

Silver diamine fluoride and resin-dentin bonding: Optimization of application protocols

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ABSTRACT

Objective: To evaluate the effect of SDF-based treatments following delayed bonding and surface treatment approaches on resin-dentin bonding efficiency of a universal adhesive under different application modes.

Methods: Mid-coronal dentin surfaces from sound third molars were randomly treated with 38% silver diamine fluoride (SDF) and/or additionally with potassium iodide (SDF/KI). Untreated dentin served as control. SDF-treated teeth were assigned to groups according to surface treatment approaches (air-abrasion and water rinsing), the application mode of a mild universal adhesive (etch-and-rinse or self-etch) and delayed bonding (immediate, 7, 15 or 30 days). Microtensile bond strength ($n = 5$), SEM analyses of hybrid layer formation and dentin etching patterns and dentin permeability were evaluated. Data were analyzed with factorial ANOVA.

Results: SDF-based treatments affected dentin bonding depending on application mode and surface treatment approaches ($p < 0.001$). Etch-and-rinse bonding was not affected by SDF-based treatments ($p < 0.05$), producing more homogenous hybrid layers. While dentin etching patterns of etch-and-rinse application were not affected by SDF-based treatments, self-etching presented limitations. Bond strength reductions of self-etched dentin were restored by silver-removal strategies containing a water-rinsing step ($p < 0.05$). Delayed bonding additionally reduced dentin permeability ($p < 0.05$), further decreasing with longer periods ($p < 0.05$).

Conclusion: Although the negative effect of SDF-based treatments on resin-dentin bonding can be avoided by strategies incorporating water-rinsing before hybridization, delayed bonding brings additional advantages due to higher mineral deposition.

Clinical significance: While the etch-and-rinse technique avoids major bonding drawbacks to SDF-treated dentin, self-etch bonding requires removal of excess silver deposits before hybridization. Performing SDF-based treatments and dentin hybridization in separate sessions (>15 days apart) potentialize mineral deposition improving caries control and service life of composite restorations.

1. Introduction

Silver diamine fluoride [$\text{Ag}(\text{NH}_3)_2\text{F}$] (SDF) is a clear alkaline topical solution composed of diamine silver and fluoride ions formulated to be brushed on active caries lesions. It is considered a simple low-cost painless treatment for both children and adults [1,2]. SDF reduces dentin sensitivity [3] and appears to have the ability to inhibit the formation of cariogenic biofilms [4]. Since the US Food and Drug Administration officially cleared SDF for tooth desensitization in 2014 and as a caries treatment in 2015, research interest and clinical

applications have greatly increased [5,6].

Indiscriminate killing of bacteria [2], at concentrations lower than 50 ppm [7] and fluoride's aid in tooth remineralization [4] contribute to the anticariogenic nature of silver ions. Interestingly, SDF treatment can additionally prevent cavitation of untreated surfaces considerably well [8–10], with minimal risk of negative systemic effects normally associated to other antimicrobials [2]. Despite SDF effectiveness in caries arrest, its use alone is limited to restore oral health in patients presenting more extensive cavitated lesions. Non-invasive caries management without or minimal tissue removal is not only currently

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accepted [11], but also constitutes the current gold standard in caries treatment. In this context, SDF emerges as a potential anticariogenic pretreatment to be performed before restorative procedures in high-caries-risk subjects [12]. Furthermore, the adjunctive use of SDF and resin-dentin bonding has grown in popularity due to possible inhibition of endogenous proteases [13,14] as a mean to reduce collagen degradation at bonded interfaces overtime. Hence, the use of SDF invariably rises as a possible off-label approach [4] to extend the longevity of resin-dentin interfaces. Nonetheless, knowledge on specific application protocols remains scarce and often controversial regarding bonding effectiveness [5,15–17].

Aside from consolidated bactericidal properties, the main mechanism involved in caries arrest results from SDF reaction with calcium and phosphate ions found in tooth tissues. Fluorohydroxyapatite [18] formation reduces solubility of tooth minerals at lower-cariogenic pHs. During this process, a layer of silver phosphate forms on SDF-treated dentin [19]. Silver particles further extend into dentinal tubules causing total or partial obstruction [14]. Even though the benefits of SDF treatments on caries arrest endorse promising clinical applications, its use remains a matter of esthetic concern due to staining of tooth and surrounding tissues by oxidation of free silver ions [19]. Application of potassium iodide (KI) immediately after SDF minimizes commonly associate discoloration issues [20]. Formation of a white silver iodide compound ameliorates black dentin stains [15]. Since bonding of methacrylate-based resins depends on proper monomer-dentin interactions [21], reduction in dentin permeability by deposition of silver phosphate and silver iodine can substantially impair resin-dentin bonding [22]. While SDF-application protocols aiming for caries arrest and desensitization are not well established, its use along with resin-dentin bonding procedures [15,17,23] further complicates the matter. To date, it is still unclear whether application mode of adhesives (i.e., etch-and-rinse or self-etch) affect [15,17,24,25] or not [16,26,27] resin bonding to SDF-treated dentin. Controversies among reports [15–17,23–31] preclude extrapolations of *in vitro* SDF protocols to clinical applications. This is a missing piece of evidence to support the role of SDF-based treatments on caries management combined with restorative procedures. Interestingly, residual silver ions increase nucleation sites on caries affected dentin resulting in a promising alternative to improve bonding, irrespective of application mode [29]. However, dealing with SDF-impregnated smear layers before hybridization may be necessary to avoid potential bonding issues [24, 25]. Therefore, the central aim of this study was to evaluate the effect of SDF-based treatments following delayed bonding periods and surface treatment approaches before resin-dentin bonding under different application modes. The tested null hypotheses were that (i) application mode of the bonding resin, (ii) delayed bonding and/or (iii) surface treatment approaches before dentin bonding would have no effect on dentin surface morphology, bond strength, hybrid layer formation and dentin permeability of SDF- or SDF/KI-treated dentin.

2. Materials and methods

Two hundred and eighty-six extracted sound third molars were obtained with informed consent from dental patients under a protocol approved by the University of Oulu, Finland (#23–2003) in accordance with local regulations. Teeth were cleaned and stored at 4 °C in 0.9% NaCl containing 0.02% NaN₃ to prevent bacterial growth, for up to 3 months before use. Teeth were coronally sectioned under water-cooling to expose flat midcoronal dentin surfaces using low speed diamond saw (Isomet 1000 Precision Saw, Buehler Ltd, USA). Absence of remaining enamel was verified with a stereo microscope (Leica M60, Leica Microsystems, Germany) at 40× magnification. Smear layer standardization was performed by wet-polishing exposed dentin surfaces with 320-grit silicon carbide (SiC) paper (CarbiMet, Buehler Ltd, USA) for 60 s at 350 rpm (MetaServ 250 Grinder-Polish, Buehler Ltd, USA).

2.1. Experimental design and bonding protocols

Coronally sectioned teeth were randomly divided into two groups according to SDF (Silver Diamine Fluoride, Riva Star, SDI) or SDF/KI treatment (Silver Diamine Fluoride + Potassium Iodide, Riva Star, SDI). Teeth within each group were randomly divided into subgroups (n = 5 teeth/group) according to the delayed bonding (immediate, 7, 15 or 30 days), surface treatment approaches (with or without air-abrasion and water rinsing for 15 s [32]) and the application mode (self-etch or etch-and-rinse) of a mild universal adhesive (Scotchbond Universal Plus Adhesive, 3M-ESPE). Control groups consisted of untreated dentin (with or without air-abrasion) immediately bonded by the same mild universal adhesive in either self-etch or etch-and-rinse mode following manufacturer's instructions. A summary of the experimental design is shown in Fig. 1. After SDF treatments following manufacturer's instructions, exposed dentin surfaces were immediately tested or stored in artificial saliva (pH 7.4) containing 5 mM HEPES, 2.5 mM CaCl₂·H₂O, 0.05 mM ZnCl₂, and 0.3 mM NaN₃ at 37 °C [33] for 7, 15 or 30 days. Airborne-particle abrasion (Cojet System, 3M-ESPE) was performed for 30 s at 3 bar using 30 µm alumina-silica particles (CoJet-Sand, 3M-ESPE). The nozzle tip was perpendicular to the dentin surface at approximately 1 mm away. Materials, bonding protocols and SDF treatments according to the manufacturers' instructions are summarized in Table 1. Bonding in self-etch mode consisted of active adhesive application for 20 s (manual light pressure of approximately 4 g, equivalent to a slight rubbing pressure), gentle solvent evaporation for 10 s and light curing for 10 s using a LED light curing unit (Valo Corded, Ultradent, USA) at 1800 mW/cm². Light intensity of curing unit was measured using MARC Light Collector (MARC-LC, Bluelight Analytics, Canada). For etch-and-rinse bonding protocol, dentin surfaces were etched with 32% phosphoric acid gel (Scotchbond Universal Etchant, 3M-ESPE) for 15 s, rinsed for 15 s, active adhesive application for 20 s, gentle solvent evaporation for 10 s and light curing for 10 s. Composite blocks were built with a nanofilled composite resin (Filtek Ultimate Universal Restorative, 3M-ESPE) in two 2-mm increments. Each increment was light cured for 20 s. All bonding procedures were carried out by a single operator.

2.2. Microtensile bond strength (µTBS) and failure mode analysis

Restored crown segments were stored in distilled water for 24 h at 37 °C and sectioned longitudinally in mesio-distal and buccal-lingual directions perpendicular to the bonded interface with a low-speed diamond saw (Isomet 1000 Precision Saw, Buehler Ltd, USA). Resin-dentin beams were produced with a cross-sectional area of approximately 0.9 mm². Microtensile bond strength testing was performed according to the Academy of Dental Materials guidelines for non-trimmed µTBS testing [34]. A minimum of 8 beams per tooth (n = 5 teeth/group) were tested for each testing condition. Beams were individually attached to a custom made micro-tensile testing jig using a cyanoacrylate adhesive (Loctite 416, Henkel Corp, Ireland) and tested under tensile forces in a universal testing machine (Autograph AGS-X Series, Shimadzu, Japan) at a crosshead speed of 0.5 mm/min until failure to obtain the maximum load (P) in N. A blinded operator performed the measurements. The cross-sectional area (CA) in mm² of each beam was measured with a digital caliper to nearest 0.01 mm. The formula $\mu TBS = P/CA$ was used to calculate µTBS values in MPa (Trapezium X Software, Shimadzu, Japan). Tooth was considered as the statistical unit, bond strengths of resin-dentin beams from each tooth were averaged to represent the bond strength of each tooth [1]. Pre-test failures (PTFs) were included in the calculations as 0 MPa [34]. Both surfaces of fractured resin-dentin beams were observed under a stereo microscope (Leica M60, Leica Microsystems, Germany) with 40× magnification to determine fracture patterns. Unidentifiable specimens were examined by scanning electron microscopy (SEM) (Phenom ProX, Phenom-World, Netherlands). The fracture modes were classified as:

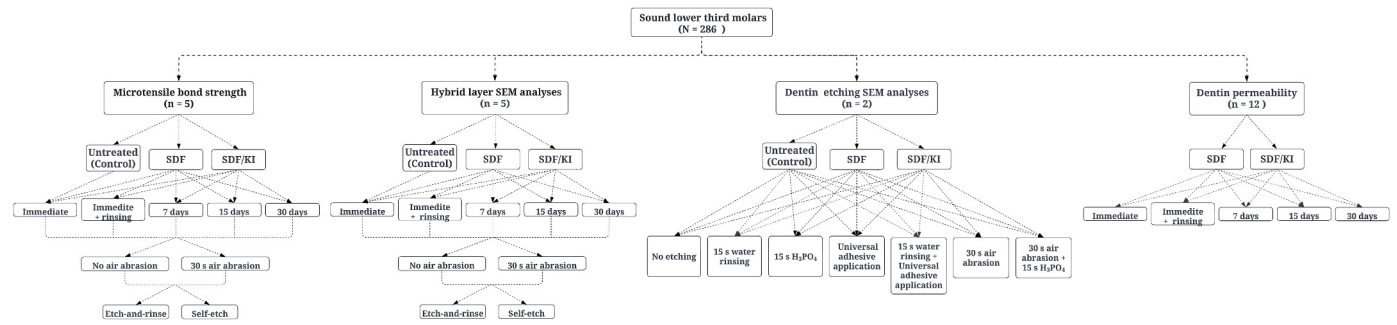


Fig. 1. Flowchart of the experimental design of the study. Abbreviations: SDF = Silver Diamine Fluoride; KI = Potassium Iodide.

Table 1
Materials, bonding protocols, and SDF application procedures.

Material Lot Number	Composition	pH	Application
Riva Star (SDI LTD, Australia) Capsule 1: (SDF) 170726 Capsule 2: (KI) ML160125	silver fluoride (38% w/v - 60.000 ppm fluoride), ammonia (15–20% w/v), water (40–60% w/v) potassium iodide (58.3% w/w)	11 -	Active application on dentin surface for 60 s. Active application on dentin surface for 60 s until the initially creamy white appearance turned to clear.
Cojet Sand (3M-ESPE, USA) 504751	30 µm aluminum oxide, crystalline free fumed amorphous silica particles	-	Air abrasion for 30 s at 1 mm distance; rinse with water stream for 30 s.
Scotchbond Universal Etchant (3M-ESPE, USA) 7367451	32% phosphoric acid, water, synthetic amorphous silica, polyethylene glycol and aluminum oxide	0.1	Etch for 15 s; rinse with water stream for 15 s; blot dry until paper filters presented no visible moisture, surface appears moist.
Scotchbond Universal Plus Adhesive (3M-ESPE, USA) 7457878	MDP phosphate monomer, dimethacrylate resins contain a BPA derivative-free, crosslinking radiopaque monomer, HEMA, methacrylate modified polyalkenoic acid copolymer, filler, ethanol, water, initiators and silane	2.7	Active adhesive application for 20 s; gentle solvent evaporation for 10 s; light cure for 10 s.
Filtek Ultimate Universal Restorative A3 (3M-ESPE, USA) NE08950	bis-GMA, UDMA, TEGDMA, bis-EMA, PEGDMA, 20 nm silica particles, 4–11 nm zirconium particles (78.5 wt % - 63.3 vol %)	-	Two incremental placements with 2 mm thick composite layers; light cure each increment for 20 s.

Abbreviations: MDP = methacryloyloxydecyl dihydrogen phosphate; BPA = Bisphenol A; HEMA = 2-hydroxyethyl methacrylate; bis-GMA = bisphenol glycidyl methacrylate; UDMA = urethane dimethacrylate; TEGDMA = triethylene glycol dimethacrylate; bis-EMA = ethoxylated bisphenol-A dimethacrylate; PEGDMA = poly(ethylene glycol) dimethacrylate.

adhesive failure (failure at resin/dentin interface); mixed failure (failure at resin/dentin interface with cohesive failure of the neighboring substrates); and cohesive failure (failure exclusive within dentin or composite resin).

2.3. Hybrid layer analyses (SEM)

Two random resin-dentin beams from each tooth (n = 5/group) were selected for hybrid layer characterization under scanning electron microscopy (SEM). Resin-dentin beams were embedded in epoxy resin and wet-polished with 600-, 1200-, 2000- and 4000-grit SiC paper,

followed by 0.05 µm aluminum oxide polishing paste (Buehler Ltd, USA). Beams were ultrasonically cleaned in distilled water after each polishing step. Bonded interfaces were treated with 50% H₃PO₄ for 5 s and 3% NaOCl for 10 min, dried in silica overnight, mounted on stubs, sputtered with gold/palladium and analyzed on backscattering mode at 10 kV (Phenom ProX, Phenom-World, USA). A series of sequential micrographs of the bonded interfaces (5500× magnification) were obtained from each resin-dentin beam by an experienced blinded operator. Three randomly selected areas on each micrograph located between adjacent resin tags were analyzed by a single-blinded experienced examiner for hybrid layer thickness using an open-source image software (ImageJ, National Institute of Health, USA). Measurements obtained from each tooth were averaged to determine the hybrid layer thickness of each bonding protocol.

2.4. Etching pattern SEM analysis

Forty-two sound third molars were coronally sectioned under water-cooling to expose flat midcoronal dentin surfaces using a low-speed diamond saw (Isomet 1000 Precision Saw, Buehler Ltd, USA). Exposed midcoronal dentin surfaces were wet polished with 320-grit SiC paper (CarbiMet, Buehler Ltd, USA) for 60 s at 350 rpm for smear layer standardization (MetaServ 250 Grinder-Polish, Buehler Ltd, USA) and were randomly assigned to 21 groups (n = 2/group) according to the experimental design shown in Fig. 1. Application protocols were performed similarly to the microtensile test. The only exception was that the bonding agent was not light cured, but copiously rinsed away with water for 30 s to expose the underlying dentin surface. Specimens were dehydrated in ascending series of ethanol (25, 50, 75, 95 and 100%), fixed in HMDS (Sigma Aldrich, USA) [35], mounted on aluminum stubs, sputter coated with gold-palladium and analyzed by SEM (Phenom ProX, Phenom-World, USA) on backscattering mode at 10 kV up to 5000× magnifications. An experienced-blinded operator examined samples.

2.5. Dentin permeability

Twenty-four sound lower third molars were sectioned perpendicularly to their long axis above the pulp chamber under water-cooling using a low-speed diamond saw (Isomet 1000 Precision Saw, Buehler Ltd, USA) to produce dentin discs measuring approximately 1 mm in thickness. Two dentin discs were obtained from each tooth (n = 12/group). Exposed midcoronal dentin surfaces were wet-polished with 320-grit SiC paper (CarbiMet, Buehler Ltd, USA) for 60 s at 350 rpm (MetaServ 250 Grinder-Polish, Buehler Ltd, USA). Dentin permeability was evaluated through a flow-measurement infiltration apparatus (SLI-1000 Liquid Flow Meter, Sensirion, Switzerland) in a modified split-chamber unit, which was linked to a deionized water container at a simulated hydrostatic pressure of 20 cm based on Zhang et al. [36]. Hydraulic conductance (Lp) was determined by dividing fluid flow (µL·min⁻¹), under simulated hydrostatic pressure (20 cm H₂O), by the available

surface area (cm^2) [36]. Maximum dentin permeability was expressed by the hydraulic conductance calculated after etching dentin discs for 30 s with 50% citric acid to remove smear layer and smear plugs and thus desobliterate dentinal tubules. After maximum permeability measurements, dentin discs were randomly divided according to SDF and SDF/KI treatments. Hydraulic conductance values were calculated after SDF and SDF/KI treatments immediately and after storage in artificial saliva for 7, 15 or 30 days. An isolated control group consisting of immediate treatment followed by rinsing for 15 s was included. Dentin permeability was represented as a percentage reduction in hydraulic conductance ($L_p\%$) considering the maximum permeability as the baseline values. Each dentin disc served as its own dentin permeability control.

2.6. Statistical analysis

Data regarding bond strength, hybrid layer thickness and permeability were analyzed separately. Tooth was considered as the statistical unit for the microtensile data. Since microtensile data was normally distributed (Kolmogorov-Smirnov test $p = 0.200$) and homoscedastic (Levene test $p = 0.784$), bond strength values were subjected to three-way ANOVA followed by the Tukey Test. Hybrid layer thickness data was analyzed by the Kruskal-Wallis test. Dentin permeability data (Levene test $p = 0.784$; Shapiro-Wilk test $p = 174$) were subjected to repeated measures ANOVA followed by Tukey Test.

Significance level (α) of 0.05 was used for all statistical tests. Statistical analyses were performed using IBM SPSS Statistics for Windows, version 28 (IBM Corp, USA).

3. Results

3.1. Microtensile bond strength (μTBS) and failure mode analysis

The mean cross-sectional area of resin-dentin beams 0.9 mm^2 ($\pm 0.06 \text{ mm}^2$) ranged from 0.84 to 0.96 mm^2 without any significant differences between groups regarding specimen size ($p = 0.221$). Three-way ANOVA showed that “surface treatment” ($p < 0.0001$; $\eta_p^2 = 0.219$), “bonding protocol” ($p < 0.0001$; $\eta_p^2 = 0.395$), “delayed bonding” ($p < 0.0001$; $\eta_p^2 = 0.165$) and the interactions between “surface treatment * bonding protocol” ($p < 0.0001$; $\eta_p^2 = 0.233$) and “bonding protocol * delayed bonding” ($p < 0.0001$; $\eta_p^2 = 0.338$) significantly affected bond strengths. Resin-dentin bond strength values for all groups and standard deviations are shown in Fig. 2. No significant differences were observed between untreated dentin bonded in etch-and-rinse or self-etch mode ($p > 0.05$). Air-abrasion of untreated dentin samples had no significant effect on bond strengths of untreated dentin irrespective of application mode (*i.e.*, etch-and-rinse and self-etch) ($p > 0.05$). Under etch-and-rinse bonding, SDF or SDF/KI treatments had no effect on dentin bond strengths regardless of the immediate water rinsing, delayed bonding or air-abrasion ($p > 0.05$).

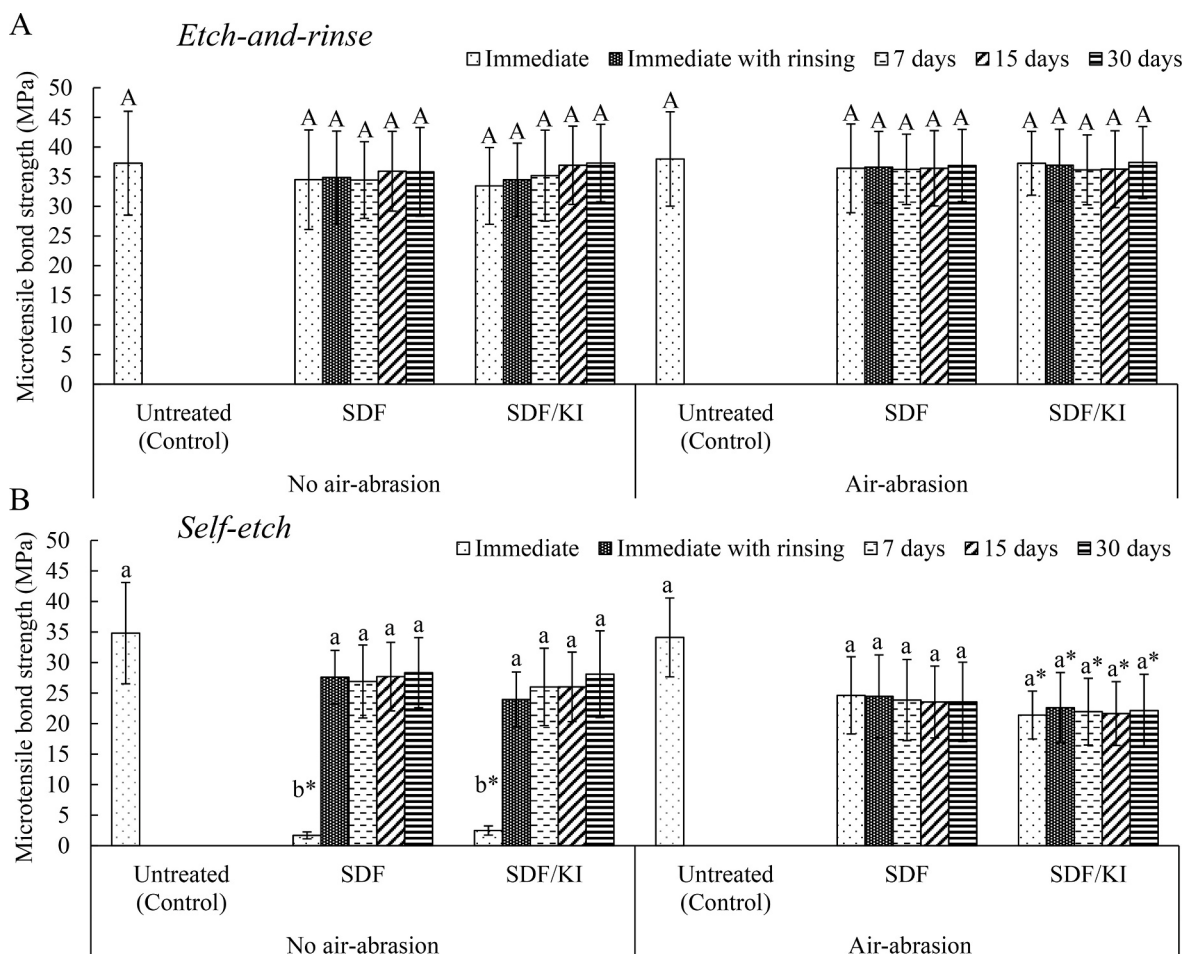


Fig. 2. μTBS mean (MPa) and standard deviations ($\pm\text{SD}$) of tested groups. Control groups indicate untreated dentin (with or without air abrasion) surfaces immediately bonded in either etch-and-rinse or self-etch mode. Different capital letters indicate significant differences between treatments, dentin abrasion and storage periods within etch-and-rinse groups according to Tukey test ($p < 0.05$). Different lowercase letters indicate significant differences between treatments, dentin abrasion and storage periods within self-etch groups according to Tukey test ($p < 0.05$). * indicates significant differences between application modes according to Tukey test ($p < 0.05$). Abbreviations: SDF = Silver Diamine Fluoride; KI = Potassium Iodide.

Under self-etch bonding, SDF and SDF/KI treatments significantly reduced dentin bond strengths (roughly 95%) when bonding was performed immediately after SDF or SDF/KI applications ($p < 0.05$). Contrary, immediate water rinsing ($p < 0.05$) and air-abrasion ($p < 0.05$) of SDF- or SDF/KI-treated dentin yielded comparable bond strengths to untreated dentin when self-etch bonding was immediately performed. Delayed bonding for 7, 15 or 30 days after SDF or SDF/KI treatments yielded comparable bond strengths to untreated dentin ($p > 0.05$) without significant differences from each other ($p > 0.05$). Air-abrasion after 7, 15 or 30 days had no significant effects on bond strengths of SDF- or SDF/KI-treated dentin under self-etch bonding ($p > 0.05$).

In general, no significant differences were detected between corresponding bonding protocols for etch-and-rinse or self-etch applications. The exceptions were SDF and SDF/KI immediately bonded (reduction of roughly 95% for self-etch application) and SDF/KI followed by air-abrasion for all storage periods (reductions of 35–40% for self-etch application) ($p < 0.05$). Fracture mode distributions are shown in Fig. 3. The predominant mode of failure was characterized by adhesive failures (roughly 50%) followed by mixed failures (roughly 40%) for all groups. Samples bonded in self-etch mode immediately after SDF or SDF/KI treatments presented mostly pre-test failures.

3.2. Hybrid layer analyses (SEM)

Representative SEM micrographs for hybrid layer analysis are shown in Fig. 4. Kruskal-Wallis revealed that bonding protocols (*i.e.* etch-and-rinse or self-etch) significantly affected hybrid layer thicknesses ($p < 0.001$; $\eta_p^2 = 0.873$), while air-abrasion, SDF and SDF/KI treatments had no significant effects on hybrid layer thickness ($p > 0.05$). Hybrid layer thickness under etch-and-rinse application with or without air abrasion for untreated dentin specimens (3.54 - 3.35 μm), SDF- (3.33 - 3.04 μm) or SDF/KI-treated (3.50 - 3.06 μm) specimens presented no significant differences from each other ($p > 0.05$). Etch-and-rinse bonding formed uniform and homogenous hybrid layers with

well-defined resin tags (Fig. 4 A1-A11; C1-C11). Resin tags extended deeply into dentinal tubules (approximately 15–30 μm) presenting substantial lateral branching. Self-etch bonding produced significantly thinner hybrid layers (between 0.98 and 0.64 μm) compared to etch-and-rinse bonding ($p < 0.05$) with shorter resin tags (approximately 2–10 μm) (Fig. 4 B1-B11; D1-D11). Hybrid layer thicknesses under self-etch application with or without air abrasion for control specimens (0.98 - 0.96 μm), SDF- (0.81 - 0.73 μm) or SDF/KI-treated (0.78 - 0.77 μm) specimens presented no significant differences from each other ($p > 0.05$). Hybrid layers produced after air-abrasion were not as homogenous as those without air-abrasion, irrespective of application modes or SDF treatments.

3.3. Etching pattern SEM analysis

Representative SEM micrographs for midcoronal dentin surfaces analysis are shown in Fig. 5. Unetched specimens presented dense smear layer covering the entire dentin extension (Fig. 5 A; C). Self-etch application partially dissolved the smear layer producing sparse tubule disobliteration (Fig. 5 J; M). Air-abrasion produced superficial irregularities and aluminum particles could be seen trapped within a more porous smear layer (Fig. 5 P). SDF and SDF/KI treatments did not expose dentinal tubules nor collagen fibrils (Fig. 5 B; K; Q; F; L; R) and silver precipitates were observed covering most of the smear layer (Fig. 5 B; C). SDF/KI treatment produced precipitates with larger dimensions more densely packed in specific areas (Fig. 5 C). Air-abrasion of SDF- and SDF/KI-treated specimens removed silver precipitates from the smear layer producing irregular surfaces (Fig. 5 Q; R). Self-etch application was unable to fully remove silver precipitates of SDF and SDF/KI-treated dentin (Fig. 5 K; L). Immediate water rinsing reduced residual silver particles from dentin surfaces (Fig. 5 E; F). Subsequent self-etch application followed by rinsing further reduced silver particle content (Fig. 5 N; O), revealing a small number of open tubules (Fig. 5 O). H_3PO_4 etching for 15 s exposed a thick layer of demineralized collagen for both untreated and SDF- and SDF/KI-treated

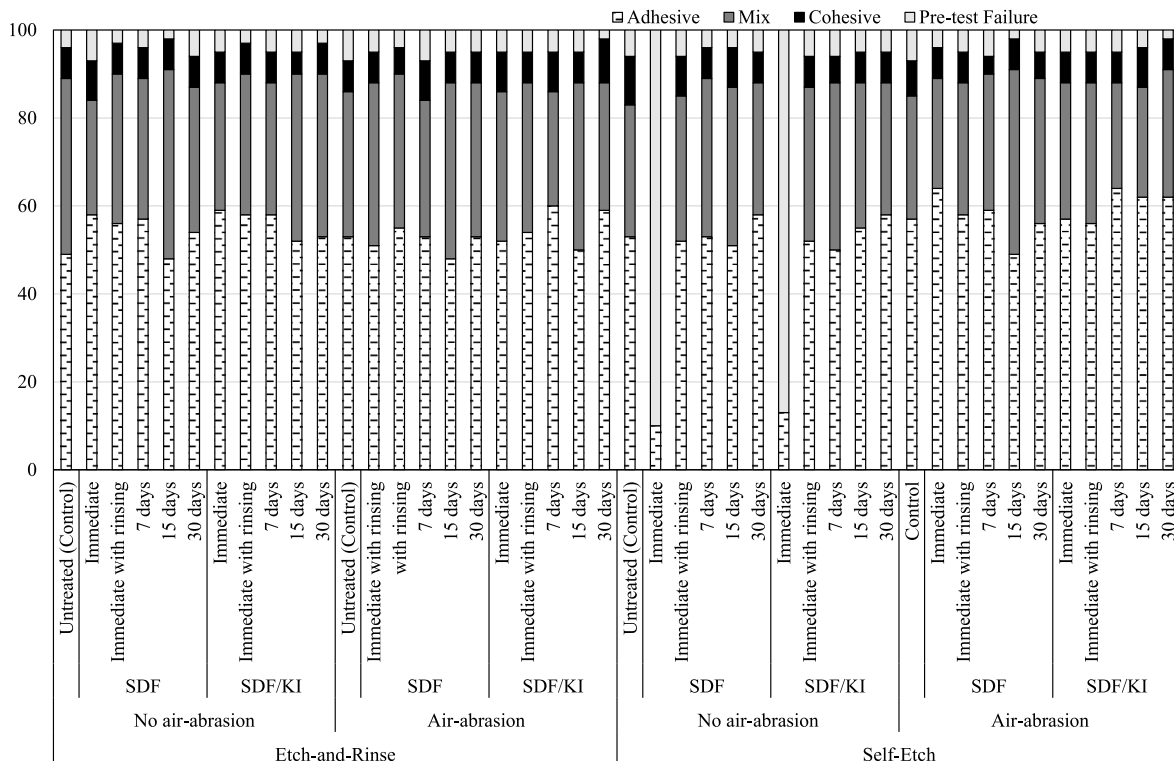


Fig. 3. Fracture modes of tested groups. Abbreviations: SDF = Silver Diamine Fluoride; KI = Potassium Iodide.

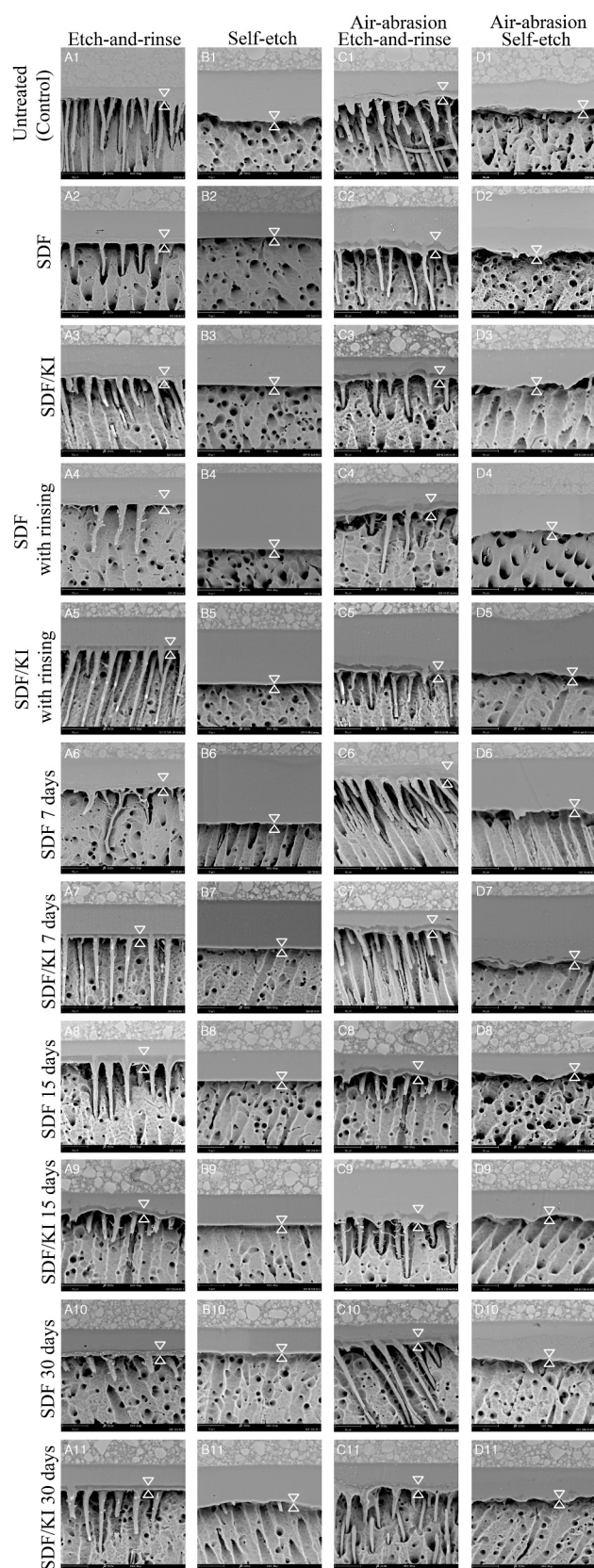


Fig. 4. Representative SEM micrographs of hybrid layer characterization. Areas between white arrows correspond to hybrid layers. *Abbreviations:* SDF = Silver Diamine Fluoride; KI = Potassium Iodide.

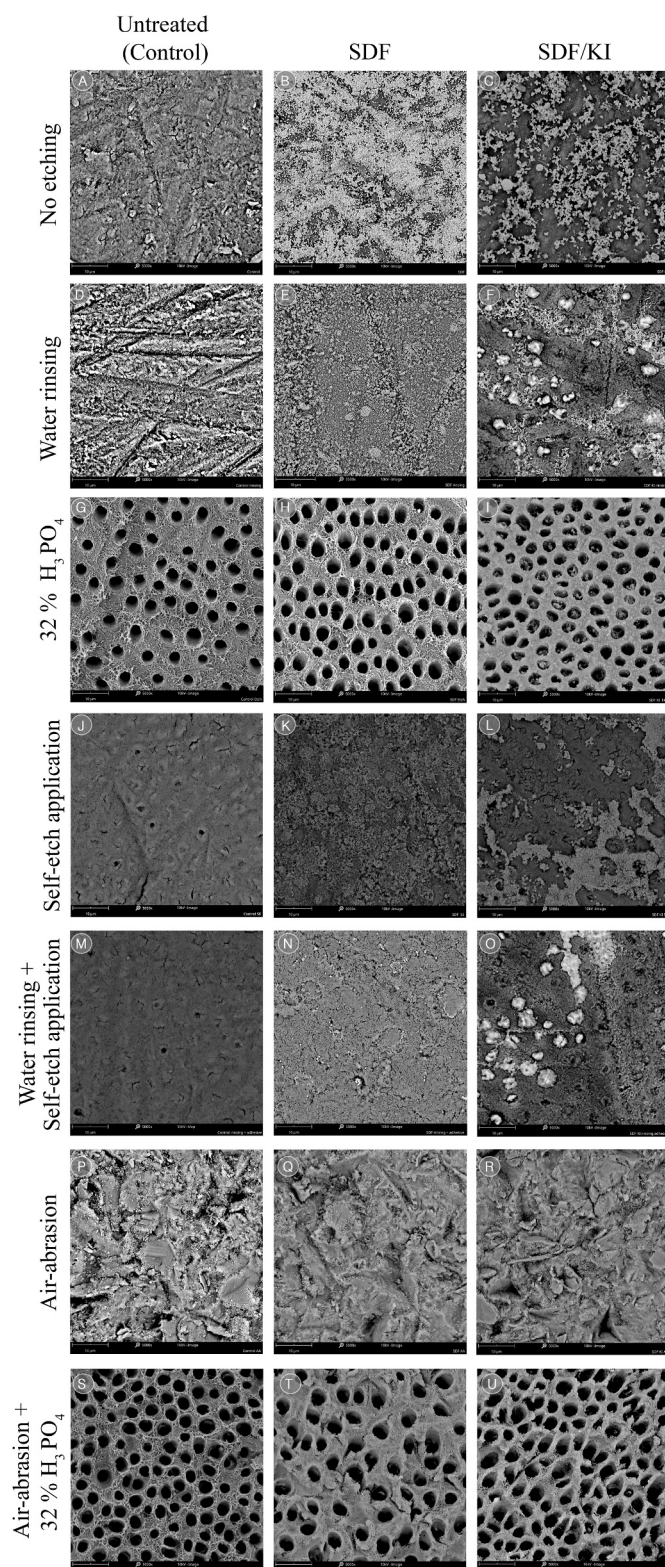


Fig. 5. Representative SEM micrographs showing etching patterns of SDF-treated dentin following different bonding protocols. *Abbreviations:* SDF = Silver Diamine Fluoride; KI = Potassium Iodide.

dentin (Fig. 5 G; H; I; S; T; U). Smear layer-free dentin surfaces presenting open tubules (Fig. 5 G; H; I) without silver precipitates were identified after H_3PO_4 etching. Air-abrasion followed by H_3PO_4 etching produced similar smear layer-free dentin surface with a thick layer of exposed collagen without silver precipitates (Fig. 5 S; T; U).

3.4. Dentin permeability

Dentin permeability (%) means and standard deviations for all groups are shown in Table 2. Repeated measures ANOVA revealed that “delayed bonding” ($p < 0.0001$) had significant effects on permeability of SDF- and SDF/KI-treated dentin. There were no significant differences between SDF treatments for corresponding storage periods ($p > 0.05$). SDF and SDF/KI treatments significantly decreased permeability showing roughly 30% reductions in hydraulic conductance immediately after application ($p < 0.05$) and 20% reductions after immediate water rinsing ($p < 0.05$), with significant differences from each other ($p < 0.05$) according to two-way ANOVA conducted between immediate and immediate with rinsing groups. Delayed bonding for 7-day had no significant effects on hydraulic conductance compared to immediate values without water rinsing ($p > 0.05$); however, delayed bonding for 15 and 30 days yielded significantly lower values ($p < 0.05$).

4. Discussion

The use of silver diamine treatments has considerably increased over the past years; however, protocols for bonding methacrylate-based resins to SDF- and SDF/KI-treated dentin are not clear [15]. Since application modes significantly affected resin bonding to SDF- and SDF/KI-treated dentin, the first null hypothesis was rejected. Choosing between self-etch or etch-and-rinse application can thereby determine whether bonding composite restorations to silver diamine-treated dentin will succeed or not. SDF treatments are most effective in arresting caries lesions at higher concentrations [37], with 38% (w/v) showing the best clinical outcomes [9]. This justifies the selection of a commercially available 38% (w/v) SDF product for this study. Even though 38% SDF is effective in preventing and arresting both early childhood caries and even root caries in elderly [38,39], higher SDF concentrations also increase the likelihood of higher silver-phosphate particulate deposition on dentin [17,29]. Depending on the extension, SDF and SDF/KI deposits block dentinal tubules and may act as surface “bonding contaminants” producing physicochemical alterations on dentin [17]. Our findings corroborate the application-mode dependency of SDF on dentin-bonding effectiveness [15,17,24,25]. The rationale for testing a mild universal adhesive was to reduce possible effects of chemical compositions between resins on dentin bonding under different testing conditions. Universal adhesives belong to a relatively

new class of user-friendly dental adhesives that propose simplification by allowing bonding to tooth structures in either self-etch or etch-and-rinse mode. Hence, solvents, photoinitiators and monomeric composition, including functional acidic monomers that chemically bond to calcium are equally present under both testing conditions. Since resin composition can affect bonding outcomes of SDF- and SDF/KI-treated dentin [24], elimination of unnecessary comparisons between distinct resins better isolated the effect of application modes on bonding efficiency. In the absence of SDF treatments, no differences in bond strengths were observed between self-etch and etch-and-rinse applications, which is consistent with previous reports [40,41]. Nonetheless, the marked underperformance of self-etch bonding in this study provides supporting evidence that application mode of adhesives indeed played an important role in resin-bonding effectiveness to SDF- SDF/KI-treated dentin.

SDF treatments (SDF and SDF/KI) followed by immediate self-etch application yielded drastic reductions in dentin-bond strengths of roughly -95%. Potassium iodide (KI) application after SDF is an attempt to minimize tooth discoloration. KI chemically reacts with residual silver ions, reducing the oxidative staining effect. The impairment of SDF on self-etch bonding was not worsened by KI application, albeit resin-dentin bonding was equally ineffective. No significant differences were observed between SDF and SDF/KI treatments under self-etch bonding. Determining the exact relationship between *in vitro* bonding studies and clinical performance is difficult to establish [42]. However, a material's dentin-bonding ability can be indirectly associated to restoration longevity [42]. Inferior laboratory performance generally indicates worse clinical performance. The high occurrence of pre-test failures, approximately 85%, clearly shows impairment in resin-dentin interaction after SDF treatments. Self-etch bonding relies on chemical interactions between specific carboxyl/phosphate groups of functional monomers (10-MDP) and residual hydroxyapatite [43]. Micro-mechanical retention, however, also plays an important role forming submicron hybrid layers. Effective bonding depends on sufficient demineralization through the smear layer reaching the underlying dentin to allow adequate monomer-dentin interaction [44]. Self-etch application was not able to effectively etch through the entire extension of silver/iodine-impregnated smear layers (Fig. 5 B; C). The high alkalinity (pH 11) and relative pH stability of SDF agents [45] certainly buffered functional acidic monomers, reducing the dentin-etching ability of the tested universal adhesive (Fig. 5 K; L). Compromised monomer-dentin interactions was likely a main cause of self-etch bonding impairment. The detrimental effect of SDF treatments on self-etch bonding agrees with previous studies [15,17,24].

The buffering effect of SDF and SDF/KI treatments was particularly important in this study design considering the more clinically relevant smear layers created before bonding (i.e., 320-grit vs. 600-grit SiC paper) [34]. The presence of thicker/denser smear layers may have exacerbated the negative-buffering effect of SDF and SDF/KI treatments on the etching ability of the tested universal adhesive, further compromising resin-dentin bonding. Immediate water rinsing after SDF treatments prevented bond strength reductions for self-etching bonding. This is corroborated by previous studies [16,26,27]. Rinsing removes high-pH ammoniacal compounds, which are readily soluble in water (Fig. 5 E; F), likely reducing the overall negative-buffering effect of SDF treatments on acidic monomers (Fig. 5 N; O). Similarly, delaying self-etch bonding restored bond strengths, producing comparable values to those of untreated dentin. This was confirmed for both SDF and SDF/KI treatments. Since delayed bonding significantly affected bonding efficiency, the second null hypothesis was rejected. To the best of our knowledge, this is the first study to evaluate the effect of delayed bonding on resin bonding to SDF- and SDF/KI-treated dentin. During the storage period, the artificial saliva slowly rinsed away alkaline compounds reducing the negative-buffering effect on functional acidic monomers. Even though no differences in self-etch bond strengths were observed between delayed bonding periods (7, 15 or 30 days), delaying

Table 2

Dentin permeability results in percentage (%) after SDF treatments following different storage periods in artificial saliva at 37 °C.

Storage period	SDF	SDF/KI
Immediate with rinsing	80.19 ± 6.53 ^{aa}	81.66 ± 7.02 ^{aa}
Immediate	69.46 ± 8.43 ^{Aa}	70.28 ± 7.22 ^{Aa}
7 days	58.96 ± 9.62 ^{ABa}	60.28 ± 9.72 ^{ABa}
15 days	49.08 ± 10.62 ^{Ba}	54.55 ± 9.12 ^{Ba}
30 days	48.44 ± 10.41 ^{Ba}	53.25 ± 7.34 ^{Ba}

Dentin permeability was reported as percentage (Lp %) and shown as means ± SD. The Lp % value after phosphoric acid application was set as 100% (n = 12). Repeated measures ANOVA was conducted between immediate, 7, 15 and 30 days. 2-way ANOVA was conducted between immediate and immediate with rinsing groups. Different capital letters indicate significant differences within columns, different lowercase letters indicate significant differences within rows and * indicate significant differences between immediate and immediate with rinsing (isolated control) according to Tukey test ($p < 0.05$). Abbreviations: SDF = Silver Diamine Fluoride; KI = Potassium Iodide.

dentin bonding additionally reduced dentin permeability. SDF and SDF/KI treatments increased mineral deposition in a time-dependent manner resulting in dentinal tubule obliteration [46]. Hence, dentin permeability indirectly measured mineral deposition. The test setup allowed repeated quantitative measurements of the same specimen non-destructively over time [47,48]. While SDF and SDF/KI treatments reduced immediate permeability by roughly 33%, significant reductions in the order of 53% occurred after 15- or 30-day waiting periods. Lower permeability levels indicated higher mineral deposition on SDF- and SDF/KI-treated dentin. SDF-related mineral deposition is a key mechanism behind improvements in immediate bonding of universal adhesives to eroded [26] and caries affected [29] dentin. Such improvements in bond strengths were obtained by rinsing SDF and SDF/KI treatments before bonding. Nonetheless, delaying bonding procedures may be more advantageous than water rinsing alone due to the considerably high mineral deposition.

Mechanical abrasion has been recommended to reduce the negative effect of SDF and SDF/KI treatments on resin-dentin bonding [15]. Instead of using diamond burs to roughen SDF- SDF/KI-treated dentin [15], a more conservative approach (*i.e.* air-abrasion) was assessed in this study. When air-abrasion particles collide with dentin, the released kinetic energy cleans and produces microscopic fractures that roughens the surface creating superficial irregularities [49]. SEM micro-morphology analysis corroborates the latter (Fig. 5 P, Q and R) depicting fewer silver residues on smear-covered dentin surfaces after air-abrasion. Even though air-abrasion had no significant effect on bond strengths of untreated dentin, immediate self-etch hybridization of SDF- and SDF/KI-treated dentin greatly benefited from it. Therefore, the third null hypothesis was rejected. Air-abrasion restored immediate self-etch bond strengths of SDF- and SDF/KI-treated dentin. This can be attributed to the water-rinsing step performed after air-abrasion and not necessarily to the mechanical abrasion of SDF-related precipitates produced by alumina and silica particles. Curiously, no significant differences were observed between SDF-treated dentin bonded in self-etch or etch-and-rinse mode; however, SDF/KI produced significantly lower values in self-etch mode. We speculate that chemical interactions between silver iodide (AgI) with alumina and silica particles [50] used for air-abrasion may form relatively stable compounds [51] at the resin-dentin interface. Even though the presence of such compounds had no effect on self-etch bonding, their removal by H₃PO₄-etching resulted in superior resin-dentin bonding.

Contrary to self-etch bonding, the etch-and-rinse approach relies on more aggressive demineralization to allow diffusion of methacrylate-based monomers into dentin for micromechanical retention [52]. H₃PO₄ strong acidity created greater demineralization depths (Fig. 5). Hence, SDF- and SDF/KI-infiltrated smear layer were fully removed facilitating adhesive resin penetration into the tubules to form resin tags and small lateral extensions. Etch-and-rinse hybrid layers created on SDF- and SDF/KI-treated dentin were more uniform and continuous (Fig. 4 A1-A11; C1-C11). H₃PO₄ etching followed by water rinsing removed not only smear layer and dentin minerals, but also SDF and SDF/KI precipitates and residual high alkalinity compounds. Silver and iodide ions remain present on dentin surfaces after H₃PO₄ etching [26] (Fig. 5 H; I). Since hybrid layer and resin tag formation were comparable to untreated dentin (Fig. 4), it is possible to speculate that monomer diffusion was not necessarily compromised by SDF and SDF/KI treatments when dentin was etched with H₃PO₄. H₃PO₄ etching followed by 15 s water rinsing eliminated any potential drawbacks of SDF and SDF/KI treatments on immediate bond strengths of etch-and-rinse applications. Differently from self-etch bonding, storage periods up to 30 days and air abrasion did not benefit etch-and-rinse bonding to SDF- and SDF/KI-treated dentin. The choice of immediate bonding to SDF- or SDF/KI-treated dentin in etch-and-rinse mode seems assertive at first, even though self-etch bonding can indeed produce comparable bonding given appropriate conditions. It is important to consider that bonding protocols that preserve SDF at the hybrid layer

resulting in higher mineral deposition emerge as a new alternative to potentialize anticariogenic properties and even reduce enzymatic degradation of hybrid layers over time [13,14]. Such possibilities should be evaluated by long-term *in vitro* studies.

5. Conclusion

Resin bonding to SDF- and SDF/KI-treated dentin should not be underestimated. Application mode selection (*i.e.*, self-etch or etch-and-rinse) and adhesive protocols are critical to avoid impairments in resin-dentin bonding. Unlike self-etch bonding, conventional H₃PO₄ etching excludes any potential drawbacks. Although rinsing residual SDF contents before self-etch bonding reverts SDF- and SDF/KI-related bonding inefficiencies, delayed bonding offers the additional benefit of reducing dentin permeability through higher mineral deposition over time. Given the right conditions, SDF and SDF/KI treatments may potentialize mineral deposition at resin-dentin interfaces for more effective caries control, contributing to improved service life of composite restorations.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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