SMART: Silver diamine fluoride reduces microtensile bond strength of glass ionomer cement to sound and artificial caries-affected dentin

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Silver-modified atraumatic restorative technique (SMART) is an emerging restorative technique; however, the effect of silver diamine fluoride (SDF) application on the bond strength of glass ionomer cement (GIC) is unknown. This study aimed to determine if SDF application to sound and artificial caries-affected dentin (ACAD) immediately prior to GIC restoration affected microtensile bond strength (μTBS). Caries was induced on extracted molars using a pH-cycling protocol that was validated against natural caries (similar μTBS). Dentin surfaces were treated with 38% SDF, control groups with de-ionized water and immediately restored. Beam-shaped specimens were sectioned and subjected to tensile forces for μTBS determination. Two hundred and eighty-seven specimens from 40 teeth were tested. SDF application significantly (p<0.001) reduced μTBS in sound dentin (19.00±8.20 MPa vs. 14.60±6.68 MPa), while no difference was found in ACAD. No difference was found in failure mode among groups. For SMART, SDF application on sound dentin before immediate GIC restoration may decrease bond strength.

Keywords: Dental atraumatic restorative treatment, Dental bonding, Glass ionomer cement, Minimally invasive dentistry, Silver diamine fluoride

INTRODUCTION

Biological treatment techniques involve altering the environment of the caries-causing biofilm to arrest caries progression while preserving tooth structure³. Some of these techniques include: Hall technique crown, atraumatic restorative technique (ART), and silver diamine fluoride (SDF) application. So far, the clinical outcomes of biological caries management techniques are comparable to conventional caries management techniques⁵, and have been suggested as an alternative to treatment under general anaesthesia for paediatric patients⁶.

ART involves the removal of carious tissue with hand instrumentation, followed by placement of an adhesive restoration such as glass ionomer cement (GIC)⁴. The restoration provides a hermetic seal which limits the remaining biofilm's access to fermentable carbohydrates, and allows the underlying dentin to remineralize⁶. The elimination of handpiece use and local anaesthesia minimizes discomfort for the child and has been associated with better child cooperation⁵. Several studies have reported comparable 2-year survival rates between conventional (e.g., amalgam and composite resin) and ART restorations⁶,⁷. However, survival rates in multi-surface restorations are evidently lower regardless of the material or technique used⁷. A significant proportion of multi-surface restorations result in failures associated with microleakage, which exposes biofilm that was left behind during the ART procedure to cariogenic substrate, leading to reactivation of the carious process.

SDF is a colorless, odorless alkaline solution composed of fluoride ions and a diamine-silver complex⁸. In a systematic review by Gao et al., the authors concluded that 65.9% of carious dentin lesions were arrested by 38% SDF⁹. The mechanism of action of SDF for caries arrest is threefold: remineralization of the carious lesion, antimicrobial action on the biofilm, and modification of enzymatic activity causing dentin degradation³⁰. The application of SDF does not require any removal of carious tissue, and is painless and quick¹¹. However, SDF stains the dentin with a dark discoloration that may be aesthetically displeasing. In addition, the cavity remains open which may continue to trap plaque, resulting in reactivation of the carious process. Thus, many dentists choose to restore SDF-treated teeth to improve cleansability, protect pulpal health and restore the function and form of the tooth¹².

Silver-modified atraumatic restorative technique (SMART) is an emerging restorative technique among clinicians that involves gross caries removal without local anaesthesia, leaving affected dentin at the base of the cavity and sound dentin at the periphery¹³. SDF is applied to the affected dentin surface, followed by placement of a GIC restoration at the same visit. Advocates of SMART propose that this technique combines the benefits of SDF and ART, and can be provided out-of-office (e.g. nursing homes) and on less cooperative patients (e.g. paediatric patients). Partial caries removal in ART reduces the likelihood of a pulp exposure, while SDF’s antimicrobial effect arrests the activity of bacterial biofilm remaining in the cavity.
Subsequent placement of a GIC restoration isolates the cariogenic biofilm from the fermentable carbohydrate substrate, minimizes food trap caused by an open cavity and lessens the dark discoloration caused by SDF. Supporters of SMART further suggest that in the event of microleakage of the restoration, the bacterial biofilm would have been deactivated by SDF’s antimicrobial action, minimizing the likelihood of the carious process reactivating. However, the two techniques appear to be diametrically opposed. SDF-treated dentin requires exposure to oral fluids for remineralization based on its mechanistic actions, while the success of an ART restoration is predicated on its seal, which may be affected by SDF application.

Currently, there are no clinical studies specifically examining the success of SMART restorations. There are several in vitro studies examining the bond strength of GIC to dentin treated with SDF; however, the research objectives and methodology vary greatly among them. Significant confounders in existing studies that could affect the comparison of bond strength were the use of caries simulation protocols resulting in higher bond strength in simulated caries compared to sound dentin and the use of different methods of bond strength testing (e.g., microshear). The objective of the present study was to determine the effect of SDF application immediately prior to restoration on the microtensile bond strength (μTBS) of GIC to sound dentin and chemically induced artificial caries-affected dentin (ACAD).

MATERIALS AND METHODS

Extracted carious and sound permanent molars with no visible dentin defects and no prior restorations were collected from patients who presented to the National University Center for Oral Health Singapore over a 15-month period from September 2019 to December 2020. The study was approved by the National Healthcare Group ethics board (DSRB: 2019/00438) and informed consent was obtained. Freshly extracted molars were stored in de-ionized water at 4ºC. Within 24 to 48 h after extraction, the molars were cleaned of any debris, classified as “non-carious” or “carious” based on the ICDAS classification system by a single examiner (MK), and were subsequently stored in 0.1% thymol for disinfection at 4ºC.

Validation of artificial caries protocol

In the preliminary experiments, natural caries was prepared by removing infected dentin with a spoon excavator and leathery, caries-affected dentin left behind. The bond strength to natural caries (6.9±4.60 MPa) was similar to the artificial caries demineralized at pH 4.5 (8.21±4.15 MPa), but significantly lower (p=0.012) compared to the artificial caries demineralized at pH 4.8 (12.57±7.28 MPa). Therefore, the former was adopted in this study.

Preparation of ACAD

This was achieved using the method detailed by Lenzi et al. Current occlusal surface and roots of each non-carious molar were sectioned off with a water-cooled precision cutter (IsoMet 1000, Buehler, Lake Bluff, IL, USA) to expose a flat occlusal dentin bonding surface. After sectioning, the occlusal surfaces were verified visually to ensure that there was no pulp exposure and enamel or carious dentin remaining on the bonding surface of each molar. Pulp chambers were filled with composite resin to reinforce the tooth structure. The prepared occlusal dentin surface was progressively polished with silicon carbide sandpaper in grits of 800 and 1200 in a grinder (EcoMet 30, Buehler) for 15 s each using manual pressure to smoothen the bonding surface.

Except for the occlusal dentin surface, all other surfaces were coated twice with acid-resistant varnish (OPL, Calabasas, CA, USA). Demineralizing solutions (2.2 mM CaCl2, 2.2 mM NaH2PO4, and 50 mM acetic acid) were prepared and adjusted to pH 4.5. The sectioned molars were suspended in 10 mL of demineralizing solution for 8 h, washed and dried, followed by suspending in 10 mL of a remineralizing solution (1.5 mM CaCl2, 0.9 mM NaH2PO4, and 0.15 M KCl, at a pH of 7.0) for 16 h. This cycle was repeated for 14 days. All solutions were replaced after every 24 h.

Experimental groups

The μTBS of four experimental groups (Sound-W, Sound-SDF, Carious-W, Carious-SDF) to GIC were determined by subjecting the different groups to procedures as described in Fig. 1. Using block randomization, 10 non-carious molars per group were assigned to the four treatment groups (n=40). For the sound dentin groups (Sound-W, Sound-SDF), the sectioned molars in both groups were suspended in 10 mL of de-ionized water. The de-ionized water was replaced at every 8- and 16-h interval, and the process was repeated for 14 days. For the ACAD groups (Carious-W, Carious-SDF), caries-affected dentin was induced on occlusal dentin as per the artificial caries protocol.

For non-SDF groups (Sound-W, Carious-W), de-ionized water was applied to the occlusal dentin surface of sectioned molars using a microbrush (Medicom, West Palm Beach, FL, USA) for 1 min, followed by drying with a 10 s stream of air from the triple function syringe at a distance of 5-mm from the dentin surface. The surface was then rinsed with de-ionized water for 30 s. For SDF treatment groups (Sound-SDF, Carious-SDF), 38% SDF solution (Advantage Arrest™, Elevate Oral Care, Quebec, Canada) for 1 min, followed by drying with a 10 s stream of air from the triple function syringe at a distance of 5-mm from the dentin surface. The surface was then rinsed with de-ionized water for 30 s.11,13

Bonding of GIC

The occlusal dentin surface of each sectioned molar...
was conditioned using 10% polyacrylic acid (Dentin Conditioner, GC, Tokyo, Japan) for 20 s, rinsed with de-ionized water for 10 s and blot-dried with a cotton pellet. Self-curing GIC (Fuji IX GP® Extra, GC) was mixed with a triturator for 10 s. GIC was applied to the occlusal dentin surface of each sectioned molar using a mould, and coated with soft paraffin (Orion, Perth, Australia) to prevent desiccation after 2.5 min. GIC was allowed to set for 10 min, following which all the sectioned molars bonded with GIC were stored at 100% relative humidity for 48 h.

**Preparation of specimens for μTBS test**

Each bonded molar was sectioned to produce beam-shaped specimens with a 1-mm² surface area of bonding between the GIC and dentin surface. The width and breadth of each beam was verified with an electronic caliper (±0.03 mm; EC-9001BL, Metrology, Kaohsiung, Taiwan) and the surface area tested was calculated. Each specimen was individually labelled and stored in de-ionized water at room temperature for 24 h prior to testing.

**μTBS testing**

Each specimen was fixed to a Geraldeli jig (Odeme, Santa Catarina, Brazil) using cyanoacrylate (Yamayo, Singapore) and tested in a universal testing machine (AG-X plus, Shimadzu, Kyoto, Japan). A tensile force was applied to each specimen at a crosshead speed of 1-mm per minute until failure. The maximum stress at failure was recorded. The maximum stress at failure (N) was divided by the recorded bonding surface area of each specimen (mm²) to determine the μTBS (σ), which was calculated using the formula $\sigma = \frac{N}{A}$. Any failures that occurred after sectioning and before the μTBS test were recorded as having a bond strength of 0 MPa and included in the analysis.

**Characterization of failures**

The dentin-side surfaces of the fractured specimens were examined by a single examiner (MK) under a stereomicroscope (SZX16, Olympus, Tokyo, Japan) to determine the failure mode, and to ensure that there

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**Fig. 1** Overview of specimen preparation and testing.

**Fig. 2** Scale of GIC percentage failure on dentin surface. The grey staining is a result of SDF application and the pink staining is a result of plaque disclosing solution to highlight exposed dentin surface.
was no cyanoacrylate contamination at the bonding surface. To determine the failure mode, failures were first classified based on the percentage (i.e. 0–19%, 20–39%, 40–59%, 60–79%, 80–99%, 100%) of fractured GIC remaining on the examined surface area (i.e., percentage failure). A graduated scale of the percentage failures was developed to facilitate the consistency of rating, shown in Fig. 2. The percentage failure scale was validated by a second examiner (SCJ) who rated 10% of the specimens. The intraclass correlation coefficient (ICC) was 0.74, representing good agreement between the two examiners.

**Scanning electron microscope (SEM)**
Representative specimens were sputter coated in a vacuum coater (EM ACE200, Leica Microsystems, Wetzlar, Germany) and viewed using SEM (Quanta 650 FEG-SEM, FEI, Hillsboro, OR, USA) at 2,500× magnification to observe the fractured tooth surface.

**Statistical analysis**
All statistical analyses were done using SPSS 26.0 (IBM, Armonk, NY, USA). The statistical significance for all tests was set at 0.05. As multiple specimens were generated from a single tooth and could not be treated independently, a mixed model analysis was performed, in which the tooth unit was taken as a random effect to account for correlation in specimens derived from the same tooth. The distribution of failure modes within the four treatment groups were compared using Pearson’s Chi-square test.

## RESULTS

### µTBS of GIC to dentin between treatment groups
A total of 287 specimens from 40 teeth were tested across the four groups, with each group containing 64 to 87 specimens. The number of specimens that failed after sectioning and before the µTBS test (pretesting failures) were 0, 0, 2, 4 for Sound-W, Sound-SDF, Carious-W, Carious-SDF respectively. There was a significant difference (p<0.001) in µTBS between the four treatment groups using the mixed model analysis, demonstrated in Table 1. The µTBS of sound dentin groups (Sound-W, Sound-SDF) was significantly higher than the ACAD groups (Carious-W, Carious-SDF) regardless of SDF application (p<0.05). The mean µTBS of Sound-W (19.00±8.20 MPa) was significantly higher (p<0.001) than Sound-SDF (14.60±6.68 MPa). Pairwise comparisons found no significant difference (p>0.05) in the mean µTBS of Carious-W (7.36±4.05 MPa) and Carious-SDF (7.95±5.24 MPa).

### Differences in bond strength between percentage failures and failure modes
Using a mixed model analysis applied to each treatment subgroup, significant differences were found between percentage failure groups in all the treatment groups except for Carious-W, with results presented in Table 2. Lower µTBS was observed in the 0–19% percentage failure group, and higher µTBS in the >80% percentage failure group. As such, adhesive failure between GIC and dentin consisted of 0–19% percentage failure of GIC.

### Table 1 Mean µTBS at specimen level for the four treatment groups (Mixed model analysis)

<table>
<thead>
<tr>
<th>Group</th>
<th>n, specimens</th>
<th>Pretesting failure</th>
<th>Mean µTBS±SD (MPa)*</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound-W</td>
<td>71</td>
<td>0</td>
<td>19.00±8.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Sound-SDF</td>
<td>65</td>
<td>0</td>
<td>14.60±6.68&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Carious-W</td>
<td>87</td>
<td>2</td>
<td>7.36±4.05&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Carious-SDF</td>
<td>64</td>
<td>4</td>
<td>7.95±5.24&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

*Values demarcated with the same superscript letters indicate that they are not significantly different (p>0.05) when analyzed with the mixed model analysis.

### Table 2 Mean µTBS for different percentage failures

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean µTBS (MPa) of percentage failures**</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–19%</td>
<td>16.43&lt;sup&gt;b&lt;/sup&gt; 12.68&lt;sup&gt;b&lt;/sup&gt; 14.71&lt;sup&gt;b&lt;/sup&gt; 21.60&lt;sup&gt;b&lt;/sup&gt; 17.83&lt;sup&gt;b&lt;/sup&gt; 21.68&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.038&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td>20–39%</td>
<td>9.07&lt;sup&gt;d&lt;/sup&gt; 9.42&lt;sup&gt;bcd&lt;/sup&gt; 13.76&lt;sup&gt;bcd&lt;/sup&gt; 18.47&lt;sup&gt;c&lt;/sup&gt; 15.84&lt;sup&gt;b&lt;/sup&gt; 17.25&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.008&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td>40–59%</td>
<td>5.65&lt;sup&gt;b&lt;/sup&gt; 8.05&lt;sup&gt;ab&lt;/sup&gt; 6.39&lt;sup&gt;b&lt;/sup&gt; 7.16&lt;sup&gt;ab&lt;/sup&gt; 6.82&lt;sup&gt;b&lt;/sup&gt; 8.92&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.253</td>
</tr>
<tr>
<td>60–79%</td>
<td>3.64&lt;sup&gt;b&lt;/sup&gt; 7.09&lt;sup&gt;ab&lt;/sup&gt; 5.96&lt;sup&gt;bc&lt;/sup&gt; 6.21&lt;sup&gt;ab&lt;/sup&gt; 8.50&lt;sup&gt;ab&lt;/sup&gt; 10.95&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.036&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

*denote values of statistical significance (p<0.05) when analyzed with a mixed model analysis.
**Values demarcated with the same lowercase superscript letters in the same row indicate that they are not significantly different (p>0.05) in terms of mean µTBS.
Table 3  Mean µTBS of the various failure modes in four treatment groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean µTBS±SD (MPa)**</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adhesive</td>
<td>Mixed</td>
</tr>
<tr>
<td>Adhesive Mixed Cohesive (GIC)</td>
<td>16.43±7.40&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>15.77±7.21&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sound-W</td>
<td>9.07±3.84&lt;sup&gt;b&lt;/sup&gt;</td>
<td>13.61±5.39&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>Carious-W</td>
<td>5.65±3.01&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.27±4.09&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Carious-SDF</td>
<td>5.46±1.22&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>6.28±2.41&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

*Denote values of statistical significance (p<0.05) when analyzed with a mixed model analysis.
**Values demarcated with the same lowercase superscript letters in the same row indicate that they are not significantly different (p>0.05).

Fig. 3  Distribution of failure modes in treatment groups. Chi square analysis showed that the distribution of failure modes was not different between the four treatment groups (p=0.165).

Mixed failure consisted of 20–79% percentage failure of GIC. Correspondingly, 80–100% percentage failure of GIC represented cohesive failure within GIC.

Differences in bond strength between failure modes
Significant differences (p<0.05) were found between failure modes within all the treatment groups except for Carious-W, shown in Table 3. Cohesive failure had significantly higher (p<0.05) µTBS than the other types of failure in three (Sound-W, Sound-SDF, Carious-SDF) of the four groups.

Cohesive failure within GIC (all groups=61.7%) was the most common failure mode in all treatment groups. Pearson’s Chi square value (9.161,  p=0.165) indicated that there was no difference in the distribution of types of failure modes between treatment groups, seen in Fig. 3.

SEM findings
Sound-W displayed mixed failure between GIC and the dentin surface, with areas of fractured GIC and areas of exposed dentin surface with patent dentinal tubules. In Sound-SDF, areas with exposed dentin tubules showed tubules occluded with material likely to be SDF residue. Carious-W showed fibrils present on the dentin surface, with patent tubules that were wider in diameter
compared to Sound-W. Carious-SDF presented with the absence of exposed fibrils on the dentin surface and patent dentinal tubules. Microscopic voids were noted in the GIC of all examined specimens as shown in Fig. 4.

DISCUSSION

In the present study, SDF application immediately prior to restoration decreased the bond strength of GIC to sound dentin, but not to the ACAD groups. Additionally, ACAD had significantly lower bond strength to GIC compared to sound dentin, regardless of SDF application. Previous similar studies had not demonstrated a difference in the bond strengths of GIC to SDF-treated and untreated sound dentin\(^{17,18}\), which is likely attributed to the small sample size. Jiang et al. employed only a tooth-level analysis (\(n=15\) per group) which may have resulted in loss of data points from individual specimens\(^{17}\). The other study by Braz et al. was insufficiently powered (range=57–95\%) to detect a statistical difference due to the small number of specimens per group (\(n=21\)\(^{18}\)). In this study, a mixed model analysis was performed and was made possible because of the large number of specimens per treatment group (\(n=64–87\) specimens per group). Overall, the study’s findings demonstrate that the bond strength of SMART restorations is not compromised by the application of SDF. However, SDF application on sound dentin may decrease bond strength to GIC and should be further investigated.

The lower µTBS of GIC to SDF-treated sound dentin compared to untreated sound dentin may be related to the basicity of SDF (pH=10), which may hinder polyacrylic acid from removing the dentin surface smear layer prior to GIC placement\(^{21}\). Additionally, the basicity of SDF can affect the acid-base setting reaction of GIC by hampering the release of calcium and aluminium ions at the tooth-GIC interface and decrease bond strength. A second theory involves the production and presence of dense precipitates such as calcium fluoride on the SDF-treated dentin surface\(^{22}\). Calcium fluoride formation depletes calcium from the dentin surface, decreasing the availability of calcium ions in the hydroxyapatite to form ionic bonds with GIC\(^{23}\), resulting in lower bond strength. The presence of precipitates could also prevent tag formation, reducing micromechanical interlocking. Lastly, silver ions from SDF are incorporated into the hydroxyapatite structure by replacing calcium ions in the hydroxyapatite molecule\(^{24}\). This reduces the calcium ions available to form bonds with carboxylate groups in GIC, contributing to the decrease in bond strength.

ACAD should result in a poorer quality interface between caries-affected dentin and composite resin and/or glass ionomer restorations compared to sound dentin due to its lower mineral content\(^{25}\). This unfortunately has not been reproduced in several \(in vitro\) studies\(^{15,16}\); a strength of this study was the use of ACAD (Artificial-1 protocol) with comparable µTBS to GIC as natural caries-affected dentin (NCAD). While ACAD cannot perfectly mirror NCAD, it is able to provide a similar bonding surface that is more consistent and reproducible which will translate to more clinically relevant results.

A scale with good inter-rater agreement using specimens displaying different percentages of GIC fracture was developed to ensure reproducibility. In spite of the significant differences in µTBS between groups, there was no difference in the distribution of failure modes. The most common failure was cohesive failure within GIC followed by mixed failure and adhesive failure, which is consistent with other studies\(^{26}\). This may be attributed to the higher tensile strength of sound dentin and ACAD, compared to tensile strength of GIC. As such, failure was more likely to occur first at the adhesive interface, or within GIC\(^{27}\). Nonetheless, the application of the Griffith-Irwin crack theory supplemented by the theory of cohesive vs. adhesive separation in an adhesive system like the GIC/dentin interface suggests theoretically, that cohesive failures in GIC may not imply that the adhesion strength is necessarily higher than the cohesive strength of the testing materials\(^{28}\). Further studies using microshear bond testing methodologies and finite element analysis may shed a light on the effects of GIC cohesive strength when bonded to SDF-treated dentin.

A limitation of this study is the use of permanent molars rather than primary molars to evaluate the SMART, which is a technique commonly used in primary teeth. For reasons of practicality, primary teeth were not used as they were difficult to obtain. While there are some structural differences between primary and permanent dentin, a study found no significant difference in µTBS of GIC to permanent and primary tooth dentin\(^{27}\).

CONCLUSIONS

In conclusion, the application of SDF immediately prior to restoration with GIC resulted in a significantly lower µTBS on sound dentin, but had no significant effect when applied to ACAD. The findings suggested that restorations using SMART are not compromised by SDF application, but there should be consideration to avoid application of SDF to sound dentin. Additionally, GIC should be bonded to sound dentin at cavity peripheries to improve overall bond strength.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. All authors have made substantive contribution to this study and/or manuscript, and all have reviewed the final paper prior
to its submission.

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