Pesquisa Brasileira em Odontopediatria e Clínica Integrada 2024; 24:e230082
https://doi.org/10.1590/pboci.2024.077
ISSN 1519-0501 / eISSN 1983-4632

SYSTEMATIC REVIEW

Does Antimicrobial Photodynamic Therapy Influence the Bond Strength of Direct Restorative Materials to Healthy and Decayed Dentin? A Systematic Review

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Academic Editor: Catarina Ribeiro Barros de Alencar

Received: May 22, 2023 / **Review:** February 29, 2024 / **Accepted:** March 05, 2024

How to cite: Mendes RM, Fernandes TO, Hidalgo R, Antunes LS, Cajazeira MRR, Antunes LAA. Does antimicrobial photodynamic therapy influence the bond strength of direct restorative materials to healthy and decayed dentin? A systematic review. Pesqui Bras Odontopediatria Clín Integr. 2024; 24:e230082. https://doi.org/10.1590/pboci.2024.077

ABSTRACT
Objective: To evaluate the influence of antimicrobial photodynamic therapy (aPDT) on the bond strength of adhesive restorative materials to healthy and caries-affected dentin. **Material and Methods:** 04 electronic databases and 02 additional searches were assessed. *In vitro* studies considering sound or caries-affected human or bovine dentin (population), use of aPDT before restorative treatment (intervention), use of other dentin disinfection techniques (comparison), and bond strength to dentin (outcome) were included. The risk of bias for *in vitro* studies was used as a method to check the evidence. The method used to present and synthesize results was data extraction. **Results:** The total number of included studies was 11, including 550 permanent teeth. Bond strength was evaluated mainly through the shear bond strength (SBS) test, with dentin affected by caries being the substrate most frequently used in studies. Six studies demonstrated that aPDT with methylene blue (MB) negatively affected the SBS values of resin-modified glass ionomer cement (RMGIC) to dentin. Regarding risk of bias assessment, all studies were at high risk of bias. **Conclusion:** The effects of aPDT on adhesion to dentin vary depending on the type of substrate and the photosensitizer used. Mainly, MB negatively affected the SBS values from RMGIC to dentin. The conclusion should be interpreted considering the high risk of bias in the studies.

Keywords: Photochemotherapy; Composite Resins; Dental Caries; Dentin.

Introduction

For years, the complete removal of carious dentin (CCR) has been considered fundamental for the long-term success of dental restoration, as sound dentin was considered a substrate capable of providing adequate support for the restorative material. In addition, it was believed that cariogenic bacteria could be mechanically eliminated through cavity preparation. Thus, CCR was also considered an indissociable part of caries treatment when this disease was considered infectious and transmissible [1,2].

A more detailed understanding of the ultrastructure of carious dentin was obtained from *in vitro* studies published in the 1970s [3-6]. According to these studies, only the superficial layer of carious dentin – defined as caries-infected dentin (CID) – should be removed because the degradation of collagen fibrils makes the remineralization of this tissue unfeasible [6]. Despite being demineralized, the layer below the CID – the caries-affected dentin (CAD) – was characterized by preserving a large part of the collagen, allowing gradual remineralization [6]. *In vivo* studies demonstrated the arrest of carious lesions in dentin subjected only to sealing with dental sealants, highlighting the effects of nutrient restriction in the oral environment on the metabolism of bacteria present in carious dentin [7,8]. Finally, studies carried out in the 1990s demonstrated the possibility of stopping carious lesions in dentin through brushing associated with the use of fluoride toothpaste, suggesting that the metabolism of the bacterial plaque located on the surface of the lesion plays a determining role in the progression of dentin lesions [9,10].

Therefore, selective removal of carious dentin (SCR) – a clinical procedure that consists of the exclusive removal of CID – has been recommended with the purposes of (i) preserving dental tissues, (ii) minimizing the risk of accidental pulp exposure, and (iii) provide minimal discomfort to the patient during dental treatment [11]. However, despite changes in the caries treatment paradigm and the scientific evidence that supports SCR, reports from professionals who indicate insecurity regarding this procedure are common, mainly due to the fear of the lesion progressing due to bacteria inside the carious dentin [12,13]. It is essential to highlight that no method of mechanical removal of decayed dentin can eliminate the bacteria in the dentin [14].

In recent years, antimicrobial photodynamic therapy (aPDT) has been proposed as a complementary method capable of reducing bacterial counts in decayed dentin in teeth undergoing SCR [15]. In this technique, photosensitizer substances are applied to the surface of the carious dentin, which is then exposed to a specific wavelength beam of light to release active oxygen species that are toxic to cariogenic bacteria [16,17].

As aPDT has been used as an adjunctive method for removing carious dentin, its influence on the adhesion of these materials has been investigated in recent years, especially in intracanal retentions [18,19]. However, there is no consensus on the influence of aPDT on adhesion to coronal dentin, which is important from a clinical point of view since adhesive restorative materials such as glass ionomer cement and composite resins are widely used. The longevity of restorations made with these materials directly depends on the quality of the adhesion they establish with mineralized tissues [20,21]. Therefore, understanding the effects of aPDT – or any other dentin disinfection method – on the composition and micromorphology of dentin is extremely important, given the relationship between these variables and the quality of adhesion to this tissue [22,23].

The assessment of *in vitro* studies to evaluate the ultrastructural level of the adhesive interface investigating parameters such as bond strength values and failure mode is essential to provide the possibility of researchers conducting clinical studies with a comprehensive review, offering insights into the ultrastructural aspects. Thus, through a systematic review of *in vitro* studies, this study aimed to evaluate the influence of aPDT on the bond strength of direct adhesive restorative materials to dentin healthy and affected by caries.

Material and Methods

This systematic review was registered in the PROSPERO database [CRD42020204126], outlined according to Cochrane recommendations (CDSR), and written according to the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews) guidelines [http://www.prisma-statement.org].

Formulation of the Question

Does antimicrobial photodynamic therapy (aPDT) affect the bond strength of direct adhesive restorative materials to healthy and caries-affected dentin?

Eligibility Criteria

In vitro studies were included without language restriction and based on the acronym PICO (P-Patient or Problem-I-Intervention; C-Comparison; O-Outcomes):

- Patient: healthy dentine and dentine affected by human or bovine caries;
- Intervention: with direct restorative adhesive materials after dentin disinfection with aPDT;
- Comparison: use of direct restorative materials after dentin disinfection with other agents;
- outcome: bond strength.

Offtopic studies, case reports, clinical studies, narrative literature reviews, book chapters, and letters from the editor were excluded.

Information Sources

A comprehensive literature search was conducted, and only articles published before September 22, 2023, were selected. The following electronic databases were accessed: PubMed, Web of Science (WOS), Virtual Health Library (VHL), Latin American and Caribbean Literature in Health Sciences (LILACS) database, and Scopus. The search strategy for Pubmed combined MeSH terms (Medical Subject Headings - www.nlm.nih.gov/mesh/meshhome.html): "Photochemotherapy," "glass ionomer cement," "composite resins," "dentin-bonding agents," "dental caries," "Dentin," "dental enamel;" and for the VHL DECS descriptors (http://decs.bvs.br/) and free terms with the use of Boolean operators (OR and AND). The search was also performed in gray literature using OpenGrey (http://www.opengrey). A manual search was performed on the reference citations of the selected studies to identify additional studies.

Search Strategy

Table 1 presents the complete search strategies for all databases, registers, and websites, including any filters and limits used.

Table 1. Electronic search strategy.

Data Base	Search Strategy
Pubmed	#1 "Photochemotherapy"[MeSH Terms] OR "Photochemotherapy"[Title/Abstract] OR "antimicrobial photodynamic therapy"[Title/Abstract] OR "PDT"[Title/Abstract] OR "photodynamic therapy"[Title/Abstract] OR "aPDT"[Title/Abstract]
Scopus	#2 "glass ionomer cement" [Title/Abstract] OR "composite resins" [Title/Abstract] OR "dentin-bonding agents "[Title/Abstract] "resin-modified glass ionomer cement "Title/Abstract]" OR "glass ionomer cement" [MeSH Terms] OR "composite resins" [MeSH Terms] OR "dentin-bonding agents" MeSH Terms]

WOS	#3 "shear bond strength"[Title/Abstract] OR "tensile bond strength"[Title/Abstract] OR "micro shear bond strength"[Title/Abstract] OR "micro tensile bond strength"[Title/Abstract] OR "bond strength"[Title/Abstract]
VHL	#3 "dental caries"[MeSH Terms] OR "dental caries"[Title/Abstract] OR "Dentin"[MeSH Terms] OR "Dentin"[Title/Abstract] OR "dental enamel"[MeSH Terms] OR "dental enamel"[Title/Abstract] OR "demineralized enamel"[Title/Abstract] OR "sound dentin"[Title/Abstract] OR "carious dentin"[Title/Abstract] OR "caries affected dentin"[Title/Abstract] OR "Enamel"[Title/Abstract]

Selection Process

The studies found were entered into reference management software (Mendeley). Duplicates were removed. The reviewers established clear criteria for selecting studies, including eligibility criteria. They conducted calibration exercises, where each reviewer independently screened a subset of articles to ensure consistency in applying the selection criteria. Any discrepancies in article selection were resolved through discussion and consensus among the reviewers or consultation with a third party if needed. After calibration, the articles were independently evaluated by two reviewers (RMM and TOF). If there was disagreement, a third reviewer (LAA) was consulted to reach a consensus.

Data Collection Process

Before data extraction, the reviewers developed a standardized data extraction form to capture relevant information from included studies. They then conducted pilot data extraction exercises on a subset of articles to refine the process and ensure consistency in extracting data across all included studies. Any discrepancies or uncertainties in data extraction were addressed through discussion and consensus among the reviewers.

After calibration, two reviewers (RMM and TOF) independently completed the data extraction table, verified by a third reviewer (MRRC). The selected articles were grouped according to the year of publication. Data from the selected articles were collected and organized according to author/year, tooth/sample (n), restorative materials, analyzed substrate, description of groups, bond strength, aPDT intervention group, comparison groups: no aPDT, and conclusion.

Study and Reporting Risk of Bias Assessment

The reviewers established criteria for assessing the risk of bias in included studies, considering The modified version of a criterion proposed in a previous study [24] that considered the following parameters: performance of the sample calculation, random allocation of teeth among experimental groups, use of restorative materials according to the manufacturer's instructions, restorative procedures performed by a single operator, description of the sample calculation, and blinding of the operator of the testing machine about the experimental groups. If the authors reported the parameter, they were marked as Y (yes). The parameter was marked as N (no) if information could not be found. Articles that reported 01 or 02 parameters were classified as high risk of bias, 03 or 04 as medium risk, and 05 as low risk.

The reviewers conducted calibration exercises, and each reviewer independently assessed the risk of bias in a subset of studies. Discrepancies in bias risk assessment were resolved through discussion and consensus among the reviewers regarding established guidelines and protocols. After the calibration, two independent authors (RM and LAAA) determined the risk of bias in the selected studies. Disagreements between the reviewers were resolved by consensus.

Results

Study Selection

Table 1 illustrates the search strategy. Initially, 94 studies were considered eligible in PubMed (36), VHL (0), Scopus (46), and Web of Science (12) (Figure 1). After removing duplicates and applying the eligibility criteria, 11 articles were considered eligible and read in their entirety, all included in this systematic review [22,25-32]. No articles were found in the grey literature or manual search.

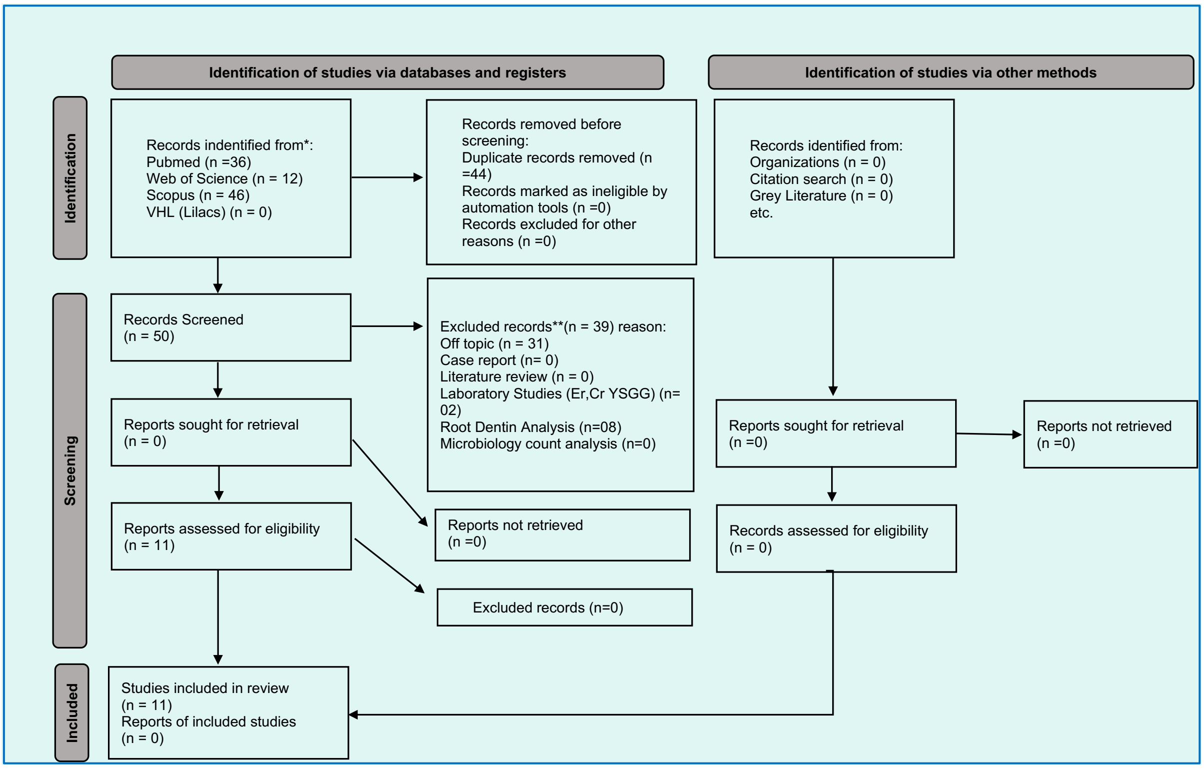

Figure1. PRISMA 2020 flow chart model for systematic review.

Study Characteristics and Results of Individual Studies

Table 2 presents the methodological characteristics and findings of the selected studies. The SBS test was used to analyze the bond strength. The sample consisted of 615 permanent molars [22,25-34]. 02 studies evaluated the SBS to sound dentin [25,28], 06 to caries-affected dentin [22,29,31-34], and 01 to caries-affected and sound dentin [27]. 02 studies reported the use of artificially produced caries-affected dentin [26,30].

Methylene blue was used as the photosensitizer in 08 studies [22,25,26,28-30,32,34]. Curcumin was used in 03 studies [22,29,34]. Indocyanine green was reported in 03 studies [29,32,34], and riboflavin was reported in 03 [31-33]. Their study did not mention the photosensitizer used by Al Rifaiy and Vohra [28] (Table 2).

According to verified in Table 2, except for one study [28], the type of failure was determined through microscopic analysis of the adhesive interface, being categorized into (i) cohesive (occurring in the body of the substrate or material], (ii) adhesive (occurring at the adhesive interface) or (iii) mixed (combination of adhesive and cohesive). RMGIC samples showed a predominance of cohesive failure in the material, probably due to the low flexural strength and inner voids typical for this material [25-27]. In contrast, adhesive failure was predominant in the groups where the photosensitizer was used. This may be related to the concentration of this agent used to disinfect dentin affected by caries.

Table 2. Data extraction – bond strength.

Authors	Tooth Sample (N)	Substrate†	Restorative Material	Bond Strength Values††, ‡‡	Failure Mode§ (%)			Conclusion
					A	C	M	
Alrahlah et al. [22]	Permanent Molar (n=50)	CAD	Clearfil SE Bond Clearfil AP-X	G1 (MBP): 14.21±0.22[a]	70	20	10	Curcumin showed potential for dentin disinfection treatment without affecting the bond strength.
				G2 (CP): 17.57±0.85[b]	60	30	10	
				G3 (SDF 38%): 11.14±0.29[c]	90	10	0	
				G4 (SDF 3.8%): 16.22±0.53[b]	30	10	60	
				G5 (ECL): 13.22±0.54[a]				
Al-Khureif et al. [25]	Permanent Molar (n=50)	SD	Fuji II LC	G1 (MBP+DL): 15.25±1.54[a]	80	10	10	MBP isn't an agent to be recommended for conditioning the dentin before CIVMR placement.
				G2 (ECL): 17.44±2.77[b]	10	20	70	
				G3 (PAA): 19.81±1.93[b]	20	60	20	
				G4 (EDTA): 18.73±1.02[b]	10	70	20	
				G5 (OSPTE): 23.15±3.21[c]				
Alshahrani [26]	Permanent Molar (n=60)	ACD SD	RMGIC	G1 (SD): 7.44±0.29[a]	10	60	30	The use of methylene blue compromises adhesive integrity applied to demineralized dentin.
				G2 (PAA): 11.39±0.54[b]	20	60	20	
				G3 (SDF38%): 12.42±0.77[b]	50	20	30	
				G4 (SDF3.8%): 14.45±0.14[c]	70	10	20	
				G5 (SDF+KI): 15.91±0.71[c]	10	70	20	
				G6 (MBP+LD): 11.52±0.86[b]				
Al Deeb et al. [27]	Permanent Molar (n=40)	CAD SD	Adper Prompt Self-Etch Adhesive Filtek Z350	G1 (SD): 24.98±1.59[a]	50	50	0	The adhesive strength of disinfected carious dentin was higher with CHX treatment compared to photodynamic therapy and Er, Cr:YSGG laser treatment.
				G2 (CAD-CHX): 18.25±1.29[b]	50	50	0	
				G4 (CAD-ECL): 15.89±3.22[b]	80	10	10	
				G3 (CAD-MBP+DL): 14.22±1.40[b]	40	10	50	
Alshahrani et al. [29]	Permanent Molar (n=50)	CAD	Fuji II LC	G1 (CHX): 18.31±1.06[a]	10	30	60	The adhesive strength of RMGIC after disinfection of caries-affected dentin with CHX showed the highest SBS, while MBP showed the lowest SBS.
				G2 (MBP+DL): 12.31±0.57[b]	80	10	10	
				G3 (ICGP+DL): 13.57±0.61[b]	70	20	10	
				G4 (CP+LED): 16.86±0.97[b]	60	0	40	
				G5 (ECL): 17.39±2.26[a]	10	20	70	
Al Rifaiy and Vohra [28]	Permanent Molar (n=90)	SD	ZirconCore (ZC) MulticCore Flow (MF)	G1 (EBZC): 15.21±1.12[a]	NP	NP	NP	ECL-related phototherapy showed better results than other techniques when it comes to adherence.
				G2 (ECLZC): 15.17±1.10[a]				
				G3 (DLZC): 10.45±0.46[b]				
				G4 (EBMF): 17.84±0.92[c]				
				G5 (ECLMF): 17.13±2.01[c]				
				G6 (DLMF): 10.96±0.61[b]				
Al-Qahtani [30]	Permanent Molar (n=80)	CAD SD	RMGIC RMGIC+GOF	G1 (RMGIC-GOF): 14.11±3.82[c]	55	30	15	The use of MBP negatively affected the adhesive bond strength applied to demineralized dentin.
				G2 (SDF 3.8%): 15.27±2.19[a]	30	20	50	
				G3 (MBP+DL): 10.13±1.65[c]	25	65	10	
				G4 (SD): 5.01±0.28[b]	30	60	10	

Al Deeb [31]	Permanent Molar (n=40)	CAD	Adper Single Bond 2 Filtek Z350	G1 (NT): 19.08 ± 1.09^{a} G2 (CHX): 18.34 ± 0.89^{a} G3 (DL): 13.22±0.33^{a} G4 (PPE): 17.71±1.03^{b} G5 (RF+LED): 18.26±1.22^{a}	50 60 90 40 10	0 10 10 10 20	50 30 0 50 70	DL displayed lower bond integrity than the other investigated groups.
Alrefeai et al. [32]	Permanent Molar (n=15)	CAD	Fuji II LC	G1 (MBP+LM): 8.82±1.08^{a} G2 (PAA): 14.26±1.67^{a} G3 (ICGP+DL): 9.47±0.21^{a} G4 (RF+LED): 11.23±0.47^{a} G5 (PA): 13.45±0.32^{b}	60 70 80 50 90	30 20 20 30 10	10 10 0 20 0	CAD conditioned with polyacrylic acid demonstrated higher bond strength than when MBP and RF were used, but their interaction with RMGIC should also be investigated.
Al-Khureif et al. [33]	Permanent Molar (n=40)	CAD	Fuji II LC	G1 (PE): 13.98±1.59^{a} G2 (CHX): 17.85±1.09^{b} G3 (RF+UVA): 14.32±0.11^{a} G4 (LCO) 16.49±0.12^{b} G5 (DL): 10.36 ±0.33^{c}	50 50 20 10 10	50 50 20 60 10	0 0 60 30 80	Riboflavin activated by photodynamic therapy, diode laser, and propolis as cavity disinfectant before bonding to resin-modified glass ionomer is not recommended.
Alrahlah et al. [34]	Permanent Molar (n=40)	CAD	Optibond Solo Plus SE Filtek Z350	G1 (MBP+DL): 15.18±0.39^{b} G2 (CP+LED): 18.21±1.39^{a} G3 (ICGPDL): 17.42±0.55^{a} G4 (H_2O_2): 13.39±1.26^{c}	80 70 60 80	10 10 10 20	10 20 30 0	Curcumin and indocyanine green increase bond strength to affected dentin.

†Substrate Type: (SD) Sound Dentin; (CAD) Caries-Affected Dentin; (ACD) Artificially Carious Dentin. ††Type of Treatment: (DL) Laser Diode; (ECL) Er,Cr:YSGG Laser; (UVA) Ultravioleta Laser; (CO2) Co2 Laser; (PAA) Polyacrylic Acid; (LED) Laser Emission Diode; (COL): CO2 Laser; (H2O2) Hydrogen Peroxide; (CHX) Chlorhexidine; (SDF); Silver Diamine Fluoride; (GOF) Graphene Oxide Fibers; (KI) Potassium Iodide; (PE) Própolis Extract.; (PA) Phosphoric Acid. Dentin Conditioner: Polyacrylic Acid; (EDTA) Ethylenediaminetetraacetic Acid; (OSPTE) Optibond Solo Plus™ Total Etch. Photosensitizer Type: (MBP) Methylene Blue Photosensitizer; (ICGP) Indocyanine Green Photosensitizer; (CP) Curcumin Photosensitizer;(RF) Riboflavin; (NP): Not Performed; §A: Adhesive; C: Cohesive; M: Mixed; ++Different letters indicate statistical difference in Bond Strength Values

aPDT was compared with other agents used for dentinal disinfection, such as polyacrylic acid [25,26], EDTA [25], 3% hydrogen peroxide [22], silver diamino fluoride [26,30,34], 2% chlorhexidine solution [27,29], propolis extract [33], CO2 laser [33], and pineapple peel extract solution [31] (Table 2). According to Table 3, different lasers have been evaluated. The wavelength and power parameters varied in function of the photosensitizer used.

The effects of aPDT on dentin SBS have been studied for two restorative materials: resin-modified glass ionomer cement (RMGIC) [25,26,29,30,32,33] and composite resin [22,27,28,31,34]. As observed in Table 2, in 06 studies, aPDT negatively affected RMGIC SBS values to CAD [25,26,29,30,32,33].

Regarding wavelength and power parameters variation, when methylene blue solution was used, the wavelength varied from 638 to 976 nm [22,26,27,29,30,32,33] and the power from 150mW to 1.5 W. The DL was used in 07 studies [25-27,30]. The ultraviolet laser (UVA) was used in 01 study [33] due to the ability of riboflavin (RF) to produce reactive oxygen species when activated by visible blue light with maximum absorption peaks at wavelengths 270, 366, and 445 nm.

Table 3. aPDTparameters.

Authors	aPDTparameters	Photosensitizer
Alrahlah et al. [22]	G1: Diode Laser 638nm 1.5W G2: LED 385-515nm 1200mW/cm²	G1: MBP 100mg/L G2: CP 500mg/L
Al-Khureif et al. [25]	G1: TFDa	G1: MBP 50mg/L
Alshahrani [26]	G6: Diode Laser 638nm 1.5W	G6: MBP 100mg/L
Al Deeb et al. [27]	G3: Diode Laser 810nm 1.5W	G3: MBP 100mg/L
Al Rifaiy and Vohra [28]	G3: Diode Laser 940nm 2W	No Photosensitizer
Alshahrani et al. [29]	G2: Diode Laser 638nm 150mW G3: Diode Laser 940nm 1W G4: LED 318-515nm 1200mW/cm²	G2: MBP 2% G3: ICGP 25mg G4: CP
Al-Qahtani [30]	G3: Diode Laser 638nm 1.5W	G3: MBP 100mg/L
Al Deeb [31]	G3: Diode Laser 976nm 1W G5: LED 660nm 150mW	G2: No photosensitizer G5: RF 150mg/ml
Alrefeai et al. [32]	G1: Monochromatic Light 810nm 1.5W G3: Diode Laser 940nm 1W G4: LED 660nm 150mW	G1: MBP 100mg/L G3: ICGP 25mg G4: RF 150mg/ml
Al-Khureif et al. [33]	G3: UVA Laser 375nm 220mW G5: Diode Laser 976nm 1W	G3: RF 100mg/100ml 0.1% G5: No photosensitizer
Alrahlah et al. [34]	G1: Diode Laser 638nm 1.5W G2: LED 385-515nm irradiant 1200W/cm² G3: Diode Laser 940mm 1W	G1: MBP 100mg/L G2: CP 500mg/L G3: ICGP 0.5 mL

MBP: Methylene Blue Photosensitizer; ICGP: Indocyanine Green Photosensitizer; CP: Curcumin Photosensitizer; RF: Riboflavin.

As Al Deeb et al. [27] verified, aPDT negatively affected the SBS values of the composite to dentin. In contrast, Alrahlah et al. [34] found that the SBS values of composite to caries-affected dentin subjected to aPDT were higher than those observed when hydrogen peroxide was used for tissue disinfection. Al Rifay and Vohra [28] recorded low SBS values for healthy dentin only for one evaluated composite (multicore) when subjected to diode laser irradiation (DL). Alrahlah et al. [22] found positive effects of aPDT on composite adhesion to caries-affected dentin compared to other disinfection techniques compared to silver diaminofluoride at concentrations of 3.8% and 38%.

Only one article used diode lasers at 638 nm and 150 mW in one group, 940 nm and 1W in another group, and conducted at 318–515 nm and 1200mW/cm² in a third group [29], 01 study used a diode laser at 638 nm and 1.5 W in one group, 940 nm, and 1 W in another and conducted at 385–515 nm to 1200 W/cm² in a third group [22], 01 used photodynamic therapy and a 635 nm 20 mW diode laser in one group and 660 nm and 150mW in another [32], 01 study did not mention the photosensitizer used [28], and 01 study used diode laser at 638 nm and 1.5 W in one group and LED at 385-515 nm and 1200mW/cm² in another [34]. Regarding photosensitizers, methylene blue was used in 04 studies [25-27,30], curcumin and indocyanine green in 01 study [34]; one study used methylene blue 100 mg/L and curcumin at 500 mg/L [22]. Two studies used diode laser at 976 nm and 1W with riboflavin 150 mg/ml [31,32]; one study used UVA laser with 375 nm and 220 mW and riboflavin 100mg/100ml – 0.1% [33].

Risk of Bias in Studies and Reporting Biases

Table 4 shows the estimates of the risk of bias for the studies analyzed, and all showed a high risk of bias [22,25,34,26-33]. No studies have performed sample size calculations. However, the allocation of specimens between the experimental groups was defined as random in all studies analyzed. Restorative materials were used per the manufacturer's recommendations in 5 studies [23,25-28]. Other information related to the parameters contemplated by the criteria used should have been addressed in all the studies analyzed.

Table 4. Risk of Bias.

Authors	Randomization of Reeth	Materials used According to Manufacturer's Instructions	Treatment Performed by a Single Operator (Laser, Adhesive, Restoration)	Sample Size Calculation	Operator Blinding During SBS Evaluation	Risk of Bias
Alrahlah et al. [22]	Yes	No	No	No	No	HIGH
Al-Khureif et al. [25]	Yes	No	No	No	No	HIGH
Alshahrani [26]	Yes	Yes	No	No	No	HIGH
Al Deeb et al. [27]	Yes	No	No	No	No	HIGH
Al Rifaiy and Vohra [28]	Yes	Yes	No	No	No	HIGH
Alshahrani et al. [29]	Yes	Yes	No	No	No	HIGH
Al-Qahtani [30]	Yes	Yes	No	No	No	HIGH
Al Deeb [31]	Yes	No	No	Yes	No	HIGH
Alrefeai et al. [32]	Yes	No	No	No	No	HIGH
Al-Khureif [33]	Yes	No	No	Yes	No	HIGH
Alrahlah et al. [34]	Yes	Yes	No	No	No	HIGH

High risk 01 or 02 parameters reported; Medium risk 03 or 04 parameters reported; and Low risk 05 parameters reported.

Discussion

From the 11 studies included and considering the 550 permanent teeth evaluated, bond strength was evaluated mainly through the shear bond strength (SBS) test, with dentin affected by caries being the substrate most frequently used in studies. Six studies demonstrated that aPDT with methylene blue (MB) negatively affected the SBS values of resin-modified glass ionomer cement (RMGIC) to dentin. Regarding risk of bias assessment, all studies were at high risk of bias.

The studies using dentin affected by caries as the substrate were the most frequently used. The SCR technique aims to minimize the unnecessary removal of sound tissues [35-37]. It advocates the preservation of CAD, which, although partially degraded, can be remineralized [35-37]. However, some professionals are concerned about not wholly removing the decayed dentin, believing that the permanence of bacteria in the tissue implies the risk of lesion progression and the occurrence of pulpal complications over time [38].

Some studies used sound dentin as a control group for test groups whose substrates consisted of caries-affected dentin [22,25-28,31-33]. This represents a problem in comparative terms since the SBS values for CAD tend to be lower than those for sound dentin because of mineral loss, collagen degradation, and increased intertubular dentin porosity caused by caries [21,23,39]. Bond strength to dentin was evaluated using the SBS test in all studies. Unfortunately, it was impossible to estimate the extent of the influence of aPDT on SBS, as there was no adequate selection of control groups (i.e., groups that included the corresponding substrate not subjected to aPDT, making comparisons unfeasible) [26].

When comparing the results of the studies, it was possible to verify that the SBS values to dentin for RMGIC and composite resin are negatively influenced by the photosensitizer used, especially methylene blue [20,22-26]. These harmful effects may be related to the hydrophilic characteristics of methylene blue, which would result in greater water retention at the adhesive interface, compromising the polymerization of the adhesive and its physical properties [40]. In contrast, the association of aPDT with curcumin resulted in higher SBS values for dentin compared to other photosensitizers [22,25]. According to Alrahlah et al. [22], this may be related to (i) the ability of curcumin to bind to calcium and phosphate ions present in dentin chemically and (ii) its hydrophobicity, which would reduce water absorption at the adhesive interface. Other photosensitizers used were riboflavin and propolis extract [29-31]. Riboflavin is a cationic photosensitizing substance derived from vitamin B2, which releases reactive oxygen when irradiated by blue light. Therefore, a probable explanation for the low SBS values is the interference caused by the oxygen released as a result of the riboflavin irradiation, which could negatively affect the polymerization of the RMGIC resin matrix. Likewise, when CAD surfaces were treated with propolis – a resinous substance extracted from bee hives and considered a natural disinfectant agent – the SBS values were lower than other groups. According to the authors, this is probably due to propolis depending on the presence of flavonoids, which may have interacted with RMGIC agents, impairing adhesion. Unfortunately, the methodological heterogeneity of the studies made it impossible to perform a meta-analysis of the results because they varied in function of the type of substrate (SD or CAD), restorative materials (RMGIC, composite resins, and bonding agents), and dentin disinfection protocol. This highlights the need for better methodological standardization of laboratory studies – a recurring recommendation in the literature – to reach a consensus on the effects of techniques and materials used in the restorative treatment of dentin lesions [24-26].

The influence of aPDT on the adhesion of dental restorative materials still constitutes a theme that needs to be more adequately explored in the scientific literature, which was also demonstrated in this review by the few studies included in the analysis. Scientific support becomes even more problematic when the quality of available studies is observed. Based on the evaluation criteria proposed by Sarkis-Onofre et al. [24] used in this research, the risk of bias in all the studies analyzed was considered high. It is essential to understand that *in vitro* studies are limited in simulating the complexity of the oral environment, and there is a need for clinical studies to obtain a more complete understanding of the effects of aPDT on the longevity of restorative treatment. The methodological variations between the studies were another limitation detected, which makes it difficult to compare the results and reach a consensus on the influence of aPDT on shear bond strength (SBS) to sound and caries affected dentin, for both restorative materials studied: RMGIC [26,27,29] and the composite resin [22,25,26,28]. Modified versions of these materials were also evaluated. Among them is the one proposed by Al-Qahtani [30], in which the RMGIC underwent the inclusion of graphene oxide nanoparticles, a compound capable of interacting with the functional groups of monomers, to improve bonding to dental tissues [41].

Although the risk of bias was considered high in the included studies, the outcomes of this systematic review are significant. These provide a foundation of knowledge that guides research priorities, ultimately contributing to improved healthcare outcomes and public well-being by highlighting the existing evidence on the topic, which involves a specific population, intervention, and outcome. Therefore, this systematic review, by gathering and interpreting the available evidence on this topic through *in vitro* studies, contributes to the identification of potential new interventions, besides providing syntheses of the state of knowledge in this subject. This information is essential for policymakers in establishing a foundation for new dentistry therapies and general health.

Conclusion

The effects of antimicrobial photodynamic therapy on adhesion to dentin vary depending on the type of dentin and the photosensitizer used, particularly methylene blue, which negatively affected the adhesion of the resin-modified glass ionomer cement to dentin.

Authors' Contributions

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MRRC	https://orcid.org/0000-0003-1628-029X	Methodology, Formal Analysis, and Writing - Review and Editing.
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All authors declare that they contributed to a critical review of intellectual content and approval of the final version to be published.

Financial Support

This systematic review was supported by Programa: 13407 - PDPG Emergencial de Consolidação Estratégica dos Programas de Pós-Graduação (PPGs) Stricto Sensu Acadêmicos com Notas 3 e 4.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

The data used to support the findings of this study can be made available upon request to the corresponding author.

References

[1] Schwendicke F, Frencken J, Innes N. Clinical recommendations on carious tissue removal in cavitated lesions. Monogr Oral Sci 2018; 27:162-166. https://doi.org/10.1159/000487843
[2] Kidd E, Fejerskov O, Nyvad B. Infected dentine revisited. Dent Update 2015; 42(9):802-806, 808-809. https://doi.org/10.12968/denu.2015.42.9.802
[3] Fusayama T, Terashima S. Differentiation of two layers of carious dentin by staining. Bull Tokyo Med Dent Univ 1972; 19(1):83-92.
[4] Fusayama T, Kurosaki N. Structure and removal of carious dentin. Int Dent J 1972; 22(3):401-411.
[5] Ogushi K, Fusayama T. Electron microscopic structure of the two layers of carious dentin. J Dent Res 1975; 54(5):1019-1026. https://doi.org/10.1177/00220345750540050301
[6] Fusayama T. Two layers of carious dentin; diagnosis and treatment. Oper Dent 1979; 4(2):63-70.
[7] Handelman SL, Buonocore MG, Heseck DJ. A preliminary report on the effect of fissure sealant on bacteria in dental caries. J Prosthet Dent 1972; 27(4):390-392. https://doi.org/10.1016/0022-3913(72)90287-9
[8] Handelman SL, Washburn F, Wopperer P. Two-year report of sealant effect on bacteria in dental caries. J Am Dent Assoc 1976; 93(5):967-970. https://doi.org/10.14219/jada.archive.1976.0007
[9] Nyvad B, ten Cate JM, Fejerskov O. Arrest of root surface caries in situ. J Dent Res 1997; 76(12):1845-1853. https://doi.org/10.1177/00220345970760120701
[10] Kidd EAM. How "clean" must a cavity be before restoration? Caries Res 2004; 38(3):305-313. https://doi.org/10.1159/000077770
[11] Banerjee A, Doméjean S. The contemporary approach to tooth preservation: Minimum intervention [MI] caries management in general practice. Prim Dent J 2013; 2(3):30-37. https://doi.org/10.1308/205016813807440119
[12] Weber CM, Alves LS, Maltz M. Treatment decisions for deep carious lesions in the Public Health Service in Southern Brazil. J Public Health Dent 2011; 71(4):265-270. https://doi.org/10.1111/j.1752-7325.2011.00258.x
[13] Crespo-Gallardo I, Martín-González J, Jiménez-Sánchez MC, Cabanillas-Balsera D, Sánchez-Domínguez B, Segura-Egea JJ. Dentist's knowledge, attitudes and determining factors of the conservative approach in teeth with reversible pulpitis and deep caries lesions. J Clin Exp Dent 2018; 10(12):e1205-1215. https://doi.org/10.4317/jced.55395
[14] Schwendicke F. Contemporary concepts in carious tissue removal: A review. J Esthet Restor Dent 2017; 29(6):403-408. https://doi.org/10.1111/jerd.12338
[15] Faria LV, Fernandes T de O, Guimarães LS, Cajazeira MRR, Antunes LS, Antunes LAA. Does selective caries removal in combination with antimicrobial photodynamic therapy affect the clinical performance of adhesive restorations of primary or permanent teeth? A systematic review with meta-analysis. J Clin Pediatr Dent 2022; 46(5):1-14. https://doi.org/10.22514/jocpd.2022.002
[16] De Melo WCMA, Avci P, De Oliveira MN, Gupta A, Vecchio D, Sadasivam M, et al. Photodynamic inactivation of biofilm: Taking a lightly colored approach to stubborn infection. Expert Rev Anti Infect Ther 2013; 11(7):669-693. https://doi.org/10.1586/14787210.2013.811861
[17] Melo MAS, de-Paula DM, Lima JPM, Borges FMC, Steiner-Oliveira C, Nobre-dos-Santos M, et al. In vitro photodynamic antimicrobial chemotherapy in dentine contaminated by cariogenic bacteria. Laser Phys 2010; 20(6):1504-1513. https://doi.org/10.1134/S1054660X10110174
[18] Hashemikamangar SS, Alsaedi RJF, Chiniforush N, Motevaselian F. Effect of antimicrobial photodynamic therapy with different photosensitizers and adhesion protocol on the bond strength of resin composite to sound dentin. Clin Oral Investig 2022; 26(5):4011-4019. https://doi.org/10.1007/s00784-022-04370-8
[19] Alshammary F, Karobari MI, Assiry AA, Marya A, Shaikh GM, Siddiqui AA, et al. Effect of Nd:YAG, Er,Cr:YSGG laser irradiation, and adjunctive photodynamic therapy on push-out bond strength of zirconia posts to radicular dentin. Biomed Res Int 2021; 2021:5523242. https://doi.org/10.1155/2021/5523242
[20] Opdam NJM, Van De Sande FH, Bronkhorst E, Cenci MS, Bottenberg P, Pallesen U, et al. Longevity of posterior composite restorations: A systematic review and meta-analysis. J Dent Res 2014; 93(10):943-949. https://doi.org/10.1177/0022034514544217

[21] Isolan CP, Sarkis-Onofre R, Lima GS, Moraes RR. Bonding to sound and caries-affected dentin: A systematic review and meta-analysis. J Adhes Dent 2018; 20(1):7-18. https://doi.org/10.3290/j.jad.a39775
[22] Alrahlah A, Naseem M, Tanveer SA, Abrar E, Charania A, AlRifaiy MQ, et al. Influence of disinfection of caries effected dentin with different concentration of silver diamine fluoride, curcumin and Er, Cr:YSGG on adhesive bond strength to resin composite. Photodiagnosis Photodyn Ther 2020; 32:102065. https://doi.org/10.1016/j.pdpdt.2020.102065
[23] Pinna R, Maioli M, Eramo S, Mura I, Milia E. Carious affected dentine: Its behaviour in adhesive bonding. Aust Dent J 2015; 60(3):276-293. https://doi.org/10.1111/adj.12309
[24] Sarkis-Onofre R, Skupien J, Cenci M, Moraes R, Pereira-Cenci T. The role of resin cement on bond strength of glass-fiber posts luted into root canals: A systematic review and meta-analysis of in vitro studies. Oper Dent 2014; 39(1):E31-44. https://doi.org/10.2341/13-070-LIT
[25] Al-Khureif AA, Mohamed BA, Al-Shehri AM, Khan AA, Divakar DD. Bond assessment of resin modified glass ionomer cement to dentin conditioned with photosensitizers, laser and conventional regimes. Photodiagnosis Photodyn Ther 2020; 30:101795. https://doi.org/10.1016/j.pdpdt.2020.101795
[26] Alshahrani A. Influence of silver diamine fluoride compared to photodynamic therapy on the bond integrity of resin modified glass ionomer cement to demineralized dentin. Photodiagnosis Photodyn Ther 2020; 32:102007. https://doi.org/10.1016/j.pdpdt.2020.102007
[27] Al Deeb L, Bin-Shuwaish MS, Abrar E, Naseem M, Al-Hamdan RS, Maawadh AM, et al. Efficacy of chlorhexidine, Er Cr YSGG laser and photodynamic therapy on the adhesive bond integrity of caries affected dentin. An in-vitro study. Photodiagnosis Photodyn Ther 2020; 31:101875. https://doi.org/10.1016/j.pdpdt.2020.101875
[28] Al Rifaiy MQ, Vohra F. Effect of phototherapy on dentin bond strength and microleakage when bonded to resin with different conditioning regimes. Photodiagnosis Photodyn Ther 2019; 25:271-274. https://doi.org/10.1016/j.pdpdt.2018.12.014
[29] Alshahrani A, Abrar E, Maawadh AM, Al-Hamdan RS, Almohareb T, AlFawaz Y, et al. Management of caries affected dentin (CAD) with resin modified glass ionomer cement (RMGIC) in the presence of different caries disinfectants and photosensitizers. Photodiagnosis Photodyn Ther 2020; 32:101978. https://doi.org/10.1016/j.pdpdt.2020.101978
[30] Al-Qahtani YM. Impact of graphene oxide and silver diamine fluoride in comparison to photodynamic therapy on bond integrity and microleakage scores of resin-modified glass ionomer cement to demineralized dentin. Photodiagnosis Photodyn Ther 2021; 33:102163. https://doi.org/10.1016/j.pdpdt.2020.102163
[31] Al Deeb L. Disinfection of caries-affected dentin using activated vitamin B2 and diode laser with total-etch technique. An assessment of adhesive bond. Photodiagnosis Photodyn Ther 2022; 39:102970. https://doi.org/10.1016/j.pdpdt.2022.102970
[32] Alrefeai MH, Aljamhan AS, Alhabdan A, Alzehiri MH, Naseem M, Alkhudhairy F. Influence of methylene blue, Riboflavin, and indocyanine green on the bond strength of caries affected dentin when bonded to resin-modified glass ionomer cement. Photodiagnosis Photodyn Ther 2022; 38:102792. https://doi.org/10.1016/j.pdpdt.2022.102792
[33] Al-Khureif AA, Mohamed BA, Khan AA. Resin modified glass ionomer bonded to caries affected dentin disinfected with carbon dioxide laser, diode lasers, bee glue and photosensitizing agents: An estimation of bond strength. Photodiagnosis Photodyn Ther 2022; 38:102829. https://doi.org/10.1016/j.pdpdt.2022.102829
[34] Alrahlah A, Niaz MO, Abrar E, Vohra F, Rashid H. Treatment of caries affected dentin with different photosensitizers and its effect on adhesive bond integrity to resin composite. Photodiagnosis Photodyn Ther 2020; 31:101865. https://doi.org/10.1016/j.pdpdt.2020.101865
[35] Schwendicke F. Removing carious tissue: Why and how? Monogr Oral Sci 2018; 27:56-67. https://doi.org/10.1159/000487832
[36] Cieplik F, Buchalla W, Hellwig E, Al-Ahmad A, Hiller K-A, Maisch T, et al. Antimicrobial photodynamic therapy as an adjunct for treatment of deep carious lesions-A systematic review. Photodiagnosis Photodyn Ther 2017; 18:54-62. https://doi.org/10.1016/j.pdpdt.2017.01.005
[37] Fusayama T. Intratubular crystal deposition and remineralization of carious dentin. J Biol Buccale 1991; 19(3):255-262.
[38] Schwendicke F, Meyer-Lueckel H, Doerfer C, Paris S. Attitudes and behaviour regarding deep dentin caries removal: A survey among German dentists. Caries Res 2013; 47(6):566-573. https://doi.org/10.1159/000351662
[39] Choi K, Oshida Y, Platt JA, Cochran MA, Matis BA, Yi K. Microtensile bond strength of glass ionomer cements to artificially created carious dentin. Oper Dent 2006; 31(5):590-597. https://doi.org/10.2341/05-108
[40] Neves PAM, Lima LA, Rodrigues FCN, Leitão TJ, Ribeiro CCC. Clinical effect of photodynamic therapy on primary carious dentin after partial caries removal. Braz Oral Res 2016; 30(1):S1806-83242016000100246. https://doi.org/10.1590/1807-3107BOR-2016.vol30.0047
[41] Khan AA, Al-Khureif AA, Saadaldin SA, Mohamed BA, Musaibah ASO, Divakar DD, et al. Graphene oxide-based experimental silane primers enhance shear bond strength between resin composite and zirconia. Eur J Oral Sci 2019; 127(6):570-576. https://doi.org/10.1111/eos.12665