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Shear Bond Strength of Different Adhesive Systems to Silver Diamine Fluoride - Treated Carious Dentine

(Kekuatan Ikatan Ricih Sistem Pelekat Berbeza kepada Fluorida Perak Diamine - Dentin Karies yang Dirawat)

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ABSTRACT

This study investigated the shear bond strength (SBS) of resin composite to silver diamine fluoride (SDF)-treated carious dentine using different adhesive systems and established their failure modes. A total of 75 sound premolars were randomly assigned as follows (n=15); sound dentine with universal adhesive (UA) and etchant (Group A), SDF-treated carious dentine with UA and etchant (Group B), UA without etchant (Group C), glass ionomer (Group D) and alloy (Group E) adhesive systems. Groups B, C, D, and E were subjected to pH cycling to form artificial caries. Resin composite cylinders were bonded to the occlusal surfaces of the treated teeth. The SBS was established using a universal testing machine with shear load of 500N and crosshead speed of 0.5 mm/min. Data for SBS and failure modes were analysed using One-way ANOVA and Pearson Chi-square test, respectively. For SDF-treated carious dentine, Group C presented the highest SBS, followed by Groups B, E, and D. The SBS of Group D and E were significantly lower than Groups A, B, and C. No significant difference in SBS was found between Groups A, B and C. While Group B had significantly fewer adhesive failures, the proportion of mixed failures was statistically insignificant among the different groups. Resin composite cohesive failures were only observed in Group B. In conclusion, UA without etchant is preferred when bonding resin composite to SDF-treated carious dentine. Failure modes were related to the type of adhesive system utilised.

Keywords: Bonding; dental adhesive; resin composite; silver diamine fluoride

ABSTRAK

Tujuan kajian adalah untuk menilai kekuatan ikatan ricih (KIR) menggunakan sistem pelekatan berbeza pada permukaan dentin berkaries yang telah dirawat dengan *silver diamine fluoride* (SDF) serta mengenal pasti mod kegagalan bagi setiap sistem pelekatan tersebut. 75 pramolar dibahagikan kepada lima kumpulan seperti berikut (n=15); dentin sihat dirawat dengan pelekat universal menggunakan etsa asid (Kumpulan A), dentin berkaries dirawat dengan SDF dan sistem pelekat universal menggunakan etsa asid (Kumpulan B), sistem pelekat universal tanpa etsa asid (Kumpulan C), sistem pelekat simen ionomer kaca (GIC) (Kumpulan D) dan sistem pelekat aloi (Kumpulan E). Kitaran pH dilaksanakan pada Kumpulan B, C, D dan E untuk menghasilkan karies tiruan. Silinder resin komposit dilekatkan pada permukaan dentin yang telah dirawat. KIR dikaji menggunakan *universal testing machine* dengan beban ricih 500N dan kelajuan *crosshead* 0.5 mm/min. Analisis data KIR menggunakan *ANOVA* satu hala dan *Pearson* khi kuasa dua digunakan untuk menganalisis mod kegagalan. Bagi kumpulan dentin berkaries yang telah dirawat oleh SDF, Kumpulan C mempunyai KIR paling tinggi, diikuti Kumpulan B, E dan D. KIR Kumpulan D dan E jauh lebih rendah daripada Kumpulan A, B dan C. Tiada perbezaan KIR antara Kumpulan A, B dan C. Kumpulan B mempunyai kegagalan pelekat jauh lebih rendah berbanding dengan kumpulan lain dan tiada perbezaan kegagalan campuran antara semua kumpulan. Kegagalan perpaduan dalam resin komposit hanya terdapat di dalam Kumpulan B. Kesimpulannya, pelekat universal tanpa etsa asid lebih diutamakan untuk mengikat resin komposit pada dentin berkaries yang telah dirawat SDF. Terdapat kaitan antara jenis kegagalan dan sistem pelekatan yang digunakan.

Kata kunci: Ikatan; resin komposit; *silver diamine fluoride*; sistem pelekat

INTRODUCTION

Advancements in medicine and dentistry have led to significant improvements in people's general and oral health thus, increasing their life expectancy. The increase in life expectancy and the presence of more teeth retained among older adults has inevitably resulted in more root caries formation. The prevalence of root caries among older adults could be as high as the occurrence of coronal caries among younger adults (Zhang et al. 2013). Studies conducted in the United States, Canada, Germany, Japan, India, and Sri Lanka showed a relatively wide range of root caries prevalence in older adults ranging from 29% to 89% (Gluzman et al. 2013; Imazato et al. 2006; Kularatne & Ekanayake 2007; Splieth et al. 2004). Therefore, the World Health Organization (WHO) advocates implementing caries preventive strategies to reduce the proportion of older adults with untreated coronal and root caries.

One of the strategies used is the application of fluoride agents. Silver diamine fluoride (SDF) has been acknowledged as a caries-preventive agent that is cost-effective, minimally invasive, safe, and easily accessible (Horst, Ellenikiotis & Milgrom 2016). The use of 38% SDF is getting more attention because of its benefits of preventing and arresting carious lesions due to its silver and fluoride contents (Quock et al. 2012). A highly mineralised layer with a high content of calcium and phosphate ions will be formed on SDF-treated carious lesions which can inhibit caries progression. In addition, a high concentration of silver in SDF can inhibit the degradation of dentine collagen and thus, further impede the demineralisation process (Mei et al. 2014, 2013). However, the main drawback of the SDF application is black discolouration of the carious teeth which can affect aesthetics. An *in vitro* study reported that the discolouration could be reduced by the application of potassium iodide to SDF-treated carious lesions (Knight et al. 2005). Besides that, tooth-coloured restorative materials such as glass ionomer cement (GIC) and resin composite could also be placed to mask the black discolouration and simultaneously fill up the cavitation to minimise further plaque and food retention (Quock et al. 2012).

Despite the progress made in resin composite adhesive systems, the adhesive interface between restoration and tooth structure remains the weakest area. da Silva et al. (2015) stated that the silver particles in SDF have an inhibitor effect on matrix metalloproteinases (MMP) activities. These MMPs are crucial in the degradation of resin-dentine bonding strength over time whereby it can initiate the degradation of collagen fibrils that are unprotected by the adhesive monomers. In an attempt to overcome this, MMP inhibitors are added to maintain the stability of resin-dentine bonding. Thus, the silver ions in SDF can contribute to dentine bonding maintenance. However, due to SDF's high content of silver ions, the collagens are more resistant which may possess possible bonding issues on the SDF-treated carious lesions (Mei et al. 2013).

Few studies reported that the application of SDF did not affect the bond strength of resin composite to SDF-treated sound dentine (Quock et al. 2012; Selvaraj et al. 2016; Van Duker et al. 2019). Despite being an effective anti-caries agent, SDF may affect the bonding of resin composite restorations to SDF-treated carious lesions by the occlusion of dentinal tubules by its silver particles and thus, may compromise the clinical success of resin composite restorations (Burgess & Vaghela 2018; Seto et al. 2017). A study reported that the application of SDF reduced the bond strength to both sound and carious dentine, which may be due to the deposition of silver and fluoride ions into the dentinal tubules which may not be removed even by rinsing. Consequently, the adhesive resin failed to infiltrate into the dentinal tubules leading to the formation of a thin and irregular hybrid layer (El Ghamrawy, Nasser & Nour 2021).

It is reported that SDF had the potential to increase the bond strength of GIC to dentine (Knight & Mclntyre 2006). Besides that, there was a significant difference between self-etch (SE) and etch-and-rinse (ER) adhesive groups in terms of bond strength after the application of SDF on the sound dentine (Quock et al. 2012). However, most available studies only focused on the bond strength of GIC and resin composite restorations to sound dentine. To date, few studies have examined the bonding of different resin composite adhesive systems to SDF-treated carious dentine. One study specified that the bond strength of resin composite restorations to carious dentine was significantly lower than sound dentine (Kucukyilmaz et al. 2016). The use of different adhesive systems including GIC and alloy bonding technology can be considered for enhancing the bond of resin composite restorations to the SDF-treated carious teeth.

This study aimed to compare the bond strengths of resin composite to SDF-treated carious dentine using different adhesive systems as well as to determine the failure modes associated with these adhesive systems. The null hypothesis is there are no significant differences in bond strengths and failure modes among the various adhesive systems when used to bond resin composite to SDF-treated carious dentine.

MATERIALS AND METHODS

ETHICAL APPROVAL

Our study protocol was approved by the Universiti Malaya Research Ethics Committee (UMREC) (DF RD 1924/0087).

STUDY DESIGN AND SAMPLE SELECTION

This study consists of two parts; (A) shear bond strength (SBS) test and (B) failure modes associated with different adhesive systems. The materials used in this study are summarised in Table 1. Seventy-five extracted sound human premolars that were free from decay, cracks, and restorations were collected. The teeth were cleaned with an ultrasonic scaler to remove hard and soft tissue debris, and stored in a 0.5% chloramine-T trihydrate solution at 4 °C until further use (Demarco et al. 2012; Inoue et al. 2004; Mobarak et al. 2010).

PART A – SHEAR BOND STRENGTH (SBS) TEST

SAMPLE PREPARATION

The root surfaces of each tooth were first marked 2.0 mm below the cementoenamel junction. Each tooth was embedded vertically in clear cold curing epoxy resin to the previously marked level (Kucukyilmaz et al. 2016). The teeth were then sectioned approximately 2.0 mm from the central fissure using a low-speed sectioning machine (Metkon®, Bursa, Turkey) with a water-cooled diamond disc to establish a flat occlusal dentine surface (Hegde & Bhandary 2008). The flat dentine surfaces were then inspected under a stereomicroscope at 10x magnifications to ensure no remnants of enamel, white spots, microcracks, and exposed pulp. The dentine surfaces were polished for 60 s with 400 grit and 600 grit silicon carbide (SiC) papers (Carvalho et al. 2014).

PRODUCTION OF ARTIFICIAL CARIES

The dentine surfaces of sixty premolars were subjected to pH cycling to produce artificial carious dentine lesions. A layer of nail varnish was applied onto the exposed tooth surfaces except for the bond area and 1.0 mm beyond the bond area to protect the remaining surfaces from the demineralisation process (Ferreira et al. 2007). The demineralisation solution was prepared using 2.2 mM NaH_2PO_4, 2.2 mM $CaCl_2$, and 50 mM acetic acid at pH 4.8. The remineralisation solution was prepared using 0.9 mM NaH_2PO_4, 1.5 mM $CaCl_2$, and 0.15 mM KCl at pH 7.0 (Kucukyilmaz et al. 2016; Turkistani et al. 2015). The specimens were immersed in 10 mL of demineralising solution at 37 °C for 8 h and remineralising solution at 37 °C for 16 h. This pH cycling was repeated for 14 days to create artificial caries (Kucukyilmaz et al. 2016).

DEPTH OF CARIES LESION

The carious lesion depth was assessed by using optical coherence tomography (Thorlabs, New Jersey, United States). The specimens were washed with deionised water and fixed on a micrometer metal stage with 5° tilt at each scanning time to reduce specular surface reflections. A thin film of a water-based gel consisting of 2% hydroxyethylcellulose was applied to standardise the hydration condition of the surface (Turkistani et al. 2015). The expected depth of the initial carious lesion depth after being exposed to 14 days of the cariogenic challenge was 80 µm to 120 µm (Fried et al. 2002).

TREATMENT GROUPING

The sixty premolar teeth with artificial caries were randomly divided into four groups of fifteen specimens each as shown in Table 2. A reference group (Group A) where a universal adhesive (UA) system with etchant was applied to sound dentine without SDF was incorporated. The light-curing unit used was the Spectrum® light curing unit (Dentsply Caulk, Milford, DE 19963) with mean intensity of the light source (460 ± 5 mW/cm^2) determined with a radiometer (Cure Rite®, EFOS Inc, Ontario, Canada). The procedure for Group A is as follows:

Group A – Super Etch® was applied on the sound dentine surface for 20 s and washed thoroughly. The dentinal surface was then rinsed thoroughly and gently air dried. Zipbond® Universal Adhesive (SDI, Victoria, Australia) was scrubbed on the sound dentinal surface for 10 s, left *in situ* for 10 s, gently blown with dry, oil-free air for 2 s to evaporate the solvent until a glossy appearance was obtained. The surface was then light-cured for 10 s.

The subsequent four groups (Group B – Group E) were the test groups whereby specimens were treated with SDF and reviewed at 2 and 4 weeks. The procedure for SDF application is as follows: The carious dentine surface was kept dry before the application of SDF. The SDF solution was applied on the carious dentine surface using a microbrush for 60 s. The surface was gently blown with dry, oil-free air for 2 s. After the application of SDF, the following adhesive systems were applied accordingly.

Group B - Super Etch® (SDI, Victoria, Australia) was applied to the SDF-treated carious dentine surface for 20 s and washed thoroughly. The dentinal surface was then rinsed thoroughly and gently air dried. Zipbond® Universal Adhesive was scrubbed on the SDF-treated carious dentine surface, gently blown with dry, oil-free air for 2 s to evaporate the solvent until a glossy appearance was obtained. The adhesive was then light-cured for 10 s.

Group C – Zipbond® Universal Adhesive was applied on the SDF-treated carious dentine surface, gently blown with dry, oil-free air for 2 s to evaporate solvent until a glossy appearance was obtained. The adhesive was then light-cured for 10 s.

Group D – Riva Conditioner® (SDI, Victoria, Australia) was applied on the SDF-treated carious dentine surface for 10 s and rinsed thoroughly with water, followed by 5 s of air drying. Riva Bond LC® (SDI, Victoria, Australia) was applied over the surface in a thin layer and light-cured for 10 s.

Group E - Super Etch® was applied to the SDF-treated carious dentine surface for 20 s and washed thoroughly. The dentinal surface was then rinsed thoroughly and gently air dried. Alloybond Primer® (SDI, Victoria, Australia) was applied on the surface, gently blown with dry, oil-free air for 2 s until a glossy appearance was obtained. The adhesive was then light-cured for 10 s. Next, a mixture of one drop of Alloybond Base® and Alloybond Catalyst® (SDI, Victoria, Australia) was applied to the surface.

RESTORATIVE PROCEDURE

A stainless-steel split mold with an internal recess of 4.0 mm diameter and 2.0 mm depth was placed on the flat dentinal surface and stabilised with sticky wax. The resin composite (Aura Easy®, shade AE1; SDI, Victoria, Australia) was placed and light-cured for 20 s to form a restoration cylinder. The light-curing unit used was the Spectrum® light curing unit (Dentsply Caulk, Milford, DE 19963) with mean intensity of the light source (460 ± 5 mW/cm^2) determined with a radiometer (Cure Rite®, EFOS Inc, Ontario, Canada). Resin composite flashes were carefully removed with a scalpel blade and inspected under a stereomicroscope at 10x magnifications. Subsequently, the specimens were thermally cycled for 500 cycles with a thermocycling machine (ATDM T6PD UM, Malaysia) following the ISO recommendation (ISO/TS11405:2003). Each thermal cycle involved a dwell time of 20 s at 5 °C and 55 °C with a 10 s transfer interval (Li, Burrow & Tyas 2002).

SHEAR BOND STRENGTH (SBS) TEST

Each specimen was positioned in the universal testing machine (UTM) (Shimadzu, Tokyo, Japan) with a custom-made notched rod jig. The long axis of the specimen was placed perpendicular to the direction of the applied force. The bonded surface was placed parallel to the shear jig. A shear load of 500N was then applied at a crosshead speed of 0.5 mm per minute using UTM (Shooter, Griffin & Kerr 2012). The force required to separate the restorative cylinders from the bonded dentine surfaces was duly recorded and bond strength computed. A shear bond strength was expressed in Mega-Pascals (MPa), by dividing the maximum value of force at failure in newtons (N) by the bonding area in square millimeters (mm^2).

PART B – FAILURE MODES ASSESSMENT

ASSESSMENT OF FAILURE MODES

The debonded surfaces were examined under a stereomicroscope using 10x magnifications to determine the mode of failure using cell^D software version 5.1 (Olympus, Tokyo, Japan). Three measurements were taken for each specimen. Failure mode was measured as a percentage of the bonding area. The failure mode of each specimen was recorded according to the following classifications (El-Din et al. 2006): Adhesive failure: More than 75% of the bonding area was exposed dentine; Cohesive failure: More than 75% of the bonding area was covered with remnants of resin composite; and Mixed failure: A combination of both adhesive and cohesive failures between 25% and 75% of the bonding area.

STATISTICAL ANALYSIS

Data were analysed using SPSS version 26. Descriptive statistics were performed and the mean SBS with standard and percentage of failure modes were reported. Numerical data were then subjected to the Shapiro-Wilk test to ascertain normality. Comparison of SBS between different adhesive systems was analysed using one-way analysis of variance (ANOVA) and post-hoc Dunnett T3 test as data was normally distributed. Differences in failure mode distributions were analysed using Pearson Chi-square and post-hoc Z test.

RESULTS AND DISCUSSION

MEAN SHEAR BOND STRENGTH (SBS)

Four adhesive strategies were selected and sound dentine with UA and etchant was used as the reference group for this study. It was assumed that the application of 37% phosphoric acid etchant onto sound dentine followed by adhesive resin was the gold standard among the adhesive systems (Al Qahtani & Alshehthri 2010; El Sayed et al. 2015; Kamel et al. 2014). The use of 37% phosphoric acid with UA on the dentine demineralises up 5 μm to 8 μm of the intertubular dentine matrix creating nanometer-sized porosities. This promotes penetration of resin monomers into and around the collagen fibrils. Besides that, the acidic monomer in the UA can partially dissolve and infiltrate through the smear layer, thus, promotes stronger bond strength.

The mean SBS for various groups are presented in Table 3. Group C presented with the highest mean SBS (22.12 ± 8.12 MPa) followed by Group B (21.15 ± 9.85 MPa). The UA system contains the acidic functional monomer 10-MDP. It was reported that the 10-MDP was able to demineralise hydroxyapatite more effectively and produced greater amounts of calcium salt as compared to other monomers such as 4-MET (Fujita & Nishiyama 2006). This was attributed to the lower acid dissociation constant value of the phosphate group of 10-MDP than that of the carboxyl group of 4-MET (Nishiyama et al. 2007). This may contribute to the high SBS of UA systems as compared to other adhesive systems used in this study.

No significant difference was found in SBS between Group A, B, and C (p > 0.05). This was supported by Perdigão, Sezinando and Monteiro (2012) which stated that the application of UA was not influenced by the use of prior etchant. The phosphate group of 10-MDP has the potential to interact with hydroxyapatite. It is thought to improve the initial bond strength to dentine due to micromechanical interlocking around the residual hydroxyapatite crystals. Moreover, 10-MDP contains two hydroxyl groups that can stimulate chelation of calcium ions forming the ionic bonds with calcium, which contributes to the long-term durability of the resin/dentine interface (Inoue et al. 2004; Matsui et al. 2015; Peumans et al. 2015).

The use of the UA system without acid etching may reduce the risk of post-operative sensitivity and collagen fibrils undergoing further demineralisation, which could compromise the bond stability over time (Van Meerbeek et al. 2011). Moreover, the high SBS following application of SDF before the UA system is assumed to be related to the occluding effect of silver ions deposition that limits intrinsic fluid movement at the adhesive interface.

Previous nanoleakage studies reported that water-filled regions were observed in the hybrid and adhesive resin layers. These regions were thought to be responsible for fluid movement from the underlying hydrated dentine, through the adhesive layer to the adhesive-composite interface (Tay & Pashley 2003; Tay, Pashley & Yoshiyama 2002; Tay et al. 2003). Since the SDF application created a dense layer of silver ions in the dentinal tubules, the fluid movement during the adhesive application was reduced as these regions may be filled with silver ions, and thus, positively influenced the bond strength of the adhesive to the resin composite (Hashimoto et al. 2004).

The SBS in Group D and E were significantly lower than Group A, B, and C. Silver particles from a silver phosphate layer formed following application of SDF extend into the dentinal tubules, causing total or partial obstructions in the dentinal tubules. It was assumed that the application of SDF would enhance the incorporation of positively charged silver ions and silver deposits into the SDF-treated carious dentine which can improve the chemical bonding to the negatively charged carboxyl groups of GIC adhesive system (Vuong 2020).

However, this contradicts previous studies that reported the application of SDF resulting in the deposition of silver ions could adversely affect the bond strength of GIC to dentine (Knight et al. 2005; Mei et al. 2013; Sayed et al. 2018). The GIC adhesive system can form a thin acid-base-resistant layer on the tooth substrate. The thin acid-base-resistant layer may prevent effective etching by polyacrylic acid. It was shown under a scanning electron microscope (SEM) that the interaction of the SDF precipitate and resin formed a more electron-dense layer and thus prevented intimate adaptation of the adhesive to the SDF-treated carious dentine (Koizumi, Hamama & Burrow 2016). This suggested that the SDF precipitate was not completely removed after the polyacrylic acid, resulting in low SBS of GIC adhesive system to SDF-treated dentine (Khor et al. 2022; Koizumi, Hamama & Burrow 2016; Ng et al. 2020).

Application of SDF onto carious dentine increases the carious dentine's microhardness by precipitation of less soluble calcium fluoride, silver phosphate and silver protein on the dentine surface (Yokoyama, Matsumoto & Murase 2000). As silver and its compound in SDF can infiltrate into the dentinal tubules following SDF application, these silver ions may improve the bond strength of resin composite to SDF-treated carious dentine by using alloy primer bonding. Hence, AlloyBond® was used as one of the test groups in the study.

The alloy adhesive system used in the study (AlloyBond®) containing 44% dimethacrylate resin with carboxylic groups is thought to provide twice the cross-linking compared to GIC adhesive system (Riva-Bond LC®). The additional cross-links led to a stronger resin matrix, greater cohesive strength and superior chemical bonding (Hicks et al. 2002). However, a low SBS value was observed when used on SDF-treated carious dentine. This may suggest that the silver ions have no potential to improve the bond strength of the resin composite to the SDF-treated carious dentine by blocking the penetration of the adhesive resins into the dentinal tubules.

TYPES OF FAILURE

The failure mode distributions are reflected in Table 4. Most groups exhibited more adhesive failure than cohesive failure in the resin composite and mixed failures. All samples in Groups D and E presented with adhesive failure (100%), while 93.3%, 80,0%, and 66.7% of the specimens in Groups A, C, and B had adhesive failures. Mixed failure was also observed in Groups A (6.7%), B (20.0%), and C (20.0%). No significant difference was observed in mixed failure among different adhesive systems (p > 0.05). A selection of stereomicroscope images taken at 10x magnification is shown in Figure 1(a)-1(c).

TABLE 1. Manufacturer and composition overview of silver diamine fluoride, resin composite and adhesive systems

Material	Type	Chemical composition
Riva Star® (SDI, Victoria, Australia)	Silver diamine fluoride	35% to 40% silver fluoride, 15% to 20% ammonia, water
Auraeasy® (SDI, Victoria, Australia)	Resin composite	3% to 20% diurethane dimethacrylate, 0.01% to 7% TEGDMA and 15% to 18% 2,2-bis[4-(2-methacryloxy)ethoxy)phenyl]propene.
Zipbond® Universal Adhesive (SDI, Victoria, Australia)	Universal Adhesive	10-MDP, fluoride, photoinitiator
Riva Bond LC® (SDI, Victoria, Australia)	Powder	15% - 25% acrylic acid homopolymer, 1% - 5% tartaric acid, 5% - 15% dimethacrylate cross-linker, 10% - 20% acidic monomer, 95% - 100% strontium fluoroaluminosilicate glass powder
	Liquid	Acrylic acid copolymer Methacrylate resin monomer, water, 25% - 40% HEMA, photoinitiator
AlloyBond® (SDI, Victoria, Australia)	Primer	54% acetone, HEMA, fluoride, 44% dimethacrylate resin with carboxylic groups monomer, UDMA, water, photoinitiator
	Base	UDMA, TEGDMA, initiator, stabiliser
	Catalyst	UDMA, TEGDMA, Benzoyl peroxide, stabiliser

10-MDP, 10-methacryloyloxydecyl dihydrogenphosphate; HEMA, 2-hydroxyethyl methacrylate; UDMA, Urethane dimethacrylate or 1,6 – di(methacryloyloxyethylcarbamoy)-3, 30, 5-trimethylhexaan; TEGDMA, Triethylene glycol dimethacrylate

TABLE 2. Treatment grouping

Group	Description
A	Reference – sound dentine with etchant and UA
B	SDF-treated carious dentine with etchant and UA
C	SDF-treated carious dentine and UA
D	SDF-treated carious dentine with dentine conditioner and GIC adhesive system
E	SDF-treated carious dentine with etchant and alloy adhesive system

TABLE 3. Mean SBS values (MPa) and standard deviation

Group	Mean SBS (MPa)	Standard deviation
A	20.22	7.55
B	21.15	9.85
C	22.12	8.12
D	12.55	3.53
E	12.77	2.06

The most frequent failure mode observed with the UA groups was adhesive failures. Findings were consistent with previous studies by Luque-Martinez et al. (2014), Munoz et al. (2014), Perdigão, Sezinando and Monteiro (2012), and Wagner et al. (2014). Moreover, adhesive failure was also the prevalent type of failure for other UA systems following SDF application (Markham et al. 2020). SDF precipitates in the dentinal tubules is postulated to have adverse effects on the adhesion to dentine with these UA systems (Markham et al. 2020).

Adhesive failure was also the predominant failure mode observed with GIC adhesive systems (Becci et al. 2017). The high percentage of adhesive failures with GIC systems may be correlated with thin cylindrical resin tag formation following dentine conditioning with polyacrylic acid (Hamama, Burrow & Yiu 2014) as well as a lack of true chemical interaction between the dentine and the adhesive system (Geiger et al. 2001).

Cohesive failures in resin composite were only observed in SDF-treated carious dentine with UA and acid etching. Table 5 compares the proportions of the various failure modes among the five groups. Group B had significantly fewer adhesive failures and more cohesive failures in resin composite than Group A, C, D, and E ($p < 0.05$). A similar finding was observed in a previous study whereby 50% of failures of UA systems containing 10-MDP with etchant were cohesive within the bonding resin (Marchesi et al. 2014). It was reported that when phosphoric acid was applied to dentine, the application of the UA resulted in stronger bond strength as compared to when the UA was applied on smear layer-covered dentine, and thus lead to more cohesive failures within the bonding resin.

Earlier studies have also stated that the most frequent failure in adhesive systems containing 10-MDP was cohesive failures in resin composite (Doi et al. 2004; Van Landuyt et al. 2006). This may be ascribed by the affinity of 10-MDP for hydroxyapatite, thus enhanced the bond between the adhesive to the dentine (Van Landuyt et al. 2006). This study only evaluated the SBS of different adhesive systems to SDF-treated carious dentine using only one resin composite material. Further studies should assess the influence of SDF in combination with other restorative materials such as GIC, resin-modified GIC and different types of resin composite. In addition, future evaluation of hybrid layer thickness and the quality of resin tags within different adhesive systems to SDF-treated carious dentine under SEM evaluations for a better understanding of the mechanism of failure between the SDF-treated carious dentine and adhesive system applied. Besides that, future studies may also be able to suggest the bonding protocol to maximise the bond strength of resin composite to SDF-treated carious dentine.

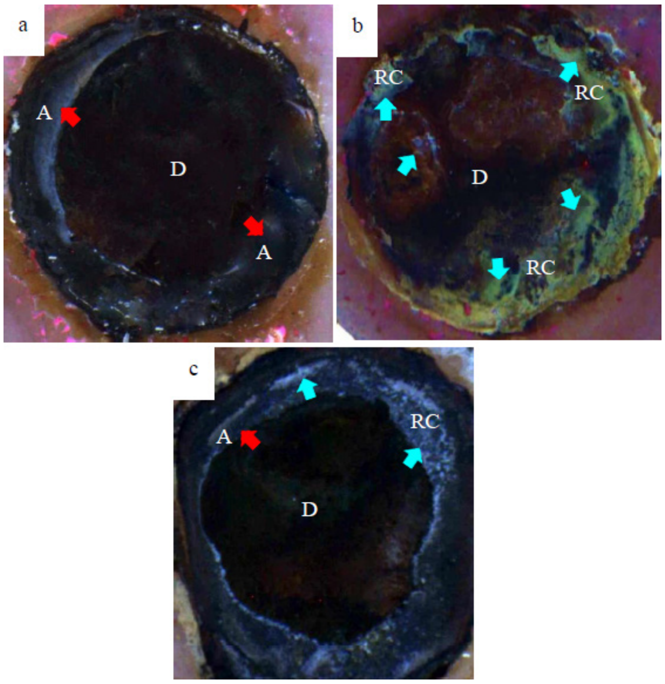
TABLE 4. Types of failure

Group	Adhesive failure	Cohesive failure	Mixed failure
A	93.3%	0%	6.7%
B	66.7%	13.3%	20.0%
C	80.0%	0%	20.0%
D	100.0%	0%	0%
E	100.0%	0%	0%

TABLE 5. Comparison of type of failures between groups

	Differences[a]		
	Adhesive failure	Cohesive failure	Mixed failure
Groups	D, E, A, C > B	B > A, C, D, E	No significance

[a] Results of post-hoc Z test ($p < 0.05$); > indicates statistically significant differences in type of failure between groups



a) Adhesive failure b) Cohesive failure in resin composite c) Mixed failure
*A = Adhesive; D = Dentine; RC = Resin composite; Red arrow = Adhesive failure; Blue arrow = Cohesive failure

FIGURE 1. Stereomicroscope images of failure modes

CONCLUSIONS

Within the limitations of the study, it was concluded that the universal adhesive system with and without prior etchant is preferred over GIC and metal adhesive systems when bonding the composite to SDF-treated carious dentine.

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