Abstract: Minimally invasive treatment protocols may leave a residual layer of carious dentin, which requires treatment for the inhibition of bacterial growth beneath restorations. We aimed to examine the *in vivo* effect of silver diammine fluoride (SDF) and SDF + potassium iodide (KI) application on bacteria present in deep carious lesions. We studied the *in vivo* efficacy in five patients, each of which had five carious lesions. Dentin samples taken before and after treatment were subjected to microbial analyses. Following treatment with SDF, the median colony-forming unit (CFU) counts per mg of dentin reduced from $9 \times 10^5$ to $1.6 \times 10^2$ ($P < 0.05$), and following that with SDF + KI, the counts decreased from $2.9 \times 10^5$ to $9.2 \times 10^3$ ($P < 0.05$). The use of chlorhexidine gluconate (CHX) reduced CFU counts from $1.1 \times 10^5$ to $4.8 \times 10^2$ ($P < 0.05$). In four of the five patients, no CFUs were found on mitis salivarius-bacitracin agar with respect to SDF or SDF + KI application. For CHX, the median CFU count before treatment was $1.6 \times 10^3$ and that after treatment was $1.1 \times 10^2$. SDF completely inhibited mutans streptococci growth in four of the five patients, while the growth of anaerobes was not completely inhibited.

Keywords: dentin; dental caries; silver diammine fluoride; antimicrobial.

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**Introduction**

Dental caries is a chronic and multifactorial disease that is influenced by a dysbiotic microbiome. Once a carious lesion in dentin reaches a completely demineralized status, in the absence of an intervention, the lesion will progress until the tooth is destroyed (1). Once a cavity is formed, the only effective intervention is to remove the demineralized tissue, dentin, and enamel and to place a permanent restoration for restoring the form, function, and aesthetic appearance.

Among the different clinical approaches used to manage carious dentin during cavity preparation, minimally invasive techniques are of significance (2). A minimally invasive technique entails partial removal of the soft dentin, ensuring that the vitality of the underlying pulp remains intact (3,4). The soft and demineralized dentin is usually superficial, and it needs to be removed because it lacks the ability to remineralize. The affected layer, deeper dentin, still holds its structural integrity; however, the collagen is exposed due to the action of acids produced by bacteria. In a clinical situation, it is challenging to differentiate between these layers; therefore, some infected dentin may remain after cavity preparation. In minimally invasive techniques, the adhesive materials used for restoration help prevent bacterial microleakage; thus, eliminating the risk of further demineralization and cavitation (5). However, there is still concern among clinicians regarding the potential consequences of leaving infected dentin after cavity preparation. Thus, it is recommended that antimicrobial agents should be applied before placing a restoration.

Chlorhexidine gluconate (CHX), an antimicrobial
agent commonly used in dentistry, has been used for disinfecting carious lesions in several in vitro and in vivo studies (6-8). Sodium hypochlorite (NaOCl) at concentrations of 2.5-5% has also been widely used as an antimicrobial agent in dentistry (9,10). Due to its simplicity and low cost, silver diammine fluoride (SDF) treatment has recently gained attention; the topical application of SDF has been shown to be effective in caries management (11). Several clinical trials have demonstrated the effectiveness of SDF in preventing and arresting caries (12-14). However, after an extensive literature search, no adequate in vivo data on the antimicrobial efficacy of SDF on carious lesions in dentin were found to support the laboratory claims. Thus, we aimed to assess the in vivo antimicrobial efficacy of SDF and SDF + KI by comparing total viable counts before and after antimicrobial treatment.

Materials and Methods

Study subjects

Study subjects (n = 5) were recruited from a pool of patients who visited the Kuwait University Dental Clinic. Informed written consent was obtained from all subjects. Patients were guaranteed follow-up after sample collection and treatment completion, as well as addressing of any discomfort that could result from the sample collection procedure. A single investigator, who was a full-time faculty member at the Faculty of Dentistry, Kuwait University, collected all the samples to minimize investigator variation. This study was conducted in full accordance with the World Medical Association Declaration of Helsinki and was approved by Kuwait University Health Science Center Ethical Committee (Ref. VDR/EC/2644). This study has also been registered with “ClinicalTrials.gov” with the ID number NCT02771704.

Inclusion criteria

Asymptomatic adults who were able to give informed consent, had at least five teeth with radiographic evidence of carious lesion that penetrated at least the inner one-half of the dentin thickness, and were good candidates for the placement of a light-cured glass ionomer liner (Vitrebond 3M, St. Paul, MN, USA) were included. Finally, the treatment plan included placement of a permanent restoration. With respect to medical history, patients classified as American Society of Anesthesiologists 1 or 2 (Anaesthesiologists ASo. (2014) ASA Physical Status Classification System) were recruited to minimize any possible health complications during the procedure. A bilingual examiner was present all times when translation was needed.

Exclusion criteria

The exclusion criteria were as follows: inability of a patient to give informed consent, teeth with temporary restoration, teeth treated with pulpectomy or root canal, and teeth where isolation with a rubber dam was not possible. In addition, if cavity preparation was contaminated due to gingival bleeding or pulp exposure, the patient was excluded.

Follow-up

A follow-up system was established for all patients to address any complaints that could result from the sampling procedure.

Determination of in vitro antibacterial activity of silver diammine fluoride and potassium iodide

Streptococcus mutans CCUG 11877 was grown on mitis salivarius-bacitracin (MSB) agar at 37°C in 5% CO₂ in air for 2 days. Colonies were harvested with a disposable sterile plastic loop and suspended in sterile phosphate-buffered saline (PBS). The cells were washed twice by centrifugation at 5,000 × g for 5 min. The Optical density at 600 nm was adjusted to 1, and a 10-fold dilution was prepared, from which 100 µL was spread on Mueller-Hinton agar plates. One blank antimicrobial susceptible disk was placed in the center of each plate, and 20 µL of SDF [38% weight/volume (w/v)] or SDF + KI (SDF application followed by KI in sequence, not as a mixture. KI was applied as a saturated solution of KI and an oxalic acid-based product containing oxalic acid, potassium, salt, and water) (SDI Ltd., Bayswater, Australia). Sterile saline (0.9% w/v sodium chloride) and 2% CHX (Ultra-dent Products Inc. South Jordan, UT, USA) were used as negative and positive controls, respectively. The plates were incubated as described above for 2-3 days, and zones of inhibition were measured using an electronic digital caliper (VWR, Radnor, PA, USA).

Study design

A schematic presentation of the study design is provided in Fig. 1. Each patient received four different treatments with the following four agents applied separately on each of the four carious lesions: SDF, SDF + KI, CHX, and sterile saline. Clinical examination was performed followed by (1) pulp vitality assessment with thermal (cold) and electrical methods (Elements Diagnostic Unit and Apex Locator, Kerr Endodontique, Bioggio, Switzerland) and (2) bitewing and periapical radiographs taken with film holders supplied by Kerr. Bitewing radiographs were used to assess the depth of the lesion, and no continuity was seen between the carious lesion.
Each tooth was anesthetized with local anesthesia using 1.7 mL carpule of lidocaine HCl 2% with 1:100,000 epinephrine (Patterson Dental, St. Paul, MN, USA). Rubber dam isolation was used, and infection control protocol was followed. To allow the assessment of efficacy, a part of the dentin material was collected before treatment from the same carious lesion and an additional sample was collected after treatment. Infected soft dentin was excavated using a sterile sharp dental excavator (EXC17WH; Hu-Friedy, Chicago, IL, USA) and collected into a pre-weighed sterile microcentrifuge tube (Eppendorf, Hamburg, Germany) for microbiological analyses before treatment. As a measure of infection control, different sterile excavators were used to collect individual samples. The external tooth surface was washed with 30% H2O2. Using a dental three-in-one air syringe, the tooth surface was cleaned using sterile distilled water and dried for 4 s. The lesions were treated with SDF, SDF + KI, CHX, or sterile saline. After 1 min, the test agents were washed away with sterile saline. Dentin samples were collected after treatment using a sterile sharp dental excavator. Since all four treatments were provided to each of the participating subjects, bacterial death due prolonged exposure to air was avoided by immediate placement of the samples in anaerobic jars after collection. After the completion of sample collection, the jars were transported to the laboratory for microbiological culture.

Microbiological analysis
After collection, the samples were immediately placed in anaerobic jars and transported to the oral microbiology laboratory of the Faculty of Dentistry within 10 min. Standard protocols were followed for microbiological cultures (Jouseimies-Somer H et al., Anaerobic Bacteriology Manual, Wadsworth-KTL, 2002). Samples collected in pre-weighed sterile microfuge tubes were weighed again to determine the weight of the excavated dentin from each lesion. Dentin samples were then suspended in sterile pre-reduced Ringer’s solution (Sigma Aldrich, St. Louis, MO, USA). After vigorously vortexing for 1 min at the maximum setting, the remaining clumps of tissue were broken with a pipette tip to ensure homogeneity. Samples were 10-fold serially diluted up to 10−5 in Ringer’s solution. One hundred microliter portions from each dilution were spread in duplicate on Brucella agar plates supplemented with 5% sheep blood and MSB agar plates supplemented with 20% sucrose, bacitracin (0.2 units/mL), and 1% potassium tellurite. For Brucella agar, plates were incubated in anaerobic atmosphere (85% nitrogen, 10% hydrogen, and 5% CO2) at 37°C for 2 days to determine the total viable count. The anaerobic condition in the jars was monitored using RT Anaero-Indicator (Mitsubishi Gas Chemical Company Inc., Tokyo, Japan). For MSB agar, plates were incubated at 37°C in 5% CO2 in air for 2 days to determine the mutans streptococci count (15). After incubation, CFUs were counted from appropriate dilutions. CFUs were calculated per milligram of the dentin sample.

Statistical analysis
The bacterial counts were transformed to log10 values after adding 1 to all data to handle zero counts. Mann-Whitney U test was used to compare CFU counts between groups. P < 0.05 was considered statistically significant. SPSS version 22 (SPSS Inc., Chicago, IL, USA) was used to perform all statistical analyses.

Results
In vitro antibacterial activity of SDF and KI
S. mutans CCUG 11877 exhibited the highest susceptibility to SDF with a mean inhibition zone of 25.7 mm (Table 1). In the case of SDF + KI, the inhibitory zone was reduced to 15.15 mm. The positive control CHX showed an inhibition zone of 23 mm, whereas the negative control saline did not show any inhibition.

| Test agent | Inhibition zone (mm) | Mean (SD) |
|------------|----------------------|-----------|
| SDF        | 25.7 (0.84)          |           |
| SDF + KI   | 15.15 (0.9)          |           |
| Chlorhexidine | 23.05 (0.21)       |           |
| Saline     | 0 (0)                |           |

Fig. 1 Flow diagram of sample collection and microbiological analyses of carious lesions.
In vivo antibacterial effect of SDF and KI

Median total viable counts from the study subjects before and after treatment with the test agents are presented in Table 2. Treatment of carious dentin with SDF or SDF + KI resulted in >90% reduction of total viable counts for anaerobes; whereas, the reduction was 100% for total viable counts on MSB agar with no colonies seen on either of the culture media (Fig. 2).

Following treatment with SDF, the median CFU counts per mg reduced from $9 \times 10^5$ to $1.6 \times 10^2$, which was statistically significant ($P < 0.05$). In the case of SDF + KI, the median CFU counts decreased from $2.9 \times 10^5$ to $9.2 \times 10^4$ per mg dentin ($P < 0.05$). Treatment with the positive control CHX reduced the median CFU counts from $1.1 \times 10^5$ to $4.8 \times 10^2$ per mg ($P < 0.05$). Treatment with the negative control sterile saline did not affect the viable counts ($P > 0.05$). The median total anaerobic counts were $3.7 \times 10^5$ before treatment and $3.3 \times 10^5$ after treatment. Additionally, the sterile saline count did not reveal any reduction of the total counts on the MSB agar.

Large variations in the reduction of total viable counts were evident following the application of the test agents on carious dentin lesions of the subjects. The bacterial growth on Brucella agar was completely inhibited in two of the five subjects after treatment with SDF alone. Similarly, in one subject, no bacterial growth was observed in the dentin samples treated with CHX. No bacterial growth was seen on the MSB agar plates for any of the five subjects treated with SDF alone. Regarding SDF + KI treatment, four of the five subjects showed complete elimination of bacterial growth. Regarding CHX treatment, there was approximately a 10-fold reduction in the CFU counts, which was not statistically significant.

Patient follow-up

All patients, except for two, reported no pain or discomfort on days 1, 3, and 7 of the procedure. The two patients presented with spontaneous moderate to severe pain that lasted for 30-65 min on day 2 after the sampling procedure. One patient took 400 mg of ibuprofen to relieve the pain and the other did not take any pain medication.

| Test agent                    | Total viable anaerobic counts on Brucella blood agar | Total viable counts on MSB agar |
|-------------------------------|-----------------------------------------------------|---------------------------------|
|                               | Median CFU/mg | Range (min-max) | Median CFU/mg | Range (min-max) |
| Silver diammine fluoride      | 9.0 × 10^5    | 1.5 × 10^3 to 3.66 × 10^8 | 3.5 × 10^1    | 5.8 × 10^2 to 3.7 × 10^6 |
| Before treatment              | 1.67 × 10^6   | 0.6 × 10^4       | 0            | 0              |
| After treatment               | 1.67 × 10^6   | 0.6 × 10^4       | 0            | 0              |
| Silver diammine fluoride + potassium iodide | 2.96 × 10^5    | 5.29 × 10^2 to 4.62 × 10^7 | 6.78 × 10^1    | 1.29 × 10^2 to 1.05 × 10^4 |
| Before treatment              | 9.2 × 10^2    | 4.7 × 10^1 to 1.07 × 10^3 | 0            | 0              |
| After treatment               | 9.2 × 10^2    | 4.7 × 10^1 to 1.07 × 10^3 | 0            | 0              |
| Chlorhexidine                 | 1.11 × 10^6   | 2.45 × 10^5 to 1.62 × 10^6 | 1.66 × 10^1    | 0 to 2.31 × 10^4 |
| Before treatment              | 4.81 × 10^2   | 0 to 1.21 × 10^5  | 1.16 × 10^2   | 0 to 2.33 × 10^2 |
| After treatment               | 4.81 × 10^2   | 0 to 1.21 × 10^5  | 1.16 × 10^2   | 0 to 2.33 × 10^2 |
| Saline                        | 3.68 × 10^5   | 1.95 × 10^3 to 4.85 × 10^7 | 5.71 × 10^1    | 1.32 × 10^2 to 2.39 × 10^4 |
| Before treatment              | 3.31 × 10^5   | 9.6 × 10^2 to 6.57 × 10^6 | 6.5 × 10^2    | 1.5 × 10^2 to 1.03 × 10^4 |
| After treatment               | 3.31 × 10^5   | 9.6 × 10^2 to 6.57 × 10^6 | 6.5 × 10^2    | 1.5 × 10^2 to 1.03 × 10^4 |

The results are median values from five subjects. *$P < 0.05$. 

**Fig. 2** Median CFU counts before and after treatment of carious dentin with different antimicrobial agents *in vivo*. Median CFU counts were calculated from 25 samples (five patients). Culturing was done on Brucella blood agar for total anaerobic counts (A) and on MSB Agar for mutans streptococci counts (B). CHX, SDF, and SDF + KI groups showed significant differences before and after treatment. *$P < 0.05$. 

SDF= silver diammine fluoride, KI=potassium iodide, CHX=chlorhexidine. 

**In vivo antibacterial effect of SDF and KI**

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A comprehensive review of both cases was completed, showing that the treatment provided was root canal therapy. All five patients were followed up for 6 months and received different dental treatments according to individual treatment plans.

Discussion

In this study, treatment of carious dentin with SDF and KI reduced the total viable counts of anaerobes by >95%, whereas mutans streptococci growth was completely inhibited in all subjects, except for one. To our knowledge, this is the first study demonstrating the in vivo antibacterial activity of silver diammine fluoride and potassium iodide on carious lesions in dentin.

In vitro susceptibility tests showed that the growth inhibition of S. mutans was higher with SDF alone than with SDF + KI. Previous in vitro studies have investigated the efficacy of SDF + KI on S. mutans, Lactobacillus acidophilus, Streptococcus sobrinus, Actinomyces naeslundii, and other bacteria by growing them as mono- or multi-species biofilms on dentin blocks (16). These studies have revealed that SDF significantly inhibited mono- and/or multi-species biofilms.

During the initial period of its clinical use, the topical application of SDF created an aesthetic problem because silver ions reacted with organic material and caused staining. Later, Knight et al. (17) developed a new approach, applying a saturated solution of KI immediately after SDF to avoid the problem. However, a few studies suggested that the use of SDF and KI in combination could cause bond strength problems (18); although, other studies reported that the bond strength was not affected (17,19). The antibacterial ability of SDF and SDF + KI in this study is in accordance with the results found in several earlier studies (16,19,20). To our knowledge, none of those previous studies reported the in vivo efficacy of these agents on human subjects. Previous studies utilized in vitro mono- or multi-species biofilms of S. mutans, A. naeslundii, L. acidophilus, and other bacteria and studies found that there was a significant reduction in total viable counts after treatment (16). While the high pH of SDF solution may have an adverse effect on bacterial viability, the antibacterial activity of SDF is attributed to the high reactivity of silver ions with bacterial cell wall components containing phosphorous and sulfur, which cause disintegration of the bacterial cell envelope (21). It is important to note that in this study, the bacterial growth was completely inhibited by treatment with SDF or SDF + KI only on MSB agar. The anaerobic bacterial counts on Brucella agar were significantly reduced but not eliminated. CHX, the gold standard antimicrobial agent commonly used for irrigating cavities (6,8), was used as a positive control in this study. SDF and SDF + KI showed more antibacterial activity than CHX, although the difference did not reach statistical significance. Similar results were reported in previous studies, where SDF was found to be more effective as an antibacterial agent than CHX (19,22).

One limitation of this study is that the species composition and/or abundance varied not only among the study subjects but also among the sites within a patient’s oral cavity. Therefore, microbial quantification data from each carious lesion were compared before and after treatment to assess the effect of a test agent within an individual. The antibacterial efficacy of SDF and SDF + KI seemed to vary among the five participants of this study. The total viable counts before treatment also varied among the subjects, suggesting individual differences in the magnitude of dentin tubule infection. Differences in microbial composition, together with differences in host factors, may contribute to variations in the efficacy of the test agents among the study subjects. Therefore, systematic and accurate comparison of the efficacy of the test agents in such circumstances is difficult. Another limitation is the small sample size. A study including a larger number of participating subjects may illuminate the in vivo efficacy of SDF.

In conclusion, our study demonstrated the potent in vivo antibacterial activity of SDF and SDF + KI. Mutans streptococci growth was completely inhibited in most of the dentin samples. Importantly, these antibacterial agents tested at the manufacturer-recommended concentrations did not completely eradicate anaerobic bacteria. Since SDF chemical burn of soft tissues is well known (23), our results warrant further investigation regarding whether lower concentrations of these agents or their use in combination with other antibacterial agents may yield similar outcomes but with greater safety.

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Conflict of interest
The authors declare no conflict of interest.

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