamel junction using a diamond bur under water cooling, and the root segments were discarded. The coronal segments were then sectioned mesiodistally, from occlusal to cervical, via a precision cutter (IsoMet 1000 Precision Cutter, Buehler Ltd., Illinois, USA), resulting in two halves. From each coronal segment, two enamel specimens ($3 \times 3 \times 3$ mm) were obtained. The specimens were subsequently polished with 600, 800, and 1200 grit paper discs attached to a sanding and polishing machine (Buehler Metaserv 250 Single Grinder Polisher, Buehler Ltd., Illinois, USA) under water cooling until a flat, smooth surface was achieved. Finally, a diamond particle paste (Pasta de Polimento Diamantada, Vigodent, Rio de Janeiro, Brazil) and a felt brush (Frank Dental, Germany) were used to polish the specimens to achieve an ideal gloss. All surfaces of each specimen, except for the flattened enamel surface, were coated with nail varnish.

Erosive challenge and treatment protocols

Each enamel specimen was subjected to four consecutive erosive cycles at 2-hour intervals. Each cycle involved immersing the enamel specimens in 10 ml of a 1% citric acid solution (pH 3.6) for 1 min, followed by a 2-hour immersion in artificial saliva. The artificial saliva solution, prepared according to the protocol by Almqvist and Lagerlof [25], consisted of 1 mM $CaCl_2$, 50 mM KCl, 2 mM KH_2PO_4, and 0.01% NaN_3 in 40 ml of distilled water, with the pH adjusted to 7 using 1 M KOH. The specimens were subsequently immersed in artificial saliva at 37 °C to reach a total immersion time of 24 h. After completing the initial erosive challenge (t1), microhardness and surface roughness measurements were conducted.

The specimens were then randomly assigned to five groups ($n = 6$) using the random number method, based on the varnish applied, as follows: CXT (Clinpro™ XT Varnish; 3 M™, USA), PRG (PRG Barrier Coat; SHOFU™ Dental Corporation, California, USA), MIV (MI Varnish™; GC Corporation, Tokyo, Japan), VPF (VOCO Profluorid Varnish-VOCO GmbH, Cuxhaven, Germany) and DW (Distilled water; negative control). The composition of the varnishes and their manufacturers are provided in Table 1. All varnishes were applied to the eroded surfaces in a single application, following the manufacturer's instructions. The samples were then stored in artificial saliva for 5 days at 37 °C. The varnishes were then removed using a scalpel blade for the light-cured varnish groups or acetone for the other groups, taking care to avoid scratching the surface. To ensure complete removal of varnish residues, the surfaces were examined under 5x magnification using a stereomicroscope. Microhardness and surface roughness measurements were conducted at t2 (post-treatment) time point.

Following the post-treatment measurements, the varnishes were reapplied to the enamel surfaces, and a second erosive challenge was initiated. To evaluate the effects of repeated acid exposure, a 7-day erosive cycle was implemented on the varnish-coated surfaces. During each cycle, the teeth were immersed in a demineralization solution containing 1% citric acid for 6 s, followed by immersion in artificial saliva for 6 s, completing 15 cycles per session [23, 26]. This process was repeated twice daily for 7 days. The citric acid solution was renewed after each exposure, and the artificial saliva was replaced daily. Throughout this period, no additional treatments were applied to the tooth surfaces, and the specimens were stored in artificial saliva except during the erosive

Table 1 Compositions and manufacturers of the varnishes used in the study

Group	Code	Composition	Manufacturer	Lot Number	Application
Clinpro™ XT Varnish	CXT	**Paste**: glass particles of silanized fluoro-alumino-silicate, HEMA, water, BIS-GMA, and silanized silica. **Liquid**: copolymer of polyalkenoic acid, water, HEMA and calcium glycerophosphate.	3 M ESPE, St Paul, MN, USA.	NF42150	Tooth surfaces were preconditioned with 35% phosphoric acid for 15 s, rinsed and air-dried. The material components were mixed for 15 s, applied as a thin layer, and light-cured for 20 s.
PRG Barrier Coat	PRG	**Base**: S-PRG filler, polymeric monomer, water, others **Activator**: carboxylic acid monomer, phosphonic acid monomer, Bis-MPEPP, TEG-DMA, polymeric monomer, photo initiator, others	Shofu, Kyoto, Japan	012201	One drop of activator was added to the base, mixed with a brush applicator, applied to the dried tooth surface, left undisturbed for 3 s, and then light-cured for 10 s.
MI Varnish®	MIV	5% NaF, CPP-ACP	GC Corp., Tokyo, Japan	220,606 A	Applied as a thin, uniform layer to the dried tooth surface and then wetted with artificial saliva.
VOCO Profluoride® Varnish	VPF	5% NaF, ethanol, artificial sweeteners, xylitol	VOCO GmbH, Cuxhaven, Germany	2,244,548	Applied as a thin, uniform layer to the dried tooth surface and then wetted with artificial saliva.

cycles. After 24 h in the incubator, any residual varnish was removed as in the t2 phase, and microhardness and surface roughness measurements were performed on the enamel surfaces.

Surface microhardness (SMH) analysis

The SMH of the samples was assessed using a Vickers microhardness tester (412 A Vickers Hardness Tester, Innovatest, Maastricht, The Netherlands) with a square−pyramid diamond indenter, applying a load of 500 g for 15 s. Three indentations, each separated by approximately 100 µm, were made at the center of the enamel samples to serve as reference points. SMH measurements were taken at three points positioned 400 µm above or below these reference points along the same vertical axis, and the average values were calculated. SMH assessments were conducted at four stages: on sound enamel surfaces (baseline) (t0), following the initial erosive challenge (pre-treatment) (t1), after the application of the agents (post-treatment) (t2), and after the second erosive challenge (t3).

The therapeutic effect of the applied varnishes on eroded enamel surfaces, expressed as the *surface microhardness recovery* percentage (SMHR%), was calculated via the following formula previously employed by Creeth et al. [27] SMHR% = [(t1 - t2)/(t1 - t0)] × 100]. The resistance of varnish-treated enamel to a second erosive challenge was defined as the *relative erosion resistance* (RER) and was calculated via the following formula: RER% = [(t1 - t3)/(t1 - t0)] × 100 [27].

Surface roughness analysis

The surface roughness of each sample was analyzed using a 3D noncontact optical profilometer (Sensofar S Lynx noncontact 3D surface profiler, Sensofar Metrology, Barcelona, Spain) in 'Confocal Microscopy' mode with a Nikon EPI 20x objective. A long-wave Gaussian filter with a cut-off value of Lc = 0.8 mm was applied to separate surface roughness from waviness. The indentations created during the microhardness test were used as reference points to define the scanning area and ensure consistency across all time points. Measurements were taken 400 microns to the right or left of these reference points, and each position was recorded accordingly. The scanned images were processed into three-dimensional models, and surface roughness parameters (Sa values) were calculated. Sa values (average roughness of a surface area) were measured at time points t1, t2 and t3. The therapeutic and anti-erosive effects of applied varnishes on Sa values, expressed as roughness progression (RP1% and RP2%, respectively), were calculated as follows [23]: RP1% = [(t2 - t1)/(t1)] × 100, RP2% = [(t3 - t2)/(t2)] × 100. All SMH and surface roughness measurements were performed by the same operator in a blinded manner.

Statistical analysis

The data were analyzed using IBM SPSS V23. Normality was assessed with the Shapiro−Wilk test. For normally distributed data, one-way analysis of variance (ANOVA) was performed, with post hoc comparisons analyzed using Tamhane's T2 test. For non-normally distributed data, the Kruskal−Wallis test was used to compare groups of three or more, followed by Dunn's test for multiple comparisons. Within-group comparisons over time were performed using the Friedman test, with results summarized using median values. Dunn's test was applied for post hoc multiple comparisons. A significance level of $p < 0.05$ was set for all tests.

Results

SMH analysis

The median (min−max) SMH values for each group at different time points are presented in Table 2. The initial erosive challenge at t1 caused a significant decrease in

Table 2 The median (min–max) SMH values (kgf/mm²: HV0.5) of each group at the t0, t1, t2, and t3 time points

	t0 Median (min–max)	t1 Median (min–max)	t2 Median (min–max)	t3 Median (min–max)	F	p*
CXT	310.2 (292.4–328.1)[B]	272.6 (264.8–278.5)[A]	294.2 (273.7–317.8)[AB]	303.1 (292.2–335.1)[B]	16.4	0.001
PRG	301.8 (286.4–332.5)[B]	261.2 (199.7–309.3)[A]	296.0 (282.3–310.0)[AB]	313.3 (275.9–343.6)[B]	14.6	0.002
MIV	322.5 (288.2–330.4)[B]	273.2 (260.3–279.3)[A]	295.1 (276.1–314.4)[AB]	294.2 (283.3–319.3)[AB]	13.4	0.004
VPF	308.1 (279.3–332.2)[AB]	242.3 (225.4–273.5)[A]	308.9 (293.7–337.4)[B]	279.2 (245.1–318.7)[AB]	11	0.012
DW	299.9 (293.7–318.7)[A]	247.4 (235.3–288.0)[BC]	258.8 (253.9–291.0)[AC]	234.3 (226.6–256.8)[B]	18	< 0.001

*The Friedman test was used to analyze the data. No significant differences in SMH were observed between timepoints sharing the same capital superscript letters. F: test statistics, CXT: Clinpro XT, PRG: PRG Barrier Coat, MIV: MI Varnish, VPF: Voco Profluoride Varnish, DW: Distilled water; t0: Initial t1: Initial erosive attack t2: Post-treatment t3: Second erosive attack

Table 3 Comparison of SMHR% and RER% values according to groups

Groups	SMHR% (Therapeutic effect)	RER% (Protective effect)
	Mean ± SD	**Median (min–max)**
CXT	57.3 ± 22.4[b]	104.5 (70.7–119.0)[B]
PRG	64.0 ± 32.4[ab]	112.9 (87.9–156.5)[B]
MIV	69.6 ± 51.6[ab]	51.7 (24.9–166.4)[AB]
VPF	110.8 ± 22.4[a]	60.0 (-66.0–122.5)[AB]
DW	24.5 ± 12.0[b]	-26.8 (−122.6 – −14.8)[A]
Test statistic	15.791	16.249
p	**< 0.001***	**0.003****

*One-way ANOVA test **Kruskal–Wallis test. Lowercase superscript letters denote significant differences in SMHR% between groups, whereas uppercase superscripts denote significant differences in RER%

SMHR%. Surface Microhardness Recovery; RER%: Relative Erosion Resistance; CXT: Clinpro XT, PRG: PRG Barrier Coat, MIV: MI Varnish; VPF: Voco Profluoride Varnish; DW: Distilled water

the SMH across all groups ($p < 0.05$), except for the VPF group ($p = 0.083$). At the t2 time point, following varnish application, a statistically significant increase in SMH values was observed only in the VPF group compared with the eroded enamel surface at t1 ($p = 0.01$). The SMH values in the other groups remained statistically similar at t2 ($p > 0.05$). After the second erosive challenge at t3, a statistically significant decrease in SMH values was observed only in the negative control group ($p = 0.44$), whereas the treatment groups showed no significant change ($p > 0.05$).

The median (min–max) values for SMHR% and RER% are presented in Table 3. The highest SMHR% was recorded in the VPF group, whereas the negative control group exhibited the lowest value. Although all the experimental groups showed an increase in the SMHR% compared with that of the negative control, only the VPF group demonstrated a statistically significant difference ($p < 0.001$). Additionally, the SMHR% in the VPF group was significantly higher than that in the CXT group ($p = 0.02$). No statistically significant differences were observed in the SMHR% among the PRG, MIV, and VPF groups ($p > 0.05$).

A statistically significant difference was found between the RER% medians across the groups ($p = 0.003$). Although all the experimental groups exhibited higher erosion resistance compared to the negative control, this increase was statistically significant only in the CXT and PRG groups ($p = 0.021$ and $p = 0.002$, respectively). No significant differences in erosion resistance were observed among the experimental groups CXT, PRG, MIV, and VPF ($p > 0.05$).

Surface roughness analysis

Table 4 presents the median (min–max) Sa values, reflecting the average surface roughness for each group at different time points. The MIV group showed a significant change in roughness medians over time ($p = 0.009$), with a significant decrease in roughness at t3 compared to t1 ($p = 0.012$). In the DW group, a significant difference in roughness medians was also observed ($p = 0.011$), with roughness values decreasing significantly from t1 to t2 ($p = 0.028$), followed by an increase at t3 compared to t2 ($p = 0.028$). No significant changes in roughness were detected in the other groups over time ($p > 0.05$).

No statistically significant differences were found among the groups when the median roughness progression values, RP1% and RP2%, were compared ($p = 0.284$ and $p = 0.151$, respectively) (Table 5).

Qualitative evaluation of 3D profilometric images

Figure 1 displays the 3D and 2D images generated by profilometry analysis, illustrating the topographic characteristics of the enamel surface at each time point. The intensity of the blue color in the images indicates greater depth of tooth structure loss, whereas the red color represents areas with less tooth structure loss. At time point t1, the surface exhibited an irregular topography, with

Table 4 The median (min.–max.) Sa values (μm) of each group at the t1, t2, and t3 time points

	Sa-t1 (μm) Median (min–max)	Sa-t2 (μm) Median (min–max)	Sa-t3 (μm) Median (min–max)	Test statistic	*p**
CXT	1.2 (0.2–4.3)	1.3 (0.3–1.6)	1.0 (0.4–2.5)	0.333	0.846
PRG	2.6 (0.9–3.5)	1.8 (0.7–3.6)	1.5 (0.5–3.3)	2.333	0.311
MIV	2.6 (0.9–4.2)a	1.3 (0.9–2.5)ab	0.7 (0.4–2.1)b	9.333	**0.009**
VPF	1.9 (1.0–7.7)	2.0 (0.7–4.0)	1.8 (0.9–2.2)	1.333	0.513
DW	1.6 (0.7–5.1)b	1.4 (0.4–3.0)a	1.7 (0.8–3.6)b	9	**0.011**

*Friedman test, a-b: Different letters in the same row indicate statistically significant differences over time. Sa: average 3D surface roughness CXT: Clinpro XT, PRG: PRG Barrier Coat, MIV: MI Varnish, VPF: Voco Profluoride Varnish, DW: Distilled water; t1: Initial erosive attack t2: Post-treatment t3: Second erosive attack

Table 5 Comparison of the therapeutic effect (RP1%) and protective effect (RP2%) values according to groups in roughness measurements

Groups	RP1% (1 (Therapeutic effect))	RP2% (Protective effect)
	Mean ± SD	**Mean ± SD**
CXT	-4.0 ± 42.3	28.4 ± 72.2
PRG	-12.3 ± 40.3	-18.2 ± 16.8
MIV	-42.6 ± 22.6	-17.9 ± 44.2
VPF	-17.7 ± 28.7	-6.2 ± 46.7
DW	-29.6 ± 19.9	37.0 ± 39.7
Test statistics	1.337	1.849
p	0.284	0.151

An analysis of variance test statistic was used. RP1%: Roughness Progression, RP2%: Roughness Progression 2, CXT: Clinpro XT, PRG: PRG Barrier Coat, MIV: MI Varnish VPF: Voco Profluoride Varnish, DW: Distilled Water

pits, peaks, and a mix of colors corresponding to uneven, indented, and protruding areas for all groups. Following the application of remineralization agents at t2, these irregularities were reduced, resulting in flatter, more uniform regions as a result of mineral deposition. The previously indented and protruding structures became smoother, with peaks and grooves spreading more evenly across the surface. After the application of fluoride varnishes and a second demineralization cycle at t3, flat areas with a uniform color were still visible. However, new irregularities reappeared, particularly in the DW and VPF groups.

Discussion

The present study assessed both the therapeutic (rehardening) and protective (erosion resistance) effects of two light-curing varnishes on eroded enamel surfaces, using microhardness and surface roughness measurements. The first null hypothesis, concerning the therapeutic effect, was rejected, as the light-curing varnish CXT showed a lower SMHR% compared to the VPF group. However, when the therapeutic effect was evaluated in terms of surface roughness, all varnishes demonstrated similar RP1% values. The second null hypothesis, related to erosion protection, was also rejected, as the light-curing varnishes (CXT and PRG) exhibited significantly higher RER% values than the negative control, while the MIV and VPF groups showed values comparable to the control. Despite these differences, all varnishes displayed similar RP2% values when the therapeutic effect was assessed via surface roughness.

In this study, microhardness and surface roughness measurements were used to evaluate the therapeutic and protective effects of varnishes on erosive enamel surfaces. Microhardness testing offers several advantages, including its ability to indirectly detect mineral loss or gain in enamel, its simplicity, speed, and non-destructive nature. Furthermore, it allows for quantitative assessment of hardness changes through repeated measurements over time with high accuracy, making it a widely utilized method in numerous studies [28, 29]. The surface roughness test was conducted to evaluate changes in the surface texture of enamel following erosive cycles and treatments. Surface roughness is a key parameter in the context of erosive demineralization, as it reflects alterations in surface morphology resulting from partial mineral loss, as highlighted by Nekrashevych and Stösser [30]. Both quantitative and qualitative assessments of surface roughness were performed using 3D non-contact profilometry.

Previous studies comparing microhardness or surface roughness values between groups at specific time points may not provide accurate comparisons, as they do not account for structural differences in the teeth. Structural variations in tooth enamel, such as differences in mineral density, crystal orientation, and surface characteristics, can significantly influence the outcomes of microhardness and surface roughness measurements [31–33]. This was true even for the specimens in the present study, particularly in the VPF group. After the initial erosive challenge, all teeth were expected to show a consistent decrease in surface microhardness (SMH). However, variability in enamel structure may explain the differences observed, underscoring the need for caution when interpreting absolute values without considering structural heterogeneity. To address this limitation, the present study employed formulas that assess changes in microhardness and surface roughness over time, providing a more reliable evaluation of the effects of the

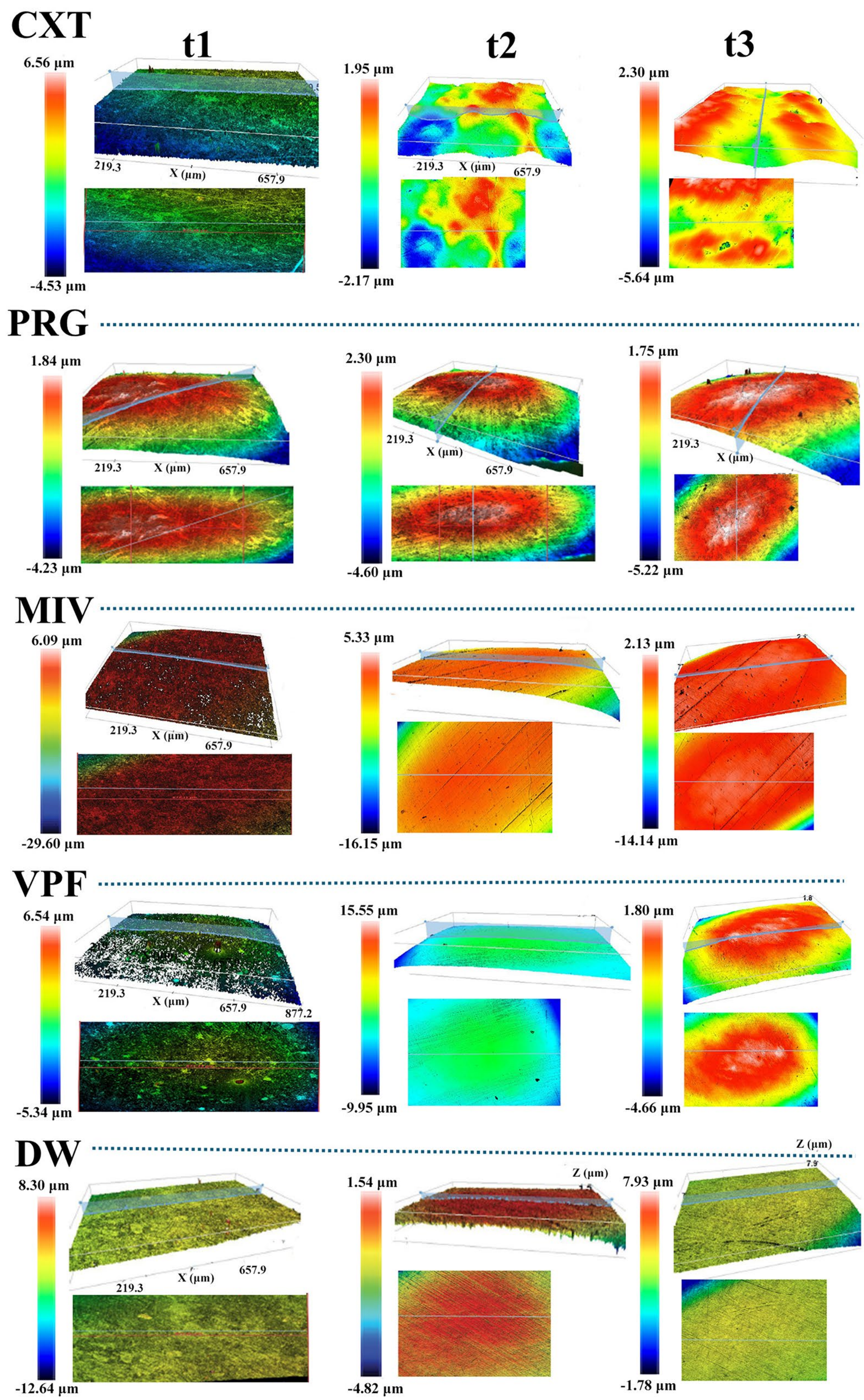

Fig. 1 2D and 3D profilometric images of representative surfaces from each group at the t1, t2, and t3 time points. The color scale represents different surface heights: red indicates the highest areas, with white dots marking the highest peaks, whereas blue represents the lowest areas, with black dots marking the deepest points in the pattern. CXT: Clinpro XT, PRG: PRG Barrier Coat, MIV: MI Varnish VPF: Voco Profluoride Varnish, DW: Distilled Water; t1: Initial erosive attack t2: Post-treatment t3: Second erosive attack

varnishes. These formulas were used to assess both the therapeutic and the anti-erosive effects of varnishes on eroded enamel surfaces [23, 27, 34]. The therapeutic effect, measured by the surface microhardness recovery percentage (SMHR%) and roughness progression (RP1%), reflects how effectively the compounds promote mineral deposition and rehardening of softened enamel. The protective effect, indicated by the relative erosion resistance percentage (RER%) and roughness progression (RP2%), evaluates the ability of materials to protect enamel from further erosive damage. The use of SMHR% and RER% formulas has been reported in previous studies [23, 27, 34], while RP1 and RP2 have been employed in a study by Creeth et al. [27]. While many previous studies have focused primarily on therapeutic effects, this study evaluated both therapeutic and protective properties. The overall success of varnishes depends not only on their ability to reharden enamel but also on their effectiveness in preventing future erosion, particularly in clinical conditions involving repeated erosive episodes.

There are few studies on light-curing varnishes, and most of them focus primarily on caries demineralization [19–22]. Zhou et al. [12] conducted a comparative analysis of the remineralization capacities of five dental materials, including a light-curing glass ionomer varnish (Clinpro™ XT) and a conventional sodium fluoride varnish (F varnish), for the treatment of enamel erosive lesions. They reported that the SMH values in the Clinpro XT group were significantly lower than those in the F varnish group after 2 weeks of remineralization. Similarly, the present study revealed that the SMHR% of the F varnish group was significantly greater than that of the Clinpro XT group. These findings suggest that light-cured varnishes may result in lower microhardness levels than fluoride varnishes during short-term contact with tooth surfaces. In Zhou et al.'s study, although Clinpro XT was the least effective material after 2 weeks of remineralization, its efficacy improved over time, eventually surpassing that of fluoride varnish by the sixth week, although this difference was not statistically significant [12]. This may be attributed to the rapid mineral deposition facilitated by conventional varnishes, with fluoride release peaking in the early stages. However, as the varnish contact time extended, the performance of both varnishes became comparable. This observation also supports the hypothesis that light-cured varnishes may require more time to achieve their full protective potential.

The SMH results of the present study, as well as those of Zhou et al. [12], differ from the findings of Elkassas and Arafa [14], who reported that while light-curing fluoride varnish (Clinpro XT) demonstrated remineralization levels similar to those of conventional varnishes (ACPF, and CPP-ACPF varnishes) after 2 weeks, it showed the lowest remineralizing potential compared with the other groups after 4 weeks. Elkassas and Arafa [14] also evaluated surface roughness (Ra) using 3D Non-Contact Optical Profilometry and found that the light-curing fluoride varnish group exhibited significantly lower Ra values after 2 weeks. In contrast, the present study found no significant differences in surface roughness between the groups. The discrepancies in both the SMH and surface roughness results may be attributed to the use of a caries demineralization model in Elkassas and Arafa's study, which likely led to different lesion depths.

Jain et al. [35] investigated changes in surface roughness in initial carious lesions following the application of different fluoride varnishes. After 2 weeks, no statistically significant difference in surface roughness was found between the Clinpro XT and conventional fluoride varnish groups, which is consistent with the findings of the present study, which assessed surface roughness after 5 days of remineralization. However, after 4 weeks of varnish application, Jain et al. [35] reported that the Clinpro XT group showed the lowest surface roughness values, along with a higher Ca/P ratio and fluoride content, indicating better remineralization. The deposition of minerals into porous zones contributed to the increased mineral content and decreased surface roughness. When examining the RER% values, which indicate the resistance of varnish applied surfaces to a second erosive challenge, both light-cured varnish groups demonstrated significantly higher resistance compared to the negative control group, whereas the conventional varnish groups showed similar values to the negative control group. This enhanced resistance in the light-cured groups is likely due to their ability to form a more durable mechanical barrier against acid attacks. During the 7-day second acid challenge, the conventional varnishes were almost entirely removed from the surface. Similarly, in a study by Canali et al. [36], dentin surfaces treated with Clinpro XT varnish and subjected to a 7-day erosive/abrasive cycle showed that while the resin matrix gradually degraded, and glass particles separated after 4 days, the majority of the varnish remained adhered to the tooth surface. In a study by Abufarwa et al. [37], Clinpro XT varnish was applied to enamel white spot lesions, and both microhardness changes and SEM images were analyzed after a 12-week period. The results showed that while the resin on the enamel surface had partially worn away, the microhardness values were still higher than those of the control group. The authors attributed this sustained higher microhardness to the protective effect of the remaining varnish on the enamel surface, even after partial wear [37]. In line with the findings of both Canali et al. [36] and Abufarwa et al. [37], the present study also showed that light-cured varnishes provided superior protection against acid attacks.

Despite PRG Barrier Coat forming a thinner film and being more easily removed from the surface compared to Clinpro XT, it demonstrated a similar RER% value. This suggests that its protective effect may not be solely due to the mechanical barrier created by the film, but rather the synergistic action of the multiple ions released from the S-PRG filler. The uptake of fluoride (F^-), aluminum (Al^{3+}), and strontium (Sr^{2+}) ions by the tooth substrate contributes significantly to enhancing remineralization [38]. In a study by Spinola et al. [19], different concentrations of S-PRG in varnishes were compared, with all other components kept constant. After varnish application, pH cycling was performed, and the microhardness of the enamel was evaluated. The study revealed significant differences between the various S-PRG concentrations and compared to sodium fluoride. This further supports the idea that if PRG Barrier Coat's protective effect were based solely on the mechanical barrier, such differences would not have been observed among the groups.

Although no significant differences in surface roughness were found between the light-cured and conventional varnish groups in terms of both therapeutic and protective effects, 3D optical profilometric images revealed that surface irregularities observed after the initial demineralization phase (t1) were reduced following varnish application (t2). The previously rough, uneven surfaces became smoother and were characterized by shallow peaks and grooves. However, after the second erosive cycle (t3), increased surface irregularities were noted only in the negative control and VPF groups. This may be due to prolonged acid exposure and the partial removal of conventional varnishes during the demineralization cycle, particularly in the VPF group.

Although three-dimensional imaging devices offer detailed surface data, the patterns generated by different devices can vary, complicating direct comparisons. In studies by Üstün and Güven [23] and Gökkaya et al. [39], surface changes were assessed via atomic force microscopy (AFM), which also produced three-dimensional images. It is hypothesized that the mineral deposits and globular formations observed in AFM correspond to the elevated regions represented by red (and white at the highest points) in the profilometric images. Similarly, pits and erosive areas likely correspond to depressions, depicted in blue (with black at the lowest points) in the profilometric images. In AFM studies, the application of remineralizing agents to erosive surfaces has been shown to transform these depressions into flat surfaces or globular deposits. Similarly, in the present study, the application of fluoride varnish smoothed the previously rough, multicolored areas, resulting in surfaces with more uniform coloration.

In a study conducted by Zhou et al. [12], surface roughness was analyzed using 3D surface profilometry, and similar to the present study, a mix of colors corresponding to irregular topography was observed on the eroded enamel surfaces. After 6 weeks of remineralization, their findings, consistent with those of the current study, showed a more uniform color distribution, indicating a reduction in surface roughness. However, when surface roughness was quantitatively assessed, no significant differences were observed among the groups in the present study. In contrast, Zhou et al. [12] reported that at 2 and 4 weeks, the fluoride varnish group exhibited lower surface roughness compared to the Clinpro XT and Tooth Mousse varnish groups. After 6 weeks of remineralization, Clinpro XT demonstrated the greatest reduction in surface roughness. This discrepancy may be attributed to the significantly shorter remineralization period of 5 days used in the current study compared to the 2–6 weeks evaluated in Zhou et al.'s study, which may have been insufficient for surface roughness changes to reach statistically significant levels.

This is the first study to evaluate the therapeutic and protective efficacy of giomer based varnish on enamel erosive lesions. However, the current study has several limitations. First, owing to the limited number of studies specifically investigating the effects of light-cured varnishes on erosive lesions, direct comparisons with similar research were not possible. Instead, the findings were compared with those of studies related to caries demineralization. Another limitation is the relatively small sample size, which may have contributed to the lack of significant differences in surface roughness between the groups. Future studies with larger sample sizes may reveal more pronounced treatment effects. Additionally, this study did not account for daily abrasive factors, such as tooth brushing, which could influence the treated surfaces. Furthermore, the mechanical removal of the strongly adhered light-cured varnishes may have introduced some degree of error in the surface measurements. Finally, only the short-term effects of the tested varnishes were evaluated in this study, limiting our understanding of their long-term efficacy. Future research should assess the therapeutic and protective capacity of these agents over longer periods.

Conclusion

This study demonstrated that the greatest recovery in surface microhardness (therapeutic effect) on eroded enamel was achieved with conventional NaF varnish. However, resistance to further acid attacks (protective effect) was observed exclusively with light-cured varnishes. These findings suggest that light-cured fluoride varnishes may offer particular advantages over conventional NaF varnishes due to their extended surface protection and potentially prolonged fluoride release over time. This could be particularly beneficial in patients at high risk for erosive tooth wear, offering a longer-lasting protective effect in managing early-stage erosion.

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Author contributions
EI was involved in all aspects of the laboratory work, contributed to data collection and interpretation, and drafted the manuscript. YG conceptualized the study, contributed to the experimental design, assisted in data interpretation, and coauthored the manuscript. Both authors reviewed and approved the final version of the manuscript.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
This in vitro investigation received approval from the Ethics Committee of Istanbul University Faculty of Dentistry (Reference No: 2022/35-REV/1).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Lussi A, Carvalho TS. Erosive tooth wear: A multifactorial condition of growing concern and increasing knowledge. Monogr Oral Sci. 2014;25:1–15.
2. Lussi A, Buzalaf MAR, Duangthip D, Anttonen V, Ganss C, Joao-Souza SH, et al. The use of fluoride for the prevention of dental erosion and erosive tooth wear in children and adolescents. Eur Arch Paediatr Dent. 2019;20(6):517–27.
3. Salas MM, Nascimento GG, Huysmans MC, Demarco FF. Estimated prevalence of erosive tooth wear in permanent teeth of children and adolescents: an epidemiological systematic review and meta-regression analysis. J Dent. 2015;43(1):42–50.
4. da Silva BM, Rios D, Foratori-Junior GA, Magalhães AC, Buzalaf MAR, Peres SDCS, et al. Effect of fluoride group on dental erosion associated or not with abrasion in human enamel: A systematic review with network metanalysis. Arch Oral Biol. 2022;144:105568.
5. Mylonas P, Austin RS, Moazzez R, Joiner A, Bartlett DW. In vitro evaluation of the early erosive lesion in polished and natural human enamel. Dent Mater. 2018;34(9):1391–400.
6. Jadeja SP, LeBlanc A, O'Toole S, Austin RS, Bartlett D. The subsurface lesion in erosive tooth wear. J Dent. 2023;136:104652.
7. Zanatta RF, Caneppele TMF, Scaramucci T, El Dib R, Maia LC, Ferreira DMTP, et al. Protective effect of fluorides on erosion and erosion/abrasion in enamel: A systematic review and meta-analysis of randomized in situ trials. Arch Oral Biol. 2020;120:104945.
8. Huysmans M-C, Young A, Ganss C. The role of fluoride in erosion therapy. In: Lussi A, Ganss C, editors. Erosive tooth wear: from diagnosis to therapy. S.Karger AG; 2014;25:0.
9. Lussi A, Carvalho TS. The future of fluorides and other protective agents in erosion prevention. Caries Res. 2015;49(Suppl 1):18–29.
10. Carvalho TS, Bönecker M, Altenburger MJ, Buzalaf MA, Sampaio FC, Lussi A. Fluoride varnishes containing calcium glycerophosphate: fluoride uptake and the effect on in vitro enamel erosion. Clin Oral Investig. 2015;19(6):1429–36.
11. Lussi A, Buzalaf MAR, Duangthip D, Anttonen V, Ganss C, João-Souza SH, et al. The use of fluoride for the prevention of dental erosion and erosive tooth wear in children and adolescents. Eur Arch Paediatr Dent. 2019;20(6):517–27.
12. Zhou SL, Zhou J, Watanabe S, Watanabe K, Wen LY, Xuan K. In vitro study of the effects of fluoride-releasing dental materials on remineralization in an enamel erosion model. J Dent. 2012;40(3):255–63.
13. Virupaxi SG, Roshan NM, Poornima P, Nagaveni NB, Neena IE, Bharath KP. Comparative evaluation of longevity of fluoride release from three different fluoride varnishes - an invitro study. J Clin Diagn Res. 2016;10(8):Zc33–6.
14. Elkassas D, Arafa A. Remineralizing efficacy of different calcium-phosphate and fluoride based delivery vehicles on artificial caries like enamel lesions. J Dent. 2014;42(4):466–74.
15. Ikemura K, Tay FR, Kouro Y, Endo T, Yoshiyama M, Miyai K, et al. Optimizing filler content in an adhesive system containing pre-reacted glass-ionomer fillers. Dent Mater. 2003;19(2):137–46.
16. Fujimoto Y, Iwasa M, Murayama R, Miyazaki M, Nagafuji A, Nakatsuka T. Detection of ions released from s-prg fillers and their modulation effect. Dent Mater J. 2010;29(4):392–7.
17. Kaga M, Kakuda S, Ida Y, Toshima H, Hashimoto M, Endo K, et al. Inhibition of enamel demineralization by buffering effect of s-prg filler-containing dental sealant. Eur J Oral Sci. 2014;122(1):78–83.
18. Moecke SE, Silva A, Andrade ACM, Borges AB, Torres CRG. Efficacy of s-prg filler varnishes on enamel caries remineralization. J Dent. 2022;119:104074.
19. Spinola MDS, Moecke SE, Rossi NR, Nakatsuka T, Borges AB, Torres CRG. Efficacy of s-prg filler containing varnishes on enamel demineralization prevention. Sci Rep. 2020;10(1):18992.
20. Varma V, Hegde KS, Bhat SS, Sargod SS, Rao HA. Comparative evaluation of remineralization potential of two varnishes containing cpp-acp and tricalcium phosphate: an in vitro study. Int J Clin Pediatr Dent. 2019;12(3):233–6.
21. Varghese E, Samson RS, Thomas A, Sam G, Hota S, Sahoo N. Effect of dental varnishes in prevention of enamel demineralization adjacent to orthodontic brackets. J Pharm Bioallied Sci. 2023;15(Suppl 1):S463–6.
22. Bergamo AZN, Miguel LP, Delgado RZR, Palma-Dibb RG, Faraoni JJ, Gatón-Hernández P, et al. Efficacy of Clinprotmxt varnish surrounding brackets on the enamel surface of white spot lesion. Braz Dent J. 2023;34(4):143–9.
23. Üstün N, Güven Y. Effect of three different remineralizing agents on artificial erosive lesions of primary teeth. Aust Dent J. 2022;67(3):271–80.
24. Alexandria AK, Vieira TI, Pithon MM, da Silva Fidalgo TK, Fonseca-Gonçalves A, Valença AM, et al. In vitro enamel erosion and abrasion-inhibiting effect of different fluoride varnishes. Arch Oral Biol. 2017;77:39–43.
25. Almqvist H, Lagerlöf F. Effect of intermittent delivery of fluoride to solution on root hard-tissue de- and remineralization measured by 125i absorptiometry. J Dent Res. 1993;72(12):1593–8.
26. Yilmaz N, Baltaci E, Baygin O, Tuzuner T, Ozkaya S, Canakci A. Effect of the usage of Er,cr:Ysgg laser with and without different remineralization agents on the enamel erosion of primary teeth. Lasers Med Sci. 2020;35(7):1607–20.
27. Creeth JE, Burnett GR, Souverain A, Gomez-Pereira P, Zero DT, Lippert F, et al. In situ efficacy of an experimental toothpaste on enamel rehardening and prevention of demineralisation: A randomised, controlled trial. BMC Oral Health. 2020;20(1):118.
28. Austin RS, Giusca CL, Macaulay G, Moazzez R, Bartlett DW. Confocal laser scanning microscopy and area-scale analysis used to quantify enamel surface textural changes from citric acid demineralization and salivary remineralization in vitro. Dent Mater. 2016;32(2):278–84.
29. Jahanimoghadam F, Gisour EF, Ranjbar M, Amdjadi P, Dehesh T, Tabatabaei Rad M. A comparison of conventional sodium fluoride varnish and nano-sodium fluoride varnish regarding enamel microhardness of deciduous teeth: an in-vitro study. Eur Arch Paediatr Dent. 2024;25(6):837–44.
30. Nekrashevych Y, Stösser L. Protective influence of experimentally formed salivary pellicle on enamel erosion. An in vitro study. Caries Res. 2003;37(3):225–31.
31. FR, DRK, CV, XR, SSR, JD. Mesoscale structural gradients in human tooth enamel. Proc Natl Acad Sci. 2022;119(52):e2211285119.
32. Kelly AM, Kallistova A, Kuchler EC, Romanos HF, Lips A, Costa MC et al. Measuring the microscopic structures of human dental enamel can predict caries experience. J Pers Med. 2020;10(1).
33. Stern D, Skobe Z. Individual variation in enamel structure of human mandibular first premolars. Am J Phys Anthropol. 1985;68(2):201–13.

34. Avila D, Augusto MG, Zanatta RF, Scaramucci T, Aoki IV, Torres CRG, et al. Enhancing the anti-erosive properties of fluoride and stannous with the polymer carbopol. Caries Res. 2020;54(3):250–7.
35. Jain A, Suprabha BS, Shenoy R, Natarajan S, Rao A. Remineralising effectiveness of two fluoride varnishes containing additives: an in vitro study. Oral Health Prev Dent. 2019;17(4):385–93.
36. Canali GD, Rached RN, Mazur RF, Souza EM. Effect of erosion/abrasion challenge on the dentin tubule occlusion using different desensitizing agents. Braz Dent J. 2017;28(2):216–24.
37. Abufarwa M, Noureldin A, Dziak R, Covell D. Efficacy of cpp-acp fluoride varnish applied with and without acid etching in preventing enamel demineralization compared to light-curable fluoride varnish. Angle Orthod. 2022;92(2):213–9.
38. Imazato S, Nakatsuka T, Kitagawa H, Sasaki JI, Yamaguchi S, Ito S et al. Multiple-ion releasing bioactive surface pre-reacted glass-ionomer (s-prg) filler: innovative technology for dental treatment and care. J Funct Biomater. 2023;14(4).
39. Gokkaya B, Ozbek N, Guler Z, Akman S, Sarac AS, Kargul B. Effect of a single application of cpp-acpf varnish on the prevention of erosive tooth wear: an Aas, Afm and Smh study. Oral Health Prev Dent. 2020;18(2):311–8.

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