RESEARCH PAPER

Comparative Effect of Photodynamic and Sonodynamic Disinfection on the Shear Bond Strength of Resin-Modified Glass Ionomer Cement to Caries-Affected Dentin: An *In vitro* Study

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ABSTRACT

Background: Effective disinfection of caries-affected dentin (CAD) is relevant to minimally invasive restorative dentistry; however, the influence of advanced antimicrobial modalities on restorative bonding remains incompletely established.

Aim: To compare the effect of photodynamic therapy (PDT) and sonodynamic therapy (SDT) on the shear bond strength (SBS) of resin-modified glass ionomer cement (RMGIC) to CAD.

Materials and Methods: Forty extracted permanent molars were allocated to four groups (n=10): sound dentin, untreated CAD, CAD treated with PDT, and CAD treated with SDT. Following the respective protocols, standardized RMGIC specimens were bonded to dentin and tested after 24 hours.

Results: A statistically significant difference in SBS was observed among the four groups. The SDT group showed the highest median SBS, whereas untreated CAD showed the lowest median SBS.

Conclusion: Within the limitations of this *in vitro* study, SDT was associated with higher RMGIC SBS to CAD than the other tested conditions. Further studies incorporating aging, microbiological assessment, failure-mode analysis, and clinical validation are required.

Keywords Caries-Affected Dentin, Sonodynamic Therapy, Photodynamic Therapy, Resin-Modified Glass Ionomer Cement, Shear Bond Strength, Dental Restoration.

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INTRODUCTION

Dental caries is still one of the most common chronic illnesses in the world and a significant public health concern. Contemporary minimally invasive dentistry highlights preservation of sound tooth structure and maintenance of pulpal vitality through selective or partial caries removal rather than complete excavation of carious dentin. This conservative approach has been associated with

improved pulp preservation and reduced risk of pulp exposure compared with complete caries removal techniques [1-3].

Caries-affected dentin (CAD) is a partially demineralized dentin substrate in which the collagen matrix is relatively preserved and which may retain the potential for remineralization. In contrast to caries-infected dentin, CAD can therefore be preserved during minimally invasive restorative procedures. Nevertheless, residual microorganisms may persist within dentinal tubules after partial caries removal, potentially influencing restoration performance and pulpal health [4-6]. Effective disinfection of the remaining dentin surface is consequently of interest in minimally invasive restorative dentistry.

Chemical disinfectants such as chlorhexidine have traditionally been used to reduce microbial contamination before restorative procedures. Although effective, their influence on dentin surface characteristics and adhesive performance may vary according to concentration, application protocol, and restorative material [7]. These considerations have stimulated interest in alternative antimicrobial approaches that may reduce microbial contamination while preserving the integrity of the dentin substrate.

A photosensitizing agent and light of the correct wavelength are combined in antimicrobial photodynamic treatment (aPDT) in the presence of oxygen. Activation of the photosensitizer can generate reactive oxygen species (ROS), which contribute to microbial inactivation [8-10]. Sonodynamic therapy (SDT) uses acoustic energy to activate a sensitizing agent. Acoustic cavitation and related physicochemical effects have been proposed to contribute to antimicrobial activity [15]. Although these modalities share the concept of sensitizer activation, their energy-delivery mechanisms differ.

Sonodynamic therapy (SDT) has recently emerged as an innovative antimicrobial modality. Similar to PDT, SDT relies on activation of sensitizing agents; however, activation occurs through low-intensity ultrasound rather than light energy. The interaction between ultrasound waves and sonosensitizers generates cavitation effects, sonoluminescence, thermal energy, and reactive oxygen species, resulting in potent antimicrobial activity [15].

Resin-modified glass ionomer cement (RMGIC) is widely used because of its chemical adhesion to tooth structure, fluoride release, and combination of an acid-base glass-ionomer reaction with resin polymerization. These properties make RMGIC relevant to minimally invasive restorative procedures involving dentin substrates.

Despite increasing interest in photodynamic and sonodynamic antimicrobial approaches, direct evidence comparing their influence on the bond strength of RMGIC to CAD remains limited. Therefore, this in-vitro study aimed to comparatively evaluate the effect of PDT and SDT disinfection on the SBS of RMGIC to CAD. The null hypothesis was that there would be no difference in SBS among the four experimental groups.

MATERIALS AND METHODS

An a priori sample size calculation was performed using G*Power software, assuming an effect size of 0.70, a significance level (α) of 0.05, and a statistical power of 80%. The analysis yielded a total required sample size of 40, with 10 samples allocated to each of the four study groups.

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A total of 40 freshly extracted human permanent molars were obtained from the Department of Oral and Maxillofacial Surgery following the applicable consent procedure. Ultrasonic scalers were used to remove any remaining calculus and soft tissue from the teeth, which were then kept at room temperature in a 0.1% thymol solution until needed.

Inclusion criteria were: human permanent molars with or without occlusal caries corresponding to ICDAS code 5 and teeth free from developmental defects, visible cracks, and fractures.

Exclusion criteria were: teeth exhibiting occlusal caries corresponding to ICDAS codes 1, 2, 3, 4, or 6 and teeth with developmental defects, visible cracks, or fractures.

SAMPLE PREPARATION

Each tooth was mounted in self-cure acrylic resin blocks up to the cementoenamel junction (CEJ) to facilitate handling during specimen preparation and testing. The occlusal enamel was removed using a water-cooled diamond disc mounted on a straight handpiece to expose the underlying dentin surface.

For carious teeth, infected dentin was removed using a slow-speed round bur. A 0.5% basic fuchsin caries detector dye was used as an adjunct to identify the excavation endpoint, with the intention of preserving the remaining caries-affected dentin. The dentin surface was subsequently polished with 600-grit silicon carbide abrasive paper under running water to obtain a standardized surface.

GROUP ALLOCATION

The specimens were randomly allocated to four experimental groups (n=10): Group I, sound dentin (SD); Group II, caries-affected dentin (CAD) without disinfection; Group III, CAD subjected to photodynamic disinfection (CAD+PDT); and Group IV, CAD subjected to sonodynamic disinfection (CAD+SDT).

- **GROUP I (SD):** Sound dentin (control).
- **GROUP II (CAD):** Caries-affected dentin without disinfection.
- **GROUP III (CAD + PDT):** Caries-affected dentin subjected to photodynamic disinfection.
- **GROUP IV (CAD + SDT):** Caries-affected dentin subjected to sonodynamic disinfection.

PHOTODYNAMIC DISINFECTION PROTOCOL

For Group III, the CAD surface was evenly coated with methylene blue (Qualigens Fine Chemicals, Mumbai, India) and left for 60 seconds as the pre-irradiation time. A diode laser (NovoLase Dual Wave Smart Diode Laser System;

Novolase Technologies, India) operating continuously at 660 nm and 2 mW/cm2 was then used to irradiate the specimens. Using a fiber-optic tip, the laser was positioned at a 45° angle from the dentin surface and ran continuously for 30 seconds at a wavelength of 400 μm. After cleaning the CAD surface with distilled water, it was left to air dry for five seconds.

SONODYNAMIC DISINFECTION PROTOCOL

For Group IV, methylene blue was used as the sonosensitizing agent and applied to the CAD surface for 60 seconds. A coupling medium was applied to facilitate transmission of ultrasonic energy. A medical ultrasonic (Electroson-608 Ultrasonic Therapy Unit, Techno med Electronics, India) coupling agent was then applied to facilitate transmission of ultrasonic energy. Ultrasound irradiation was performed at a frequency of 1 MHz and power density of 3 W/cm² for 5 minutes using an ultrasonic therapy unit. After cleaning the CAD surface with distilled water, it was left to air dry for five seconds.

For the control groups, sound dentin and untreated caries-After cleaning the CAD surface with distilled water, it was left to air dry for five seconds before restoration.

RMGIC BONDING PROCEDURE

After completing the designated disinfection procedures, the dentin surfaces were conditioned in accordance with the manufacturer's recommendations. GC Gold Label Light-Cured Universal Restorative (GC Corporation, Tokyo, Japan) was prepared as per the specified instructions. A transparent cylindrical plastic mold was then placed perpendicular to the prepared dentin surface, and the resin-modified glass ionomer cement (RMGIC) was introduced into the mold in successive increments. Each increment was polymerized using an LED light-curing unit for 20 seconds, ensuring a uniform restorative height of 4 mm across all specimens. Following restoration, the specimens were immersed in distilled water and maintained at 37 °C for 24 hours before undergoing mechanical testing.

SHEAR BOND STRENGTH TESTING

Specimens were mounted in a universal testing machine, and a knife-edge loading blade was positioned as near as possible to the dentin-restoration interface. A shear load was applied at a crosshead speed of 0.5 mm/min until failure occurred. The maximum failure load was recorded in Newtons (N). Where SBS was expressed in MPa, the value was calculated by dividing the failure load (N) by the bonded surface area (mm²).

STATISTICAL ANALYSIS

All statistical analyses were conducted using IBM SPSS Statistics for Windows, Version 20 (IBM Corp., Armonk, NY, USA). The normality of the data was evaluated using the Shapiro-Wilk test. As the data deviated from a normal distribution, non-parametric statistical tests were selected for analysis. Data were summarized using the median, interquartile range (IQR), and minimum and maximum values. Differences across the four study groups were initially examined using the Kruskal-Wallis test. For pairwise comparisons, Dunn's post-hoc test with Holm adjustment was recommended to account for multiple testing, with adjusted P values reported accordingly. Effect sizes and their corresponding 95% confidence intervals were also to be included wherever feasible. Statistical significance was determined using two-sided tests, with the significance threshold set at 0.05.

RESULTS

The descriptive statistics and mean ranks of SBS for the four study groups are presented in Table 1. Group IV (CAD+SDT) showed the highest median SBS [5.338 (IQR 0.373)], followed by Group III (CAD+PDT) [4.393 (IQR 0.930)], Group I (SD) [4.045 (IQR 0.677)], and Group II (CAD) [3.323 (IQR 0.131)]. The Kruskal–Wallis test demonstrated a statistically significant difference among the four groups (χ^2=31.231, df=3, P<0.001).

Post-hoc pairwise comparisons are given in Table 2. In the original analysis, the reported unadjusted Mann-Whitney P values indicated differences for several pairwise comparisons. However, because six pairwise comparisons were performed, the final manuscript should report multiplicity-adjusted P values. In particular, the original text describes the Group I versus Group III comparison (P=0.023) as non-significant, which is inconsistent with an unadjusted alpha of 0.05; the final interpretation should therefore be based on the corrected post-hoc analysis.

Table 1: Descriptive statistics and mean ranks of shear bond strength among the study groups

Group	Median (IQR)	Minimum	Maximum	Mean Rank	p-value
Group I	4.045 (0.677)	3.248	4.387	16.10	<0.001
Group II	3.323 (0.131)	3.184	3.423	6.90	
Group III	4.393 (0.930)	3.882	5.175	24.00	
Group IV	5.338 (0.373)	5.015	5.971	35.00	

Kruskal-Wallis test; p<0.05 was considered significant.

Group I (SD), sound dentin (control); Group II (CAD), caries-affected dentin without disinfection; Group III (CAD + PDT), caries-affected dentin subjected to photodynamic disinfection; Group IV (CAD + SDT), caries-affected dentin subjected to sonodynamic disinfection.

Table 2: Pairwise comparison of shear bond strength among the study groups

Comparison	Mann-Whitney U	Z value	p-value

Group I vs. Group II	14.000	-2.721	0.005
Group I vs. Group III	20.00	-2.268	0.023
Group I vs. Group IV	0.000	-3.780	<0.001
Group II vs. Group III	0.000	-3.780	<0.001
Group II vs. Group IV	0.000	-3.780	<0.001
Group III vs. Group IV	5.000	-3.402	<0.001

Mann Whitney U test; P <0.05 was considered significant.

Group I (SD), sound dentin (control); Group II (CAD), caries-affected dentin without disinfection; Group III (CAD + PDT), caries-affected dentin subjected to photodynamic disinfection; Group IV (CAD + SDT), caries-affected dentin subjected to sonodynamic disinfection.

DISCUSSION

This *in vitro* investigation examined the influence of photodynamic therapy (PDT) and sonodynamic therapy (SDT) on the shear bond strength of resin-modified glass ionomer cement (RMGIC) bonded to caries-affected dentin (CAD). Variations in bond strength were observed across the experimental groups, with the SDT-treated specimens exhibiting the highest values, followed by the PDT group, sound dentin, and untreated caries-affected dentin. These results indicate that the effect of dentin disinfection on adhesive performance may vary according to the disinfection method used and the properties of the underlying dentinal substrate

Photodynamic therapy is an antimicrobial approach that involves the interaction of a photosensitizing agent with light of an correct wavelength in the presence of oxygen, resulting in the generation of reactive oxygen species. These species can damage microbial cellular components and contribute to microbial inactivation. PDT has been investigated as a minimally invasive method of reducing the microbial load in carious dentin while preserving affected dentin that may be suitable for remineralization and restoration [4], [6].

In current investigation the PDT-treated group showed greater bond strength than the untreated caries affected dentin group. Possible explanations include a reduction in microbial contamination and changes in the dentin surface that may affect interaction with the restorative material. However, these mechanisms were not directly evaluated and should therefore be interpreted cautiously.

Previous investigations have examined the influence of PDT on the bonding performance of restorative materials to caries-affected dentin, with findings varying according to the photosensitizer, irradiation parameters, dentin condition, and restorative material used [4], [5], [7]. The literature indicates that PDT does not produce a uniform effect on adhesion across all materials and clinical conditions. Accordingly, the results of this investigation should be considered within relation to the specific photosensitizer, light source, treatment protocol, and RMGIC used.

Although the PDT group demonstrated improved bond strength compared with untreated caries-affected dentin, its performance remained lower than that of the SDT group. This suggests that the two disinfection approaches may influence the dentin substrate differently. Further investigations incorporating surface characterization, mineral content analysis and assessment of dentinal collagen would help clarify the mechanisms underlying these differences.

Sonodynamic therapy is an emerging antimicrobial approach that combines ultrasound with a sonosensitizing agent or other ultrasound-mediated mechanisms to enhance antimicrobial activity. Ultrasound may produce mechanical effects, including acoustic streaming and cavitation, which can improve fluid movement and interaction with surfaces. The potential application of sonodynamic therapy in dentistry has attracted interest because of its possible role in biofilm management and minimally invasive disinfection [15], [16].

In the current investigation, the SDT group exhibited the greatest bond strength among the groups investigated. This finding suggests that the sonodynamic protocol used may have produced a dentin substrate more favourable for bonding with RMGIC than the other tested conditions. However, the precise mechanism responsible for this observation remains uncertain.

Possible explanations include ultrasound-mediated changes in surface cleanliness, fluid movement, or the accessibility of dentinal surface irregularities. These changes could affect the interaction between the dentin and the restorative material. Nevertheless, because the study was not designed to determine surface morphology, collagen integrity, mineral composition, or acoustic cavitation, these explanations remain hypothetical.

The findings are consistent with the growing interest in SDT as an adjunctive antimicrobial approach in dentistry [11]. Research directly comparing PDT and SDT in caries-affected dentin and evaluating their [5], [6] effects on restorative bond strength is particularly relevant to the interpretation of the present results [17]. Differences in treatment parameters, restorative materials and experimental methods must be considered when comparing findings across studies.

The greater bond strength observed following SDT should not automatically be considered as an indicative of greater clinical effectiveness. Bond strength is an important laboratory outcome, but long-term restoration success also depends on marginal integrity, resistance to degradation, moisture control, occlusal stresses and the biological condition of the remaining dentin.

The untreated caries-affected dentin group demonstrated the least interfacial adhesion in the present investigation. Caries-affected dentin differs from sound dentin in its mineral content, collagen structure, permeability and mechanical properties. These changes can influence the interaction between dentin and the restorative material [1, 2,

3].

Unlike infected dentin, which is heavily contaminated and structurally compromised, caries-affected dentin may retain the potential for remineralization and may be preserved during selective caries removal. However, its altered structure can affect restorative bonding and choosing a suitable restorative material and clinical technique important [1], [2], [3].

The comparatively lower bond strength observed in untreated caries-affected dentin may be associated with these substrate-related differences. Nevertheless, the present study does not establish which specific structural or chemical characteristic was responsible for the observed result.

The results demonstrate the relevance of considering the condition of the remaining dentin when evaluating restorative adhesion. At the same time, they do not establish that routine disinfection is necessary in every clinical situation. The choice of caries-removal strategy and any adjunctive disinfection procedure should be based on the clinical context and available evidence.

Resin-modified glass ionomer cement combines the acid-base reaction characteristic of conventional glass ionomer cement with a resin-mediated polymerization mechanism. Its clinical advantages include chemical interaction with tooth structure, fluoride release, and suitability for selected restorative situations. These properties make RMGIC a relevant material for evaluating restorative bonding to caries affected dentin [13], [14], [18].

Bonding to dentin is influenced by the substrate's mineral composition, surface condition, moisture, and the material's setting and interaction mechanisms. In caries-affected dentin, alterations in the mineral and organic components may affect these interactions. Disinfection procedures may also modify the surface or residual organic components, potentially influencing bond strength [9, 17].

The differences observed among the groups in the present study indicate that the pre-treatment condition of the dentin may influence the adhesive performance of RMGIC. However, shear bond strength alone cannot fully explain the quality of the dentin-restoration interface or predict the long-term behaviour of a restoration.

The findings suggest that PDT and SDT may warrant further investigation as adjunctive approaches for managing microbial contamination in caries-affected dentin before restoration. The comparatively favourable bond strength observed in the treated groups, particularly the SDT group, provides a basis for additional laboratory and clinical research.

Further studies should evaluate the effects of these disinfection approaches on dentin surface morphology, mineral content, collagen integrity, nanohardness, and the nature of bond failure. Ageing procedures, thermocycling, long-term water storage, and complementary bond-strength methods may provide additional information about durability. Further research should also evaluate antimicrobial efficacy, pulpal compatibility, and patient related outcomes.

CONCLUSION

Considering the limitations of the present *in vitro* investigation, sonodynamic disinfection demonstrated a greater shear bond strength of resin-modified glass ionomer cement to caries-affected dentin compared with the other experimental groups. However, further research involving standardized aging protocols, microbiological evaluations, analysis of failure patterns, and clinical studies is necessary to establish the long-term effectiveness and clinical relevance of these findings before their adoption in routine dental practice.

ETHICS APPROVAL

INSTITUTIONAL ETHICS COMMITTEE APPROVAL/WAIVER NUMBER: PMVIDS&RC/IECICONS/PR/652-25.

CONSENT FOR USE OF EXTRACTED TEETH

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