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RDE
Restorative Dentistry & Endodontics

Research Articles

Case Report

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RDE Restorative Dentistry & Endodontics

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Aims and Scope

The *Restorative Dentistry and Endodontics* (officially abbreviated as Restor Dent Endod; RDE) is a peer-reviewed and open access journal providing up-to-date information regarding the research and developments on new knowledge and innovations pertinent to the field of contemporary clinical operative dentistry, restorative dentistry, and endodontics. In the field of operative and restorative dentistry, the journal deals with diagnosis, treatment planning, treatment concepts and techniques, adhesive dentistry, esthetic dentistry, tooth whitening, dental materials and implant restoration. In the field of endodontics, the journal deals with a variety of topics such as etiology of periapical lesions, outcome of endodontic treatment, surgical endodontics including replantation, transplantation and implantation, dental trauma, intracanal microbiology, endodontic materials (MTA, nickel-titanium instruments, etc), molecular biology techniques, and stem cell biology. RDE publishes original articles, review articles and case reports dealing with aforementioned topics from all over the world.

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History

RDE (eISSN 2234-7666) is the official journal of the Korean Academy of Conservative Dentistry and was renamed from the *Journal of Korean Academy of Conservative Dentistry* (pISSN 1225-0864; eISSN 2093-8179), which was first published in 1975. It was initially published once a year but became a biannual journal in 1986, a quarterly journal in 1999, and then a bimonthly journal in 2001. From 2012, the journal name was renamed, the official language of the journal was changed to English, and it is currently published quarterly. This journal is supported in part by a Grant from the Korean Federation of Science and Technology Societies funded by the Korean Government (MEST).

Distribution

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Effect of surface treatment on glass ionomers in sandwich restorations: a systematic review and meta-analysis of laboratory studies

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ABSTRACT

Objectives: This study aimed to evaluate the effect of different surface treatments on the bond strength between new or aged glass ionomers (GI) and resin composites in sandwich restorations.

Methods: A comprehensive search was conducted in three databases to identify studies focusing on the bond strength of new or aged GIs and resin composites in laboratory settings. The selected studies were assessed for potential biases based on predetermined criteria. Additionally, a meta-analysis was performed using three studies.

Results: A total of 29 studies were included, with 24 investigating the bond strength of new GIs and five focusing on GI repair. Three studies were included in the meta-analysis (with a 95% confidence interval) which revealed no significant difference in the mean MPa values of resin-modified glass ionomer (RMGI) treated with phosphoric acid or Er,Cr:YSGG laser before the application of an etch-and-rinse adhesive. Surface treatment was found to be crucial for achieving optimal bonding between GI and resin composite, regardless of the GI's condition.

Conclusions: The combination of mechanical and chemical surface treatments does not significantly affect the bond strength between new RMGI and composite. However, for GI repair, it is recommended to use both treatments to enhance the bond strength.

Keywords: Bond strength; Glass ionomers; Sandwich restorations; Surface treatment

INTRODUCTION

The use of glass ionomer cement (GIC) in dental restoration is highly regarded for its strong bond with enamel and dentin, sustained fluoride release, and thermal expansion similar to dentin [1,2]. However, GICs have limited aesthetics and lower abrasion resistance compared to resin composites, limiting their use in high-

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stress areas. To address this, the “sandwich technique” or “bilayered technique” was developed [3].

The lamination technique uses two restorative materials to create a single restoration, aiming to combine their physical and aesthetic benefits [4]. It pairs the dentin-adhesion and fluoride release of GIC with the aesthetics and polishability of resin composite for optimal results [5]. This method is ideal for deep cavities or those with undermined areas, where resin composite is preferred [5]. When restoration margins contact with dentin, applying lamination over GIC enhances adhesion and reduces microleakage [2]. Conventional and RMGI can be used, differing in adhesion, setting reaction, and moisture sensitivity [6].

The weak cohesive strength of GIC, combined with the limited chemical interaction between GIC and resin composite resulting from their distinct chemical reaction mechanisms, reduces the bond strength between the two materials [7]. To improve this, RMGI, which includes polymerizable functional groups, replaced conventional GIC, enhancing bond strength through both chemical and mechanical bonding [8].

In sandwich restorations, the bond between GIC and resin composite is crucial for retention, durability, and sealing [7]. Inadequate bonding is a primary cause of failure, often leading to caries and restoration breakdown [9]. Factors affecting the bond include the base material’s tensile strength, bonding agent viscosity, and the polymerization shrinkage and bonding capacity of the overlay composite [10].

Despite the use of sandwich restorations, the water-based nature and brittleness of GIC can lead to fractures or wear, necessitating repairs by adding fresh material [11]. Repair is needed in cases of technique errors or unaesthetic marginal staining. While resin composite repair is well-studied and routine in minimally invasive dentistry [12], the protocol for repairing GI-based restorations with resin composite remains unclear.

The literature examines various chemical and mechanical surface treatments for GICs in sandwich restorations or resin composite repairs [13]. Early studies recommended etching GICs to improve bonding with composite resin [14], but recent research warns that etching may weaken GICs and cause cracks [15]. It is suggested that GICs may already have sufficient surface roughness for bonding, and excessive etching can damage the material [15]. Studies on bonding agents show mixed results, with some recommending mild self-etch adhesives [16], while others favor GI-based adhesives [7].

There is ongoing debate about the necessary mechanical surface treatment for aged GICs to ensure a durable bond with resin composite. Studies have used various methods for mechanical roughening, such as bur use [17] and air abrasion [13]. Additionally, alternative treatments like photodynamic therapy (PDT) and laser treatments (Er,Cr:YSGG and Nd:YAG) have shown promising results [18].

Given the variety of adhesive systems, advancements in GIs, and differences in adhesion and setting mechanisms, no consensus exists on the optimal surface treatment for GICs in sandwich restorations. This includes cases where GICs are bonded or repaired with resin composite. This review aims to assess the literature to identify the most effective surface treatment (chemical or mechanical) for new or aged GIs, focusing on bond strength in resin composite sandwich restorations.

METHODS

Using the PICO (Participant, Intervention, Comparator, and Outcome) framework, this systematic review aimed to address the following research questions [19]:

1. What is the most effective surface treatment (mechanical and/or chemical) (C) for achieving optimal bond strength (O) when bonding (I) new GI and resin composite in sandwich restorations (P)?
2. What is the most effective surface treatment (mechanical and/or chemical) (C) for achieving optimal bond strength (O) when bonding (I) aged GI and either resin composite or GI in sandwich restorations (P)?

The systematic review procedure was registered with Prospero and assigned the identification number CRD42024614235. This review strictly followed the protocols outlined in the recently revised PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [20]. To acquire pertinent data, a comprehensive search was conducted across three electronic databases: the National Library of Medicine (MEDLINE/PubMed), Scopus, and ScienceDirect. The

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specific search methodologies used for each database are detailed hereafter.

#1 AND #2 AND #3 AND #4 AND #5

#1 "glass ionomer" OR "ionomer" OR "ionomers" OR "glass ionomer restoration" OR "glass ionomer cement"

#2 "glass ionomer repair" OR "dental restoration repair" OR "aged glass ionomer"

#3 "sandwich restoration" OR "bilayered restoration" OR "bilayered resin composite" OR "sandwich technique" OR "laminate technique"

#4 "surface treatment" OR "chemical treatment" OR "mechanical treatment" OR "laser treatment" OR "surface roughening" OR "bonding agents" OR "adhesives"

#5 "bond strength" OR "shear bond strength" OR "microshear bond strength" OR "tensile bond strength" OR "microtensile bond strength"

The following filters were applied to each database:

a. Pubmed
   Year: 2010-2024
   Article type: Comparative study, evaluation study, and observational study
   Language: English

b. ScienceDirect
   Year: 2010-2024
   Article type: Research articles
   Subject area: Medicine and Dentistry
   Language: English

c. Scopus
   Year: 2010-2024
   Subject area: Dentistry and materials science
   Document type: Limited to article
   Language: limited to English

Non-internet sources were manually checked to ensure comprehensive coverage. The retrieved articles from the searches were transferred into EndNote X7.7 software (Clarivate Analytics, Philadelphia, PA, USA), which was utilized to detect and eliminate duplicate entries.

Search strategy

The comprehensive search strategy, collaboratively developed by the review team, underwent peer review by a second information specialist. Eligibility criteria for the studies were evaluated by each author based on three factors: the relevance of the title, the abstract, and the full text. The laboratory studies included in this review focused on investigating the required surface treatment (mechanical and/or chemical) for bonding new or aged glass ionomers (GIs) and resin composites in sandwich restorations, with a specific emphasis on bond strength. The exclusion criteria included: review papers, clinical trials, and case reports, implant-supported restorations, primary and endodontically treated teeth, studies that evaluated the bonding of pulp capping materials to GIs, and studies that evaluated the GI/resin composite interface when bonded to dentin or in a cavity. To be included in the review, all three authors had to reach a consensus. Any disagreements were resolved either through consensus or discussions with a senior researcher.

Risk of bias assessment

In order to evaluate potential bias, two researchers independently evaluated the research utilizing criteria established in earlier systematic reviews of laboratory experiments [2,21]. If a criterion was specifically addressed in the research, it was labeled as "yes" to indicate its presence. Conversely, if the information was absent or a criterion was not detailed, it was marked as "no." Studies that documented 1 to 3 criteria were deemed to possess a significant risk of bias, those documenting 4 or 5 criteria were considered to have a moderate risk of bias, and studies detailing 6 or 7 criteria were categorized as having a low risk of bias.

Statistical analysis

The meta-analysis focused on studies that compared the shear bond strength values in RMGI (Fuji II LC) treatments when either phosphoric acid or Er,Cr:YSGG laser was used before the application of an etch-and-rinse adhesive. Information such as sample sizes, averages, and standard deviations (SD) in MPa were extracted from these studies and analyzed using Stata for Windows, ver. 17 (StataCorp. LLC, College Station, TX, USA), with a confidence level of 95%. The average MPa data following both surface treatments were calculated using either fixed-effect or random-effects models, which were selected based on statistical assessments for heterogeneity outcomes. The heterogeneity of the data was assessed through the Q homogeneity test, with significance determined at $p < 0.05$. The thresholds for interpreting I^2 are as follows: 0% to 40%, heterogeneity might not be considered significant; 30% to 60%, heterogeneity may indicate moderate levels; 50% to 90%, heterogeneity may suggest substantial levels; and 75% to 100%, heterogeneity is considered considerable. A funnel plot, along with Egger's test, was later employed to evaluate the possibility of publication bias.

RESULTS

Search results

Electronic searches, utilizing the aforementioned filters for each database, were conducted and identified 11,007 published articles. The authors independently evaluated the titles and abstracts of the search results. However, 10,960 studies were excluded for one or more of the following reasons: they were not related to dental research, were case reports or clinical trials, focused on implant-supported restorations, primary teeth, endodontically treated teeth, or indirect restorations.

Forty-seven studies underwent full-text assessment to determine eligibility. Subsequently, based on the inclusion and exclusion criteria, 18 studies were excluded. These excluded studies focused on assessing the bonding of pulp capping materials to GIs or the bond strength of the GI/resin composite interface when bonded to dentin or within a cavity. Ultimately, 29 studies met the originally specified inclusion criteria for this review. The stages of the search process are depicted in the flowchart (Figure 1).

Data extraction

The current review evaluated 29 studies that investigated the effect of surface treatment approach (either mechanical or chemical) on new or aged GIs, particularly in terms of bond strength in resin composite sandwich restorations. Twenty-four studies were included for the

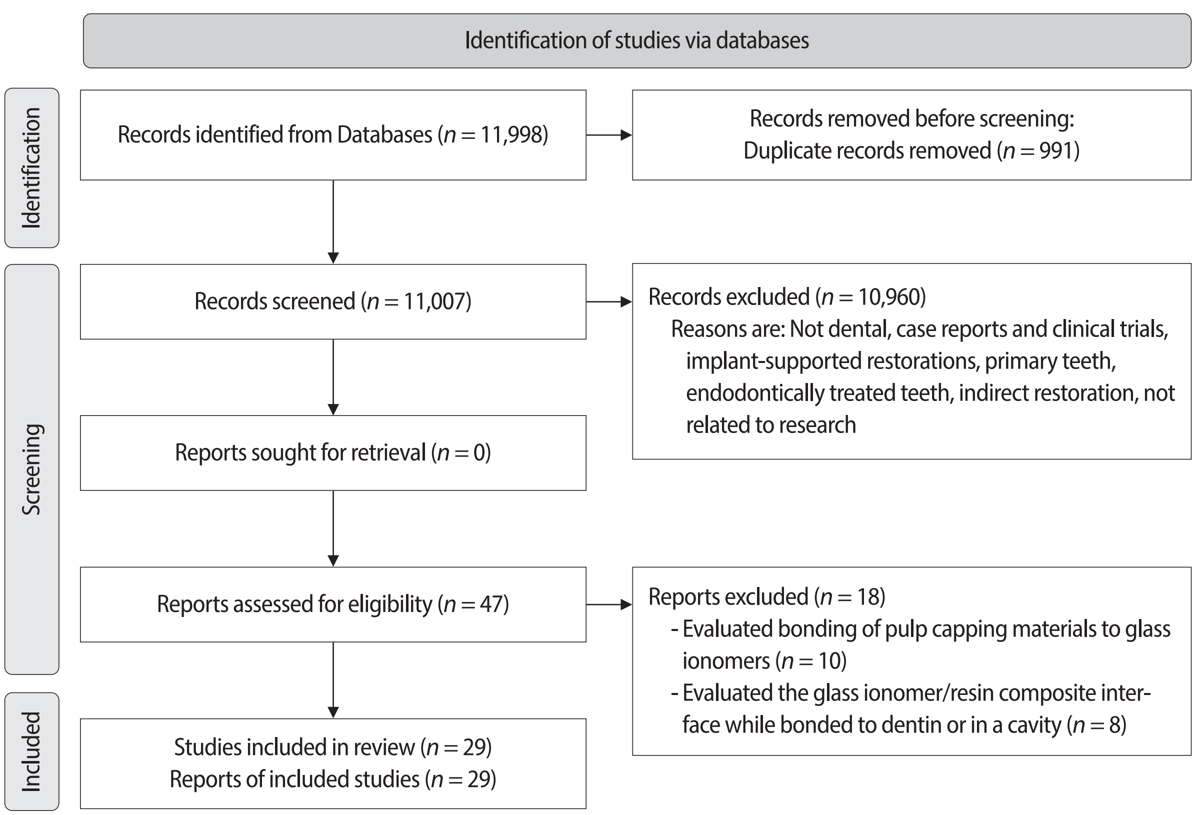

Figure 1. A flowchart depicting the search process, modified from the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Statement.

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first review question, and five studies were included for the second question. Extracted data from the studies are summarized in Tables 1 to 4.

Analysis of study design and methodology

After conducting a thorough evaluation of the included studies, the primary parameters examined in the analysis of study design and methodology were as follows: (1) control groups, (2) finishing and polishing (F/P) prior to bonding, (3) type of GI and the composite material used, (4) surface treatment method, (5) aging before testing, and (6) testing methods.

These parameters were consistent across the included studies for both the first and second research questions.

Table 1. Assessment of sample size, surface treatment types, and test types in the included studies

Study	Sample size per group and specimens' dimensions	Aging for GI	Surface treatment	Test type	
				1ry	2ry
Arora *et al*. (2010) [22]	12 per group Dimensions for GI: 8 × 2.5 mm Dimensions for composite: 5 × 5.5 mm		Chemical	SBS	
Boushell *et al*. (2011) [32]	10 per group Dimensions for GI: 5 × 2 mm Dimensions for composite: 2.38 × 2 mm		Chemical	SBS	Failure mode analysis
Zhang *et al*. (2011) [14]	20 per group Dimensions for GI: not specified Dimensions for composite: 1.5 × less than 2 mm		Chemical	µSBS	Failure mode analysis
Chandak *et al*. (2012) [23]	10 per group Dimensions for GI: 6 × 2.5 mm Dimensions for composite: 5 × 3 mm		Chemical	SBS	
Kandaswamy *et al*. (2012) [15]	25 per group Dimensions for GI: 6 × 3 mm Dimensions for composite: 6 × 3 mm		Chemical	SBS	FESEM/EDX analysis
Navimipour *et al*. (2012) [24]	20 per group Dimensions for GI: 5 × 4 mm Dimensions for composite: 2.5 × 2 mm		Chemical and mechanical	SBS	Failure mode analysis Surface evaluation using SEM
Pamir *et al*. (2012) [33]	15 per group Dimensions for GI: 4 × 6 mm Dimensions for composite: 4 × 6 mm		Chemical	SBS	Failure mode analysis
Fragkou *et al*. (2013) [25]	7 per group Dimensions for GI: 22 × 5 × 1 mm Dimensions for composite: 22 × 5 × 1 mm		Chemical	TBS	Failure mode analysis Tensile strain Young's elastic modulus
Kasraie *et al*. (2013) [26]	4 per group Dimensions for GI: 15 × 2 mm Dimensions for composite: 0.8 × 2 mm		Chemical	µSBS	Failure mode analysis
Otsuka *et al*. (2013) [13]	10 per group Dimensions for GI: 6 × 4 mm Dimensions for composite: 4 × 2 mm		Chemical and mechanical	SBS	Failure mode analysis Surface free energy measurement
Babannavar and Shenoy (2014) [34]	5 per group Dimensions for GI: 6 × 3 mm Dimensions for composite: 6 × 3 mm		Chemical	SBS	
Boruziniat and Gharaei (2014) [35]	10 per group Dimensions for GI: 2 × 2 mm Dimensions for composite: 2 × 4 mm		Chemical	SBS	Failure mode analysis

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Table 1. Continued

Study	Sample size per group and specimens' dimensions	Aging for GI	Surface treatment	Test type	
				1ry	2ry
Jaberi Ansari *et al.* (2014) [36]	10 per group Dimensions for GI: 6 × 4 × 2 mm Dimensions for composite: 0.7 × 1 mm		Chemical	μSBS	
Ozer *et al.* (2014) [37]	10 per group Dimensions for GI: 10 × 1 mm Dimensions for composite: 8 × 2 mm		Chemical	SBS	Failure mode analysis
Panahandeh *et al.* (2015) [38]	10 per group Dimensions for GI: 2 × 4 × 6 mm Dimensions for composite: 0.7 × 1 mm		Chemical	μSBS	Surface evaluation using SEM
Sharafeddin and Choobineh (2016) [39]	10 per group Dimensions for GI: 6 × 3 mm Dimensions for composite: 6 × 3 mm		Chemical	SBS	
Francois *et al.* (2019) [16]	22 per group Dimensions for GI: 7 × 3 mm Dimensions for composite: 7 × 3 mm		Chemical	SBS	Failure mode analysis E-SEM evaluation
Pandey *et al.* (2019) [27]	10 per group Dimensions for GI: 10 × 2 mm Dimensions for composite: 5 × 6 mm		Chemical	SBS	
Bin-Shuwaish *et al.* (2020) [10]	10 per group Dimensions for GI: 8 × 4 mm Dimensions for composite: 4 × 4 mm		Chemical	SBS	Failure mode analysis
Ghubaryi *et al.* (2020) [18]	10 per group Dimensions for GI: 6 × 4 mm Dimensions for composite: 4 × 3 mm		Chemical and mechanical	SBS	Failure mode analysis
Bilgrami *et al.* (2022) [28]	8 per group Dimensions for GI: 4 × 2 mm Dimensions for composite: 4 × 2 mm		Chemical	SBS	Failure mode analysis
Farshidfar *et al.* (2022) [29]	10 per group Dimensions for GI: 10 × 5 × 6 mm Dimensions for composite: 5 × 5 × 6 mm		Chemical	μTBS	
Zakavi *et al.* (2023) [30]	10 per group Dimensions for GI: 3 × 5 mm Dimensions for composite: 2 mm		Chemical and mechanical	SBS	Failure mode analysis
Dawood *et al.* (2024) [31]	10 per group Dimensions for GI: 10 × 2 mm Dimensions for composite: 4 × 2 mm		Chemical and mechanical	SBS	Failure mode analysis
Maneenut *et al.* (2010) [12]	15 per group Dimensions for GI: 8.5 × 4 mm Dimensions for composite: 5.8 × 4 mm	4 days of water storage	Chemical	SBS	Failure mode analysis
Welch *et al.* (2015) [41]	20 per group Dimensions for GI: 5 mm Dimensions for composite: 4 mm	One-week water storage with one TC 500 TC 24-hour delay in a dry environment, followed by 500 TC	Chemical and mechanical	SBS	Failure mode analysis

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Table 1. Continued

Study	Sample size per group and specimens' dimensions	Aging for GI	Surface treatment	Test type	
				1ry	2ry
Vural and Gurgan (2019) [40]	12 per group Dimensions for GI: 8 × 2 × 2 mm Dimensions for composite: 8 × 2 × 2 mm	5,000 TC	Chemical	µTBS	Failure mode analysis SEM evaluation for the bonded interface
Ozaslan *et al*. (2023) [17]	10 per group Dimensions for GI: 10 × 2 mm Dimensions for composite: 1.6 × 2 mm	10,000 brushing cycles and 10,000 TC	Chemical	µSBS	Failure mode analysis Surface evaluation using SEM
Silva *et al*. (2024) [42]	8 per group Dimensions for GI: 8 × 8 × 4 mm Dimensions for composite: 8 × 8 × 4 mm	14 days' water storage and 5,000 TC	Chemical	µTBS	Failure mode analysis

E-SEM, environmental scanning electron microscopy; FESEM/EDX, finite element scanning electron microscopy/energy dispersive X-ray analysis; GI, glass ionomer; SBS, shear bond strength; µSBS, microshear bond strength; TBS, tensile bond strength test; µTBS, microtensile bond strength test; SEM, scanning electron microscope; TC, thermal cycle.

However, the second research question also considered an additional parameter: the technique used to age the tested GIs.

Bonding new glass ionomer and resin composite in sandwich restorations

1. Control groups

Fourteen studies included a control group (without the use of the tested mechanical or chemical surface treatments) [10,13,16,18,22–31], while 10 studies did not include a separate control group [14,15,32–39] (Table 5). Nine of the controlled studies did not involve any surface treatment prior to bonding with resin composite [10,13,22,23,25–29,31]. In contrast, the remaining studies included a control group that underwent some form of surface treatment, either using an adhesive [16,24,30] or a phosphoric acid etchant [18].

2. Finishing and polishing before bonding

Four studies performed F/P on the surface of new GI before bonding procedures [14,26,33,37], while one study performed F/P only on the surface of conventional GI and not on the tested RMGI [32]. Nineteen studies did not perform any F/P on the surface of the GI before bonding [10,13,15,16,18,22–25,27–31,34–36,38,39] (Table 3).

3. Type of glass ionomer and overlying composite

All included studies tested RMGIs except four studies [14,15,28,39]. Nine studies did not test conventional GIC [10,18,22,23,25–27,30,35], while the remaining studies did. Eleven studies included and compared both RMGIs and conventional GICs [13,16,24,29,31–34,36–38]. Only two of the included studies tested glass hybrid [16,36]. Five of the included studies tested nanofilled composite [10,16,22,25,39], while nine studies tested nanohybrid composite [10,18,24,26,27,29,32,33,37]. Seven studies used microhybrid composite [13–15,28,30,36,38], while three studies used silorane-based composite [32,34,37]. One study used packable resin composite [23], and one study tested nanoceramic resin composite [28]. Only one study included bulk-fill composites [10], and one used submicron-filled resin composite [31] (Table 2).

4. Type of surface treatment

Nineteen studies included chemical surface treatment [10,14–16,22,23,25,26–29,33–39], while five studies tested both mechanical and chemical surface treatments [13,18,24,30,31].

Seventeen studies used etch-and-rinse adhesives for chemical bonding between GIs and composites [10,14,16,18,22–27,30,31,33,35,36,38,39]. Similarly, 16 of the included studies used various self-etch adhesives, either two-step, one-step, or two-component self-etch adhesives [10,13,14–16,22,23,26,27,32,33,35–39]. Three studies used silorane-based adhesive [32,34,37], additionally, four studies used universal adhesives with different adhesive strategies [10,16,29,31]. Two studies in-

Table 2. Scientific categories, brand names, and placement techniques of restorative materials used in the included studies

Study	Materials used	Classification	Commercial name	Placement technique
Arora *et al*. (2010) [22]	GI	RMGI	Vitrebond	Bulk
	Overlying composite	Nanofilled resin composite	Filtek Z350	Incremental
Boushell *et al*. (2011) [32]	GI	RMGI	Vitrebond plus	Bulk
		Conventional GIC	GC Fuji IX GP EXTRA	
	Overlying composite	Silorane-based composite	Filtek LS	One increment (2 mm depth)
		Nanohybrid resin composite	Filtek Z250	
Zhang *et al*. (2011) [14]	GI	Two types of conventional GIC	GC Fuji IX GP EXTRA	Not specified
			Riva Self Cure	
	Overlying composite	Microhybrid resin composite	Gradia Direct Anterior	One increment (2 mm depth)
Chandak *et al*. (2012) [23]	GI	RMGI	Vitrebond	Bulk
	Overlying composite	Packable microhybrid resin composite	Filtek F-60	Incremental
Kandaswamy *et al*. (2012) [15]	GI	Conventional GIC	Fuji IX	Bulk
	Overlying composite	Microhybrid resin composite	Solare	Incremental
Navimipour *et al*. (2012) [24]	GI	Conventional GIC	Fuji II	Bulk
		RMGI	Fuji II LC	
	Overlying composite	Nanohybrid resin composite	Filtek Z250	One increment (2 mm depth)
Pamir *et al*. (2012) [33]	GI	Conventional GIC	Ketac Molar Quick Aplicap	Bulk
		RMGI	Photac Fil Quick Aplicap	
	Overlying composite	Nanohybrid resin composite	Filtek Z250	Incremental
Fragkou *et al*. (2013) [25]	GI	RMGI	Vitremer Tri-Cure	Not specified
	Overlying composite	Nanofilled resin composite	Filtek Supreme XT	Not specified
Kasraie *et al*. (2013) [26]	GI	RMGI	Vitrebond	Bulk
	Overlying composite	Nanohybrid resin composite	Filtek Z250	One increment (2 mm depth)
Otsuka *et al*. (2013) [13]	GI	Conventional GIC	Fuji IX GP	Bulk
		Two RMGI	Fuji II LC EM, Fuji Filling LC	
	Overlying composite	Microhybrid resin composite	Clearfil AP-X	One increment (2 mm depth)
Babannavar and Shenoy (2014) [34]	GI	RMGI	Vitrebond	Incremental
		Nanofilled RMGI	Ketac N100	Incremental
		Conventional GIC	Ketac Bond	Bulk
	Overlying composite	Silorane-based composite	Filtek P90	Incremental
Boruziniat and Gharaei (2014) [35]	GI	RMGI	Fuji II LC	Bulk
	Overlying composite	Microfilled resin composite	Heliomolar	Incremental
Jaberi Ansari *et al*. (2014) [36]	GI	Conventional GIC	Fuji II	Bulk
		RMGI	Fuji II LC	
	Overlying composite	Microhybrid resin composite	Filtek Z100	Bulk
Ozer *et al*. (2014) [37]	GI	Conventional GIC	Riva Self Cure	Bulk
		RMGI	Fuji II LC	
	Overlying composite	Nanohybrid resin composite	Filtek Z250	Bulk
		Silorane-based composite	Filtek Silorane	
Panahandeh *et al*. (2015) [38]	GI	Two RMGI	Riva Light Cure and Fuji II LC	Bulk
		Two conventional GIC	Riva Self Cure and Fuji II	
	Overlying composite	Microhybrid resin composite	Filtek Z100	Bulk
Sharafeddin and Choobineh (2016) [39]	GI	Conventional GIC	ChemFil Superior	Bulk
	Overlying composite	Nanofilled resin composite	Filtek Z350	Incremental

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Table 2. Continued

Study	Materials used	Classification	Commercial name	Placement technique
Francois *et al*. (2019) [16]	GI	One glass hybrid + one conventional GIC	EQUIA Forte Fil and Fuji IX GPFast	Bulk
		RMGI	Fuji II LC	
	Overlying composite	Nanofilled resin composite	Filtek Z350	Incremental
Pandey *et al*. (2019) [27]	GI	RMGI	Fuji II LC	Bulk
	Overlying composite	Nanohybrid resin composite	Filtek Z250	Incremental
Bin-Shuwaish (2020) [10]	GI	RMGI	Fuji II LC	Incremental
	Overlying composite	Nanofilled bulk fill resin composite	Filtek One Bulk Fill	Bulk
		Nanohybrid bulk fill resin composite	Tetric N-Ceram Bulk Fill	Bulk
		Nanofilled resin composite	Filtek Z350 XT	Incremental
Ghubaryi *et al*. (2020) [18]	GI	RMGI	Fuji Filling LC	Bulk
	Overlying composite	Nanohybrid resin composite	Filtek Z250	Incremental
Bilgrami *et al*. (2022) [28]	GI	Conventional GIC	Ketac Molar	Bulk
			Easy mix	
	Overlying composite	Nanofilled resin composite	Filtek Z350	Bulk (2 mm depth)
		Nanoceramic resin composite	Ceram X	
		Microhybrid resin composite	Spectrum	
Farshidfar *et al*. (2022) [29]	GI	One glass hybrid and one conventional GIC	Equia Forte Fil	Bulk
			Riva Self Cure	
		Two RMGI	Fuji II LC	
			Riva Light cure	
	Overlying composite	Nanohybrid resin composite	GC Kalore	Incremental
Zakavi *et al*. (2023) [30]	GI	RMGI	Fuji II LC	Bulk
	Overlying composite	Microhybrid resin composite	Gradia direct	One increment (2 mm)
Dawood *et al*. (2024) [31]	GI	Conventional GIC	Securafil	Bulk
		RMGI	Glass Liner	
	Overlying composite	Submicron-filled resin composite	PALFIQUE LX5	One increment (2 mm)
GI repair				
Maneenut *et al*. (2010) [12]	GI (Both materials used also for repair)	Nanofilled RMGI	Ketac N100	Bulk
		RMGI	Fuji II LC	
	Overlying composite	Nanofilled resin composite	Filtek Supreme	Bulk
		Microfilled resin composite	Solare	
Welch *et al*. (2015) [41]	GI	RMGI	Fuji II LC	Bulk
	Overlying GIC	RMGI	Fuji II LC	Bulk
Vural and Gurgan (2019) [40]	GI (The material was used also for repair)	Glass hybrid	EQUIA Forte Fil	Bulk
	Overlying composite	Microhybrid resin composite	G-aenial posterior	Not specified
Ozaslan *et al*. (2023) [17]	GI	Glass hybrid	EQUIA Forte HT Fil	Bulk
	Overlying composite	Nanoceramic resin composite	Neo Spectra ST HV	Bulk (2 mm depth)
Silva *et al*. (2024) [42]	GI (The material was used also for repair)	RMGI	Riva Light Cure	Incremental
	Overlying composite	Nanofilled resin composite	Z350 XT	Incremental

GI, glass ionomer; RMGI, resin-modified glass ionomer; GIC, glass ionomer cement.

Table 3. Detailed specifications for surface treatments used in the included studies

Study	Finishing and polishing for GI	Type of surface treatment	Commercial brand and specification
Arora *et al*. (2010) [22]	No	Two-step etch-and-rinse adhesive	Adper Single Bond 2
		Two-component self-etch adhesive	Adper Prompt L Pop (pH: 0.8)
Boushell *et al*. (2011) [32]	Only for the Conventional GIC	Two-step silorane-based adhesive	Filtek LS adhesive (pH: 2.7)
		Two-step self-etch adhesive	Adper Scotchbond SE (pH: 1)
Zhang *et al*. (2011) [14]	Yes	37% phosphoric acid + two-step etch-and-rinse adhesive	SDI acid etch gel + Adper Single Bond Plus
		Two-step self-etch adhesives	Adper Scotchbond SE
			Clearfil SE Bond (pH: 2)
		One-step self-etch adhesives	Clearfil S3 Bond (pH: 2.3)
			One Coat 7.0
Chandak *et al*. (2012) [23]	No	Two-step etch-and-rinse adhesive	Adper Scotch Bond 2
		Two-component self-etch adhesive	Adper Prompt L Pop
Kandaswamy *et al*. (2012) [15]	No	Self-etch adhesives	Adper prompt self-etch (pH: 1)
			AdheSE (pH: 1.4)
			Clearfil SE
			One coat SE (pH: 2.2)
Navimipour *et al*. (2012) [24]	No	35% phosphoric acid gel + two-step etch-and-rinse adhesive	Scotchbond Etchant
			Adper Single Bond
		Er,Cr:YSGG laser + etch-and-rinse adhesive	Waterlase YSGG; Biolase Europe GmbH
			A pulse energy setting of 1 W was applied for 15 seconds using a G-type tip with a diameter of 600 µm, accompanied by 10% water and 11% air.
Pamir *et al.* (2012) [33]	Yes	%35 phosphoric acid + two-step etch-and-rinse adhesive	Scotchbond Etch
			Adper Single Bond 2
		Two-component self-etch adhesive	Adper Prompt L Pop
Fragkou *et al*. (2013) [25]	No	Two-step etch-and-rinse adhesive	Adper Single Bond 2
Kasraie *et al*. (2013) [26]	Yes	37% phosphoric acid	Scotchbond™ Etchant
		Two-step etch-and-rinse adhesive	Single Bond
		Self-etch adhesives	Clearfil SE Bond self-etch primer
			Clearfil S^3 Bond self-etch adhesive
Otsuka *et al*. (2013) [13]	No	35% phosphoric acid + one-step self-etch adhesive	Gel Etchant (Kerr)
			G-Bond Plus
		Air abrasion acid + one-step self-etch adhesive	Airborne particle abrasion with 50-µm aluminum oxide at 0.3 MPa for 5 seconds
Babannavar and Shenoy (2014) [34]	No	Two-step self-etch silorane-based adhesive	Filtek P90 adhesive (pH: 2.7)
Boruziniat and Gharaei (2014) [35]	No	Two-step etch-and-rinse adhesive	Tetric N-Bond
		Two-step self-etch adhesive	AdheSE
		One-step self-etch adhesive	AdheSE One F (pH: 1.5)
Jaberi Ansari *et al*. (2014) [36]	No	Two-component one-step self-etch adhesive	Adper Prompt L Pop
		Two-step self-etch adhesives	Clearfil SE Bond
			Clearfil Protect bond (pH: 2)
			AdheSE
		Two-step etch-and-rinse adhesive	Adper Single bond
Ozer *et al*. (2014) [37]	Yes	Two-step self-etch adhesive	Clearfil SE Bond
		Two-step self-etch silorane-based adhesive	Filtek P90 adhesive

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Table 3. Continued

Study	Finishing and polishing for GI	Type of surface treatment	Commercial brand and specification
Panahandeh *et al*. (2015) [38]	No	37% phosphoric acid + two-step etch-and-rinse adhesive	Stae, SDI
		Two-step self-etch adhesive	Frog, SDI (pH: 2)
Sharafeddin and Choobineh (2016) [39]	No	Two-step self-etch adhesive	Clearfil SE Bond
		One-step self-etch adhesive	Optibond (pH: 1.4)
		Two-component one-step self-etch adhesive	Adper Prompt L Pop
		37% phosphoric acid + two-step etch-and-rinse adhesive	Adper Single Bond 2
Francois *et al*. (2019) [16]	No	One-step universal adhesive used in self-etch mode	Scotchbond Universal (pH: 2.7)
		32% phosphoric acid + universal adhesive used in etch-and-rinse mode	Scotchbond Universal Etchant + Scotchbond Universal
		32% phosphoric acid + two-step etch-and-rinse adhesive	Scotchbond Universal Etchant + Scotchbond 1XT
		One-step self-etch adhesive	Optibond All-In-One (pH: 2.5)
		Universal primer + one-step self-etch adhesive	Monobond Plus + Optibond All-in-One
		Coating material	EQUIA Forte Coat
Pandey *et al*. (2019) [27]	No	Two-step etch-and-rinse adhesive	Adper Single Bond 2
		One-step self-etch adhesive	Optibond All-In-One
Bin-Shuwaish (2020) [10]	No	35% phosphoric acid + Two-step etch-and-rinse adhesive	Ultra-Etch + OptiBond Solo Plus
		Two-step self-etch adhesive	Clearfil SE Bond 2
		Universal adhesive used in both etch-and-rinse (with 35% phosphoric acid) and self-etch modes	Single Bond Universal
Ghubaryi *et al*. (2020) [18]	No	Methylene blue photosensitizers activated with photodynamic therapy + Two-step etch-and-rinse adhesive	Sisco Research Lab A single-wavelength light source with an 810 nm wavelength and a power output of 1.5 W was used at a concentration of 100 mg/L. This light was directed perpendicularly onto the RMGI and continuously applied for 60 seconds. Adper Single Bond 2
		Er,Cr:YSGG laser + etch-and-rinse adhesive	Biolase- Waterlase iPlus For a duration of 5 seconds at 2.8 MPa
		Nd-YAG laser + etch-and-rinse adhesive	NianSheng A noncontact circular motion technique was used with a power setting of 1.5 W for a duration of 60 seconds. During the procedure, the 400 µm quartz micro tip was kept at a 90-degree angle to the cement surface.
		Aluminum oxide sandblasting + etch-and-rinse adhesive	Aluminum trioxide, Dentsply With a power of 1.5 W and a frequency of 30 Hz, the MZ8 tip was used in a circular motion for 60 seconds, held 2 mm away from the surface.
		37% phosphoric acid + etch-and-rinse adhesive	Aqua Etch
Bilgrami *et al*. (2022) [28]	No	37% and 36% phosphoric acid gel	Scotchbond Etchant Dentsply
Farshidfar *et al*. (2022) [29]	No	35% phosphoric acid	Ultra-Etch
		Two universal adhesives (used in both etch-and-rinse and self-etch modes)	CLEARFIL Universal Bond (pH: 2.3) G-Premio Bond (pH: 1.5)

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Table 3. Continued

Study	Finishing and polishing for GI	Type of surface treatment	Commercial brand and specification
Zakavi *et al*. (2023) [30]	No	Two-step etch-and-rinse adhesive	Adper Single Bond 2
		37% phosphoric acid + etch-and-rinse adhesive	Morva Etch
		Aluminum oxide sandblasting + etch-and-rinse adhesive	Microblaster Dento-Prep, Dental Micro-blaster
			30-µm Al2O3 particles for 10 seconds
		Rough diamond bur + etch-and-rinse adhesive	012 Cylinder Flat End
			The diamond bur was employed for 3 seconds at high speed with an accompanying water spray.
		Er: YAG laser + etch-and-rinse adhesive	M021-3AF/4, Fotona
			With a 1,064 nm wavelength, delivering 1.5 W of power, at a frequency of 5 Hz, with 8% water output and 4% air output, positioned 10 mm away from the target. The laser was operated in micro-short pulse mode, delivering energy at 300 mJ
		Er, Cr: YSGG laser + etch-and-rinse adhesive	Water Lase iPlus, Biolase
			An MZ8 tip with a diameter of 800 µm and a spot size of 0.502 mm^2 was used. This tip emitted laser light at a 2,780-nm wavelength, 1 W of power, and a frequency of 20 Hz. The water output was set at 20%, and the air output was 10%, with the tip held 1 mm from the surface for 15 seconds. This setup provided an intensity of 53.07 J/cm^2
Dawood *et al*. (2024) [31]	No	Sandblasted	Air Prophy Unit
		Sandblasted + two-step etch-and-rinse adhesive	For 30 seconds with an air abrasion unit using 50-µm aluminum oxide particles
		37% phosphoric acid + two-step etch-and-rinse adhesive	Scotchbond 1XT Scotchbond Universal
		Universal adhesive used in self-etch mode	
Maneenut *et al*. (2010) [12]	Yes	Repair with nanofilled RMGI	Ketac Nano-ionomer Primer
		Nanofilled RMGI Primer	GC Dentin Conditioner
		Dentin Conditioner + Nanofilled RMGI Primer	
		37% phosphoric acid gel + Nanofilled RMGI Primer	
		Repair with both resin composites	Scotchbond Etching Gel
		37% phosphoric acid gel + two-step etch-and-rinse/or one-step self-etch adhesive	Single Bond G-Bond (pH: 2.8)
		Etch-and-rinse/or one-step self-etch adhesive	
		Repair with RMGI	
		One-step self-etch adhesive	
		Dentin Conditioner + one-step self-etch adhesive	
		37% phosphoric acid gel + one-step self-etch adhesive	
Welch *et al*. (2015) [41]	No	Sanding using wet 800-grit silicon carbide paper	Leco
		Sanding + 37.5% phosphoric acid	
		Sanding + 37.5% phosphoric acid + two-step etch-and-rinse adhesive	Kerr Gel Etchant Optibond Solo Plus

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Table 3. Continued

Study	Finishing and polishing for GI	Type of surface treatment	Commercial brand and specification
Vural and Gurgan (2019) [40]	No	Repair using glass hybrid	DIATECH, Swiss Dental
		Roughened using a diamond coarse fissure bur	Cavity conditioner, GC
		20% mild polyacrylic acid	G-premio Bond
		20% mild polyacrylic acid + a universal adhesive	
		A universal adhesive	
		Repair using resin composite	GC etching gel
		Roughened using a diamond coarse fissure bur	
		Roughening + universal adhesive	
		40% phosphoric acid + universal adhesive	
		Universal adhesive	
Ozaslan *et al*. (2023) [17]	Yes	Silane + universal adhesive	Clearfil Ceramic Primer Plus
			Prime & Bond Universal (pH: 2.7)
Silva *et al*. (2024) [42]	Yes	Universal adhesive in self-etch mode	Scotchbond Universal
		37% phosphoric acid + universal adhesive	

Er,Cr:YSGG, erbium, chromium:yttrium, scandium, gallium garnet; Er:YAG, erbium-doped yttrium aluminum garnet; GI, glass ionomer; GIC, glass ionomer cement; ; Nd-YAG, neodymium-doped yttrium aluminum garnet; RMGI, resin-modified glass ionomer.

cluded a group in which the surface treatment consisted solely of phosphoric acid, without any adhesive application [28,29]. One of the included studies used a universal primer and a coating material as a surface treatment for the tested GIs before bonding to resin composite [16]. Five of the included studies used mechanical surface treatment in combination with chemical treatment [13,18,24,30,31]. The mechanical treatment included laser (Er,Cr:YSGG and Nd-YAG) [18,24,30], air abrasion [13,18,30,31], and Methylene blue photosensitizers activated with photodynamic therapy [18]. These mechanical treatments were used as a replacement for the phosphoric acid etching. It is worth mentioning that none of the studies that used any type of mechanical treatment did any sort of F/P for the specimens before receiving the treatment (Table 3).

5. Aging before testing

Four of the included studies tested the specimens after 48 hours of water storage [16,18,33,35], one study made 1 and 6 months of water storage [14], and four studies performed thermal cycling for 5,000 [10,30], and 500 [28,37] cycles. The rest of the included studies tested the specimens after 24 hours of water storage without any aging (Table 4).

6. Testing methods

Four of the included studies performed micro shear bond strength (μSBS) tests [14,26,36,38], while one study performed a tensile test [25], and one performed a microtensile bond strength test (μTBS) [29]. The rest of the included studies performed SBS tests. The cross-head speed was 0.5 mm/min in 13 of the included studies [10,16,18,22,24,26,27,29,32–36], while 10 studies used a cross-head speed of 1 mm/min [13–15,25,28,30,31,37–39]. Additionally, one study utilized a cross-head speed of 3 mm/min [23] (Table 4). Fifteen studies examined the failure mode after testing using either an optical microscope [13,14,18,30,33], a stereomicroscope [10,16,24–26,28,31,35,37], or a binocular microscope [16]. Two studies did not specify the examination technique [28,32]. The magnifications used differed among the studies and ranged from ×2.5 to ×40 (Table 4).

Bonding aged glass ionomer and either resin composite or glass ionomer in sandwich restorations

1. Control groups

One study included a control group (without the use of the tested chemical or mechanical surface treatments) [40], while four studies did not include a separate control group [12,17,41,42] (Table 5).

Table 4. Assessment of bond strength testing methodologies in the included studie

Study	Test type	Testing machine and speed	Aging condition	Method of failure analysis
Arora *et al*. (2010) [22]	SBS	UTM, 0.5 mm/min	After 24 hours	-
Boushell *et al*. (2011) [32]	SBS	UTM, 0.5 mm/min	After 24 hours	×2.5
Zhang *et al*. (2011) [14]	μSBS	UTM, 1 mm/min	After 24 hours, 1- and 6-month water storage	Light microscope at ×40
Chandak *et al*. (2012) [23]	SBS	UTM, 3 mm/min	After 24 hours	-
Kandaswamy *et al*. (2012) [15]	SBS	UTM, 1 mm/min	After 24 hours	-
Navimipour *et al*. (2012) [24]	SBS	UTM, 0.5 mm/min	After 24 hours	Stereomicroscope at ×20
Pamir *et al*. (2012) [33]	SBS	UTM, 0.5 mm/min	After 48 hours	Light microscope at ×10 or ×20
Fragkou *et al*. (2013) [25]	TBS	UTM, 1 mm/min	-	Stereomicroscope at ×16
Kasraie *et al*. (2013) [26]	μSBS	UTM, 0.5 mm/min	After 24 hours	Stereomicroscope at ×40
Otsuka *et al*. (2013) [13]	SBS	UTM, 1 mm/min	After 24 hours	Optical microscope at ×10
Babannavar and Shenoy (2014) [34]	SBS	UTM, 0.5 mm/min	After 24 hours	-
Boruziniat and Gharaei (2014) [35]	SBS	UTM, 0.5 mm/min	After 48 hours	Stereomicroscope
Jaberi Ansari *et al*. (2014) [36]	μSBS	MTT, 0.5 mm/min	After 24 hours	-
Ozer *et al*. (2014) [37]	SBS	UTM, 1 mm/min	500 TC	Stereomicroscope at ×25
Panahandeh *et al*. (2015) [38]	μSBS	MTT, 1 mm/min	After 24 hours	-
Sharafeddin and Choobineh (2016) [39]	SBS	UTM, 1 mm/min	After 24 hours	-
Francois *et al*. (2019) [16]	SBS	UTM, 0.5 mm/min	After 48 hours	Binocular microscope at ×30
Pandey *et al*. (2019) [27]	SBS	UTM, 0.5 mm/min	After 24 hours	-
Bin-Shuwaish (2020) [10]	SBS	UTM, 0.5 mm/min	5,000 TC	Digital stereomicroscope at ×30
Ghubaryi *et al*. (2020) [18]	SBS	UTM, 0.5 mm/min	After 48 hours	Optical microscope at ×10
Bilgrami *et al*. (2022) [28]	SBS	UTM, 1 mm/min	500 TC	The exact technique and magnification are not specified
Farshidfar *et al*. (2022) [29]	μTBS	UTM, 0.5 mm/min	After 24 hours	-
Zakavi *et al*. (2023) [30]	SBS	UTM, 1 mm/min	5,000 TC	Light microscope
Dawood *et al*. (2024) [31]	SBS	UTM, 1 mm/min	After 24 hours	Stereomicroscope at ×10
GI repair				
Maneenut *et al*. (2010) [12]	SBS	UTM, 0.75±0.25 mm/min	After 24 hours	Light microscope at ×2
Welch *et al*. (2015) [41]	SBS	UTM	-	SEM at ×13
Vural and Gurgan (2019) [40]	μTBS	MTT, 1 mm/min	-	Stereomicroscope at ×40
Ozaslan *et al*. (2023) [17]	μSBS	UTM, 0.5 mm/min	After 24 hours	Stereomicroscope at ×30
Silva *et al*. (2024) [42]	μTBS	UTM, 1 mm/min	After 24 hours	Stereomicroscope at ×40

GI, glass ionomer; SBS, shear bond strength; μSBS, microshear bond strength; TBS, tensile bond strength; μTBS, microtensile bond strength; MTT, microtensile tester; SEM, scanning electron microscope; TC, thermal cycle; UTM, universal testing machine.

2. Finishing and polishing before bonding

Three studies performed F/P on the surface of aged GI before any bonding procedures, one before the aging of the GI [17], and the other two after the aging of the specimens and immediately before bonding [12,42]. Two studies did not perform F/P on the surface of the GI [40,41] (Table 3).

3. Type of glass ionomer and overlying composite

Three of the included studies tested RMGIs [12,41,42], while the other two studies tested glass hybrid [17,40]. Two of the included studies tested nanofilled resin composite [12,42], microfilled resin composite [12], while one used microhybrid [40], and one tested nanoceramic resin composite [17]. Two studies used both GI or RMGI and resin composite as a repair material [12,40], while two studies used only RMGI as a repair material [41,42], and one included only resin composite for repair [17] (Table 2).

4. Technique of aging the tested glass ionomers

The aging techniques for the tested GIs varied before

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Table 5. Risk of bias assessment

Study	Description of sample size calculation	Specimen preparation carried out by the same operator	Randomization of specimens	Use of control group (without the tested surface treatment)	Use of materials according to manufacturers' instructions	Evaluation of failure mode	Blinding of examiner	Risk of bias
Arora *et al.* (2010) [22]	No	No	Yes	Yes	Yes	No	No	High
Boushell *et al.* (2011) [32]	No	No	Yes	No	Yes	Yes	No	High
Zhang *et al.* (2011) [14]	No	No	No	No	Yes	Yes	No	High
Chandak *et al.* (2012) [23]	No	No	Yes	Yes	Yes	No	No	High
Kandaswamy *et al.* (2012) [15]	No	No	No	No	No	No	No	High
Navimipour *et al.* (2012) [24]	No	No	Yes	Yes	Yes	Yes	No	Moderate
Pamir *et al.* (2012) [33]	No	No	No	No	No	Yes	No	High
Fragkou *et al.* (2013) [25]	No	No	No	Yes	Yes	Yes	No	High
Kasraie *et al.* (2013) [26]	No	No	Yes	Yes	Yes	Yes	No	Moderate
Otsuka *et al.* (2013) [13]	No	No	No	Yes	Yes	Yes	No	High
Babannavar and Shenoy (2014) [34]	No	No	No	No	Yes	No	No	High
Boruziniat and Gharaei (2014) [35]	No	Yes	Yes	No	Yes	Yes	No	Moderate
Jaberi Ansari *et al.* (2014) [36]	No	No	No	No	Yes	No	No	High
Ozer *et al.* (2014) [37]	No	No	No	No	No	Yes	No	High
Panahandeh *et al.* (2015) [38]	No	No	No	No	Yes	No	No	High
Sharafeddin and Choobineh (2016) [39]	No	No	No	No	Yes	No	No	High
Francois *et al.* (2019) [16]	No	No	Yes	Yes	No	Yes	No	High
Pandey *et al.* (2019) [27]	No	No	Yes	Yes	Yes	No	No	High
Bin-Shuwaish (2020) [10]	No	No	Yes	Yes	Yes	Yes	No	Moderate
Ghubaryi *et al.* (2020) [18]	No	No	Yes	Yes	Yes	Yes	No	Moderate
Bilgrami *et al.* (2022) [28]	Yes	No	No	No	Yes	Yes	No	High
Farshidfar *et al.* (2022) [29]	No	No	Yes	Yes	Yes	No	No	High
Zakavi *et al.* (2023) [30]	No	No	Yes	Yes	Yes	Yes	No	Moderate
Dawood *et al.* (2024) [31]	No	No	No	Yes	Yes	Yes	No	High
Maneenut *et al.* (2010) [12]	No	No	Yes	No	Yes	Yes	No	High
Welch *et al.* (2015) [41]	No	No	No	No	Yes	Yes	No	High
Vural and Gurgan (2019) [40]	No	No	Yes	Yes	Yes	Yes	No	Moderate
Ozaslan *et al.* (2023) [17]	Yes	No	No	No	Yes	Yes	No	High
Silva *et al.* (2024) [42]	Yes	Yes	Yes	No	Yes	Yes	Yes	Low

the bonding procedures, including water storage [12], thermal cycling [40], both water storage and thermal cycling [41,42], and brushing simulation and thermal cycling [17] (Table 4).

5. Type of surface treatment

Four of the included studies tested chemical surface treatments [12,17,41,42], while only one study included both mechanical and chemical surface treatments [41]. Two studies used etch-and-rinse adhesives for chemical bonding between GIs and composites [12,41], while one of the included studies used a one-step self-etch adhesive [12]. Three of the included studies tested universal adhesives [17,40,42]. Two of the included studies used dentin conditioner [12,40], one used a nanofilled RMGI primer [12], and one study used silane [17] as a chemical surface treatment for the surface of the aged GI. One of the included studies used wet 800-grit silicon carbide paper for roughening the surface of the aged GI, referred to as "sanding," and considered it a separate mechanical surface treatment [41] (Table 3).

6. Aging before testing

None of the included studies performed any aging before testing (Table 4).

7. Testing methods

One of the included studies performed a μSBS test [17], while two studies performed μTBS tests [40,42]. The other two included studies performed SBS tests. The cross-head speed in the included studies ranged from 0.5 mm/min in one study [17], 0.75 ± 0.25 mm/min [12], and 1 mm/min [40,42]. One study did not specify the cross-head speed used [41]. All of the included studies examined the failure mode using either a light microscope [12], a stereomicroscope [17,40,42], or scanning electron microscopy (SEM) [41]. The magnifications used varied across the studies and ranged from ×2 to ×40 (Table 4).

Analysis of results

Following a thorough evaluation of the studies included, the key parameters examined during the result analysis were as follows: (1) comparison of various types of GIs; (2) comparison of different surface treatment methods, including control, mechanical, and chemical treatments; (3) universal adhesives; (4) assessment of the type of resin composite or repair material used in general, specifically for studies related to the second research question; and (5) failure mode analysis.

Bonding new glass ionomer and resin composite in sandwich restorations

1. Comparing different types of glass ionomers

Regardless of the surface treatment employed, seven studies consistently demonstrated that RMGIs exhibited statistically significantly higher bond strength values when bonded to resin composites compared to conventional GIC [13,16,24,29,31,33,36]. Conversely, three studies reported comparable bond strength values between RMGIs and conventional GICs [32,37], including nanofilled RMGI [34]. Two studies reported statistically significantly higher bond strength for RMGI compared to glass hybrid [16,29]. However, their findings regarding glass hybrid compared to conventional GI were contradictory. One study reported higher bond strength for glass hybrid compared to conventional GICs [16], while the other found no significant difference between them [29]. Two studies found that the type of RMGI used significantly affected the bond strength results [13,38], and another two studies found that the type of conventional GIC also affected the results [14,38].

2. Control vs surface treatment

Seven studies indicated a statistically significant difference in the chemical treatment of the surface of RMGI [10,22,23,26,27,29,31], conventional GIC [13,29], and glass hybrid [29] compared to the control groups, which received no chemical or mechanical treatment. However, one study reported the opposite outcome for RMGI [13]. Furthermore, one study found comparable bond strength values between the control and chemically treated RMGI [25].

3. Effect of combining mechanical and chemical surface treatments

Three studies investigating the bond strength of conventional GIC yielded contradictory results. One study [24] found no statistically significant difference in bond strength when combining mechanical treatment (laser)

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with etch-and-rinse adhesive, regardless of whether acid etching was used or not. Another study found that combining both treatments (mechanical sandblasting) resulted in lower bond strength compared to using the chemical treatment alone [31]. On the other hand, another study [13] reported a statistically significant difference in bond strength when air abrasion was used as a mechanical treatment before chemical treatment with self-etch adhesive. Furthermore, the use of acid etching enhanced the bond strength to the resin composite.

Three of the included studies compared different mechanical surface treatments (laser [24,30], sandblasting [31]), and roughening by bur [30]) with chemical treatment alone (etch-and-rinse adhesive and universal adhesive). One study found that laser treatment resulted in significantly higher bond strength than acid etching or the control group [24]. Another study found that sandblasting or bur treatment of RMGI resulted in a statistically significant difference compared to other treatment methods [30]. However, another study reported higher bond strength values for the chemical treatment alone (universal adhesive used in both adhesive strategies) on the surface of RMGI compared to combining chemical and mechanical treatments (sandblasting) [31]. Additionally, one of the included studies found that using Er,Cr:YSGG laser and acid etching before applying the etch-and-rinse adhesive resulted in significantly higher bond strength values compared to photodynamic therapy, Nd-YAG laser, or sandblasting before adhesive application [18].

4. Etch-and-rinse vs self-etch adhesives

Six studies compared the effect of etch-and-rinse vs self-etch adhesives on conventional GIC [14,33,36,38,39], and glass hybrid [16]. Among these, three studies found no significant difference [33,36,38], while the other three reported higher bond strength values for conventional GIC [14,39] and glass hybrid [16] with the use of self-etch adhesive surface treatment.

On the other hand, nine studies evaluated the same comparison on RMGI. Among these, three studies found no significant difference between the two adhesive types [33,36,38], while four studies concluded that the use of self-etch adhesive yielded higher bond strength values [22,23,27,35]. One study found no significant difference when the RMGI was bonded to bulk-fill composites, while the self-etch adhesive performed better when the RMGI was bonded to incremental composite [10]. Additionally, one study reported no significant difference between etch-and-rinse and one-step self-etch, while two-step self-etch showed higher bond strength values [26].

5. The use of phosphoric acid solely or etch-and-rinse adhesive without phosphoric acid

One of the included studies compared the use of phosphoric acid without adhesive application on the surfaces of conventional GIC, RMGI, and glass hybrid materials. The findings revealed that applying only phosphoric acid, as opposed to no surface treatment, led to higher bond strength values exclusively for RMGI. However, when phosphoric acid was combined with a universal adhesive, significantly higher bond strength values were observed for all tested materials compared to acid etching alone [29].

In another study, etch-and-rinse adhesive was used with or without phosphoric acid etchant on the surfaces of conventional GIC and RMGI. The researchers found no significant difference when phosphoric acid was applied before adhesive application for 15 seconds. However, the difference became statistically significant when both the acid and adhesive were applied for 30 seconds or longer [33].

6. Comparing different self-etch adhesives

For the conventional GIC, two studies compared a two-step silorane-based adhesive with a two-step methacrylate-based adhesive [32,37]. The first study found no significant difference in bond strength when compared to the strong self-etch adhesive [32], while the other study found that the mild self-etch adhesive had significantly higher bond strength values [37]. Additionally, one study did not find a significant difference between two-step and one-step adhesives [14]. Three of the included studies found statistically significantly higher bond strength values when using a mild self-etch adhesive compared to intermediate and strong self-etch [15,36,39], and two of them found a significant difference between intermediate and strong self-etch adhesives [15,39].

For RMGI, the same findings observed with con-

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ventional GIC were reported in both included studies [32,37]. One study found that a mild two-step self-etch had a statistically significant difference compared to the one-step self-etch [26]. Regardless of the number of steps, one study found that mild self-etch had significantly higher bond strength than intermediate and strong self-etch adhesives [36]. Furthermore, one of the included studies found comparable bond strength values between one-step and two-step intermediate self-etch adhesives [35].

7. Universal adhesive

A study evaluated the application of a universal adhesive on the surface of glass hybrid material using both the etch-and-rinse and self-etch techniques, comparing its performance to that of traditional etch-and-rinse and self-etch adhesives. The findings revealed that the universal adhesive performed similarly in both modes and produced results comparable to the self-etch adhesive. Furthermore, the universal adhesive exhibited significantly higher bond strength values than the etch-and-rinse adhesive [16].

Three studies compared the use of universal adhesive on the surfaces of RMGI [10,31], conventional GIC [31], and glass hybrid [29] in both bonding modes. Two of these studies reported comparable bond strength values when using the universal adhesive in both modes [10,31], which were also comparable to those of the self-etch adhesive [10]. However, the etch-and-rinse mode of the universal adhesive differed from the etch-and-rinse adhesive among the tested resin composite groups. The other study reported higher bond strength values for the etch-and-rinse mode of the universal adhesive tested compared to the self-etch mode of the same adhesive, regardless of the material tested [29].

8. Type of composite

Two separate studies examined the performance of methacrylate-based composites in comparison to silorane-based composites [32,37], but their findings were inconsistent. One study concluded that there was no statistically significant difference between the bond strength of the two materials [32]. In contrast, the other study determined that the methacrylate-based composite exhibited significantly higher bond strength values than its silorane-based counterpart [37].

In another investigation, the performance of nanohybrid and nanofilled bulk fill composites was contrasted with that of nanofilled incremental composite [10]. The outcomes were found to vary based on the type of adhesive used. When both etch-and-rinse and self-etch adhesives were employed, the bond strength values for both bulk fill composites surpassed those of the incremental composite. In the case of the universal adhesive category, the nanohybrid composite demonstrated the highest bond strength values. Furthermore, a separate study compared nanofilled, nanoceramic, and microhybrid composites, uncovering notably superior bond strength values for the nanoceramic composite compared to the other two varieties [28].

9. Effect of aging

Among the studies analyzed, only one study investigated the influence of aging on the bond strength between the examined GI and resin composite [14]. The results revealed that following 6 months of water immersion, the bond strength values decreased compared to the immediate testing conducted after 24 hours. Nevertheless, this discrepancy did not reach statistical significance, except for the specific etch-and-rinse adhesive that was tested.

10. Failure mode analysis

Six studies [13,14,16,18,24,26] reported that the most commonly observed failure mode in the tested GI was cohesive. Two studies [14,16] found no statistically significant differences in failure modes among the tested groups. One study [33] observed that the predominant failure mode in conventional GIC was mixed, whereas in RMGI, it was cohesive. Another study [25] reported that adhesive failure was predominant when RMGI was bonded using an etch-and-rinse adhesive. In contrast, a separate study [35] found that the predominant failure modes were adhesive and mixed for self-etch adhesives, while cohesive failure was more common for RMGI with etch-and-rinse adhesive.

One study [37] reported that the cohesive failure mode was predominant when using a methacrylate-based restorative system, whereas the adhesive failure mode was predominant with a silorane-based restorative system. In another study [10], adhesive failure was observed

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when no surface treatment was applied between the tested GI and resin composite. However, when a universal adhesive was used in etch-and-rinse mode, cohesive failure was observed across all groups with different surface treatments. Similarly, another study [30] reported varying failure modes depending on the surface treatment: adhesive failure without any surface treatment, cohesive failure with laser treatment, and mixed failure when air abrasion was performed prior to adhesive application. Finally, one study [31] found a higher incidence of cohesive failure compared to adhesive failure, which correlated with increased bond strength.

11. Risk of bias assessment

Based on the criteria applied in the analysis, six studies (25%) had a medium risk of bias [10,18,24,26,30,35], while 18 studies (75%) were identified as having a high risk of bias (Table 5).

Meta-analysis results

Owing to the variations in experimental setups, only three studies fulfilled the criteria for inclusion in the meta-analysis [18,24,30]. In one of these selected studies, the data were originally presented in Newton and were later converted to MPa by dividing the values by the area of the bonded surfaces. Essential details such as sample sizes, means, SD, and mean differences with 95% confidence intervals (CIs) for each study are summarized in Table 6. The combined sample size for both the phosphoric acid and Er,Cr:YSGG laser-treated groups amounted to 40 each.

As depicted in Table 7, a random-effects model was utilized due to the presence of heterogeneity ($p < 0.001$). The calculated overall mean difference was 1.555 (95% CI, –2.857 to 5.968). This overall mean difference did not yield statistical significance, as indicated by a p-value of 0.490 (significance was set at < 0.05). The outcome of this meta-analysis suggested no substantial variance in the aggregated mean MPa values of RMGI surfaces treated with either phosphoric acid or Er,Cr:YSGG laser before the application of an etch-and-rinse adhesive (Table 6, Figure 2). Notably, the funnel plot and Egger's test at 95% CIs hinted at potential publication bias (p = 0.043) (Figure 3).

Bonding aged glass ionomer and either resin composite or glass ionomer in sandwich restorations

1. Comparing different types of glass ionomers

Only one study examined nanofilled RMGI and RMGI. However, the results for each material were analyzed independently, and no direct comparison between the two materials was made [12].

2. Control vs surface treatment

Among the included studies, only one study compared a control group of glass hybrid being repaired either with glass hybrid or resin composite, along with chemical surface treatment. This study found statistically significantly higher bond strength values in the surface treatment groups [40].

3. Effect of combining mechanical and chemical treatment

One of the studies included in the analysis examined

Table 7. Test for heterogeneity among included studies in the meta-analysis

Statistic	Value
Q	26.66
Degree of freedom	2
p-value	<0.001
I^2 (inconsistency)	0.9083

Table 6. Results of meta-analysis

Study	Er,Cr:YSGG laser-treated		Phosphoric acid-treated		Difference, mean (95% CI)	p-value	Weight
	n	Mean ± SD	*n*	Mean ± SD			
Ghubaryi *et al*. [18]	10	14.26 ± 1.67	10	16.45 ± 0.32	–2.19 (–3.244 to –1.136)		36.46
Navimipour *et al*. [24]	20	22.81 ± 4.27	20	17.44 ± 5.18	5.37 (2.428 to 8.312)		31.95
Zakavi *et al*. [30]	10	17.22 ± 3.36	10	15.20 ± 3.61	2.02 (–1.037 to 5.077)		31.59
Total (random effects)	40		40		1.555 (–2.857 to 5.968)	0.490	100

CI, confidence interval; *n*, number of specimens; SD, standard deviation.

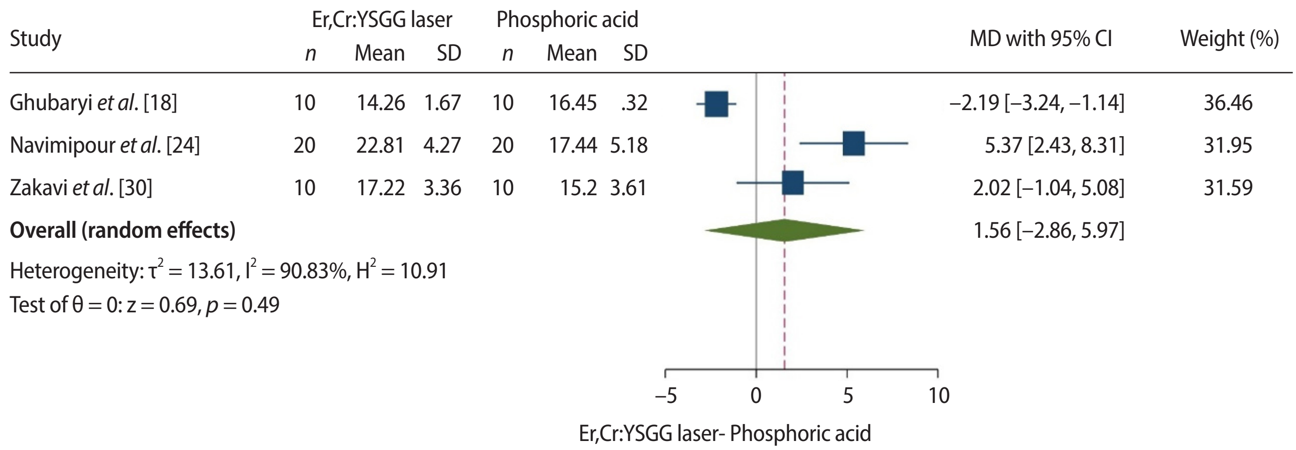

Figure 2. Forest plots of the meta-analysis. CI, confidence interval; MD, mean difference; SD, standard deviation.

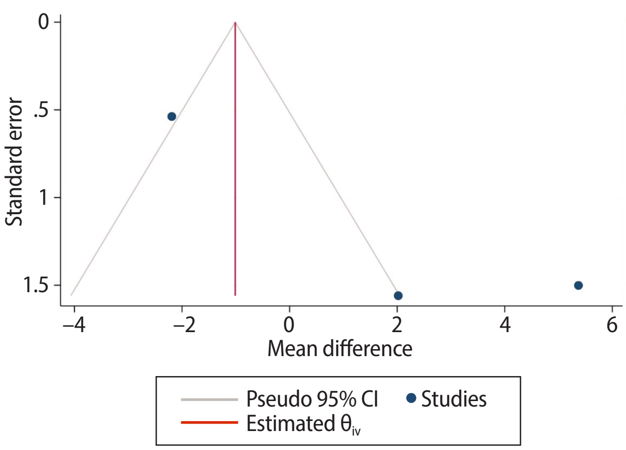

Figure 3. A funnel plot used to evaluate the possibility of publication bias. CI, confidence interval.

the effectiveness of combining mechanical treatment (sanding) with chemical treatment, specifically acid etching alone or acid etching followed by the application of a bonding agent [41]. The results of this study varied depending on the aging conditions applied to the samples. During the initial 5 minutes of RMGI setting, surface treatment had no impact on the bond strength results. However, when the specimens were immersed in water and subjected to thermal cycling, the group that underwent both mechanical and chemical treatment, including the application of the bonding agent, exhibited the highest bond strength values. Another study reported that combining roughening with a bur before chemical treatment with a universal adhesive demonstrated a statistically significant difference compared to using only the chemical treatment (universal adhesive) alone. However, it showed comparable values to using universal adhesive with prior phosphoric acid etchant [40].

4. The use of phosphoric acid solely or etch-and-rinse adhesive without phosphoric acid

One of the studies included in the analysis observed that applying an acid etchant prior to using either an etch-and-rinse or self-etch adhesive did not produce a statistically significant improvement in bond strength when compared to the use of the adhesives alone for nanofilled RMGI and conventional RMGI, respectively [12]. In contrast, a different study reported that treating the RMGI surface with sanding and acid etching alone significantly reduced bond strength values compared to when an adhesive was applied after these surface treatments [41].

5. Universal adhesives

Three studies utilized a universal adhesive as the chemical surface treatment in their respective research [17,40,42]. In one study, the adhesive was not compared with any other chemical treatment [17]. However, in the second study, the use of the adhesive was compared in two bonding modes: when bonding glass hybrid to resin composite and when applying a repair material of glass hybrid with prior application of polyacrylic acid primer vs using the self-etch mode [40]. The results indicated that utilizing the universal adhesive in the etch-

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and-rinse mode, along with the prior application of polyacrylic acid on the surface of the aged glass hybrid, resulted in significantly higher bond strength values compared to the self-etch mode of the universal adhesive. The third study did not find a statistically significant difference when using the universal adhesive in either bonding strategy when bonding RMGI to the repair composite [42].

6. Type of repair material

One of the studies included in this analysis compared the use of nanofilled RMGI and RMGI as repair materials for the same material, alongside nanofilled and microfilled resin composites [12]. The findings indicated higher bond strength values for the nanofilled composite compared to the nanofilled RMGI. Furthermore, no statistically significant difference was observed between the RMGI and microfilled resin composite. In another study, statistically significantly higher bond strength values were found for microhybrid resin composite when compared to glass hybrid as a repair material for an aged glass hybrid [40]. Contrary to previous findings, another included study reported higher bond strength values for repairing RMGI using the same material compared to nanofilled resin composite, irrespective of the adhesive mode of the universal adhesive used for bonding to the composite [42].

7. Failure mode analysis

Three of the studies included in the analysis reported adhesive failure as the predominant mode [17,40,42], whereas one study identified cohesive failure as the predominant mode in the aged GI [12]. However, when repairing nanofilled RMGI with the same material, the predominant failure mode was adhesive. Another study reported that premature failure was more frequent when the universal adhesive was used for bonding aged RMGI to the overlying composite in self-etch mode [42].

8. Risk of bias assessment

Based on the criteria evaluated in the analysis, one study (20%) was determined to have a low risk of bias [42], another was assessed to have a moderate risk of bias [40], while the majority of the studies (60%) were found to have a high risk of bias.

DISCUSSION

The authors of this review intentionally limited the inclusion of studies to those published within the past decade. This decision was driven by the rapid advancements in dental adhesives and restorative materials. Consequently, earlier research focusing on older generations of restorative materials and adhesives, which may no longer be commercially available, was excluded.

The inclusion of laboratory studies in this review was necessitated by the limited number of clinical studies conducted in the past decade that specifically examined various surface treatments for GIs prior to resin composite restorations. Notably, the primary objective of the available clinical studies was to compare different types of GIs [5,43], rather than to evaluate surface treatments.

Most of the studies included in this analysis utilized SBS testing due to its easier specimen preparation and alignment during measurements [18]. Previous research revealed that SBS testing is considered reliable and less questionable compared to μTBS when examining GIs [44]. However, it has been suggested that SBS evaluation may be less reliable than μTBS evaluation because the adhesive interface in μTBS analysis is relatively small, leading to more uniform stress distribution and better access to the true interfacial bond strength [40]. It should be noted that during sectioning for μTBS testing, there is a risk of premature micro-cracking of samples [44]. In contrast to μTBS testing, the procedure and preparation of samples for μSBS testing are comparatively simpler. Scholars have observed that reducing the sample diameter in μSBS tests can mitigate stress formation and minimize potential errors [44].

Initial observations from the review suggest that the bond strength between GIC and glass hybrid materials with resin composites is relatively lower when compared to the bond strength between RMGI and resin composites. The bonding mechanisms between GIC and resin composite predominantly rely on micromechanical retention, which is influenced by surface irregularities, roughness, and porosities [16]. In contrast, RMGI is thought to involve chemical bonding, resulting in a stronger bond. The incorporation of resin constituents in RMGI has been shown to effectively enhance both bond strength and mechanical properties [13].

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Regardless of the type of GI, using surface treatment (either mechanical or chemical) resulted in a stronger bond compared to no treatment. When applying resin composite over various GIC bases, the weaker bond strength between the two materials can be explained by the relatively lower cohesive strength of GIC compared to the resin composite [10]. This difference may also be attributed to the high viscosity of the resin composite, which impedes proper flow on the surface of conventional GIC unless a wetting agent is used [29]. Furthermore, the distinct chemical properties and reactions of these materials are likely to significantly contribute to adhesion failure without surface treatment [10].

The recent examination uncovered contradictory outcomes in the comparison of etch-and-rinse adhesives with self-etch adhesives on GIC surfaces. Certain studies included in the review rejected the use of acid etching and provided the rationale for their findings. They argued that the application of 37% phosphoric acid during acid etching leads to the degradation of the underlying layers of the GIC matrix, thereby diminishing the cohesive strength of the material [14,39]. Consequently, this reduction in cohesive strength can have a detrimental effect on the bond strength between the composite and GIC. It is important to highlight that the porosity created on the GIC surface by phosphoric acid differs from that induced by self-etch adhesives [14,39]. Conversely, other studies that did not observe a significant distinction between the two adhesive types or favored etch-and-rinse adhesives proposed an alternative rationale for their results. They suggested that acid etching of the GIC solely weakens the surface of the cement, leading to cohesive failure within this weakened region rather than affecting the interfacial resin bond strength [33,38].

Regarding the combination of mechanical and chemical surface treatments, the results of the current review did not find evidence supporting a synergistic effect in terms of bonding new GI to resin composite. However, it is possible that this combination could increase the bond strength of aged GIs. One possible explanation for this is that the use of a bur or silicon carbide paper may not only increase the roughness and irregularities on the surface of RMGI, thereby enhancing the micromechanical bond strength [30], but it may also expose glass particles in the 'old' material that could react with the polyacrylic acid in the 'new' material (in the case of using GI for repair) or unreacted methacrylate monomers that could interact with the overlying adhesive and resin composite (in the case of using resin composite for repair) [12]. However, this may not be critical for newly placed RMGI, as they already contain unreacted glass particles and methacrylate groups on their surface.

The predominant RMGI used in the studies was Fuji II LC, prompting a meta-analysis to examine the impact of surface treatments (mechanical or chemical) on RMGI surfaces before applying an etch-and-rinse adhesive. The findings indicated no significant difference in bond strength to resin composite when comparing phosphoric acid treatment with the Er,Cr:YSGG laser.

The Er,Cr:YSGG laser, with a wavelength of 2790 nm, has a high affinity for water and strong absorption capacity for hydroxyl groups (OH), enabling effective surface modifications. Since RMGI primarily consists of fluoroaluminosilicate glass and water-based polymeric acid, it is hypothesized that the laser-induced micro-irregularities and increased porosity, enhancing composite adhesion [18]. These laser-induced porosities and irregularities may resemble those created by phosphoric acid, explaining the lack of a significant difference between the two techniques. Notably, one of the studies in the meta-analysis used a microhybrid resin composite instead of the nanohybrid composite used in the other two studies. An earlier systematic review demonstrated comparable clinical performance among nanofilled, nanohybrid, and microhybrid composites [45].

While asymmetry in the funnel plot suggests potential publication bias, caution is warranted when interpreting these results due to the limited inclusion of only three studies. The reliability of such tests generally improves with a minimum of ten studies in a meta-analysis [46]. With fewer studies, the statistical power is significantly reduced, making it difficult to distinguish between random variation and true asymmetry in the data [46].

The acidity of the self-etch adhesives tested in the included studies is likely a key factor influencing the outcomes. An increase in the acidity of self-etch adhesives has been associated with reduced bond strength values of resin composites, regardless of the type of GI. One possible explanation for this is that stronger acids lead to greater neutralization of cations and the formation of

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weaker structures, such as salt crusts, which ultimately result in weaker bonding [15].

Additionally, other studies have suggested that highly acidic self-etching adhesives contain elevated solvent levels to facilitate the full ionization of acidic monomers. As a result, after solvent evaporation, the adhesive layer becomes thinner, potentially leading to insufficient polymerization due to the formation of an air-inhibited layer. This can cause the accumulation of unpolymerized acidic monomers within the layer [36,39].

The results of the current review did not provide conclusive evidence to support a specific bonding protocol when using universal adhesive for bonding GIs to resin composites. However, it is highly probable that a chemical bond is formed between the universal adhesive and GIs through interactions between the functional monomers present in the adhesive and the calcium ions (or strontium ions) found in the GIs matrix [16]. Furthermore, the hydrophilic nature of the functional groups facilitates their penetration into the hydrophilic matrix. Other interactions may occur between the acrylic and itaconic acid, as well as between the silane present in the universal adhesive and GIs [10,16].

In one of the studies reviewed, the decline in bond strength noted following 6 months of water immersion could be associated with the deterioration of GIC caused by the plasticizing effect of water on the resin [14]. Furthermore, persistent by-products from the bonding procedure, like uncured monomers and degradation products arising from resin hydrolysis, could also contribute to the bond weakening [47].

Several studies focusing on failure modes have highlighted the common occurrence of cohesive failure in GIC. This outcome is frequently observed in adhesive assessments of GICs. While some sources suggest that cohesive fracture within the substrate indicates stronger bond strength [48], other research has not found a definitive correlation between fracture mode and SBS value [49].

The tendency for GIC to exhibit cohesive failure is likely due to limitations in its physical characteristics. However, bond failure is a complex event influenced by various factors. These factors may include uneven stress distribution during testing, micro-porosities within the cement that can serve as potential stress points, differences in the setting reactions between materials, and the curing contraction of the resin composite, which could lead to detachment of the GIC from the margins [14].

It is important to note that the majority of the included studies employed macro-bond strength testing, which reported a higher occurrence of cohesive and mixed failures [17,50]. Conversely, in μSBS tests, where the surface area is reduced, force can be applied from a more specific area targeting the entire interface, making adhesive failures more common [44].

During the research phase of the current review, there was a lack of studies aimed at investigating GI repair, particularly concerning the recent types of GIs. Additionally, the included studies exhibited a high degree of heterogeneity in terms of study design, testing parameters, and the use of restorative materials and chemical treatments that were not based on manufacturer instructions. Furthermore, most of the included studies did not subject the samples to any form of aging before testing, raising concerns about the durability of the bonding interface between different GIs and composites. Heintze [50] argues that immediate bond tests do not yield clinically relevant results, nor do they show meaningful outcomes after 24 hours. Instead, such tests should be viewed merely as baseline values, serving as a reference point to assess the reduction in bond strength due to stress and extended storage.

Another point that warrants discussion is that most of the studies did not perform any form of F/P prior to surface treatment for the new GI restoration, while half of the studies included GI repair did perform such procedures. Research indicates that F/P significantly influence the surface properties of GIs [51]. This raises the question of whether the results of the included studies would have been influenced by the pre-surface treatment of F/P, especially considering that two of the included studies examined the effect of using a bur in combination with chemical treatment [30,40].

The review encountered several limitations, including the exclusion of non-English publications and inconsistencies in test materials and methodologies. Additionally, a significant number of the studies lacked an aging process before testing, and some deviated from the manufacturer-recommended material usage. It is suggested that laboratory bond strength assessments should replicate clinically relevant conditions to enhance the applicability of findings. Another notable limitation was the absence of examiner blinding, with only one study explicitly mentioning blinding procedures. While discrepancies in surface treatments among the included studies likely contributed to result variations and limited the number of studies suitable for quantitative analysis, the review attempted to address this heterogeneity by categorizing treatments into specific groups (eg, chemical, mechanical, or combined).

The authors recommend conducting more detailed investigations to determine the most suitable surface treatment for different GIs, particularly the more recent types. This research should adhere to internationally accepted standards to ensure standardization and validation, enabling comparisons across studies. Further studies are needed to explore the use of universal adhesives in both bonding modes, in order to identify the preferred method for bonding with GIs.

CONCLUSIONS AND CLINICAL RECOMMENDATIONS

Regarding the first research question:

1. Evidence suggests that the use of RMGIs is preferable to conventional GICs for sandwich restorations.
2. Surface treatment of the GI is essential, regardless of the type of GI or the chosen surface treatment method.
3. There is no conclusive evidence indicating that combining mechanical and chemical surface treatments produces a synergistic positive effect on the bond strength of RMGIs to resin composites.
4. No conclusive evidence to support the preference for self-etch adhesives, particularly one-step systems, over etch-and-rinse adhesives in terms of bond strength between GI and resin composite. This also applies to the two bonding modes of universal adhesives.
5. The acidity of self-etch adhesives may have a greater effect on bond strength results than the number of steps involved in the self-etch adhesive technique.
6. There is no conclusive evidence indicating that the type of resin composite used affects the results.

Regarding the second research question:

1. Surface treatment is necessary for aged GIs before repair.
2. Mechanical treatment (eg, roughening) prior to applying an adhesive enhances the bond strength. Additionally, using the etch-and-rinse mode of universal adhesive on the surface of aged GIs may improve the bond strength to the repair material in comparison to self-etch modes.
3. Resin composite is recommended for repairing conventional GIC and glass hybrid restorations. However, RMGI can also be used for repairing aged RMGI.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization: Ismail HS, Garcia-Godoy F; Data curation: Formal analysis, Methodology, Resources, Software: Ismail HS; Investigation: Ali AI; Supervision: Ali AI, Garcia-Godoy F; Writing – original draft: Ismail HS; Writing - review & editing: Ali AI, Garcia-Godoy F. All authors read and approved the final manuscript.

DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

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Evaluation of the effects of different file systems and apical functions of integrated endodontic motors on debris extrusion: an *ex vivo* experimental study

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ABSTRACT

Objectives: This study aimed to evaluate the effects of two different file systems operated with three apical functions of an endodontic motor integrated with an electronic apex locator on debris extrusion.
Methods: Sixty single-rooted teeth were prepared and divided into two main groups and three subgroups based on the file system (OneShape [Micro-Mega SA] and WaveOne [Dentsply Maillefer]) and apical function of the endodontic motor used (auto apical stop [AAS], auto apical reverse [AAR], and auto apical slowdown [ASD]). The teeth were mounted in pre-weighed glass tubes filled with 0.9% sodium chloride to complete the circuit with the apex locator. Files were advanced until the respective apical function (stop, reverse, or slowdown) was activated. The extruded debris was collected, dried, and weighed by subtracting pre-weighed values from post-weighed values. Preparation time was also recorded. Statistical analyses were performed to compare the groups.
Results: OneShape was associated with significantly less debris extrusion compared to WaveOne, regardless of the apical function ($p < 0.05$). The ASD function resulted in the least debris extrusion compared to AAS and AAR ($p < 0.05$). Preparation time was significantly longer in the ASD function ($p < 0.05$), while no differences were observed between the file systems ($p > 0.05$).
Conclusions: The OneShape file system and the ASD function produced the least amount of apical debris. While the ASD function requires more preparation time, its potential to minimize debris extrusion suggests it may reduce postoperative symptoms.

Keywords: Apical extrusion; Apical function; Endodontics; Reciprocal; Rotary

INTRODUCTION

An accurate working length (WL) assessment is crucial for a successful endodontic treatment since it allows a complete disinfection and obturation of the root canal space by preserving the periapical tissues [1]. WL can

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be defined as the distance between a coronal reference point and the apical constriction, which is the natural narrowing of the root canal and almost the termination of the pulp [2]. In routine endodontic treatments, the WL is measured with the aid of dental radiographs and electronic apical locators (EAL) [3]. Based on the present findings, EALs have shown to be a faster and more reliable visualization method under different conditions that avoid radiation exposure, compared to conventional radiographs [4,5].

During the mechanical instrumentation process, irrigation solutions, debris, pulp tissue, and microorganisms can be extruded beyond the apical foramen. These events have been related to postoperative pain, flare-ups, and reduced long-term success of the endodontic treatment [6]. All currently used endodontic file systems and preparation techniques have been associated with apical debris extrusion [7], but controlling the WL and the position of the endodontic instruments during the root canal treatment with EALs could limit these possible complications [8]. For this purpose, endodontic motors with integrated EALs have been developed as more straightforward and faster devices to measure WL and maintain apical constriction throughout root canal preparation [9].

Endodontic motors with integrated EALs have two main apical functions as follows: auto apical stop (AAS) and auto apical reverse (AAR) [3]. In the AAS function, the file tip stops and moves upwards slightly when it reaches the reference point and starts rotating again. In the AAR function, the file automatically reverses the rotation when the reference point is reached or passed, moves upwards slightly, and then returns to the original rotation direction [10]. All apical functions start to work through the insertion of the instrumentation into the root canal space, and the WL can be detected with indicators on the endodontic motor during mechanical preparation. In addition to the previously described apical functions, a new one has been recently introduced called apical slowdown (ASD). In this function, the motor automatically starts rotating at the canal orifice, reverses direction, slows down to a set final speed as the file tip approaches the apical reference point, and stops when leaving the canal entrance. Therefore, it was stated by the manufacturers that this motion preserves the cementodentinal junction and provides a safer preparation even in the narrowest root canals along with reduced risk of file separation [11].

It is considered that the above-mentioned apical functions have an impact on the apical debris extrusion of instrumentation systems with different kinematics and designs that already cause varying degrees of debris extrusion [12,13]. In this sense, while the ASD function represents a relatively recent innovation, its influence on debris extrusion and clinical outcomes warrants further investigation. To date, no study has comprehensively evaluated the influence of different file systems utilized with distinct apical functions on apical debris extrusion, while simultaneously assessing preparation time. Therefore, this study aimed to compare the effects of rotary and reciprocal file systems (OneShape [Micro-Mega SA, Besançon, France] and WaveOne [Dentsply Maillefer, Ballaigues, Switzerland]) when operated with three different apical functions—AAS, AAR, and ASD—of an endodontic motor integrated with an electronic apex locator, on debris extrusion and preparation time. The null hypothesis of the study was that different apical functions and file systems would not differ regarding the apical debris extrusion and preparation time.

METHODS

Sample size calculation and teeth selection

The protocol of the study was approved by the Ethics Committee of the University of Health Sciences (No. 2024-494). The G*Power ver. 3.1 (Heinrich Heine University Düsseldorf, Düsseldorf, Germany) software was employed to perform the sample size calculation. The test family was set to F tests, and the statistical test was selected as analysis of variance (ANOVA): fixed effects, omnibus, and one-way. Input parameters included the effect size (0.57), which quantifies the expected magnitude of differences among the groups, the alpha level (set at 0.05), and the desired power (set at 0.90) based on a similar study in the literature [14]. The required teeth number per group was determined as 10.

Sixty extracted human teeth with caries-free, single-rooted, mature apex, and less than 10º curvature were collected and evaluated under a stereo microscope

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for any possible fractures or anatomical malformations. Cone-beam computed tomography (PlanmecaProMax 3D; Planmeca, Helsinki, Finland) images of teeth were obtained, and the angle of curvature of the root canal was measured according to the method of Schneider [15], which is widely used in endodontic studies to measure canal curvature. The exclusion criteria for the selected teeth were calcified root canals, the presence of external or internal root resorption, and apical constriction greater than a size #15 K-file (Dentsply Maillefer). Subsequently, the periodontal tissues of selected teeth were removed from the external root surfaces with periodontal curettes, and teeth were stored in 0.1% thymol solution at 4°C until use. Access cavities were prepared with a round bur (856L314-014; G&Z Instrumente, Lustenau, Austria) by a high-speed handpiece with water-cooling. The WL was determined as 1 mm short of where a #15 K-file became visible at the apical foramen and adjusted to 16 mm under a dental operating microscope (LABOMED; Labo America, Inc., Fremont, CA, USA).

Experimental design

A method previously reported was followed to assess apical extrusion, with some modifications [16,17]. Firstly, 20-mL ampules with rubber stops were selected, and holes were punctured in the middle of the plastic rubbers to place the teeth. After that, tubes were cleaned and placed in an incubator to remove residual materials. Glass tubes were filled with 0.9% sodium chloride (NaCl) to simulate the electric current in the human body and close the circuit between the EAL and the tooth. The same NaCl preparation was used for all samples to avoid differences in the ion capacity between solutions that may affect the measurements. Additionally, the same amount of NaCl was added to all tubes, ensuring that the root apexes of all teeth were in contact with the solution. A 27-gauge irrigation needle was stabbed into the rubber stopper to equalize the inner and outer pressure (Figure 1). Filled tubes were pre-weighted three times using an analytical microbalance (Mettler Toledo AT201, Greifensee, Switzerland) with an accuracy of 10^{-4} g. The mean values of the obtained measurements were recorded as a baseline. The outer surfaces of all glass tubes were covered with aluminum foil to ensure the researcher was blinded with respect to the used apical functions.

Mechanical instrumentation

Following the stabilization of the teeth with cyanoacrylate in the experiment apparatus, they were divided using randomization software (https://www.randomizer.org/) into two main groups as follows: OneShape (n = 30) and WaveOne (n = 30) to reduce the number of files, and detecting the apical extrusion more accurately. Afterward, each main group was divided into three subgroups according to the used apical functions: AAS (n = 10), AAR (n = 10), and ASD (n = 10). Mechanical instrumentation was performed using Woodpecker Ai-Motor (Woodpecker Medical Instrument Co., Ltd, Guilin, China). The OneShape file was operated in a continuous rotary motion at a speed of 400 revolutions/min (rpm) and a torque of 4 N/cm. The WaveOne file was used with "Reciproc ALL" mode (170°/50° at 350 rpm) [18]. To evaluate the different apical functions of EAL, the lip clip was placed on the syringe, and the file holder was attached above the stopper on the metal shank of the files. The endodontic motor started to rotate automatically when the files were inserted inside the wet root canal system. File systems were allowed to move through apical constriction until the apical action of the endodontic motor stopped, reversed, and slowed

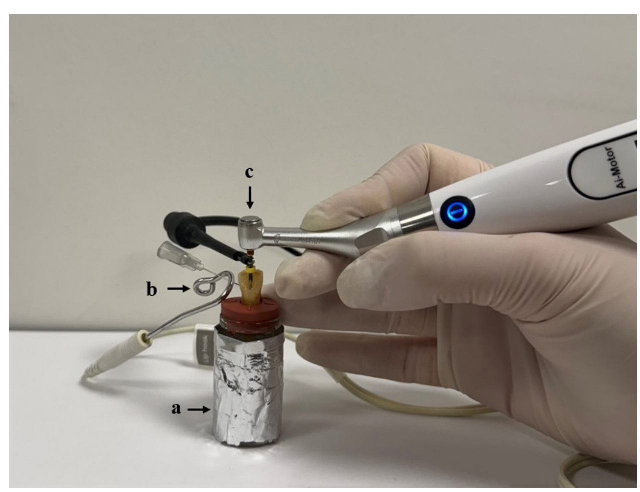

Figure 1. Experimental apparatus used to evaluate apically extruded debris. (a) The cover of the outer surface of a glass tube with aluminum foil. (b) The placement of the lip clip on the syringe in order to complete the circuit. (c) The operation of the file.

down the motion. Root canals were irrigated with 2.5-mL 0.9% NaCl and 2.5-mL distilled water, respectively, using a 27-gauge syringe after completion of the instrumentation process. Vacuum suction was used to remove the overflow of the irrigation solution. The preparation time was also recorded in seconds by a chronometer. All instrumentation procedures were performed by a single operator (SNU) with more than 5 years of experience under a dental operating microscope, and the later assessment of the debris extrusion was observed by a different blinded operator (CA) for the experimental groups, as previously described.

Teeth were removed from the tubes carefully, and filled tubes were incubated for 5 days at 70°C to evaporate the irrigation solution. Furthermore, tubes were post-weighted three times in the same conditions, and the mean values of all measurements were recorded. The amount of apically extruded debris was calculated by subtracting the baseline mean values from the final mean values.

Statistical analysis

Data were analyzed using a specific statistical package software (IBM SPSS version 16.0, IBM Corp, Armonk, NY, USA). Shapiro-Wilk test showed a non-normal and normal distribution for debris extrusion value and preparation time, respectively. The Kruskal-Wallis and Mann-Whitney *U* tests with Bonferroni correction were used to compare the different apical functions and file systems. A two-way ANOVA test was used to compare the three functions and two file systems in terms of preparation time. The level of significance was set at $p < 0.05$.

RESULTS

Table 1 shows the mean and standard deviation values of the apically extruded debris based on the different apical functions and file systems. Regardless of the used apical functions and file systems, OneShape and ASD were associated with statistically lower debris extrusion, respectively ($p < 0.05$). For the OneShape group, while AAS and AAR functions resulted in similar debris extrusion ($p > 0.05$), ASD caused significantly lower extruded debris values ($p < 0.05$). Moreover, extruded debris values were significantly higher in AAR function followed by AAS and ASD in the WaveOne group.

Both OneShape and WaveOne file groups have caused similar apical debris extrusion when they were operated with AAS and ASD functions ($p > 0.05$). However, the WaveOne group was associated with significantly higher debris extrusion compared to the OneShape group when it operated with the AAR function ($p < 0.05$).

The preparation time was significantly affected by the apical functions ($p < 0.05$) as shown in Table 2. For both OneShape and WaveOne groups, the mean preparation time was slightly higher in the ASD function; however, time values did not significantly differ between AAS and AAR ($p > 0.05$). Additionally, the used file system had no

Table 1. The apically extruded debris in terms of three different apical functions and two file systems

File system	Auto apical stop	Auto apical reverse	Apical slowdown	*p*-value
OneShape	0.0090 ± 0.0030[a,1]	0.0081 ± 0.0025[a,1]	0.0045 ± 0.0021[a,2]	0.037
WaveOne	0.0103 ± 0.0042[a,1]	0.0263 ± 0.0203[b,2]	0.0050 ± 0.0025[a,3]	
p-value		< 0.001		

Values are presented as mean ± standard deviation.
Different superscript lowercase letters in the same column indicate a statistically significant difference ($p < 0.05$).
Different superscript numbers in the same row indicate a statistically significant difference ($p < 0.05$).

Table 2. The preparation time in terms of three different apical functions and two file systems

File system	Auto apical stop	Auto apical reverse	Apical slowdown	*p*-value
OneShape	43.078 ± 1.700[a]	45.131 ± 1.880[a]	48.875 ± 2.241[b]	0.929
WaveOne	43.126 ± 1.815[a]	45.120 ± 1.939[a]	48.698 ± 2.411[b]	
p-value		< 0.001		

Values are presented as mean ± standard deviation.
Different superscript lowercase letters in the row indicate a statistically significant difference ($p < 0.05$).

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significant impact on the preparation time regardless of the apical function ($p > 0.05$).

DISCUSSION

The use of endodontic motors integrated with the EALs ensures a more controlled and faster root canal preparation and prevents over-extended instrumentation [19]. Monitoring the WL during mechanical instrumentation allows the endodontic files to work within the root canal system, thereby minimizing apical debris extrusion from the apical region [20]. Since different apical functions and file systems operate with variable kinematics in apical constriction, it is important to investigate the effect of these variables on apical debris extrusion. This study stands out due to its investigation of the effects of different apical functions on apical debris extrusion by an advanced endodontic motor with an integrated electronic apex locator. Moreover, this is the first study that has evaluated and compared the effect of three apical functions (AAS, AAR, and ASD) in both rotary and reciprocal file systems (OneShape and WaveOne) in terms of debris extrusion and preparation time. The findings of this study provide new insights into the interplay between file systems and apical functions, being a valuable contribution to endodontic practice and future research. According to the present findings of this study, the null hypothesis was rejected due to the fewer debris extrusion values in ASD function and the OneShape group.

Tooth morphology and the file systems used could have had an impact on *in vitro* debris extrusion. Although teeth with similar anatomy were selected for the experiments, the results may have been affected due to different factors such as microhardness and mineralization of dentine [21]. Moreover, single-file rotary and reciprocal file systems, OneShape and WaveOne, were used to assess the effect of different apical functions on debris extrusion more objectively since the reduced number of files could improve the quality of measurement of the debris extrusion by minimalizing possible complications during chemomechanical preparation of the samples [22].

In this study, glass tubes were filled with NaCl solution to allow EAL readings, and NaCl was also used as an irrigation solution. However, the remaining crystals after the evaporation of the solution could have caused an increase in the amount of debris collected [23]. To overcome this limitation, baseline values of the tubes were obtained after they were filled with NaCl. Moreover, the same bottle of solution was used to ensure standardization and reduce manufacturing errors. Another important point to address is the inability to mimic periapical tissues and periapical backpressure due to insufficient laboratory conditions [24]. Although the use of agar gel or foam has been suggested to simulate clinical conditions, these materials could not be utilized due to the working mechanism of the EALs and the process of collecting extruded debris.

The accuracy of the AAS and AAR functions in detecting apical constriction has been previously indicated in the literature [8,25]. However, there is limited information regarding their effects on apical debris extrusion. Apical functions are designed to help determine the WL through electrical signals sent by a file inserted into the root canal. Different operational settings of the apical functions influence the movement of the endodontic file and, consequently, may result in apically extruded debris at varying rates. Based on the findings of this study, the AAR function caused more debris extrusion than other tested functions for both file systems. This result can be explained by the fact that AAR automatically reverses the direction of the file towards the coronal direction when apical constriction is reached. Compared to the AAS, the disengagement of the flutes of the files during their removal from the root canal space in the AAR function may perform additional mechanical preparation and cause the extrusion of more debris [5]. Moreover, the potentially increased safety of the AAS function, achieved by disengaging the flutes of the endodontic instrument before completely stopping the motion while preventing jamming or tip lock could limit the instrumentation and cause lower debris extrusion [3,25].

ASD is a relatively new function that has been integrated into endodontic motors, and therefore, there is limited information regarding the possible effects and accuracy of this function in the literature [11,26]. This function allows the endodontic motor to slow down to a set final speed as the file tip approaches the apical reference point. In this study, all apical functions caused apical debris extrusion at different levels; however, the values were significantly lower with the ASD function. It was considered that ASD function controlled the mechanical preparation limits at a continuous and slowing rate, resulting in safer and more efficient performance. Therefore, this controlled movement of the files, particularly in the apical region, may have caused less extrusion of debris. However, it is important to note that the ASD function does not guarantee the complete prevention of apical debris extrusion alone. Other factors, such as the skill and technique of the clinician, the type of instrumentation used, proper irrigation protocols, the type of tooth, the apical diameter, and the preparation size, also play a significant role in minimizing debris extrusion [4,27–29].

Regardless of the apical functions and file systems, OneShape resulted in lower debris extrusion in this study. Similarly, Sinha *et al.* [30] reported lower debris extrusion values in the OneShape group compared to the WaveOne Gold. Moreover, Topçuoğlu *et al.* [31] also reported that the WaveOne files produced significantly more debris compared with OneShape. This result can be explained by the fact that OneShape, operating with continuous rotational motion, has a mechanism that may enhance the coronal transportation of dentine chips and debris, functioning like a screw conveyor [31]. Another possible explanation could be the different taper sizes of instruments. It can be hypothesized that the larger taper at the tip of WaveOne files may lead to increased debris extrusion compared to OneShape files, as it results in more extensive preparation of the dentinal walls. However, some studies in the literature have shown that the amount of apical debris extrusion is higher in rotary files [32] or similar [33] compared to reciprocal systems. Differences in methodologies and clinician-based factors could account for these varying results.

There is only one study that assessed the effect of different apical functions on apical debris extrusion, which demonstrated no statistically significant difference between groups, contrary to the findings of this study [13]. However, some concerns should be noted regarding that study. Firstly, a multiple rotary file system was used for the root canal preparation, which may have jeopardized apical debris extrusion due to the increased sensitivity. Moreover, the authors did not consider the presence of remaining crystals after the evaporation of the solution. Therefore, there is a gap regarding the elimination of the weight of crystals in the apical debris calculation. These methodological differences may explain the different outcomes found in our study.

Although the modified model of Myers and Montgomery [16] has a leading role in the measurement of debris extrusions due to advantages such as practicality, simplicity, reproducibility, and the possibility of comparison between different systems and methodologies, some drawbacks need to be underlined [21]. Addressing the artificial representation of periapical tissues [34], the lack of backpressure [35], being technique-sensitive and the contact of moist or greasy fingertips [34] are crucial to improve the reliability and applicability of findings. In this sense, micro-computed tomographic assessment could be a valid alternative by allowing a volumetric analysis of apical debris extrusion rather than weight [36].

The EALs provide advantages to clinicians in the WL control; however, their accuracy and working mechanism can be affected by many factors [37,38]. This may change the efficiency of the file in the canal, resulting in the extrusion of different amounts of debris *in vivo* which could be associated with postoperative pain and inflammation [39,40]. Although ASD function has the potential to minimize apical debris extrusion, this hypothesis is based on theoretical considerations and indirect evidence. Thus, further well-designed clinical studies are required to understand the additional impacts of the apical functions on debris extrusion using different types of instruments and teeth.

CONCLUSIONS

Within the limitations of this study, all apical functions caused apically debris extrusion. OneShape and ASD were associated with statistically lower debris extrusion. The preparation time was significantly longer in ASD function.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization: Usta SN, Magan-Fernandez A, Aydın C; Data curation: Usta SN; Formal analysis Usta SN, Magan-Fernandez A; Investigation: Usta SN; Methodology: Usta SN, Magan-Fernandez A, Aydın C; Software: Usta SN; Supervision: Aydın C; Validation: Usta SN, Magan-Fernandez A, Aydın C; Visualization: Usta SN, Magan-Fernandez A, Aydın C; Writing - original draft: Usta SN; Writing - review & editing: Usta SN, Magan-Fernandez A, Aydın C.

DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

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Impact of the use of high-power 810-nm diode laser as monotherapy on the clinical and tomographic success of the treatment of teeth with periapical lesions: an observational clinical study

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ABSTRACT

Objectives: The aim of this study was to demonstrate the impact of a high-power 810-nm diode laser as monotherapy on the clinical and tomographic success of treating teeth with periapical lesions, through a series of 31 cases.
Methods: Teeth with apical lesions underwent endodontic treatment in which a high-power 810-nm diode laser with saline solution was used as monotherapy for disinfection. This type of therapy aimed to replace the traditional irrigation protocol with sodium hypochlorite. This research is the first to assess the clinical success of this alternative treatment, along with tomographic evaluations conducted over periods ranging from 2 to 7 years, analyzed using the periapical index based on cone-beam computed tomography (CBCTPAI). All cases were performed by a single clinician following the same laser protocol, which involved using 1 W of continuous power and four cycles of 20 seconds of laser activation.
Results: All teeth showed no clinical symptoms upon follow-up examination. However, the tomographic evaluation revealed that the success rates for teeth receiving primary treatment were 60% and 80% according to strict and loose criteria, respectively. For teeth requiring retreatment, the success rates were 12.5% and 37.5% using strict and loose criteria, respectively.
Conclusions: The teeth with apical lesions that underwent primary treatment did not present clinical symptoms, but they showed a moderate success rate on tomographic evaluation. However, despite lacking clinical symptoms, teeth with apical lesions that required retreatment had a very low success rate on tomographic evaluation.

Keywords: Cone-beam computed tomography; Laser therapy; Disinfection; Endodontics; Root canal therapy

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INTRODUCTION

Pulpal and apical issues are closely linked to various factors, with bacteria being the predominant factor [1]. Bacteria play a pivotal role in the failure of root canal treatments, affecting both primary and persistent infections [2]. The bacterial microbiota comprises both positive and negative bacteria that infect the root canal lumen, ramifications, and dentinal tubules [3]. Presently, the primary objective in endodontics is the thorough cleaning and disinfection of the root canal, aiming to eliminate a substantial microbial burden and smear layer [4]. Standard protocols involve mechanically preparing the root canal, irrigating with substances such as sodium hypochlorite (NaOCl), chlorhexidine, and ethylenediaminetetraacetic acid (EDTA), and activating the irrigant [5–9].

The literature indicates certain limitations associated with these irrigants, such as chlorine, which exhibits intradentinal penetration of only 130 µm, whereas certain bacteria like *Enterococcus faecalis* and *Streptococcus mutans* can penetrate up to 1,000 µm or more [10,11]. Additionally, the extravasation of these chemical substances can lead to damage in periapical tissues also some studies show that the adverse effects are linked to the breakdown of the collagen matrix within mineralized dentin, the hypochlorite anion can penetrate the mineralized collagen, damaging the collagen fibrils. This results in a mineral-dense but collagen-deficient ghost mineral matrix, which has diminished flexural strength [12–14]. Emerging alternatives in the market include high-power lasers that can complement disinfection by utilizing various power levels and wavelengths, generating photothermal and photoacoustic effects [15–17]. Diode lasers are currently in use for routine procedures in endodontics, serving in disinfection processes, and with specific wavelengths and power levels, they can induce microbial death [18,19]. Studies suggest that high-power diode lasers can also function as monotherapy procedures in endodontics, implying that disinfection can be achieved solely through laser therapy [20].

Various case reports, clinical studies, and *in vitro* investigations have highlighted the effectiveness of the 810-nm diode laser as an optimal wavelength for both superficial and deep dentin disinfection [16,20,21]. However, there is currently a lack of extensive clinical evidence in the literature regarding the clinical and tomographic success of diode laser monotherapy. Therefore, this series presents 31 clinical cases demonstrating long-term clinical success with follow-up controls using cone-beam tomography, assessed with the periapical index based on cone-beam computed tomography (CBCTPAI) [22]. The cases in this study underwent treatment solely utilizing a high-power 810-nm diode laser for disinfection.

METHODS

All treatments described in this article were performed after obtaining written informed consent from the patient and conducted in compliance with research ethics.

Twenty-three Hispanic patients, with an average age of 53 years (range, 16–80 years), presented a total of 31 teeth. Among the inclusion criteria were all teeth that had higher lesion apical, incisive, canines, premolar, and molar with type I, II, and IV. The systematic condition and pulp and periapical diagnosis of the teeth are presented in Table 1. Among them were 15 female and eight male patients seeking treatment due to spontaneous pain, swelling, or low-intensity discomfort during chewing upon clinical evaluation. All patients exhibited signs and symptoms of both primary and secondary infections during clinical assessment, with radiographs confirming apical periodontitis in all teeth. Clinically, the teeth were sensitive to percussion and palpation, and all responded negatively to cold testing. The observed signs and symptoms indicated dental infections associated with the teeth, leading to focused consideration of pulp and periapical diagnoses without exploring alternative possibilities. As a result, all patients received diagnoses ranging from pulp necrosis to previously performed endodontic treatment with symptomatic and asymptomatic apical periodontitis. The chosen treatment for all cases involved nonsurgical root canal therapy, including initial root canal treatment and root canal retreatment.

Before consenting, patients were thoroughly informed about the treatment's benefits and drawbacks, comparing them to alternative options. Once informed consent was obtained, covering both the treatment and the pub-

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Table 1. Preoperative conditions of each tooth type

Teeth	Diagnosis	Sinus tract	Swelling	Systemic disease	Obturation
1	Pulp necrosis with chronic periapical abscess	Yes	No	No	-
2	Previously treated and asymptomatic apical periodontitis	No	No	No	Improper density/short
3	Previously initiated therapy with acute periapical abscess	No	Yes	No	Improper density/short
4	Previously initiated therapy with symptomatic apical periodontitis	No	No	No	Adequate
5	Previously treated with symptomatic apical periodontitis	No	No	No	Improper density/short
6	Pulp necrosis with asymptomatic apical periodontitis	No	No	Kidney stones and allergies	-
7	Pulp necrosis with asymptomatic apical periodontitis	No	No	Kidney stones and allergies	-
8	Pulp necrosis with asymptomatic apical periodontitis	No	Yes	No	-
9	Pulp necrosis with asymptomatic apical periodontitis	No	No	Controlled periodontal disease	-
10	Pulp necrosis with asymptomatic apical periodontitis	No	No	Controlled periodontal disease	-
11	Pulp necrosis with asymptomatic apical periodontitis	No	No	Coronary stent	-
12	Pulp necrosis with asymptomatic apical periodontitis	No	No	Coronary stent	-
13	Pulp necrosis with chronic apical abscess	Yes	No	No	-
14	Pulp necrosis with asymptomatic apical periodontitis	No	No	No	-
15	Previously treated with symptomatic apical periodontitis	No	No	No	Improper density/short
16	Previously treated with asymptomatic apical periodontitis	No	No	No	Improper density/short
17	Previously treated with symptomatic apical periodontitis	No	No	Arterial hypertension, functional heart disease	Improper density/short
18	Pulp necrosis with symptomatic apical periodontitis	No	No	No	-
19	Previously treated with symptomatic apical periodontitis	No	No	No	Improper density/short
20	Pulp necrosis with acute periapical abscess	No	No	No	-
21	Pulp necrosis with acute periapical abscess	No	No	No	-
22	Previously treated with Chronic periapical abscess	Yes	Yes	No	Improper density/short
23	Previously treated With asymptomatic apical periodontitis	No	No	Allergic to penicillins and thyroid disease	Improper density/short
24	Previously treated With asymptomatic apical periodontitis	No	No	Allergic to penicillins and thyroid disease	Improper density/short
25	Previously treated With asymptomatic apical periodontitis	Yes	No	Allergic to penicillins and thyroid disease	Improper density/short
26	Previously treated With asymptomatic apical periodontitis	No	No	Arterial hypertension, hepatitis A	Improper density/short
27	Previously treated with acute periapical abscess	No	Yes (spreading/extraoral)	No	Improper density/short
28	Pulp necrosis with acute periapical abscess	No	No	Kidney stone	-
29	Pulp necrosis with symptomatic apical periodontitis	No	Yes	Diabetes mellitus	-
30	Pulp necrosis com symptomatic apical periodontitis	No	No	No	-
31	Pulp necrosis with symptomatic apical periodontitis	No	No	No	-

lication of clinical cases in journals, the treatments were conducted. All cases were not treated under magnification. The teeth were anesthetized with 2% lidocaine containing 1:80,000 epinephrine, and all procedures were conducted under absolute isolation and surgical field disinfection. Nonselective caries removal involved the following steps: caries were excavated using a sterile round diamond bur, starting from the outermost area and progressing inward. Once all carious lesions were eliminated, a new bur was employed to access the pulp

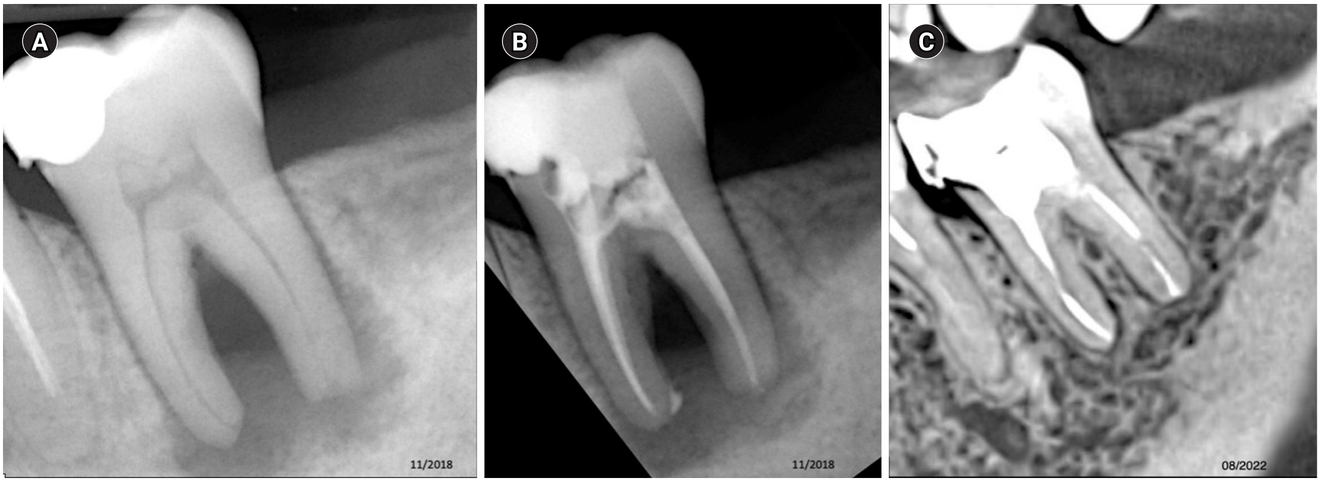

Figure 1. This image shows tooth 37 diagnosed with pulp necrosis with a chronic periapical abscess. (A) Diagnostic X-ray. (B) Immediate after obturation. (C) Tomographic control where complete healing is evident after 45 months.

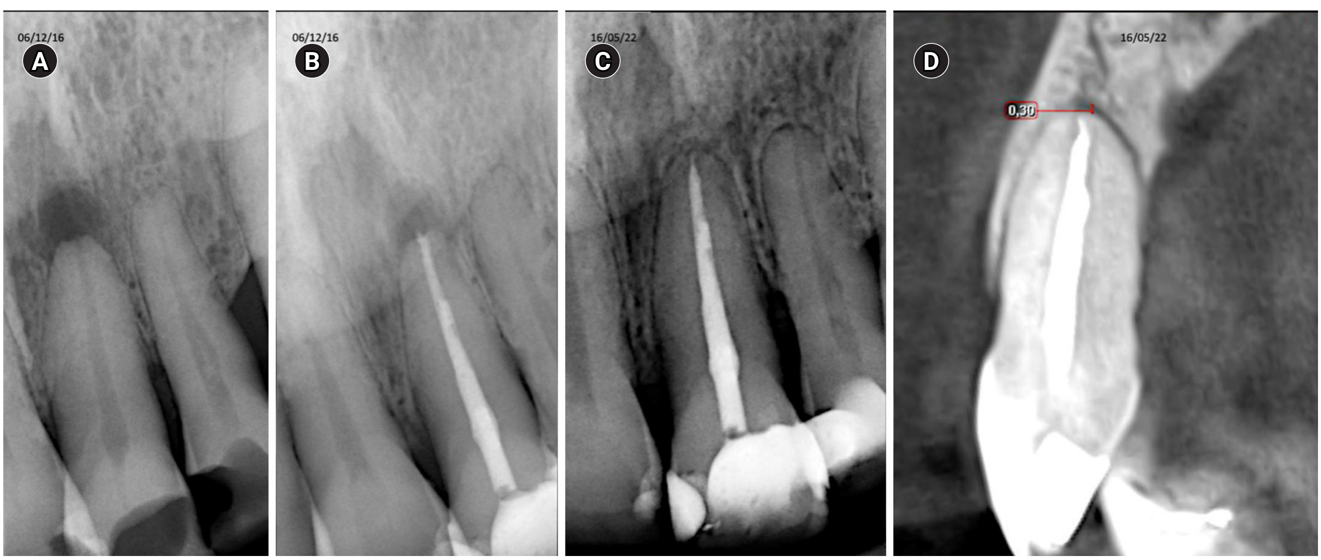

Figure 2. This image shows tooth 11 diagnosed with pulp necrosis with an asymptomatic apical periodontitis. (A) Diagnostic X-ray. (B) Immediate after obturation. (C) X-ray control. (D) Tomographic control where complete healing is evident after 65 months.

chamber. This procedure was carried out using a high-speed handpiece with cooling. Upon reaching the pulp chamber, an opening was created using a sterile tapered diamond bur. The clinical diagnosis of pulp necrosis was confirmed by observing the presence or absence of bleeding from the pulp chamber, while the diagnosis of previously performed endodontic treatment was confirmed by identifying the presence of obturation material.

Treatment protocol for teeth with pulp necrosis (Figures 1–5)

Following the creation of the access opening, the pulp chamber was flushed with saline solution, and the mechanical preparation of the cervical third of the root canal was carried out to neutralize the infected content using the Silver Reciproc motor (VDW GmbH, Munich, Germany). The rotary file system utilized was Mtwo (VDW GmbH). Electronic canal length measurement was conducted with the Apex NRG locator (Medic NRG

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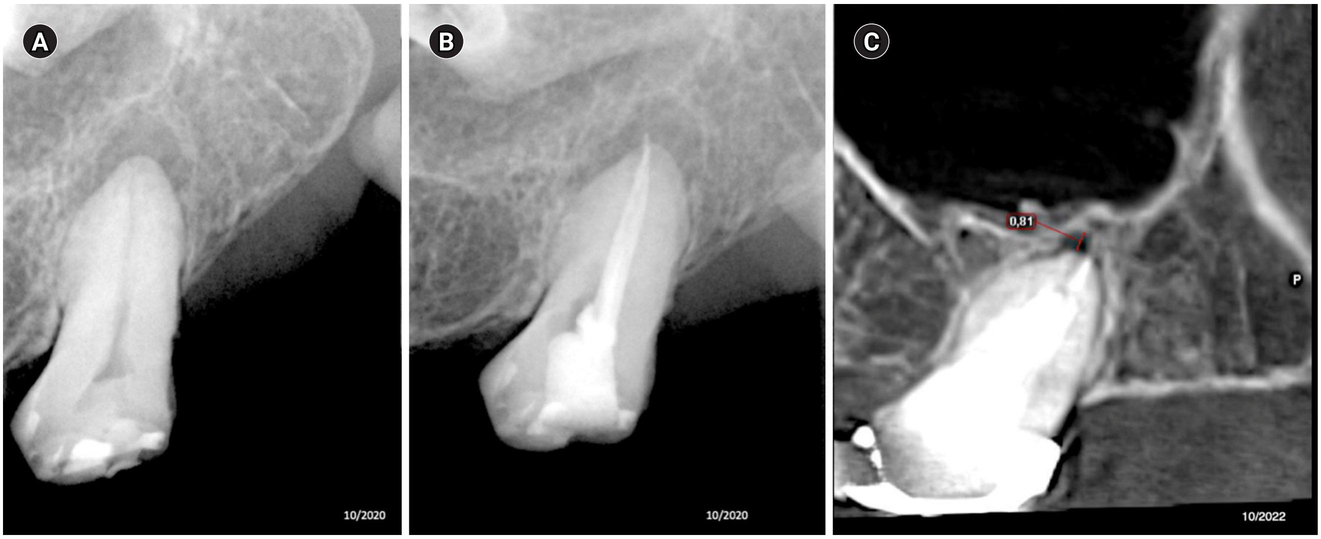

Figure 3. This image shows tooth 27 diagnosed with pulp necrosis and asymptomatic apical periodontitis. (A) Diagnostic X-ray. (B) Immediate after obturation. (C) Tomographic control where an apical image in the process of healing is observed after 24 months.

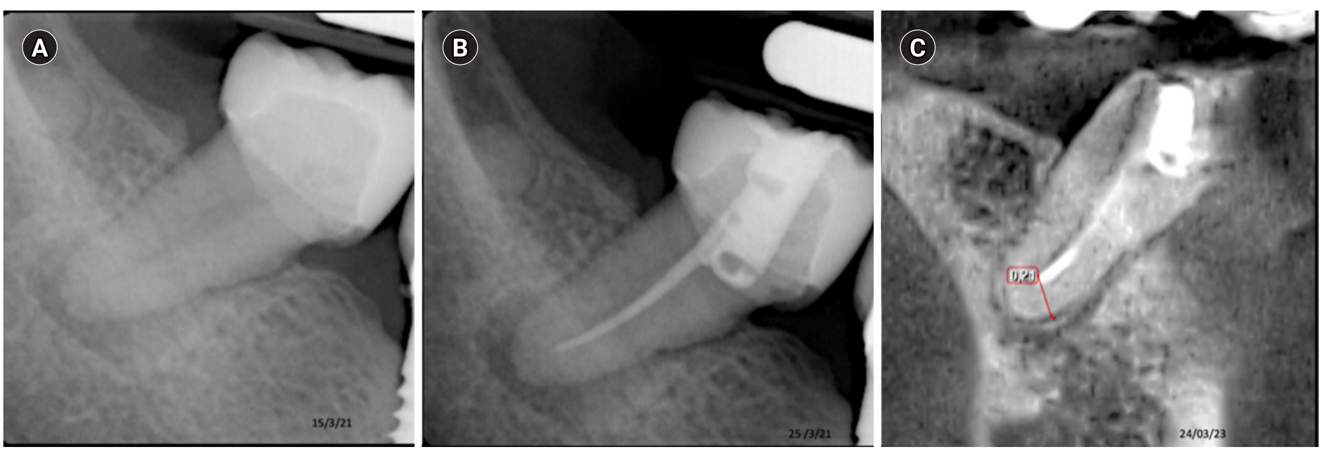

Figure 4. Tooth 36 with a diagnosis of Pulp necrosis with acute periapical abscess. (A) Diagnostic X-ray. (B) Immediate after obturation. (C) Tomographic control after 24 months. showing the apical lesion in the same manner as in the initial X-ray, considered a failure.

Ltd, Tel Aviv, Israel). The root canals were filled with saline solution, and a size of 15 K file, connected to the electronic apex locator, was introduced until it displayed a reading of 1 on the equipment's display. The rubber stop was positioned at the corresponding cusp, a periapical radiograph was taken to confirm the measurement, and this measurement was recorded. These procedures were applied to both single-rooted and multi-rooted teeth.

The apical third was prepared using the sequence recommended by the manufacturer. Abundant irrigation with 3 mL of saline solution was performed between each file. The final preparation was standardized for all teeth and root canals in size 25 and taper 0.06. After completing the root preparation, 17% EDTA (Maquira Ltda, Maringá, Brazil) was applied for 3 minutes. It was introduced into the root canal using a syringe and needle, a procedure repeated for all cases. Subsequently, decontamination irrigation with saline solution was performed using Fotona XD-2 (Fotona, Ljubljana, Slovenia), a high-power 810-nm diode laser set at 1 W of power in continuous wave mode. A 200-µm diameter optical fiber was utilized. Once ready, the actual disinfection was conducted by inserting the optical fiber to

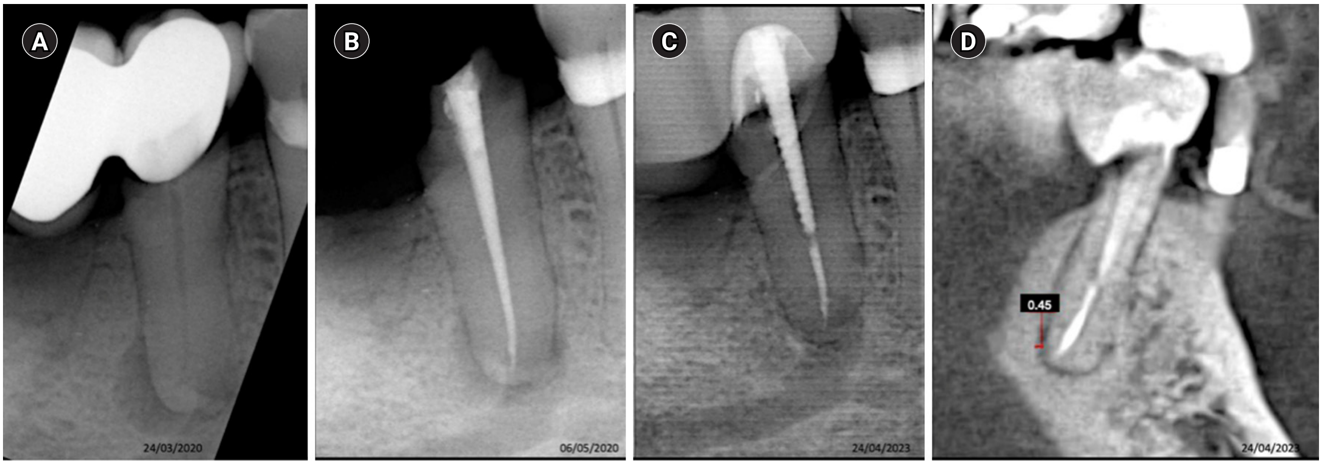

Figure 5. Tooth 36 with a diagnosis of pulp necrosis with symptomatic apical periodontitis. (A) Diagnostic X-ray. (B) Immediate after obturation. (C) Radiographic control. (D) Tomographic control after 35 months, showing the apical lesion in the same manner as in the initial X-ray, considered a failure.

1 mm short of the working length. Once in position, irradiation commenced with the established parameters. The optical fiber moved in and out at a speed of 2 m/sec with a helical motion in a counterclockwise direction. There were four cycles of 20 seconds each, with 3 mL of saline solution irrigation between each cycle, and a 15-second rest period at the end of each cycle. After this, the root canal was dried with sterile paper points, and the presence of purulent exudate was evaluated (some teeth could be obturated in one appointment, while others required two or more appointments). In the absence of purulent exudate, obturation was performed using gutta-percha cones and a zinc oxide and eugenol-based sealer called Grossdent (Laboratorios Farmadenta SA, Lima, Perú) with the single-cone technique. Restoration was then done immediately for some cases using direct light-cured composite resins, while others required posts and crowns (Tables 2 and 3).

Treatment of teeth with previously initiated endodontic therapy (Figures 6 and 7)

All procedures, encompassing anesthesia, isolation, biomechanical preparation, smear layer removal, decontamination, obturation, and restoration, were executed in a manner consistent with the approach employed for the group of teeth with necrosis. Conversely, root canal filling removal was carried out using K-files (Dentsply Maillefer, Ballaigues, Switzerland) and orange oil (Maquira Dental Group, Maringá, PR, Brazil). The canals were gradually enlarged with manual files until a K-file size of 20 achieved canal patency. Subsequently, the preparation was reiterated using rotary Mtwo files until size 25 and taper 0.06, all teeth were standardized with this size. Following this step, all subsequent procedures were conducted identically to those outlined earlier for the previous group.

For both teeth diagnosed with necrosis and those previously treated, immediate post-obturation controls were conducted using periapical radiographs. Long-term follow-up assessments were performed through cone-beam computed tomography (CBCT) scans, with patients being monitored over a span of 2 to 7 years. All CBCT scans were acquired using a Promax 3D CBCT scanner (Planmeca, Helsinki, Finland) with the following parameters: image size of 8 × 8 cm, voxel size of 15 μm, 84 kV, 14 mA, 15 seconds of exposure time, and 0.30 mm resolution. The analysis of images was carried out using Planmeca Romexis Viewer software (Planmeca) with the CBCTPAI, as proposed by Estrela *et al.* [22]. The tomographic images were evaluated in three planes (sagittal, coronal, and horizontal) to identify the presence or absence of apical lesions. When lesions were identified, they were measured and classified according to the CBCTPAI (Table 4). The data collected were tabulated for better comprehension (Tables 2 and 3).

Strict and loose criteria were used to classify the suc-

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Table 2. Classification categories, case frequency, and success rate based on strict criteria

Variable	General frequency	Success	
		Yes	No
General	31 (100)	11 (35.5)	20 (64.5)
Sex			
Female	20 (64.5)	6 (30.0)	14 (70.0)
Male	11 (35.5)	5 (45.5)	6 (54.5)
Tooth group			
Incisive	5 (16.1)	3 (60.0)	2 (40.0)
Canine	2 (6.5)	2 (100)	0 (0)
Premolar	9 (29.0)	1 (11.1)	8 (88.9)
Molar	15 (48.4)	5 (33.3)	10 (66.7)
Treatment type			
Initial treatment	15 (48.4)	9 (60.0)	6 (40.0)
Retreatment	16 (51.6)	2 (12.5)	14 (87.5)
No. of visits			
Single	25 (80.6)	11 (44.0)	14 (56.0)
Multiple	6 (19.4)	2 (33.3)	4 (66.7)
Quality of coronal seal on follow-up			
Absent	0 (0)	-	-
Unsatisfactory	0 (0)	-	-
Satisfactory	31 (100)	11 (35.5)	20 (64.5)
Type of coronal sealing			
Absent	0 (0)	-	-
Crown	23 (74.2)	7 (30.4)	16 (69.6)
Direct restoration	8 (25.8)	4 (50.0)	4 (50.0)
Filling limit			
Ideal	22 (71.0)	9 (40.9)	13 (59.1)
Overextension	4 (12.9)	0 (0)	4 (100)
Underfilling	5 (16.1)	2 (40.0)	3 (60.0)
Post-endodontic pain			
Present	0 (0)	-	-
Absent	31 (100)	18 (58.1)	13 (41.9)
Follow-up period, >3 yr	20 (64.5)	9 (45.0)	11 (55.0)

Values are presented as number (%).

Table 3. Classification categories, case frequency, and success rate based on loose criteria

Variable	General frequency	Success	
		Yes	No
General	31 (100)	18 (58.1)	13 (41.9)
Sex			
Female	20 (64.5)	11 (55.0)	9 (45.0)
Male	11 (35.5)	8 (72.7)	3 (27.3)
Tooth group			
Incisive	5 (16.1)	4 (80.0)	1 (20.0)
Canine	2 (6.5)	2 (100)	0 (0)
Premolar	9 (29.0)	7 (77.8)	2 (22.2)
Molar	15 (48.4)	9 (60.0)	6 (40.0)
Treatment type			
Initial treatment	15 (48.4)	12 (80.0)	3 (20.0)
Retreatment	16 (51.6)	6 (37.5)	10 (62.5)
No. of visits			
Single	25 (80.6)	15 (60.0)	10 (40.0)
Multiple	6 (19.4)	3 (50.0)	3 (50.0)
Quality of coronal seal on follow-up			
Absent	0 (0)	-	-
Unsatisfactory	0 (0)	-	-
Satisfactory	31 (100)	18 (58.1)	13 (41.9)
Type of coronal sealing			
Absent	0 (0)	-	-
Crown	23 (74.2)	12 (52.2)	11 (47.8)
Direct restoration	8 (25.8)	6 (75.0)	2 (25.0)
Filling limit			
Ideal	22 (71.0)	13 (59.1)	9 (40.9)
Overextension	4 (12.9)	1 (25.0)	3 (75.0)
Underfilling	5 (16.1)	4 (80.0)	1 (20.0)
Post-endodontic pain			
Present	0 (0)	-	-
Absent	31 (100)	11 (35.5)	20 (64.5)
Follow-up period			
≥3 yr	11 (35.5)	9 (81.8)	2 (18.2)
<3 yr	20 (64.5)	9 (45.0)	11 (55.0)

Values are presented as number (%).

cess of root canal treatment. The strict criteria were associated with a tomographic reduction in lesion size, evidence of normal periodontal space, and follow-up controls where the CBCTPAI score was '0.' The loose criteria were associated with scores showing a reduction in apical lesion size (loose criteria) when compared to the initial diagnostic radiograph.

RESULTS

Findings from follow-up checks (Tables 2 and 3)

All the treated teeth exhibited no reported clinical pain or discomfort by the patients, and percussion and palpation tests yielded negative findings. Additionally, no alterations in the gum tissue or signs of swelling were observed during the clinical evaluations.

All patients were evaluated with a single follow-up CBCT scan during evaluation periods ranging from 2 to 7 years, aiming to avoid excessive tomographic radiation exposure. The tomographic evaluations were conducted by assessing the three planes: sagittal, axial, and coronal. This approach provided a three-dimensional evaluation with follow-up controls [23].

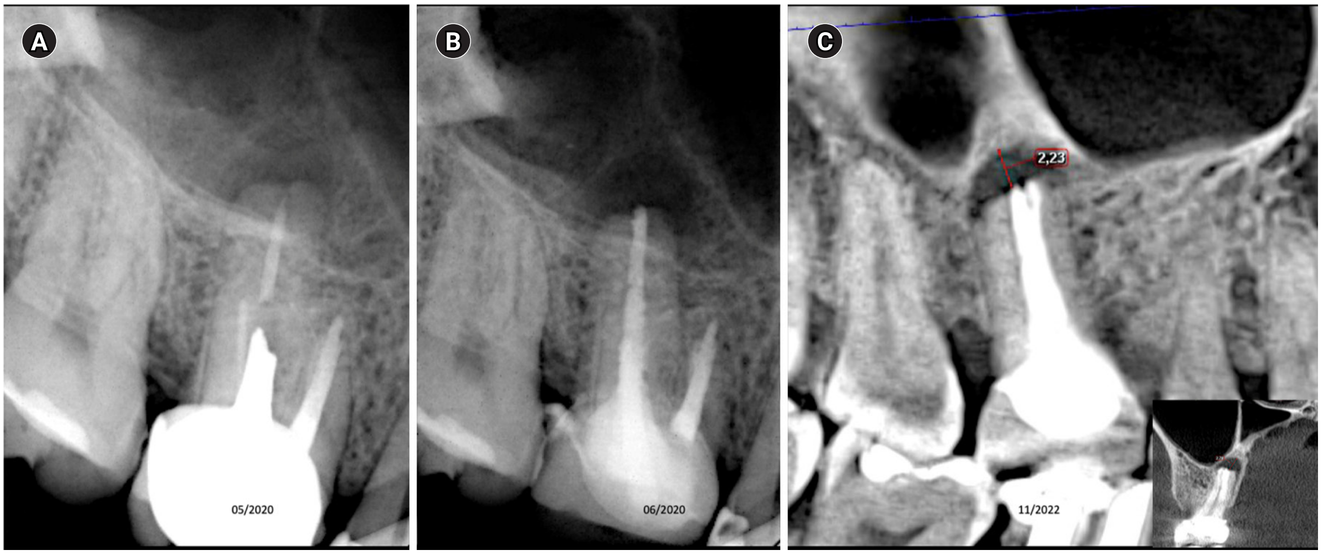

Figure 6. Tooth 16 with a diagnosis of previously initiated endodontic treatment and acute periapical abscess. (A) Diagnostic X-ray. (B) Immediate after obturation. (C) Tomographic control after 30 months, showing the apical lesion in the same manner as in the initial X-ray, considered a failure.

Figure 7. Tooth 36 with a diagnosis of previously treated with symptomatic apical periodontitis. (A) Diagnostic X-ray. (B) Immediate after obturation. (C) Tomographic control after 40 months, showing the apical lesion in the same manner as in the initial X-ray, considered a failure.

Table 4. Classification of CBCTPAI and case distribution by tooth type and success rate

Tooth type	CBCTPAI						
	0	1		2		3	Total
Incisive (%)	3	1	1	-	-	-	5
Canine (%)	2	-	-	-	-	-	2
Premolar (%)	1	1	5	-	2	-	9
Molar (%)	5	4	3	1	-	2	15
Total	11 (strict success)	6 (loose success)	9 (fail)	1 (loose success)	2 (fail)	2 (fail)	31
Strict criteria	35.48% success			64.52% fail			1
Loose criteria	58.06% success			41.94% fail			1

CBCTPAI, periapical index based on cone-beam computed tomography (proposed by Estrela *et al*. [22]).

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Considering strict criteria, out of 31 cases (100%), in 35.5% [11] of the cases, there was topographic repair compatible with success, while in 64.5% [20], the apical lesions did not reduce sufficiently to be considered a total success according to the CBCTPAI by Estrela *et al.* [22]. Segmenting the data by the type of treatment revealed that initial treatments had a clinical and tomographic success rate of 60% [9] and a failure rate of 40.0%, while retreatments achieved a 12.5% success rate [2]. Direct restorations had a success rate of 50.0% [4] compared to those restored with crowns at 30.4% [7]. There was a higher clinical and tomographic success rate in anterior teeth, including incisors (60.0%) and canines (100%), compared to posterior teeth, including premolars (11.1%) and molars (33.3%). Controls conducted over a period of more than 3 years (45.0%) exhibited greater success compared to those with shorter follow-up periods (18.2%) (Figures 2 and 3).

Using loose criteria, out of 31 cases, the majority of cases showed a reduction in the size of apical lesions. In total, 18 cases (58.1%) were considered successful, considering cases with tomographic repair and those in the process of repair. Males had a higher success rate at 72.7% compared to females at 55.0%. When considering the type of treatment, teeth that received initial treatment achieved an 80.0% success rate, while retreatments reached a 37.5% success rate. Direct restorations had a success rate of 75.0% when compared to restorations with crowns at 52.2%.

The data analysis revealed that suboptimal obturations demonstrated an 80% success rate, while ideal obturations had a 59.1% success rate. Additionally, cases with follow-up controls conducted in less than 3 years achieved an 81.81% success rate, in contrast to those with longer follow-up periods, which showed a success rate of 45.0%.

DISCUSSION

The persistence of apical periodontitis arises from the presence of intra- or extraradicular infections and their byproducts, sustaining a persistent inflammatory process. Consequently, complete healing of periapical lesions is often challenging, leading to the categorization of root canal treatment as a failure [24]. Despite advancements in technology enabling effective root canal disinfection, the degree of success varies based on clinical and microbiological diagnoses [25]. Challenges arise particularly in cases of pulp necrosis and symptomatic or asymptomatic apical periodontitis, where achieving cleaning levels compatible with clinical and tomographic success is a significant hurdle. Studies indicate that larger apical lesions are associated with a greater diversity of bacterial species and a higher failure rate [26]. Moreover, current challenges extend to secondary or persistent infections, as their bacterial microbiota tends to exhibit higher resistance compared to primary infections. Research has demonstrated that the microbiota of teeth with previously conducted root canal treatments and subsequent failures contains a higher prevalence of resistant gram-positive bacteria, such as *E. faecalis* [27].

Current irrigation procedures involving NaOCl or chlorhexidine, combined with chelating agents like EDTA, have significantly improved the cleaning and disinfection of infected teeth [24]. These procedures have been further optimized by incorporating additional devices to enhance their effectiveness, such as ultrasonic tips, irrigant agitators, and, more recently, lasers [6,28–31]. Although lasers have been utilized in endodontics for many years, a new type of laser has gained notable interest among clinicians due to its cost-effectiveness and versatility. These lasers are referred to as high-power diode lasers, capable of performing various clinical procedures, from surgical cutting to the disinfection of periodontal pockets and root canals [21,32].

The application of high-power diode lasers in root canal disinfection is currently under investigation through *in vitro* studies, where different wavelengths and power settings have demonstrated disinfectant effects [33,34]. Some *in vivo* studies have also assessed disinfection capabilities, with particularly promising results, especially for the high-power 810-nm diode laser [35]. The impact of the high-power 810-nm diode laser on disinfection in saline solution is a topic of debate in some studies, with findings ranging from no significant effect to a very low effect. However, other research indicates a maximum effect. According to certain authors, the laser's impact is attributed to three potential mechanisms: direct heat absorption by the bacterium, heating through absorption of the substrate surrounding the bacterium, and a photodamage effect [16].

Certain research evaluates diode lasers as adjuncts to current root canal disinfection methods, producing varied results [19,36]. Other studies explore diode lasers as monotherapy treatments, where primary disinfection is exclusively accomplished with the diode laser, eliminating the use of NaOCl or chlorhexidine [10]. In this presented series of 31 clinical cases, a high-power 810-nm diode laser was utilized with a consistent disinfection protocol for all cases. The programming involved 1 W in continuous mode with four cycles of 20 seconds and a 15-second thermal relaxation period between each cycle. Notably, this protocol replaced the use of NaOCl. All cases were diagnosed as necrosis or previously treated with radiographically evident apical lesions. The laser disinfection protocol deviates from the standard NaOCl disinfection protocol, as irrigation during instrumentation is conducted using saline solution throughout the procedure. Following root canal instrumentation, 17% EDTA was applied, followed by the laser disinfection protocol as previously described. Teeth without purulent exudate were obturated in a single appointment, while those requiring multiple appointments were left with saline solution in the canal and sealed with polycarboxylate until the next session, where disinfection and corresponding obturation procedures were reiterated. Similar procedures were carried out for cases with previously treated endodontics, involving the removal of previous obturations using orange oil. The overall results demonstrated success rates, based on both strict and less strict criteria, at 35.48% and 58.06%, respectively.

When specifically analyzing the type of diagnosis, it was observed that for primary treatments with a diagnosis of necrosis, the success rate was 60% and 80% according to strict and loose criteria, respectively, all with follow-up controls using cone-beam tomography. In the overall results, the success rates appeared lower due to the cases of retreatments, where success was notably low. However, in primary treatment cases, the results were quite comparable to other studies where they used NaOCl. For instance, Friedman *et al.* [37] reported a success rate of 74% in necrotic teeth with radiolucent images in the apical region, though follow-up assessments were conducted using radiographs. In another study by Karaoğlan *et al.* [38] a success rate of 71.8% with complete healing and 84.6% with healing in progress was reported, also with radiographic evaluation. Sjogren *et al.* [39] found success rates of 83% for lesions larger than 5 mm with an evaluation period of 8 to 10 years. For teeth with previously performed treatments and apical lesions less than 5 mm, the success rate was 65%, and for lesions larger than 5 mm, it was 38% (all with radiographic evaluation) [39]. In another study by Gorni and Gagliani [40], with a 2-year follow-up using radiographic assessment, a success rate of 84.4% for complete healing and 86% for healing in progress was reported in teeth with apical lesions. Ricucci *et al.* [41], in a study of 1,369 teeth with a 5-year evaluation, found success rates ranging from 78.2% to 86.8% for teeth with apical lesions. Similarly, Ng *et al.* [42], in a study on the success of primary root canal treatment, found success rates ranging from 31% to 96% based on strict criteria and between 60% and 100% based on loose criteria.

In our results, endodontic retreatments exhibited a success rate of 37.5% based on less strict criteria, closely resembling the findings of Ng *et al.* [43] who reported a success rate of 41.7% for teeth retreated with lesions larger than 5 mm. However, some other research on retreatment success rates has reported higher levels of success than what we found [44,45]. The disparity in our results could potentially be attributed to the lack of removal of the sealing material, which prevents the bactericidal effect of the laser on dentin. Additionally, the influence of the absence of intracanal medication and the use of an irrigant with bactericidal properties may have contributed to a greater reduction in microbial load and, consequently, increased success in retreatments. The influence of chemical agents has demonstrated significant assistance in resolving apical periodontitis [6,7,46].

Nowadays, magnification plays an important role in root canal treatment. With magnification, it is possible to see and locate canals that would not be visible to the naked eye, and it also allows for better visualization of materials like gutta-percha for removal when they remain inside the canal. Our clinical research did not use magnification, which could have been a valuable aid in the treatment of teeth with previous root canal therapy and possibly in primary infections as well [47].

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Post-endodontic pain was assessed in all patients, and none of them experienced pain after root canal treatment. The effect of laser therapy has been shown to be a promising alternative for reducing and controlling pain in endodontic therapy. Our results are consistent with findings in several articles by Nunes *et al.* [48], Abbara *et al.* [49], and Ismail *et al.* [50] (Tables 2 and 3).

Utilizing tomography for evaluations offers the advantage of enhanced visualization of apical lesions, even when they are very small and might not be detectable in traditional radiographic images. A study by Aminoshariae *et al.* [51] demonstrated that CBCT images were twice as likely to detect a periapical lesion compared to traditional periapical radiography in endodontic success studies. This highlights that our successful results, while somewhat lower compared to other research, could be attributed to the evaluation method used, which provides greater reliability in detecting the presence or absence of apical lesions. This is in contrast to radiographic techniques used in other studies, where an apical lesion may have been described as completely healed when it was not. The CBCTPAI was used because it presents advantages for clinical applications. Additionally, CBCTPAI scores are calculated by analyzing the lesion in three dimensions, obtaining computed tomography slices in the mesiodistal, buccopalatal, and diagonal directions. This shows superiority over conventional radiographic analysis, which only evaluates in two planes. CBCTPAI was the method of choice in our research because, although we have other methods to evaluate, such as the CBCT ERI (endodontic radiolucency index) method or the CBCT COPI (complex periapical index) method, one of the limitations we had was the use of large-field tomographies, which reduced image resolution. Therefore, using another more accurate method like CBCT ERI, which works with smaller volumes and high resolution to analyze images smaller than 0.5 mm, was not necessary in our case because our tomographies were not small fields [52].

The lower success in cases requiring retreatment may be attributed to the limited apical preparation, which was 25.06. This could have resulted in obturation material remaining inside the root canal, impeding the penetration of laser energy into the dentin and allowing bacterial viability in the root canal. Limited apical preparation can contribute to bacterial persistence, as demonstrated in a study by Rodrigues *et al.* [53] which found that a larger apical preparation size improved the disinfection effect in the root canal. Despite the final apical preparation size being 25.06 in primary treatments, the disinfection effect of the high-power diode laser helped achieve success rates comparable to the studies mentioned earlier.

Intracanal medication is a crucial step in the root canal disinfection process. Multiple research investigations have identified various benefits of using calcium hydroxide as the preferred medication, mainly due to its strong alkalinity, capacity to dissolve tissues, capability to neutralize endotoxins, and antibacterial properties, calcium hydroxide, also known as $Ca(OH)_2$, is extensively employed as an intracanal medicament, a published review has identified prognostic factors related to lower healing rates or tooth loss, including the presence of apical periodontitis, lesion size, and preoperative sinus tract [54]. In our cases, all presented periapical lesions, but the majority were treated in a single appointment. Even in cases requiring two or more sessions, intracanal medication was not utilized. While intracanal medication is considered an essential part of endodontic treatment, its usage appears to be decreasing [54]. Other studies have indicated that the completion of endodontic treatment in one or two appointments does not result in a significant difference in clinical and radiographic success rates [38]. In our cases, the high-power diode laser served as the sole means of disinfection for both primary treatments and retreatments, whether completed in one appointment or multiple appointments. Our results show that laser can help to restore health in the patient without the need for calcium hydroxide, with outcomes comparable to those shown in studies where, with large apical lesions, success rates reached 86.6% for small lesions, 78.2% for large lesions, and 54.5% for extremely large lesions [41,55]. The benefits of intracanal medication in the described cases, both in teeth undergoing initial treatment and retreatment, could have improved success rates. However, more randomized clinical studies are necessary to assess the combination of intracanal medication and laser therapy, which could help increase success rates, particularly in cases of teeth with large apical lesions where the prognosis is affected by the number of microorganisms present, as described in other studies. Additionally, evaluating the increase or decrease in symptoms during the period of intracanal medication could help in planning other possible treatments [26]. This approach was designed to assess the laser's potential as a disinfectant, aligning with other research where the use of the laser alone was adequate to achieve a high level of disinfection success, in *in vivo* studies [19].

This case series demonstrates a moderate potential of high-power 810-nm diode lasers with saline solution in the process of root canal disinfection, achieving clinical and tomographic success rates ranging from 60% to 80%, depending on the criteria used. These cases primarily involved primary treatments with diagnoses of pulp necrosis and large apical lesions, with the majority completed in a single session. While the use of disinfection monotherapy can be a subject of discussion and debate, it paves the way for potential application in other procedures where NaOCl disinfection may be limited, such as in cases of immature apices or pulp regeneration. Randomized clinical studies with tomographic controls may help in the future to assess how safe and effective monotherapy procedures for disinfection can be. The limitations of the investigation were related to the inability to obtain previous control tomographies, which could have provided better visualization of each case for comparing pre- and posttreatment sizes. Some benefits that this research shows are that through evidence from clinical cases, it was found that the high-power 810-nm diode laser has the capability of disinfection and achieving success levels comparable to the well-known NaOCl, as demonstrated in comparisons with previously cited literature.

Future studies using a larger apical preparation size could have been considered for improved results. Additionally, having a larger sample of patients would be important to validate the findings, providing more weight to the clinical case report.

CONCLUSIONS

The teeth with apical lesions that underwent primary treatment did not present clinical symptoms, but they showed a moderate success rate on tomographic evaluation. However, teeth with apical lesions that required retreatment, despite lacking clinical symptoms, had a very low success rate on tomographic evaluation.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization, Investigation: all authors; Formal analysis, Methodology: Teves-Cordova AVI, Alcalde MP, Pedraza FH, Duarte MAH; Writing–Original Draft: Teves-Cordova AVI, Alcalde MP,Pedraza FH, Duarte MAH; Writing–Review & Editing: Teves-Cordova AVI, Alcalde MP, Duarte MAH. All authors read and approved the final manuscript.

DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

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The effect of limonene extract on the adhesion of different endodontic cements to root dentin: an *in vitro* experimental study

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ABSTRACT

Objectives: The study aimed to evaluate the effect of limonene extract (LE) on push-out bond strength (BS) to root dentin in endodontically treated teeth.
Methods: Single-rooted teeth were selected and instrumented using the reciprocating technique, then divided into three groups based on the final irrigating solution: 2.5% sodium hypochlorite (NaOCl), 17% ethylenediaminetetraacetic acid (EDTA), and 5% LE. The roots were further divided ($n = 12$) and obturated using the single-cone technique with epoxy resin-based (ERB) or bioceramic sealer (Bio-C). After 3 days, the roots were sectioned into 2-mm slices, obtaining two slices from each root third. Push-out BS testing was conducted at 0.5 mm/min, followed by failure pattern and adhesive interface analysis using scanning electron microscopy. Push-out BS data were analyzed by three-way analysis of variance and Tukey *post-hoc* test ($p < 0.05$).
Results: ERB showed higher BS when irrigated with EDTA (5.0 ± 2.3 MPa) compared to NaOCl (1.8 ± 1.1 MPa) ($p = 0.0005$), particularly in the cervical third. LE yielded intermediate values without significant differences from the other irrigants (3.5 ± 1.9 MPa) ($p > 0.05$). For Bio-C, the highest BS was observed in the apical third, especially with LE (9.4 ± 5.0 MPa), differing from other thirds and final irrigating solutions ($p < 0.05$). Mixed failure patterns were most prevalent, regardless of the irrigant solutions.
Conclusions: The combination of LE with Bio-C demonstrated superior BS in the apical third, suggesting its potential as a final irrigating solution in endodontic treatments.

Keywords: Biocompatible materials; Dental cements; Dentin; Limonenes; Root canal irrigants; Tensile strength

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INTRODUCTION

Endodontic treatment is based on the biomechanical cleaning of the root canal system (RCS), involving the physical-chemical removal of inflamed and necrotic pulp tissue using instruments, along with irrigation, and obturation of the RCS [1]. The success of endodontic therapy relies on the elimination of microorganisms from the RCS and the prevention of reinfection. The objectives of instrumentation are to facilitate irrigation, cleaning, and shaping of the RCS, as well as three-dimensional obturation [2].

During and after instrumentation, irrigators facilitate the removal of microorganisms and the smear layer from the root canal by means of a flushing mechanism. Irrigators can also contribute to preventing the compaction of hard or softened tissue in the apical third, as well as to avoid debris extrusion into the periapical region [2]. Currently, instrumentation is widely regarded to provide access to apical anatomy for irrigant, which should perform most of the cleaning and shaping [3,4].

The most widely used irrigant is sodium hypochlorite (NaOCl), which is a highly destructive, nonselective oxidant that readily reacts with biomolecules, giving it the ability to dissolve biofilm components and necrotic debris [4]. Additionally, it contributes to reducing bacterial virulence factors such as endotoxins and lipoteichoic acids and serves as a lubricant for endodontic instruments [5].

NaOCl is used in dentistry as an irrigating solution in endodontic treatments, with its effect attributed to the free available chlorine (OCl^- and HOCl), which are strong oxidants whose properties depend on pH. The ideal concentration of NaOCl ranges from 0.5% to 8.25% [5]. Its limitations include cytotoxicity, inability to completely remove the inorganic smear layer, and adverse effects on the mechanical properties of roots, such as dentin brittleness at high concentrations [3,6].

Demineralizing or chelating agents, such as ethylenediaminetetraacetic acid (EDTA), constitute another group of endodontic irrigants. These agents bind to and form ring-shaped complexes with metal ions, allowing for the effective dissolution of inorganic material. EDTA does not affect organic tissue and has limited antimicrobial effects by chelating metal cations from the outer membrane of bacteria [2,7].

Monoterpenes are secondary plant metabolites commonly used as antiseptics [8]. Limonene, a type of monoterpene, is a monocyclic compound found in citrus oils, such as those from oranges, grapefruits, and lemons. It is widely used in perfumes, soaps, pharmaceuticals, and foods due to its citrus scent. Additionally, limonene is employed in medical practices [9–12].

Limonene, an organic compound found in citrus oils, has been studied in dentistry for its potential as a treatment for dental caries. A study has shown that limonene may have a stronger inhibitory effect on *Streptococcus sobrinus* than chlorhexidine and can potentially inhibit the progression of caries [10]. This compound can inhibit the growth of cariogenic bacteria, their adhesion, acid production, and other cariogenic virulence factors such as insoluble glucan [11,12]. Additionally, limonene exhibits antimicrobial, anti-inflammatory, anticarcinogenic, and anticariogenic activities. It is considered safe with low toxicity, and its lipophilicity allows for good cellular absorption, particularly in the intestines, providing good bioavailability in systemic circulation [8,10]. Studies have also demonstrated that d-limonene has relevant clinical activity against both gram-positive and gram-negative bacteria [13,14].

The aim of this *in vitro* study was to evaluate the effect of using limonene extract (LE) as a final irrigating solution during endodontic treatment in teeth obturated with different root canal sealers, namely epoxy resin-based (ERB) and bioceramic (Bio-C), regarding push-out bond strength (BS) and failure pattern after push-out using a stereomicroscope. The null hypotheses tested were that irrigation and obturation with different compositions do not interfere in the BS of endodontically treated teeth and in the failure pattern between the gutta-percha, the root canal sealer, and the intraradicular dentin.

METHODS

The sample size was calculated based on a pilot study, comparing means of push-out BS among the treatments and using OpenEpi app (www.openepi.com), with a 95% confidence interval and power of 80%. The minimum estimated number of specimens was 11 for each

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group; however, considering eventual sample loss, 12 specimens were included in each group.

This study used human tooth roots, such as maxillary and mandibular premolars, which were obtained from the teeth bank of the institution, where it was reviewed and approved by the Institutional Ethics Committee of Ribeirao Preto School of Dentistry (approval No. 67552923.8.0000.5419). The extracted teeth were initially stored at 4°C in 0.1% thymol solution until use to preserve their integrity during storage [15]. Following endodontic treatment, the teeth were transferred to artificial saliva at 37°C, mimicking the body's natural temperature to simulate clinical conditions prior to sectioning.

They were macroscopically analyzed and scanned using a cone-beam computed tomography scanner PreXion 3D (Prexion Co. Ltd, Tokyo, Japan), with an endodontic acquisition protocol of 90 kV, 4 mA, 37 seconds exposure time, isotropic voxel size of 0.10 mm, and a field of view of 5 × 5 mm. Two-dimensional morphometric data, including circularity and major and minor diameters, were obtained using the OnDemand 3D Project Viewer software (Cybermed Inc., Tustin, CA, USA) to determine the degree of root canal flattening [16–19]. Thus, 72 roots with oval-shaped root canals (major diameter/minor diameter ratio between 1 and 2), vestibulolingual/mesiodistal dimension ≤1.5 mm, and 16-mm root length were selected.

After sample selection, the root canals were irrigated with 2.5 mL of 2.5% NaOCl (Coltene/Whaledent AG, Altstatten, Switzerland) using a 21-mm disposable plastic syringe with a 27-gauge tip (Ultradent Products Inc., South Jordan, UT, USA) and explored with a #15 K-file (Dentsply Maillefer, Ballaigues, Switzerland) until the tip of the instrument emerged at the apical foramen. From this measurement, 1.0 mm was subtracted to establish the working length [19,20].

The biomechanical preparation was performed using the reciprocating motion instrumentation technique with WaveOne Gold files Medium 35.06 (Dentsply Maillefer), with torque and speed preset by the manufacturer. The final irrigation protocol was divided according to the final irrigating solution used for this purpose, into groups with 2.5 mL of 2.5% NaOCl, 2.5 mL of 17% EDTA (CanalPro EDTA; Coltene/Whaledent AG), and 2.5 mL of 5% LE (Sigma-Aldrich, St. Louis, MO, USA) (Table 1). The LE was diluted in distilled water to achieve the tested concentration (5%). For this, 0.5 mL of limonene was added to 95 mL of distilled water. Subsequently, 2.5 mL of the solution was used for the final irrigation of the root canal. A fresh limonene solution was prepared for each use. The irrigation process involved continuous flushing of the root canal with the solution for 5 minutes after instrumentation was completed. Canal drying was accomplished using a Capillary Tip aspiration cannula (Ultradent Products Inc.) and 35.06 absorbent paper points (Dentsply Maillefer).

The canals were obturated using the single-cone technique with WaveOne Gold Conform Fit Medium 35.06. The groups were divided into two subgroups: one obturated with ERB sealer (AH Plus; Dentsply De Trey, Konstanz, Germany) and the other with Bio-C Sealer (Angelus, Londrina, Brazil) (Table 2). The roots were stored in an incubator at 37°C for 3 days. All procedures, including biomechanical preparation and obturation, were performed by the same operator.

To obtain slices for the push-out BS test, the roots were embedded in self-curing acrylic resin (Jet; Clássico, São Paulo, Brazil) and adapted to a metallographic cutter (Isomet 1000; Buehler, Lake Bluff, IL, USA) to be sectioned perpendicularly to their long axis in the mesiodistal direction. A double-sided diamond disc with a thickness of 0.3 mm was used, operating at a speed of 350 rpm under continuous cooling.

From each root third, two dentin slices, each 2.0 mm (±0.2 mm) thick, were obtained, totaling six slices per

Table 1. Irrigating solutions with commercial name, manufacturer, and composition

Solution	Commercial name	Manufacturer	Composition
Limonene	Pro Lyks - Natural	Hydroplan EB, São Paulo, SP/Brazil	Citrus sinensis peel oil expressed
Sodium hypochlorite	NaOCl	Asfer Chemical Industry. São Caetano do Sul – SP/Brazil	2.5% Sodium hypochlorite base
Ethylenediaminetetraacetic acid	EDTA	Chemical and Pharmaceutical Biodynamics LTDA. Ibiporã – PR/Brazil	Disodium ethylenediaminetetraacetic acid, sodium hydroxide, and deionized water

Table 2. Endodontics root canal sealers

Material	Mainly compounds	Lot	Manufacturer
Epoxy resin-based: AH Plus	Paste A: bisphenol-A epoxy resin, bisphenol-F epoxy resin, calcium tungstate, zirconium oxide, silica, iron oxide pigments	210400657	Dentsply De Trey, Konstanz, Germany
	Paste B: dibenzylamine, aminoadamantane, tricyclodecane-diamine, calcium tungstate, zirconium oxide, silica, silicone oil		
Bioceramic: Bio-C Sealer	Calcium silicate, calcium aluminate, calcium oxide, zirconium oxide, iron oxide, silicon dioxide, and dispersing agent.	64766	Angelus, Londrina, Brazil

root for the push-out test and analysis of the adhesive interface using scanning electron microscopy (SEM).

Push-out bond strength test

The slices were positioned on stainless steel metal bases attached to the bottom portion of the universal testing machine model 2519-106 (Instron, Canton, MA, USA). Depending on the diameter of the root canal filling material in the cervical, middle, and apical thirds, metal bases with holes of 1.2-, 1.5-, and 2.5-mm diameter in their central portion were selected, along with metal rods with active tips of 0.8-, 1-, and 1.5-mm diameter. The specimens were positioned in the same direction as the hole in the metal base, with their cervical face facing downwards, and the rods were fixed to the upper portion of the testing machine and positioned over the intracanal material. The testing machine was operated at a constant speed of 0.5 mm/min until the maximum tension required for displacement of the material was reached [18–21].

The force required for displacement was measured in Newtons (N). To calculate the BS, the resulting force was converted into megapascals (MPa) by dividing it by the lateral area (LA) of the intracanal material. For the accurate calculation of the adhered LA, the geometric aspect of the intracanal material (sealer + gutta-percha) was considered based on the level of the slice obtained. For this purpose, before the test, the height of each slice was measured using a digital caliper, as well as the radius (major and minor) using a Leica M165C stereomicroscope (Leica Microsystems, Mannheim, Germany) with Las ver. 4.4 software (Leica Microsystems).

Thus, the area of adhesion of the sealer (in mm^2) was calculated using the formula for lateral area (LA):

$$\mathrm{LA} = \pi\,(R + r)\,\sqrt{(h^2 + [(R - r)]^2)}$$

In this formula, "R" is the measurement of the radius of gutta-percha and sealer in its coronal portion, "r" is the measurement of the radius of gutta-percha and sealer in its apical portion, and "h" is the height/thickness of the slice. From these data, the BS in MPa was calculated by dividing the force required for the displacement of the gutta-percha by its lateral area (BS = F/LA).

For the analysis of failure type, the slices were evaluated using the Leica M165C stereomicroscope at 25× magnification and the Las ver. 4.4 software. The observed failures were determined as percentages and classified as follows: (a) adhesive to dentin: when the obturation material detached from the dentin; (b) adhesive to sealer: when the gutta-percha detached from the sealer; (c) mixed: when the obturation material detached from both the dentin and the sealer; (d) dentin cohesive: when dentin fracture occurred; and (e) gutta-percha cone cohesive: when the gutta-percha cone fractured.

Scanning electron microscopy

For analysis by SEM, the second dentin slice from each root third (cervical, middle, and apical) was used. Preparation for SEM involved polishing the dentin specimens with progressively decreasing water sandpaper up to 1,200 grit. Subsequently, the specimens were rinsed in distilled water and superficially decalcified in 6-M hydrochloric acid (HCl) for 30 seconds and deproteinized in 2% NaOCl for 10 minutes. Afterward, the specimens were rinsed, dehydrated, and fixed onto aluminum cylindrical structures (10 × 10 mm) using double-sided adhesive tape as described in previous studies [19–23]. Following vacuum metallization, the specimens were analyzed using a scanning electron microscope (JSM 5410; JEOL Ltd., Tokyo, Japan) operating at 20 kV.

Data analysis

The BS data were initially analyzed for normal distribu-

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tion using the Shapiro-Wilk test ($p > 0.05$) and homogeneity using the Levene test, showing normal distribution and homogeneity.

The parametric three-way analysis of variance (ANOVA) was used to analyze the influence and interaction among final irrigating solutions (NaOCl, EDTA, and LE), root canal sealers (ERB and Bio-C), and root thirds (cervical, middle, and apical). The Tukey *post-hoc* test was used for multiple comparisons with a significance level of $p < 0.05$.

To analyze the prevalence of failure patterns found after the push-out BS test, the Fisher exact test was performed.

RESULTS

Bond strength

The mean and standard deviation values obtained from the push-out BS test for the variables of root canal sealers, final irrigating solutions, and root thirds are presented in Table 3.

The three-way ANOVA (Tukey, $p < 0.05$) showed that, for the ERB sealer, there was no significant difference in the BS of the sealer to dentin among the analyzed thirds ($p > 0.05$). Regarding the Bio-C sealer, there was a higher BS of the sealer when treated with LE in the apical third, a statistically different result ($p > 0.05$) compared to the other thirds, which did not differ from each other ($p > 0.05$). The other irrigating solutions did not result in BS differences between them ($p > 0.05$), regardless of the analyzed third.

Analyzing the BS of the root thirds in relation to the irrigating solutions performed for each of the root canal sealers, it was found that the ERB sealer exhibited higher BS to cervical dentin when treated with EDTA (5.0 ± 2.3 MPa). This result was statistically significantly different ($p = 0.0005$) compared to the irrigating solution with NaOCl (1.8 ± 1.1 MPa), which resulted in the lowest BS values among all solutions.

The irrigating solution with LE yielded intermediate values in relation to the other irrigating solutions, with no statistically significant difference compared to them ($p > 0.05$). Regarding the Bio-C sealer, there was a difference ($p < 0.0001$) in the BS to dentin in the apical third, such that after irrigating solution with LE, there was a higher BS (9.4 ± 5.0 MPa). This result was statistically different compared to the other irrigating solutions ($p > 0.0001$). NaOCl and EDTA did not show statistically significant differences among themselves ($p = 0.282$).

When comparing the BS of different sealers to dentin treated with the same type of irrigating solution and in the same third, it was found that, when dentin was treated with LE, the Bio-C sealer exhibited higher BS (9.4 ± 5.0 Mpa) in the apical third, with a statistically significant difference from the ERB sealer (2.2 ± 1.5 Mpa) ($p < 0.001$).

When the dentin was irrigated with EDTA, the ERB sealer exhibited higher BS (5.0 ± 2.3 MPa) in the cervical third, with a statistically significant difference ($p = 0.0008$) when compared to the Bio-C sealer (1.9 ± 1.5

Table 3. The bond strength (MPa) of endodontic root canal sealers to root dentin treated with different irrigating solutions in the cervical, middle, and apical thirds

Root canal sealer	Final irrigating solution		
	Limonene extract	EDTA	NaOCl
ERB			
Cervical third	3.5 ± 1.9^{abA}	$5.0 \pm 2.3^{aA\#}$	1.8 ± 1.1^{bA}
Medium third	2.5 ± 1.0^{aA}	3.4 ± 2.1^{aA}	1.4 ± 0.6^{aA}
Apical third	2.2 ± 1.5^{aA}	3.3 ± 2.1^{aA}	1.9 ± 0.9^{aA}
Bio-C			
Cervical third	2.4 ± 1.6^{aB}	$1.9 \pm 1.5^{aA*}$	1.4 ± 0.5^{aA}
Medium third	2.6 ± 1.9^{aB}	1.5 ± 0.9^{aA}	1.9 ± 1.4^{aA}
Apical third	$9.4 \pm 5.0^{aA*}$	1.4 ± 0.9^{bA}	3.0 ± 2.1^{bA}

Values are presented as mean ± standard deviation.
Bio-C, bioceramic; EDTA, ethylenediaminetetraacetic acid; ERB, epoxy resin-based; NaOCl, sodium hypochlorite.
Lowercase letters in the row and uppercase letters in the column, for the same sealer, indicate statistically significant differences ($p < 0.05$). Different symbols within the same final irrigating solutions and root third indicate statistically significant differences between sealers.

MPa). All other final irrigating solutions did not show statistically significant differences ($p > 0.05$), regardless of the root canal sealer used or the third analyzed.

Fracture pattern analysis

The results of the Fisher exact test analysis and the percentage data of the distribution of failure types for each group are described in Tables 4 and 5. The Fisher exact test demonstrated that, regardless of the root canal sealer used, there was a higher percentage of mixed failures to dentin compared to other types of failures. Analyzing the final irrigating solutions, it was found that, regardless of the root canal sealer used, the use of EDTA and LE resulted in almost 30% cohesive fractures to dentin and around 2% of adhesive fractures. Additionally, when treated with NaOCl, no adhesive fractures occurred, indicating that the irrigating solution is a significant factor for the prevalence of the fracture pattern with this type of sealer (ERB, $p = 0.020$; Bio-C, $p < 0.001$).

Analysis of the adhesive interface using scanning electron microscopy

The statistical analysis observed in the evaluation of the experimental groups can be confirmed by the qualitative analysis of the SEM images (Figure 1), which allowed the observation of areas of misfitting (yellow arrows) and adaptation at the adhesive interface between the gutta-percha cone, root canal sealers, and root dentin in the different irrigating solution types (NaOCl, EDTA, LE).

DISCUSSION

This study evaluated the BS and adhesive interface analysis of dentin irrigating solutions with LE, EDTA, and NaOCl as final irrigating agents in teeth filled with REB (AH Plus) and Bio-C (Bio-C Sealer). According to the results, the null hypothesis cannot be accepted, as teeth treated with LE showed higher BS values in the apical third compared to the other final irrigating solutions.

Prior to tooth selection, a thorough analysis of the teeth was conducted by evaluating images obtained from cone-beam computed tomography [16]. Root canal anatomy may exhibit varied cross-sectional shapes within the same dental group, depending on the ratio between buccolingual and mesiodistal dimensions. This analysis for sample selection is necessary because the single-cone technique may have limitations, especially in oval canals, regardless of the root canal sealer used. The sample was standardized by selecting circular

Table 4. Result of the Fisher exact test analysis of fracture pattern prevalence in relation to root canal sealers and final irrigating solution factors

Comparison group	χ^2 value	df	p-value (χ^2)	p-value (Fisher exact test)	Number of specimens
Failure pattern × ERB	11.9	6	0.064	0.020	232
Failure pattern × Bio-C	20.7	6	0.002	<0.001	234
Failure pattern × Total	22.3	6	0.001	<0.001	466

Bio-C, bioceramic; df, degree of freedom; ERB, epoxy resin-based.

Table 5. Failure rate following the push-out bond strength test for different root canal sealers and dentin irrigating solution

Root canal sealer	Failure pattern	LE (%)	EDTA (%)	NaOCl (%)
ERB	AD	1.4	1.3	0.0
	AC	0.0	1.3	0.0
	CD	12.8	29.5	14.5
	M	85.9	69.2	85.5
Bio-C	AD	0.0	1.3	0.0
	AC	2.6	3.9	0.0
	CD	9.0	26.9	36.8
	M	88.5	68.0	67.1

AD, adhesive to dentin; AC, adhesive to sealer; Bio-C, bioceramic; CD, cohesive in dentin; EDTA, ethylenediaminetetraacetic acid; ERB, epoxy resin-based; LE, limonene extract; M, mixed; NaOCl, sodium hypochlorite.

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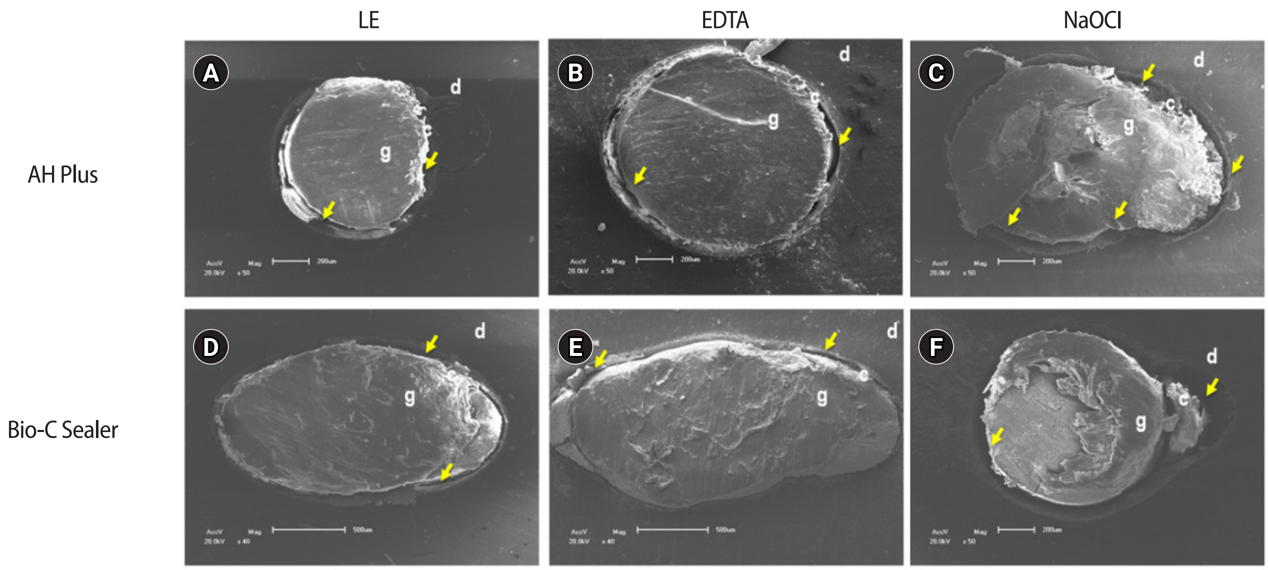

Figure 1. Areas of misfitting (yellow arrows) and adaptation at the adhesive interface between the gutta-percha cone (g), root canal sealer (c), and root dentin (d) in the different final irrigating solution types (limonene extract [LE], ethylenediaminetetraacetic acid [EDTA], and sodium hypochlorite [NaOCl]). For the epoxy resin-based sealer group (AH Plus; Dentsply De Trey, Konstanz, Germany) treated with LE (A) and EDTA (B), and Bio-C sealer group (Bio-C Sealer; Angelus, Londrina, Brazil) treated with LE (D) and EDTA (E), it is possible to observe adaptation at the adhesive interface, with integrity of the obturation margins and a lower percentage of gaps. In NaOCl, regardless of the experimental group, sealer predominance can be observed in the polar areas (C and F) with areas of misfitting.

root canals (ratio equal to 1) of single-rooted teeth to minimize bias risk.

Root canal irrigation in endodontic treatment is one of the steps in dentin preparation for the removal of the smear layer and intracanal disinfection. Different irrigation techniques are developed, studied, and observed in the literature, effectively removing debris and microorganisms from the root canals and thereby assisting in the adhesion between root canal sealers, gutta-percha, and root dentin [20–22,24].

In the present study, there was no statistically significant difference ($p > 0.05$) among the root canal sealers, except for the results of the LE groups in the apical third and EDTA groups in the cervical third. The use of LE for final irrigation followed by root canal obturation with ERB sealer yielded BS values like those obtained with Bio-C sealer, except in the apical third, where LE showed higher BS values with a mixed failure pattern in the obturation material. SEM photomicrographs allowed for the observation of a more uniform and thinner layer of endodontic root canal sealer at the adhesive interface.

In the remaining thirds, the use of LE did not lead to a decrease in BS compared to the other final irrigating solutions, resulting in values without statistically significant differences between them ($p > 0.05$). Furthermore, the analysis of fracture patterns showed that this irrigating solution resulted in a low prevalence of the number of adhesive fractures, with nonadhesive fractures being the most prevalent, demonstrating good bonding at the tooth/sealer interface. The use of EDTA for final irrigation, followed by obturation with ERB sealer and Bio-C sealer, showed BS without statistically significant differences with a mixed failure pattern. SEM photomicrographs allowed for the observation of a uniform and thin layer of ERB sealer and Bio-C sealer on the obturation material and the presence of gaps at the adhesive interface, with greater penetration into the dentinal tubules occurring regularly and homogeneously.

Dentin irrigating solution with NaOCl may result in lower BS values with a mixed failure pattern in the obturation material. This can be explained by the formation of an oxygen layer on the dentin surface, resulting from the cleavage of NaOCl into chlorine and oxygen

[25]. Studies support that NaOCl did not demonstrate a positive effect on adhesion to root dentin, which may increase tensions and generate larger gaps at the adhesive interface, resulting in less uniform root canal sealer penetration and more void spaces. Nonetheless, NaOCl is considered an endodontic irrigating solution with antibacterial effects and the ability to dissolve organic tissues [26–29]. According to a previous study [30], dentin samples treated with LE showed smear layer removal and open dentinal tubules. Considering this, the higher BS results of LE suggest an efficient removal of the smear layer from root dentin.

D-limonene, a monoterpene abundant in citrus essential oils, has attracted attention in dentistry for its low toxicity, sustainability, and diverse biological properties, including antimicrobial, antioxidant, anti-inflammatory, anticancer, and anticariogenic effects [11]. Its antioxidant activity neutralizes reactive oxygen species (ROS), reducing oxidative stress and protecting cells, while its anti-inflammatory effects involve the inhibition of cytokines and prostaglandins via cyclooxygenase-2 and nuclear factor kappa-B pathways. Additionally, it disrupts microbial membranes and inhibits biomolecule synthesis in certain pathogens. Although widely studied in medicine for conditions like cancer and respiratory issues, its potential in restorative dentistry lies in its ability to inhibit matrix metalloproteinases through ROS scavenging, potentially improving restoration longevity [31].

Despite the promising results observed for the use of limonene as a final irrigating solution, the study is limited by having been conducted on teeth without microbiological contamination caused by caries progression. Therefore, further studies are needed to evaluate the effect of limonene on contaminated teeth.

CONCLUSIONS

This *in vitro* study concludes that combining LE with Bio-C sealer results in superior BS in the apical third of the root, while BS in the cervical and middle thirds is consistent across different root canal sealers when LE is used for final irrigation. The most common failure type between sealer and dentin was mixed, regardless of the irrigation method and root canal sealer type. Additionally, final irrigation with EDTA and LE enhances the adaptation of the adhesive interface, irrespective of the root canal sealer type used.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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The authors have no financial relationships relevant to this article to disclose.

AUTHOR CONTRIBUTIONS

Conceptualization: Aguiar NLF, Panzeri FC. Methodology, Investigation: Aguiar NFL, Santos GNA, Romano LK. Validation, Formal analysis: Panzeri FC. Soares EJ. Supervision, Project Administration: Silva RG. Writing - original draft: Soares EJ, Santos GNA, Pimenta ALA. Writing - review & editing:

DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

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Bibliometric analysis of the GentleWave system: trends, collaborations, and research gaps

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ABSTRACT

Objectives: The study aimed to conduct a bibliometric analysis of the GentleWave system (Sonendo, Inc.).
Methods: An electronic search was conducted in June 2024 using the Web of Science Collection database. Two reviewers independently screened publications, extracting data on authorship, publication details, study design, and citation metrics. Statistical analyses were performed in R to assess variable correlations, while the VOSviewer (Visualization of Similarities Viewer) software was used to map author and keyword networks.
Results: The search yielded 47 records, with 32 studies included. Publications spanned 2014 to 2024. The Journal of Endodontics published the highest number of studies ($n = 15$), and *the International Endodontic Journal* had the highest impact factor (5.4). The University of British Columbia and Sonendo, Inc. were the most frequent affiliations. Among the 32 articles, 28 were *in vitro* studies, primarily focusing on microbiology ($n = 9$). A total of 95 authors were identified, with Haapasalo and Shen being the most cited ($n = 229$). The articles accumulated 495 citations, demonstrating a strong positive correlation between the number of studies and citation counts ($r = 0.98$).
Conclusions: The analysis highlights a predominance of *in vitro* studies. Geographic concentration in the United States and Canada limits diversity, while the strong correlation between study numbers and citations suggests that increased publication volume enhances visibility.

Keywords: Bibliometrics; Endodontics; Multisonic; Root canal irrigants; Root canal therapy

INTRODUCTION

Biomechanical preparation of the root canal system is a critical step for the success of endodontic treatment. This process relies on the combined action of mechanical instrumentation and the physicochemical properties of irrigating solutions, along with their application protocols [1,2]. The primary objectives of irrigation include

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the removal of intracanal medicaments [3], eliminating the smear layer and debris [4,5], and enhancing disinfection. The latter is particularly crucial, as a substantial portion of the root canal walls remains unaffected by instrumentation alone [6,7].

To effectively promote disinfection and organic tissue dissolution, irrigation solutions must be adequately distributed within the root canal system [8]. Given the limitations of conventional syringe-and-needle irrigation [9,10], alternative irrigation protocols have been explored. Passive ultrasonic irrigation (PUI), for example, has been extensively investigated as a method for enhancing irrigant agitation [11,12]. Studies have demonstrated that PUI outperforms conventional irrigation in several aspects, including tissue dissolution [10], smear layer removal [13], and biofilm disintegration [14]. However, for PUI to be effective, canals must be enlarged to allow the insert to vibrate freely. Since it is typically performed with metal inserts, there is a potential risk of unnecessary wear on the dentin walls [12,15].

Recently, the GentleWave system (Sonendo, Inc., Laguna Hills, CA, USA) was developed to promote cleaning of the root canal system without the need for significant canal enlargement. The system comprises a console and a sterile, single-use handpiece designed for individual patients. It delivers a continuous stream of treatment fluid—3% sodium hypochlorite (NaOCl), 8% ethylenediaminetetraacetic acid (EDTA), and distilled water—from the handpiece tip into the pulp chamber. Simultaneously, excess fluid and debris are removed through a built-in suction mechanism integrated into the handpiece, which channels waste into a canister within the console. The GentleWave system utilizes a broad spectrum of sound waves, known as multisonic technology, to generate advanced fluid dynamics for agitating irrigating solutions. When the treatment fluid is introduced, it interacts with the stationary fluid in the pulp chamber, creating a strong shear force that leads to hydrodynamic cavitation. The treatment begins with 3% NaOCl, followed by a water rinse, and concludes with 8% EDTA. This flow induces a gentle vortical motion and generates a slight negative pressure within the root canal system, ensuring effective cleaning from the coronal to apical regions [14,16]. This system has shown promise in the disinfection of the root canal system [17,18], removal of intracanal medication [19], tissue dissolution [16], and retrieval of fractured instruments [20].

Bibliometric analyses offer a valuable approach to evaluating emerging trends, collaboration patterns, and the intellectual structure of a specific research domain within the existing literature [21]. Due to the benefits and conveniences, bibliometric analyses have become increasingly popular in endodontics. Recent studies have employed this approach to investigate topics such as regenerative endodontics [22], calcium silicate cements [23], guided endodontics [24], and photodynamic therapy [25]. To date, there has been no bibliometric analysis in the literature specifically assessing studies on the GentleWave system. Thus, this study aims to conduct a bibliometric analysis of the GentleWave system to identify potential gaps in the literature and generate new insights for future research.

METHODS

Databases and search strategies

An electronic search was conducted in June 2024 using the Web of Science Collection database (https://www.webofscience.com). The search strategy included terms related to the GentleWave system and the agitation method (multisonic). The complete search strategy employed was: ("gentlewave" OR "gentlewave system" OR "multisonic").

Eligibility criteria and study selection

Studies related to the GentleWave system were selected for this bibliometric analysis. Publications not pertinent to the topic and general literature reviews on endodontic irrigation were excluded. No filters were applied to restrict the years or language of publication. The search results were exported to the reference management software EndNote Web (Clarivate, London, UK).

The full texts were reviewed by two independent reviewers, and in cases of discrepancies, a third reviewer with expertise in the field was consulted to reach a consensus.

Data extraction

Data extraction was conducted by one reviewer, considering only the information present in the selected

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studies. The extracted data included authors, title, journal, year of publication, keywords, number of citations, country, institution, study design, impact factor (from Journal Citation Reports by Clarivate), and the Journal Citation Indicator (JCI from Clarivate). Regarding study design, the studies were classified according to their methodology into categories such as reviews, *in vitro*/*ex vivo*, and clinical studies.

Data analysis

The extracted data were compiled into a database and organized in a Microsoft Office Excel 2016 spreadsheet (Microsoft Corp., Redmond, WA, USA). The graphical representation of the data was conducted using the Visualization of Similarities Viewer software (VOSviewer, version 1.6.17.0; Centre for Science and Technology Studies of Leiden University, Leiden, the Netherlands) to assess the connections between authors and keywords. For keyword analysis, a threshold of a minimum of three occurrences was established. In the network analysis, the major clusters and their primary sources were identified based on their frequency of occurrence. Less frequent terms indicate lower emphasis or less-utilized sources. The lines connecting the terms represent collaborations among them.

Correlation matrix

The statistical analyses were carried out using the R programming language version 4.3.0 (The R Foundation for Statistical Computing, Vienna, Austria; https://www.r-project.org). The Shapiro-Wilk normality test was performed on each numerical variable in the dataset, including the Journal Impact Factor (JIF), JCI, number of studies, and number of citations. Based on the results of this test, appropriate correlation tests were selected. For variables that followed a normal distribution, the Pearson correlation test was applied, while for variables that did not follow a normal distribution, the Spearman correlation test was used. The significance level was set at $\alpha \leq 0.05$.

RESULTS

The data extracted from the selected studies are grouped in Supplementary Table 1.

Search and study selection

The initial database search yielded 47 records. Two non-article records were excluded. After reviewing the titles, abstracts, and full texts by two independent reviewers, 15 studies were excluded for not meeting the inclusion criteria. A total of 32 studies [14,16–20,26–51] were included in this bibliometric analysis (Figure 1).

Year of publication

The studies included spanned from 2014 to 2024. The year 2019 had the highest number of publications (n = 6), while both 2014 and 2024 had the lowest number of publications (n = 1). The earliest study was published by Haapasalo *et al.* [16], titled "*Tissue dissolution by a novel multisonic ultracleaning system and sodium hypochlorite*," while the most recent article was titled "*Efficacy of the GentleWave system in the removal of biofilm from the mesial roots of mandibular molars before and after minimal instrumentation: an ex vivo study*," published in 2024 by Kim *et al.* [50]. The description of the number of publications by year can be found in Figure 2.

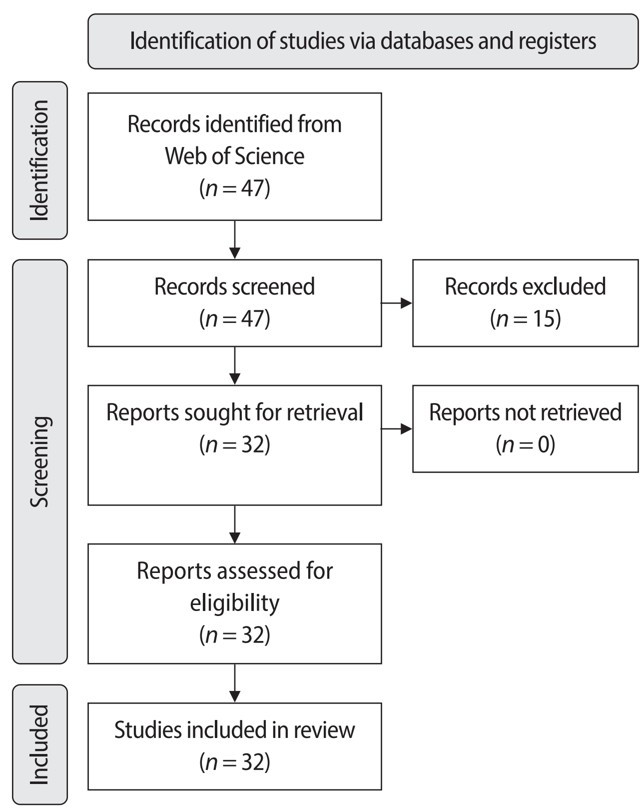

Figure 1. Flowchart of the study selection protocol.

Journals, Journal Impact Factor, and Journal Citation Indicator

The articles were published in 11 journals. *The Journal of Endodontics* (JOE) had the highest number of studies related to the GentleWave system (n = 15), followed by *the International Endodontic Journal* (IEJ, n = 4). According to the Journal Citation Reports, the IEJ has the highest impact factor (5.4), followed by Scientific Reports (3.8) and the JOE (3.5). Additionally, the IEJ exhibited the highest JCI (1.9), followed by the JOE (1.86) and *Clinical Oral Investigations* (1.33). Data on the JCI and JIF were not available for *Restorative Dentistry and Endodontics*.

A description of the journals, their JIFs, JCIs, number of studies, and citations of articles published on the GentleWave system can be found in Table 1.

Affiliations

The following affiliations were the most frequent: University of British Columbia (10 studies and 229 citations), Sonendo, Inc. (six studies and 208 citations), University of Minnesota (five studies and 28 citations), Huazhong University of Science and Technology (four studies and 73 citations), New York University (three studies and 61 citations), São Paulo State University (three studies and 15 citations), University of Maryland

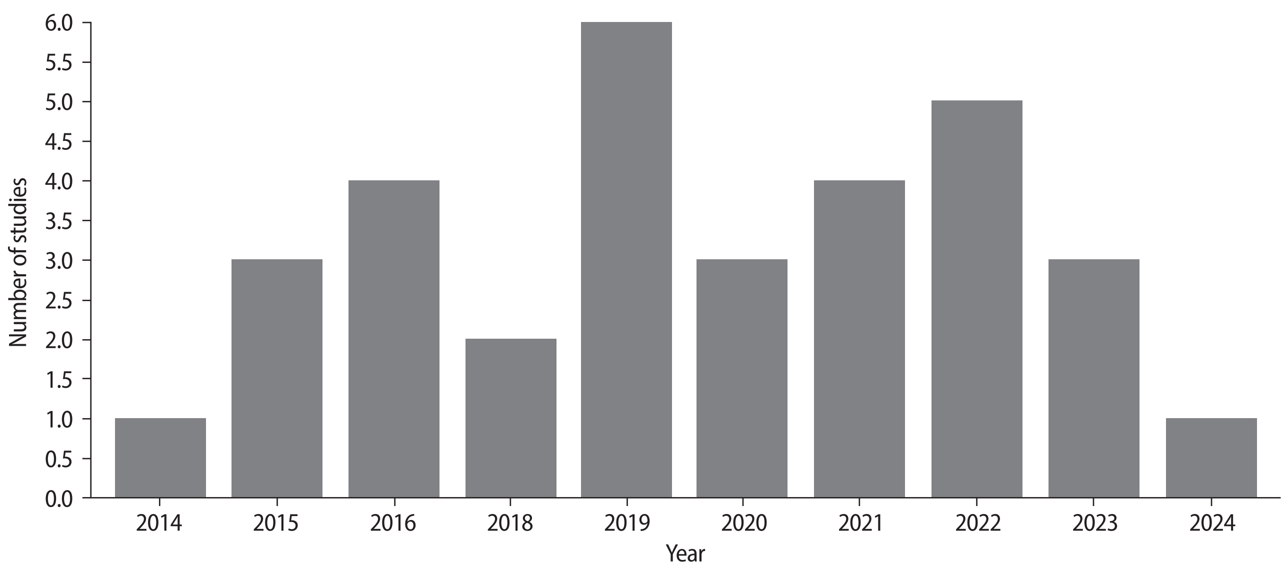

Figure 2. Distribution of the number of studies published over the years.

Table 1. Journals, Journal Impact Factor[a)], Journal Citation Indicator[a)], and citation counts of studies published on the GentleWave system[b)]

Source title	Journal Impact Factor	Journal Citation Indicator	Number of studies	Number of citations
Journal of Endodontics	3.5	1.86	15	376
International Endodontic Journal	5.4	1.9	4	15
Journal of Pharmacy and Bioallied Sciences	0.7	0.2	1	0
Scientific Reports	3.8	1.05	2	8
Restorative Dentistry And Endodontics	-	-	2	10
Applied Sciences-Basel	2.5	0.56	1	0
Odontology	1.9	0.95	2	18
Medicina-Lithuania	2.4	0.67	1	10
Materials	3.1	0.58	1	10
Australian Endodontic Journal	1.3	0.62	1	9
Clinical Oral Investigations	3.1	1.33	2	39

[a)]Clarivate, London, UK. [b)]Sonendo, Inc., Laguna Hills, CA, USA.

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(three studies and 12 citations), and University of Toronto (three studies and 65 citations).

Study design and themes

Among the 32 studies included, 28 were *in vitro*/*ex vivo* studies. Other study designs included clinical studies (n = 3), and one narrative literature review. No systematic reviews, meta-analyses, or bibliometric analyses on the GentleWave system were found. Microbiology emerged as the most prevalent research theme (n = 9), followed by root canal debridement (n = 4), apical pressure (n = 3), retreatment (n = 3), healing rate (n = 2), calcium hydroxide removal (n = 2), dentin structure analysis (n = 2), obturation (n = 1), tissue dissolution (n = 1), removal of calcification (n = 1), removal of separated instruments (n = 1), postoperative pain (n = 1), apical extrusion (n =1), and others (literature review, n =1).

Authors

A total of 95 authors were identified from 10 countries: the United States, Canada, Brazil, China, Saudi Arabia, South Korea, India, Japan, Mexico, and Spain. Most authors are from the United States (n = 22), followed by Canada (n = 13) and Brazil (n = 6) (Table 2). The three most cited authors are Haapasalo, M (n = 229); Shen, Y (n = 229); and Khakpour, M (n = 172). The authors with the highest citations and their number of published studies are presented in Table 3.

Keywords

A total of 207 keywords were identified, with 33 keywords appearing at least three times across the selected studies. The most frequently occurring keywords were “GentleWave system” (n = 20) and “Irrigation” (n = 19). The frequency distribution and co-occurrence patterns of these keywords are illustrated in Figure 3.

Studies

The 32 selected articles collectively accumulated 495 citations. The article published by Haapasalo *et al.* [16] in the JOE was the most cited in the literature (51 citations). The journals with the highest number of citations were JOE, *Clinical Oral Investigations*, and *Odontology*, with 376, 39, and 18 citations, respectively (Table 2). Complete citation data for all included are available in Supplementary Table 1.

Correlation matrix

According to the correlation matrix analysis, there is a strong positive correlation between the number of studies and the number of citations (0.98). A moderate positive correlation was observed between the number of citations and the JCI (0.57), and a low positive correlation with the JIF (0.24). The number of studies showed a positive correlation coefficient of 0.65 with the JCI and 0.34 with the JIF. Additionally, a strong positive correlation was found between the JIF and the JCI (0.85) (Figure 4).

DISCUSSION

Bibliometric reviews play a crucial role in contemporary academic research by providing a systematic and quan-

Table 2. Countries and number of studies and citations on the GentleWave system[a)]

Country	Number of studies	Citations
United States	22	365
Canada	13	294
China	6	93
Brazil	6	65
Saudi Arabia	3	8
South Korea	2	20
Spain	1	5
Mexico	1	0
Japan	1	31
India	1	0

[a)]Sonendo, Inc., Laguna Hills, CA, USA.

Table 3. The authors with the highest number of studies and citations in GentleWave system[a)]

Author	Number of studies	Citations
Haapasalo, M	10	229
Shen, Y	10	229
Khakpour, M	4	172
Wang, Z	5	139
Curtis, A	3	114
Patel, P	3	114
Vandrangi, P	3	78
Ma, J	4	73
Basrani, B	3	65
Friedman, S	2	65

[a)]Sonendo, Inc., Laguna Hills, CA, USA.

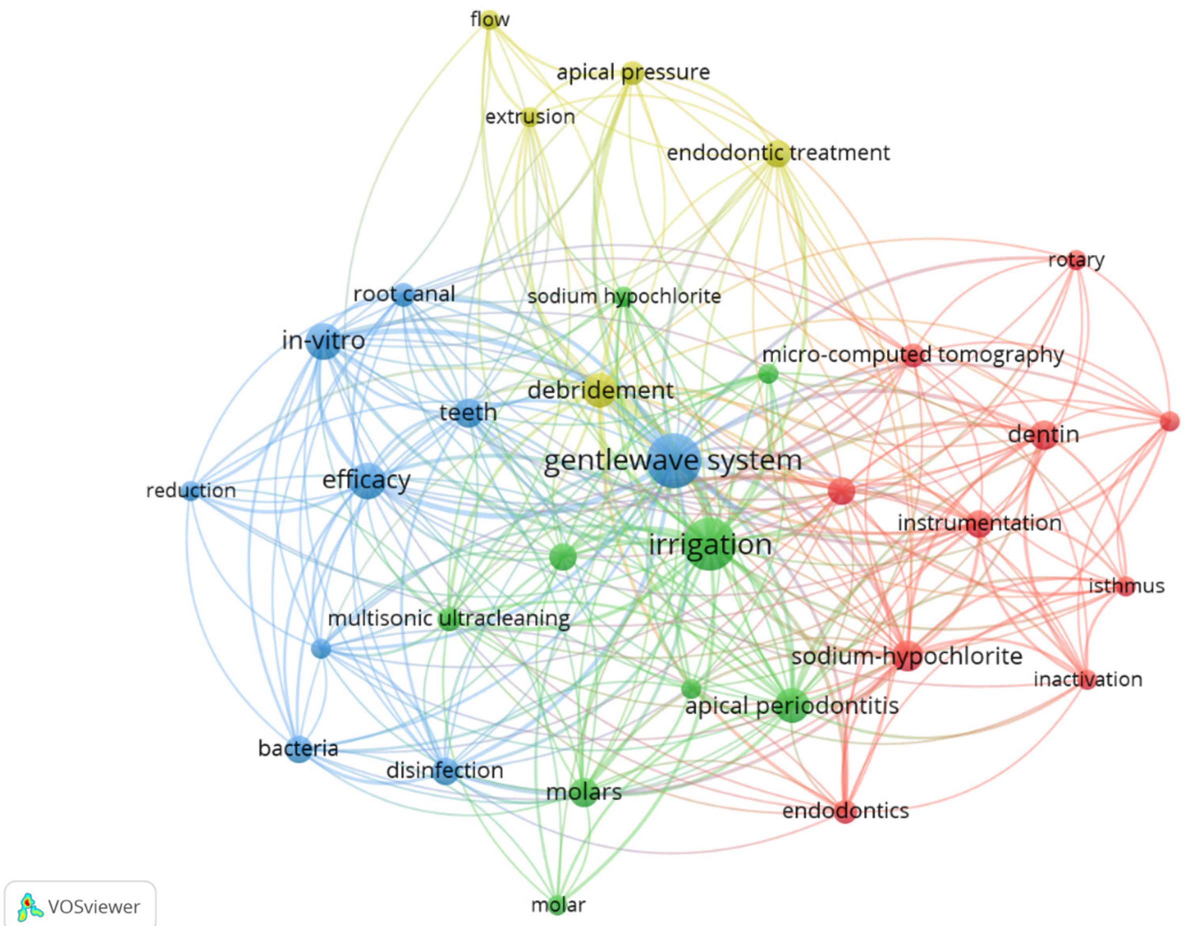

Figure 3. Frequency and interaction between keywords. Larger circles indicate the most used keywords. Lines between circles indicate relationships between keywords. Different colors indicate different clusters according to year. VOSviewer (Visualization of Similarities Viewer software): Centre for Science and Technology Studies of Leiden University, Leiden, the Netherlands.

titative analysis of scientific production. Emerging fields of study, such as the rise of new technologies, offer a comprehensive view of the current state of knowledge [52]. The GentleWave system is a new device designed to promote minimally invasive root canal treatment by facilitating the cleaning of anatomically complex areas through the propagation of acoustic energy and powerful agitation of irrigating solutions, thereby reducing the need for endodontic instruments and canal enlargement [32]. The first study on GentleWave was published 10 years ago, in 2014 [16]. The year 2019 saw the highest number of publications on GentleWave, reflecting a growing interest in studying this device. Since then, the number of publications has experienced another peak in 2022, indicating the current relevance of discussing topics related to irrigation in the field of endodontics. These publication peaks correlate with promising results associated with GentleWave, particularly in the effective removal of the smear layer [26], tissue dissolution [16], and improved healing outcomes [32]. Such advancements not only encourage further research but also underscore the significance of GentleWave in modern clinical practice.

The JOE has published the most studies on GentleWave, followed by IEJ. These two journals are considered leaders in research and clinical practice in endodontics, and their high JIFs reflect the quality and relevance of the information they provide to researchers and clinicians in this field. Previous bibliometric reviews have consistently demonstrated more publications for

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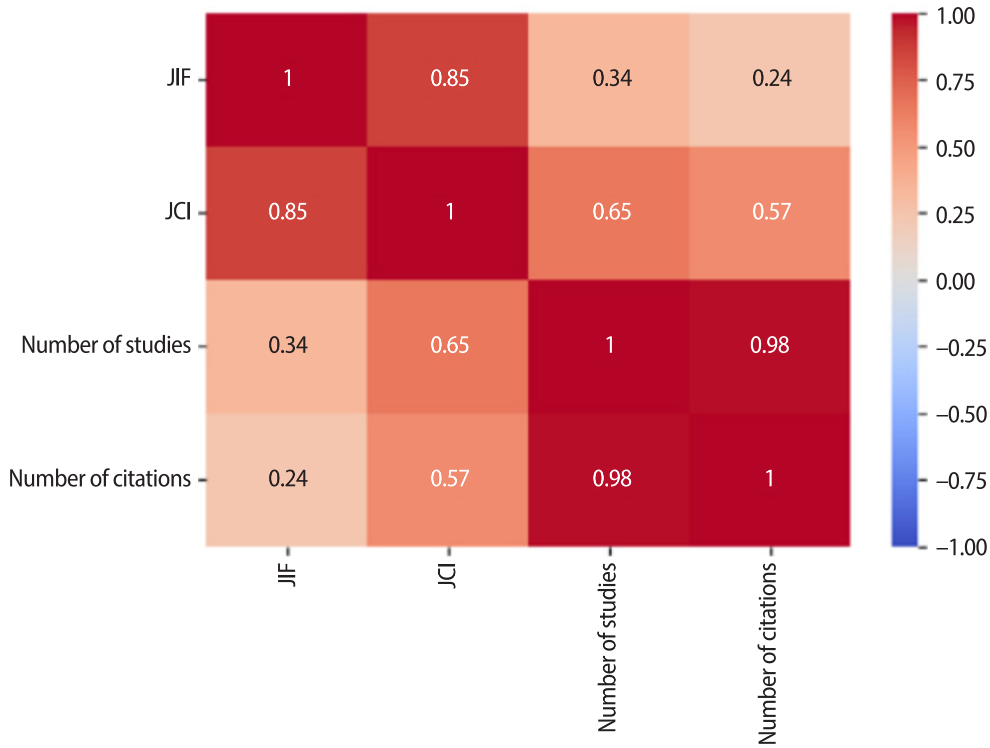

Figure 4. Correlation matrix between the following variables: Journal Impact Factor (JIF), Journal Citation Indicator (JCI), number of studies, and number of citations. Correlation coefficients range from –1 (perfect negative correlation) in blue to 1 (perfect positive correlation) in red, with significance set at $\alpha = 0.05$.

both JOE and IEJ [24,53–58]. The significant influence of these publications on endodontic practice justifies their prominence in this bibliometric review.

Haapasalo and Shen were the most cited authors and had the highest number of published articles, attributed to their pioneering investigations of this new technology. The most cited article, "*Tissue dissolution by a novel multisonic ultracleaning system and sodium hypochlorite*" [16], was also the first published on GentleWave, which explains its high citation count as it has become a foundational reference for other authors. Despite being the most cited work on the subject, it has yet to reach 100 citations to be considered a classic in the field [52,59], illustrating that, even 10 years after the publication of the first article, the topic has not been thoroughly studied and explored.

This bibliometric analysis revealed that the United States and Canada dominate the scientific production on this topic, with the United States leading in total publications and citations. The University of British Columbia stands out as the most productive institution on GentleWave studies, with the highest volume of published articles and citations. The fact that this equipment is manufactured by an American company may contribute to the concentration of research in North America, particularly in the United States and Canada. Additionally, the high cost of the equipment may limit the ability to conduct studies in other regions of the world. It is also worth noting that previous bibliometric analyses in endodontics have similarly found that the United States ranks among the countries with the highest number of publications and citations [24,55,56,60,61].

Microbiology was the most frequently addressed topic in the studies, as the disinfection of the root canal system is the primary goal of GentleWave. Additionally, microorganisms are the main cause of periapical diseases and the most common contributors to endodontic treatment failure [62–64]. This topic was followed by root canal debridement and apical pressure, which are directly related to the equipment's mechanism of action and the need for canal enlargement for cleaning, as well as the potential extrusion of septic-toxic content beyond the apex due to operational pressure. The most prevalent keywords identified in the analyzed literature were “GentleWave system,” “Irrigation,” and “Debridement.” These terms directly correspond to the primary research focus and the predominant *in vitro* study designs employed to evaluate this new technology.

The correlation matrix conducted in our study revealed a strong positive correlation (0.98) between the number of published studies and the number of citations, suggesting that as the number of studies on a topic increases, the total number of citations tends to rise consistently. This is expected, as a higher volume of studies often leads to greater recognition and serves as a reference for other researchers [65]. A moderate positive correlation (0.57) was observed between the number of citations and the JCI, indicating a significant relationship between the citations an article receives and the JCI of the journal in which it was published. The JCI reflects the influence of a journal by considering the citations received by its published articles. This moderate correlation suggests that journals with a higher indicator tend to have articles with more citations, but this relationship is not as direct or strong as that between the number of studies and citations. The correlation of 0.65 between the number of studies and the JCI is positive and moderate to strong. This implies that journals publishing a greater number of studies tend to have a higher JCI, reflecting that journals with a larger volume of publications often have greater visibility and influence in the scientific community. The strong positive correlation of 0.87 between the JIF and the JCI indicates a very strong and positive relationship. This suggests that journals with a higher JIF also tend to have a similarly high JCI, as demonstrated in a previous study [66]. Both metrics reflect the impact and influence of a journal, and this strong correlation is expected, as they both assess the relevance and recognition of journals within the scientific community, albeit through slightly different approaches. The correlations between the number of citations and the JIF (0.24) and between the number of studies and the JIF (0.34) were considered low. In summary, the analysis of the correlation matrix reveals that while the number of studies and the number of citations are strongly correlated, the relationship between journal impact metrics (JCI and JIF) and citations is more variable.

In vitro/ex vivo studies currently dominate the research landscape due to their ability to evaluate new equipment and techniques under controlled conditions, enabling precise control and isolation of experimental variables. These controlled investigations provide fundamental evidence that supports subsequent clinical research development. However, while such findings offer valuable preliminary data, they cannot be fully extrapolated to the clinical setting, which involves multifactorial issues and complex variables that influence outcomes [67]. The current literature reflects this gap, with only three clinical studies published to date [30,32,42]. This underscores the critical need for more rigorous clinical investigations, particularly well-designed randomized controlled trials that would provide higher levels of evidence. Additionally, conducting systematic reviews that consolidate and critically analyze the available information is essential for advancing the understanding and practical application of these findings.

A notable strength of this study is the absence of filters based on publication year, citation count, or language, allowing for a broad and comprehensive analysis of all relevant publications available at the time of research. Although this bibliometric study has limitations that should be considered, such as the use of a single database for article extraction, the Web of Science remains the most established database for bibliometric research. The selection of this database was intentional, as it aligns with standard methodological approaches in endodontic research and ensures compatibility with VOSviewer software [23,24,52,55]. Web of Science provides standardized, high-quality citation data from rigorously indexed journals, offering reliable metrics while maintaining methodological consistency with previous studies in the field. While multi-database analyses can expand search scope, our approach prioritizes data integrity and reproducibility within a well-structured citation index system [68].

CONCLUSIONS

The bibliometric analysis reveals a predominance of

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in vitro/*ex vivo* studies published on the GentleWave system, highlighting the need for more clinical research and systematic reviews. The concentration of scientific production in the United States and Canada limits the geographic diversity of publications. The strong correlation between the number of studies and citations reflects the growing recognition of this technology.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization, Project administration, Supervision: Oliveira Neto RS, Alcalde MP, Duarte MAH. Data curation: Oliveira Neto RS, Amorim JVO, Duarte MAH. Formal analysis: Oliveira Neto RS, Souza TM, Duarte MAH. Funding acquisition, Resources: Oliveira Neto RS, Duarte MAH. Investigation: Oliveira Neto RS, Souza TM, Amorim JVO, Duarte MAH. Methodology: Oliveira Neto RS, Souza TM, Lima TO, Silva GF, Vivan RR, Alcalde MP, Duarte MAH. Software: Neto RS, Souza TM. Validation: Lima TO, Silva GF, Vivan RR, Alcalde MP, Duarte MAH. Visualization: Oliveira Neto RS, Souza TM, Amorim JVO. Writing - original draft preparation: Oliveira Neto RS, Souza TM, Amorim JVO. Writing - review & editing: Oliveira Neto RS, Lima TO, Silva GF, Vivan RR, Alcalde MP, Duarte MAH. All authors read and approved the final manuscript.

DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

SUPPLEMENTARY MATERIALS

Supplementary Table 1. Articles on GentleWave

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Dentin thickness of C-shaped root canal walls in mandibular premolars based on cone-beam computed tomography: a retrospective cross-sectional study

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ABSTRACT

Objectives: This study aimed to measure the dentin thickness of C-shaped canals in mandibular first and second premolars at coronal, middle, and apical root levels using cone-beam computed tomography (CBCT).
Methods: Dentin thicknesses of buccal, lingual, mesial, and distal root walls of 41 C-shaped premolars were measured at three different root levels on axial CBCT slices. The measurements were made at the midpoint of each third, along with 1 mm below and above the midpoint. C-shape configurations of the premolar root canals were also recorded. Analysis of variance, Kruskal-Wallis, and the independent samples t-tests were used for the comparisons ($p = 0.05$).
Results: The thickest walls for both premolars were buccal and lingual walls at all three root levels ($p < 0.05$). The thinnest walls for the first premolar teeth were mesial and distal walls of the lingual canal, while it was the mesial end of the buccal and lingual canals for the second premolars ($p < 0.05$). Dentin wall thicknesses at the mesial end of buccal and lingual canals of C1-shaped first premolars were thinner than C2-shaped first premolars at the apical level ($p < 0.05$).
Conclusions: Danger zones for C-shaped mandibular first and second premolars are predominantly mesial walls facing the radicular groove and distal wall of the lingual canal. CBCT imaging during endodontic treatment is recommended to avoid complications.

Keywords: Cone-beam computed tomography; Cross-sectional anatomy; Premolar; Tooth root

INTRODUCTION

The C-shaped canal morphology is an anatomical variation in which independent root canals are merged or connected through isthmuses or fins, forming a C-shaped appearance at cross-sectional views. As re-

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ported previously, it is a well-defined anatomical variation frequently related to mandibular second molars, and it has been thoroughly studied, including its anatomic, histologic, and radiologic features [1–3].

C-shaped canal morphology in mandibular molars is often associated with the fusion of the roots and a longitudinal radicular groove on the root surface [2,4]. The radicular groove is described as a developmental depression area that occurs because of root fusion and creates a danger zone, increasing the risk of stripping perforation during endodontic preparation [5]. It has been reported that the root canal wall facing the radicular groove was thinner than the other walls in C-shaped mandibular molars [3]. In accordance with this finding, histological evaluation of C-shaped mandibular second molars demonstrated that the dentin thickness between the root canal and the external surface of the root was less than 1 mm in some sections [6].

Although limited in number, recent case reports and scientific studies have also described the presence of C-shaped canal morphology in mandibular premolars [7–11]. The prevalence of C-shaped canal configuration in mandibular premolars varies depending on ethnicity, and its prevalence was reported to be between 1.1% to 10.9% for mandibular first premolars and 0.6% to 2% for second premolars [9–11]. While the Chinese population demonstrated a lower prevalence of C-shaped canal morphology [9], the prevalence rates were relatively higher in the Argentine population [11]. Morphologic features of C-shaped canals in mandibular premolars have been found similar to C-shaped mandibular molars, including longitudinal radicular groove [5,7]. Due to the smaller size of mandibular premolar teeth, the longitudinal radicular groove is particularly important and requires considerable attention with regard to endodontic mishaps [5]. Considering anatomical complexities including isthmuses, transverse anastomoses, irregularities, concavities, and thin dentin thickness, endodontic treatment of C-shaped root canals presents a clinical challenge. Removal of pulp and necrotic tissue, working length determination, and proper irrigation and disinfection will be key problems during root canal instrumentation and shaping. Consequently, the awareness of dentin thickness in premolars with c-shaped canals is particularly important to maintain the integrity of the canal walls.

To our knowledge, there are few studies evaluating the root dentin thickness of C-shaped mandibular first premolars [12–15]. Given the low prevalence of C-shaped morphology in mandibular second premolars, the number of scientific reports evaluating the prevalence and morphology of C-shaped canals in such teeth is even scarce [11,16]. In fact, no study can be found investigating the root dentin thickness of C-shaped mandibular second premolar teeth. Therefore, the aim of this study was to measure the dentin thickness of C-shaped canals in both mandibular first and second premolars at coronal, middle, and apical root levels using cone-beam computed tomography (CBCT) images.

METHODS

This study was approved by the Medical Research Ethics Committee of Ege University (No. 22-2.1T/33) and followed the principles of the Declaration of Helsinki. A general formal consent is obtained from every patient who applies to our clinic, stating that the data can be used in an anonymized fashion for scientific purposes.

A total of 2,024 CBCT volumes from 1,061 patients of the Turkish population (654 females, 407 males; mean age, 31.57 ± 15.35 years) taken for various reasons between the years of October 2018 and March 2020 at the Department of Oral and Maxillofacial Radiology were examined retrospectively. Images of patients showing at least one C-shaped mandibular premolar tooth were included in the study. Teeth with previous endodontic treatment, internal and/or external root resorptions, immature apices, periapical lesions, full-crown restorations, and CBCT images with severe artifacts were excluded. CBCT images had been previously obtained using a Kodak 9000 3D device (Kodak Carestream Health, Trophy, France) at 70 kV, 10 mA, and 10.8 seconds exposure time, using a 50 × 37-mm small field of view (FOV), and a 76-μm isotropic voxel resolution.

The diagnosis of C-shaped configuration was made according to the description of Fan *et al.* [7] and teeth with a partial or complete external radicular groove on the mesiolingual or distolingual root surface and C1 or C2 canal configuration at any axial root level (coronal, middle, and apical) were considered as having C-shaped

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canal morphology. According to Fan *et al*. [7], C1 canal configuration was identified as a continuous "C" with no separation or division, whereas C2 was discontinuous in the "C" outline resembling a semicolon (Table 1). When a C1 or C2 configuration was detected at any axial root level, coronal and sagittal CBCT slices were also examined to confirm the root level of the C shape (Figure 1). Forty-nine premolar teeth of 37 patients were determined to have a C-shaped canal configuration. Images of five first premolars and three second premolars were excluded due to the presence of severe artifacts and low image resolution interfering with the correct measurement of dentin thickness.

Table 1. Classification of C-shaped canal configuration in mandibular premolar teeth according to Fan *et al*. [7]

C-Shaped configuration	Definition
C1	Continuous 'C' with no separation or division
C2	Discontinuation in the 'C' outline resembling a semicolon
C3	Two separate round, oval, or flat canals
C4	One round, oval, or flat canal
C5	Three or more separate canals
C6	No canal lumen or no intact canal

Concisely, 39 small FOV CBCT volumes of 41 C-shaped mandibular premolars (32 first and nine second premolars) of 33 patients with a mean age of 31.8 ± 14.6 years were used to measure dentin thicknesses at three different root levels (coronal, middle, and apical) on axial CBCT slices.

CS 3D Imaging Software (Kodak Carestream Health) was used for the measurements of dentin thicknesses. The root lengths of premolars were measured from the cementoenamel junction (CEJ) to the root apex and divided into three equal parts. The first level beginning from the CEJ to the middle third of the root was named as the coronal level, the third level beginning from the apex to the point where the middle third ends was named as the apical level and the level between the coronal and apical levels was named as the middle level (Figure 2A). At each root level where C-shaped canal

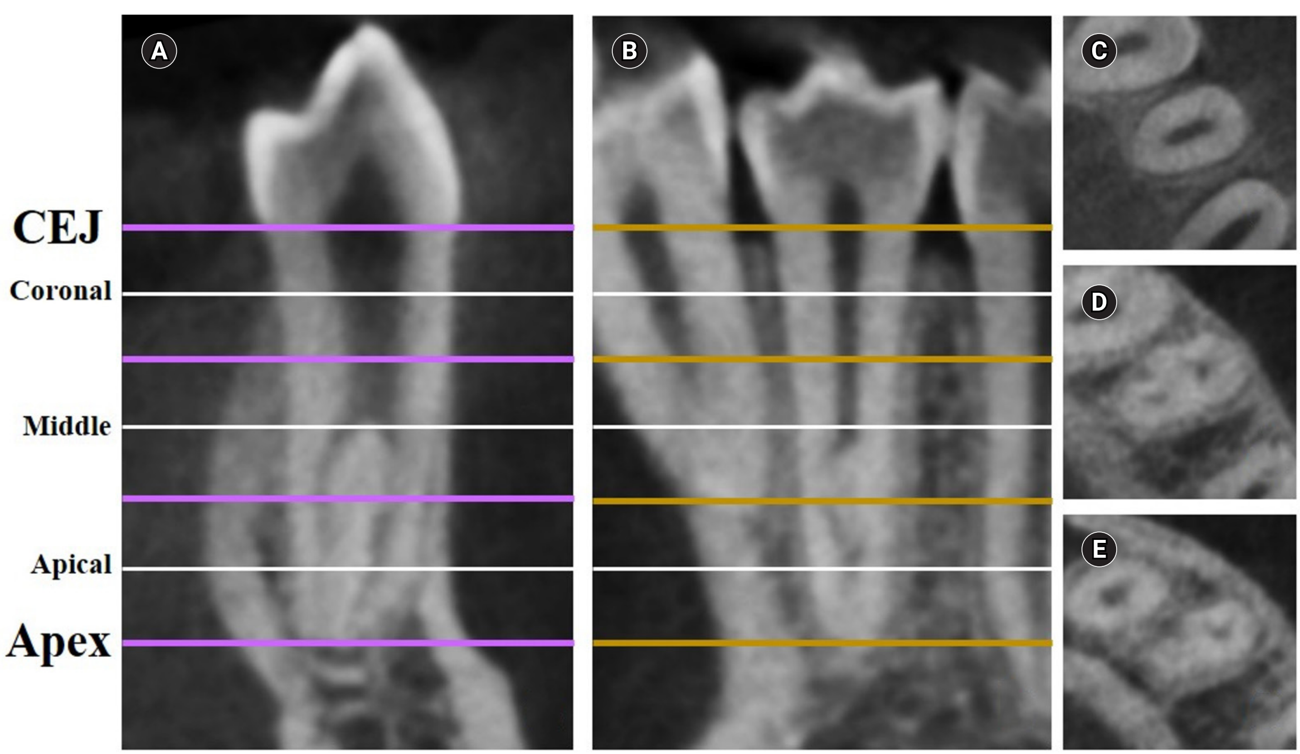

Figure 1. Cone-beam computed tomography (CBCT) image illustrating the diagnosis of C-shaped configuration. (A) Coronal and (B) sagittal CBCT images showing a C-shaped mandibular first premolar. Axial CBCT images showing (C) a C4-type configuration at the coronal level, (D) a C2-type configuration at the middle level, and (E) a C3-type configuration at the apical level. CEJ, cementoenamel junction.

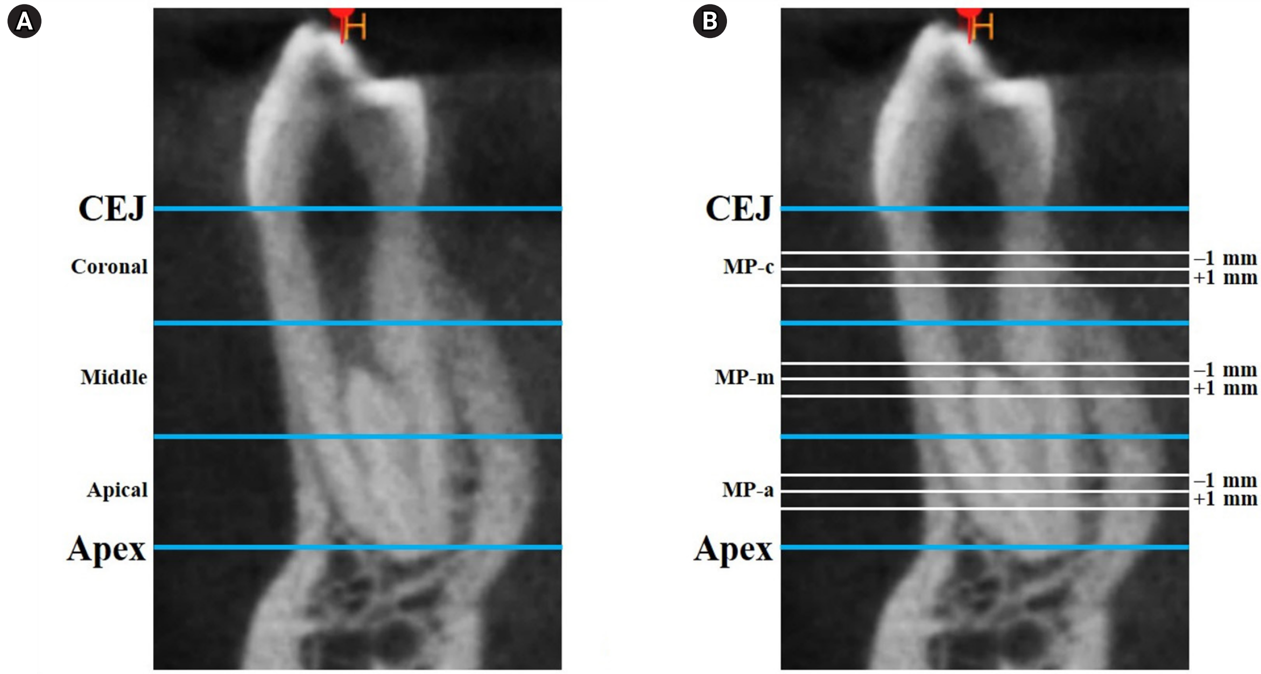

Figure 2. Coronal cone-beam computed tomography images showing (A) the coronal, middle, and apical root levels beginning from the cementoenamel junction (CEJ) to the root apex and (B) the dentin thickness measurement slices and midpoints of coronal (MP-c), middle (MP-m), and apical (MP-a) root thirds.

morphology was present, the dentin thicknesses were measured on three consecutive axial CBCT slices: midpoint of each root level, 1 mm below the midpoint, and 1 mm above the midpoint (Figure 2B).

The dentin thicknesses measured on three consecutive CBCT slices were calculated as the mean wall thickness and recorded along with the C-shaped canal type (C1 or C2).

Dentin thickness measurements were made on eight separate dentin walls at all root levels, demonstrating a C-shaped canal configuration. For each root level presenting with C1 or C2 configuration, primarily, thicknesses of buccal (Bu), lingual (Li), distal (D), and mesial (M) walls were measured. Then additional thickness measurements were done at both buccal and lingual canal walls as the distances between: (1) mesial end of the buccal canal and the external root surface facing the radicular groove (M1), (2) distal end of the buccal canal and the external root surface facing the radicular groove (M2), (3) lingual canal and the external mesial root surface facing the radicular groove (M3), (4) mesial end of the buccal canal and external mesial root surface (M4), (5) lingual canal and external distal root surface (D1)

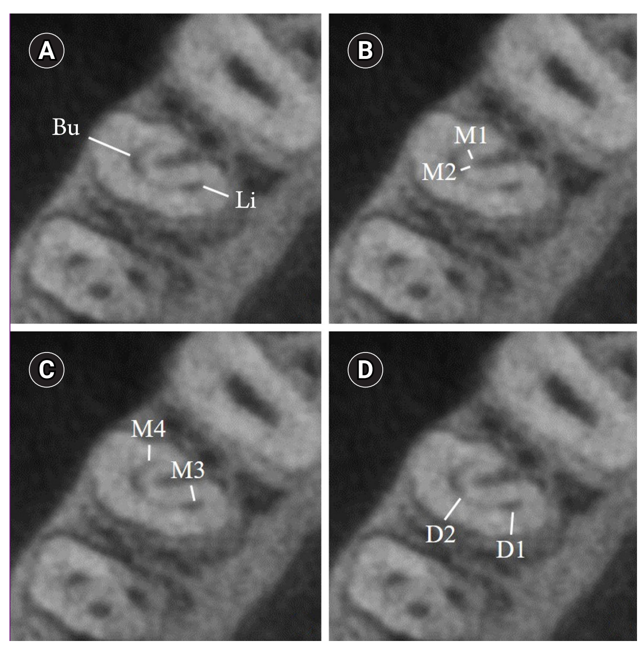

Figure 3. Axial cone-beam computed tomography images showing (A) the root dentin thickness measurements of buccal (Bu) and lingual (Li) walls, (B) mesial and distal ends of the buccal canal facing the radicular groove (M1, M2), (C) between mesial ends of lingual and buccal canals and the external mesial root surface (M3, M4) and (D) between distal ends of lingual and buccal canals and external distal root surface (D1, D2).

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and (6) distal end of the buccal canal and the external distal root surface (D2) (Figure 3) [12].

Two investigators performed the measurements separately, and the mean of their measurements was used for statistical analysis.

Analysis of variance and Kruskal-Wallis tests were used to compare the dentin thickness measurements of different dentin walls. The independent samples t-test was used to compare the dentin thickness measurements of the first and second premolars, and C-shape canal types (C1 and C2). For all groups, a p-value of <0.05 was considered significant.

RESULTS

Among 32 first premolars, C-shaped morphology was present at the coronal level of three teeth, at the middle level of 29 teeth, and at the apical level of 16 teeth. All nine second premolar teeth showed a C-shaped configuration at the middle level, and four of them also continued at the apical level. No C-shaped morphology was found at the coronal level of the second premolars. Both first and second premolars exhibited an external radicular groove on the mesiolingual surface of the root.

In general, mean dentin thicknesses for first premolars were listed as Bu, Li, D2, M4, M2, M1, D1, and M3 beginning from the thickest to thinnest at all three root levels. For the second premolars, the list was similar to the first premolars; however, M1 was the thinnest wall, followed by M3 and D1 at all root levels.

Root dentin thickness at coronal level

Table 2 shows the mean dentin thicknesses of C-shaped first and second premolars at the coronal, middle, and apical levels of the root. No difference was found between the mean dentin thicknesses of any walls at the coronal level of the first premolars ($p > 0.05$). Since no C-shaped morphology was found at the coronal level of the second premolars, no comparison could be made.

Root dentin thickness at middle level

At the middle level, the buccal wall was significantly thicker than all the other walls ($p < 0.05$), followed by the lingual and D2 walls for both the first and second premolars (Table 2). However, the lingual wall was significantly thicker than only M1, D1, and M3 for both premolars ($p < 0.05$). D1 and M3 walls were significantly thinner for both first and second premolars ($p < 0.05$). Although the mean thickness of the M3 wall was lower than that of the D1 wall, the difference was not significant for both premolars ($p > 0.05$).

At this root level, the MB1 wall was significantly thinner than the M2 and M4 walls for the first premolars ($p < 0.05$). However, the measurements done at the middle level of the second premolar roots showed that M1 was significantly thinner than D1 and M3 walls as well ($p < 0.05$).

The minimum wall thickness measured at the middle level was 0.63 mm for the first premolars and 0.54 mm for the second premolars.

Root dentin thickness at apical level

At the apical level of first premolars, the buccal wall was

Table 2. The root dentin thickness measurements of C-shaped first and second premolars at coronal, middle, and apical levels of root dentin

Premolar	Number of axial cross-sections (n)	Buccal	Lingual	Dentin thickness (mm)				D1	M3
				D2	M4	M2	M1		
First premolar									
Coronal third	3	1.51 ± 0.50	1.48 ± 0.75	1.25 ± 0.22	1.08 ± 0.18	0.91 ± 0.34	0.83 ± 0.34	0.80 ± 0.30	0.76 ± 0.30
Middle third	29	1.44 ± 0.24*	1.10 ± 0.25	1.02 ± 0.21	0.97 ± 0.22	0.95 ± 0.40	0.78 ± 0.32	0.75 ± 0.18*	0.63 ± 0.10*
Apical third	16	1.05 ± 0.25*	0.75 ± 0.23	0.72 ± 0.15	0.72 ± 0.27	0.62 ± 0.22	0.59 ± 0.20	0.56 ± 0.16*	0.47 ± 0.11*
Second premolar									
Coronal third	0	-	-	-	-	-	-	-	-
Middle third	9	1.37 ± 0.11*	1.20 ± 0.26	0.97 ± 0.20	0.96 ± 0.29	0.86 ± 0.35	0.54 ± 0.19*	0.75± 0.18*	0.72 ± 0.23*
Apical third	4	0.83 ± 0.24	0.72 ± 0.22	0.68 ± 0.25	0.60 ± 0.08	0.37 ± 0.20	0.36 ± 0.25	0.56 ± 0.21	0.54 ± 0.36

Values are presented as number only or mean ± standard deviation.
*Statistically significant ($p < 0.05$).

significantly thicker than the other walls ($p < 0.05$). The thicknesses of the M3 and D1 walls were significantly lower than all the other walls ($p < 0.05$); however, the difference was not significant for M1, M2, and M4 ($p > 0.05$). Although the mean thickness of the M3 wall was lower than that of the D1 wall, the difference was not significant ($p > 0.05$).

The minimum dentin thickness measurement at the apical level was 0.47 mm for the first premolars and 0.36 mm for the second premolars. The mean dentin thicknesses of the M3 wall for the first premolars and M1 and M2 walls for the second premolars were below 0.5 mm at the apical level.

Comparison of the first and second premolars for root dentin thickness

No C-shaped morphology was observed at the coronal level of second premolars; therefore, no comparison could be made between the measurements of the two premolars at this root level. Regarding middle level, the M1 wall was significantly thinner in the second premolars ($p = 0.04$). No difference was observed between dentin thicknesses of the first and second premolars at the apical level ($p > 0.05$).

Comparison of the first and second premolars for root dentin thickness of C1- and C2-type canals

The mean dentin thicknesses of the C1- and C2-shaped first premolars are presented in Table 3. Among 32 C-shaped first premolars, six canals exhibited C1-type and 26 canals showed C2-type canal configuration (Figure 4A and D, 4B and E). The buccal wall was the thickest, followed by L and D2 walls at all levels of C1- and C2-type premolar roots; however, the difference was significant only at middle and apical levels of the C2-type first premolars ($p < 0.05$). At the apical level, the M1 and M3 walls of C1-type first premolars were thinner than those of C2-type first premolars ($p = 0.036$ and $p =$

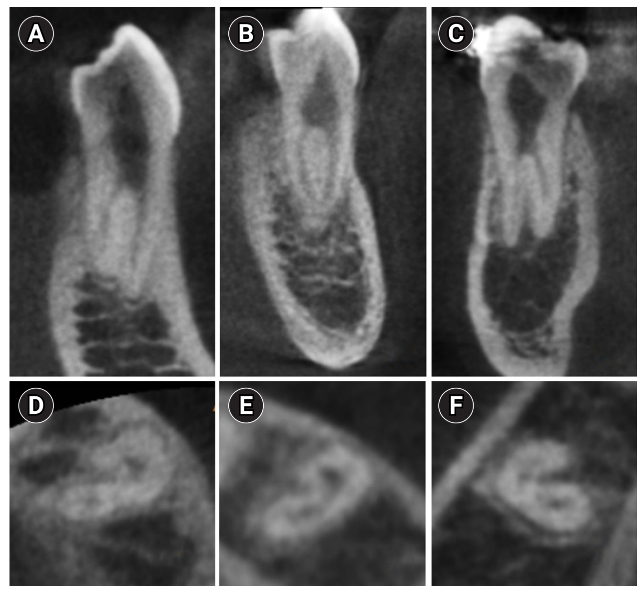

Figure 4. Cone-beam computed tomography (CBCT) images depicting the most prevalent C-shaped canal configurations in mandibular first and second premolars. Coronal and axial CBCT images showing (A, D) mandibular first premolar with a C2-type canal configuration, (B, E) mandibular first premolar with a C1-type canal configuration, and (C, F) mandibular second premolar with a C2-type canal configuration.

Table 3. The root dentin thickness measurements of C1 and C2-shaped first premolars

Premolar	Number of axial cross-sections (*n*)	Mean dentin thickness (mm)							
		Buccal	Lingual	M1	M2	M3	M4	D1	D2
C1-shaped first premolar									
Coronal third	1	1.55	1.55	0.60	0.65	0.60	0.95	1.00	1.05
Middle third	6	1.25 ± 0.15*	1.13 ± 0.14	0.72 ± 0.14	0.82 ± 0.29	0.57 ± 0.08	0.82 ± 0.21	0.65 ± 0.10	0.96 ± 0.09
Apical third	6	0.83 ± 0.15*	0.79 ± 0.30	0.46 ± 0.16*	0.51 ± 0.08	0.39 ± 0.10*	0.58 ± 0.24	0.48 ± 0.19	0.67 ± 0.20
C2-shaped first premolar									
Coronal third	2	1.50 ± 0.70	1.45 ± 1.06	0.90 ± 0.42	1.05 ± 0.35	1.00 ± 0.28	1.15 ± 0.21	0.90 ± 0.42	1.35 ± 0.21
Middle third	26	1.48 ± 0.24*	1.09 ± 0.27	0.80 ± 0.35	0.97 ± 0.42	0.64 ± 0.10	1.01 ± 0.21	0.77 ± 0.18	1.03 ± 0.23
Apical third	10	1.17 ± 0.21*	0.73 ± 0.19	0.68 ± 0.18*	0.69 ± 0.26	0.53 ± 0.09*	0.81 ± 0.26	0.61 ± 0.12	0.75 ± 0.12

Values are presented as number only, mean only, or mean ± standard deviation.
*Statistically significant ($p < 0.05$).

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0.02, respectively). Since all of the nine second premolars showed only C2 canal configuration (Figure 4C and F), no further comparison could be done.

DISCUSSION

The C-shaped canal morphology is a challenging anatomical variation associated dominantly with mandibular second molars. However, it can be seen in mandibular premolar and maxillary molar teeth as well [8,17]. Although few studies have investigated the C-shaped canal morphology in premolar teeth, it has been generally accepted that the C-shaped configuration has a lower prevalence in mandibular premolars as compared to mandibular molar teeth. Yet, similar anatomical characteristics were reported [5,7]. A longitudinal radicular groove on the external root surface, which is associated with the presence of C-shaped canal anatomy, is a common feature in both C-shaped mandibular molar and premolar teeth [4,7]. It is acknowledged that the proximity of C-shaped canals to radicular grooves, as well as the increase in the depth of the groove, creates danger zones resulting in decreased thickness in dentin walls of the root canal, creating a higher risk for stripping perforation [18,19]. Therefore, knowledge of the minimum thickness of dentin walls close to the radicular groove is critical to avoid complications and failures during endodontic instrumentation.

The C-shaped canal morphology, including the structural features of danger zones, has been extensively evaluated in maxillary and mandibular molars [20,21] and maxillary premolars [22,23]. On the other hand, there are only a couple of studies that have evaluated the prevalence and morphology of C-shaped canals in mandibular first and second premolar teeth [8–10]. However, to our knowledge, the presence of danger zones, in other words, the assessment of root dentin thickness in C-shaped mandibular first premolars, has been rarely studied [12–14], and no study has investigated the root dentin thickness in C-shaped mandibular second premolars. Furthermore, all of the above-mentioned studies have used micro-computed tomography (micro-CT) and ex vivo methodology for the evaluation of C-shaped canals. Therefore, the present study is the first to evaluate the root dentin thicknesses of C-shaped second premolar teeth along with the first premolars using clinical CBCT images.

According to the results obtained, the cross-sectional morphology of the root canals of mandibular premolar teeth showed a wide range of anatomical variations from the coronal to the apical root level. According to the results, C-shaped morphology was rarely observed in the coronal level of first premolars and not seen at the coronal level of second premolars. C2 was predominant in the middle and apical root levels of both first and second premolars. These findings suggest complex canal morphology in C-shaped premolars is compelling for clinicians both from a diagnostic and practical perspective. Anatomically complex canals or additional root canals in mandibular premolar teeth may be easily overlooked in periapical radiographs. Moreover, the C-shaped canals cannot be easily detected with two-dimensional images [24]. Even though the sudden narrowing of the root canal and a change in density as well as taurodont appearance [25] resulting from the deeply placed pulp chamber [26] in periapical images give a clue about the canal bifurcation (groove) signaling a thin root dentin, definitive diagnosis of C-shaped canal and details regarding morphology requires three-dimensional imaging [27]. In this context, CBCT is the primary three-dimensional imaging method widely recommended for the diagnosis of anatomically complex root canal systems since the clinical use of micro-CT is not suitable [28]. However, it should be noted that, as used in the present study, only high-resolution images with sub-millimeter spatial resolution obtained with a limited FOV are applicable for the detection of C-shaped canals and for the accuracy of measurement of dentin wall thicknesses.

Our results revealed that the thinnest dentin wall in the first premolars was M3, while it was M1 wall for the second premolar teeth. This finding supports the previous results that all C-shaped premolars had an external radicular groove in the mesiolingual position, and the minimum dentin thickness was dominantly found at the mesial walls in the middle and apical root thirds [12,14]. Similar to the presented findings, previous studies have demonstrated that D1 and M3 walls were significantly thinner than the other dentin walls for the C-shaped mandibular first premolars and that the mesial wall was significantly thinner than the distal wall at the middle and apical thirds of C-shaped first premolars [12,14]. This finding is also valid for second premolar teeth however, no significant difference was found between dentin thicknesses of M3 and D1 walls at the apical third of C-shaped second premolars. The discrepancy in the results may be due to the use of different classification methods for C-shaped canals, as well as due to the quality of the images used to evaluate C-shaped morphology and measure dentin thicknesses. Many previous studies have demonstrated that the spatial resolution of the images has a significant impact on measurement accuracy [29–31].

In accordance with previous findings, the presented results revealed that danger zones for mandibular first premolars are D1 and M3 walls [13]. Given the low prevalence of C-shaped morphology in premolar teeth [10,16], no studies can be found in the literature that have investigated the root dentin thickness of mandibular second premolars. Our findings revealed that in addition to the D1 and M3 walls, dentin thicknesses of M1 and M2 walls were thinner than 0.5 mm and therefore present high potential danger zones for mandibular second premolars at the apical root third. Even though the sample size of C-shaped second premolars was low in this study, our findings provide important information regarding the complex morphology of C-shaped canals and the thinness of M1, M2, M3, and D1 walls of mandibular second premolars. Although more studies with higher sample sizes are required to support these findings, it is still possible to recommend meticulous choice of endodontic instrument type and use of advanced equipment such as operating microscopes and dental loupes to sufficiently visualize and locate root canals with complex anatomy and avoid perforation in these thin dentin zones of second premolars. It may be advisable to further recommend the use of conservative shaping methods, meticulous irrigation, and warm gutta-percha obturation techniques during endodontic treatment of C-shaped premolar teeth [32–34].

According to the classification of Fan *et al.* [7], C1 and C2 were the most common C-shaped canal configurations often observed at the middle and apical levels. Using Fan's classification, Gu *et al.* [12] did not find any difference in root dentin thicknesses of C1 and C2 canal configurations. Contrary to this finding, we demonstrated a significant difference in dentin thicknesses of M1 and M3 walls at the apical level of C2-shaped first premolars. This finding is important considering that the C-shaped canal in mandibular premolar teeth may not continue as a single C-shaped form from the CEJ up to the apex [7,25]. In this case, C-shaped morphology may go easily undetected and may create an increased risk of stripping perforation, inadequate irrigation and disinfection, and accordingly, incomplete obturation, which may all lead to endodontic treatment failure.

The mean dentin thickness of C-shaped canals was reported to range from 0.25 to 0.66 mm in the apical and middle portions of the root [35]. In our study, these values varied from 0.36 mm to 1.44 mm for the same regions. As these measurements have been done before root canal instrumentation, one can expect that the root canals would be thinner, particularly in apical regions, after instrumentation. If conservative techniques such as anti-curvature filing and rotary instrumentation with low tapers are not employed, excessive dentin may be removed, causing complications from ledge formation to perforation [36–38]. In addition, root canal filling of C-shaped teeth also poses a problem. It has been speculated that compaction forces during obturation can exceed the resistance of the root canal wall when the remaining thickness of dentin is 0.2 to 0.3 mm after instrumentation [39]. This may inevitably cause a root fracture. Therefore, warm gutta-percha techniques instead of cold lateral compaction will be safer and more suitable for the three-dimensional filling of C-shaped root canals [38,40].

CONCLUSIONS

The findings suggest that C-shaped canals in mandibular first and second premolars were predominantly found in the middle third of the root. In general, while the buccal and lingual dentin walls were the thickest, the mesial dentin walls facing the external radicular groove were the thinnest. The results revealed that potential danger zones for C-shaped mandibular first and second premolars are predominantly the mesial and distal walls of the lingual canal. However, the mesial walls of buccal canal facing the external radicular groove were extreme-

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ly thin at the apical root third of second premolar teeth, demonstrating additional danger zones.

Clinicians should be aware of this variation in dentin thicknesses of C-shaped root canals in mandibular premolars. CBCT imaging and further precautions are recommended to avoid complications during endodontic treatment of C-shaped root canals of mandibular premolar teeth.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Supervision: Sen BH, Baksi BG. Data curation: Aslan E, Ulusoy AC. Investigation: Aslan E, Ulusoy AC, Onem E. Formal analysis: Mert A. Writing - original draft: Aslan E, Ulusoy AC. Writing - review & editing: Sen BH, Baksi BG, Onem E. All authors read and approved the final manuscript.

DATA SHARING STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Impact of post adhesion on stress distribution: an *in silico* study

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ABSTRACT

Objectives: This study aimed to evaluate the stress distribution in teeth restored with different post materials and bonding conditions using finite element analysis (FEA).
Methods: A two-dimensional FEA model of a maxillary central incisor restored with IPS-Empress-2 crown (Ivoclar Vivadent), composite resin core, and posts were created. The model simulated bonded and non-bonded conditions for both fiber-reinforced composite (FRC) and titanium (Ti) posts. Stress distribution was analyzed using ANSYS 14.0 software under a 100-N load applied at a 45° angle to the long axis of the tooth.
Results: The results revealed that stress concentration was significantly higher in non-bonded posts compared to bonded ones. FRC posts exhibited stress values closer to those of dentin, whereas Ti posts demonstrated higher stress concentration, particularly in non-bonded states, increasing the potential risk of damage to surrounding tissues.
Conclusions: FRC posts, with elastic properties similar to dentin and proper adhesion, minimize stress concentration and potential damage to surrounding tissues. Conversely, materials with higher elastic modulus like Ti, can cause unfavorable stress concentrations if not properly bonded, emphasizing the importance of post adhesion in tooth restoration.

Keywords: Dental materials; Finite element analysis; Post; Stress; Titanium

INTRODUCTION

Endodontically treated teeth are generally considered mechanically compromised due to the loss of dental tissue resulting from caries, previous restorations, crown fractures, and the access cavity preparation for root canal treatment. The reduction in dentin moisture content and structural integrity further decreases their fracture resistance [1]. Consequently, such teeth require additional restorative interventions, ranging from direct composite resin restorations and onlays to full-coverage crowns, depending on the extent of tissue loss. In cases where substantial coronal destruction compromises retention and resistance, a post is inserted into the root

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canal to serve as a core substitute, subsequently supporting the final restoration [2].

Posts are available in various materials, shapes, and dimensions, broadly categorized into prefabricated and cast posts [2,3]. Prefabricated posts are advantageous in terms of time efficiency and cost-effectiveness; however, they may exhibit interfacial gaps or bubbles between the post and core material, and their adaptability to the canal morphology is limited. In contrast, cast posts, fabricated as a single unit with the core, offer superior adaptation but necessitate additional clinical visits and laboratory procedures.

The reinforcement effect of post placement in endodontically treated teeth remains a subject of debate [4–6]. Some studies have reported that posts reduce stress within dentin, while others have suggested that they increase the risk of root fractures [7,8]. Finite element analysis (FEA) and experimental studies have provided conflicting findings, with evidence indicating that posts do not significantly enhance the strength of root dentin under static or fatigue conditions [7,8].

Post materials vary from metals to fiber-reinforced composites (FRC), each exhibiting distinct mechanical properties. Materials with a high elastic modulus, such as titanium (Ti) and zirconia, efficiently withstand applied forces but may induce stress concentration within the root structure due to their rigidity [9]. Duret *et al.* [10] proposed that the ideal post should possess an elastic modulus similar to dentin, advocating for carbon fiber posts due to their comparable mechanical behavior (elastic modulus, 21 GPa vs. dentin, 18 GPa). Similarly, FRC posts have been shown to distribute stress more evenly, reducing the risk of catastrophic root fractures [3,11]. In contrast, metal posts, including Ti, stainless steel, and zirconia, exhibit significantly higher elastic moduli, leading to increased apical stress concentration and a greater likelihood of unfavorable root fractures [11–15].

Initially, post retention relied on mechanical retention, but due to the associated risk of root fractures, adhesive bonding techniques have become the preferred approach [2]. Zinc phosphate and polycarboxylate cements, which offer inadequate adhesion to both dentin and posts, have largely been replaced by resin cements. Resin cements demonstrate superior adhesion, particularly when used with FRC posts, and have been associated with improved long-term survival rates in clinical practice [16].

Post retention is influenced by multiple factors, including post material, shape, surface texture, thickness, length, and adhesion to the luting cement [17–19]. Among these, post length is particularly critical, with various studies recommending it be at least equal to the crown length, extend to at least two-thirds of the root length, or reach at least the midpoint between the alveolar crest and the root apex [2,14,20–22]. Unlike metal posts, FRC posts achieve retention through adhesion with resin cement. The effectiveness of this bond is determined by the resin cement type, post surface treatment, and the bonding protocol used [23–26].

The present study aims to evaluate stress distribution variations between bonded and non-bonded conditions of FRC and Ti posts under identical loading conditions using FEA. In clinical practice, Ti posts are typically used in a non-bonded state, relying on mechanical retention. In contrast, FRC posts benefit from adhesive bonding, which enhances retention and stress distribution within the root canal. This fundamental difference between FRC and Ti posts allows for a direct comparison of their mechanical behavior under bonded and non-bonded conditions. By analyzing the impact of post adhesion, this study seeks to provide insights into the biomechanical behavior of different post systems. We hypothesize that bonded post conditions will result in lower stress concentrations compared to non-bonded conditions, regardless of post material.

To the best of our knowledge, no studies have separately evaluated the stress distribution within the post itself and in the surrounding dentin under both bonded and non-bonded conditions. Most FEA studies focus on overall stress patterns without distinguishing between stresses concentrated in the post and those affecting the dentin structure. However, in clinical practice, stress distribution in these two areas can differ significantly, influencing the long-term prognosis of post-retained restorations. Most previous FEA studies have assumed complete bonding between the post and dentin, which does not fully represent clinical reality. Metal posts, such as Ti, cannot achieve adhesion, whereas FRC posts rely on adhesive bonding, which serves as a sig-

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nificant advantage in clinical applications. However, the implications of this difference in bonding on stress distribution remain insufficiently explored. Therefore, this study addresses this gap by comparing bonded and non-bonded states for both Ti and FRC posts, providing clinically relevant insights into their stress behavior and implications for long-term success. Furthermore, by analyzing stress distribution separately in both the post and dentin, this study provides a more detailed understanding of how bonding conditions influence mechanical behavior. This differentiation is crucial, as non-bonded conditions can lead to localized stress accumulation in the post or dentin, potentially affecting clinical outcomes.

METHODS

Design and materials of the finite element model

Based on the human maxillary central incisors, a two-dimensional (2D) tooth model was created by sectioning buccolingually. After removing the coronal portion, the crown was reconstructed with a post, core, and a 2 mm thick IPS-Empress-2 ceramic (Ivoclar Vivadent, Schaan, Liechtenstein) crown (Figure 1A). The total length of the tooth was set to 23 mm, the diameter of the post to 1.4 mm, and the total length of the post to 13 mm, based on previous studies that utilized the same anatomical dimensions for FEA of maxillary central incisors in post-retained restorations [27,28]. The exposed post above the root was fixed at 1.6 mm, with 11.4 mm of the post embedded in the root, and 4 mm of gutta-percha. The embedded post was subjected to bonded or non-bonded conditions with core composite, dentin, and gutta-percha. The dimensions of the tooth model, including the 1.4 mm post diameter and 2 mm crown thickness, are shown in Figure 1B. The IPS-Empress-2 ceramic crown was modeled with a total thickness of 2 mm, comprising 0.8 mm inner thickness and 1.2 mm outer thickness. Both Ti posts and FRC posts were used, and the core was modeled with core composite resin. The FRC post used in this study was the D.T. Light-Post (BISCO Inc., Schaumburg, USA), and its material properties were obtained directly from the manufacturer. The Ti post used in this study was the ParaPost XH Titanium Post (Coltène/Whaledent Inc., Cuyahoga Falls, OH, USA), and its mechanical properties were referenced from a previous study [27]. Ti posts were included in this study as a positive control due to their significantly higher elastic modulus compared to dentin and their typical use in a non-bonded state [11,27,28]. This allows for a clearer evaluation of the effect of post adhesion by providing a distinct contrast with FRC posts. The material properties of the designed 2D model, including the elastic modulus (E) and Poisson's ratio (υ), are shown in Table 1 [27–29].

The mesh generation, boundary conditions, and load-

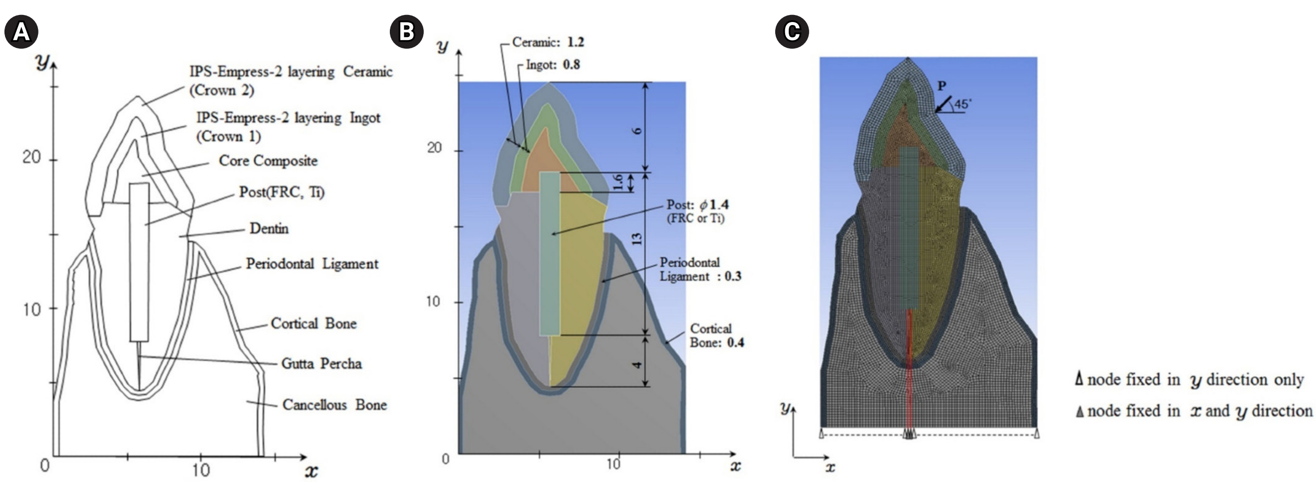

Figure 1. Materials and finite element model design for tooth restoration analysis. (A) Materials involved in the investigated model. (B) Dimensions of the investigated model of a tooth restored with a cylindrical post and IPS-Empress-2 crown. (C) Finite element model for analysis. FRC, fiber-reinforced composite; Ti, titanium. IPS-Empress-2: Ivoclar Vivadent, Schaan, Liechtenstein.

ing directions for the 2D FEA model of this study are shown in Figure 1C. The number of elements and nodes for each material in the entire model used for analysis is listed in Table 2. Each element was modeled as a 4-node quadrilateral element with incompatible nodes under plain strain conditions using Auto Mesh function of ANSYS Workbench ver. 14.0 (ANSYS Inc., Canonsburg, PA, USA) .

Finite element analysis and boundary conditions

A finite element model was created based on measurements of an extracted maxillary central incisor fully restored with a ceramic crown, composite resin core, and cylindrical posts (either Ti or FRC). Figure 1C shows the mesh generation and boundary conditions of the 2D finite element model. For the boundary conditions of the analysis, the nodes along the x-axis at the bottom of the cancellous bone were fixed either in the y-direction or in both the x- and y-directions. The nodes in the same length portion as the upper part of the gutta-percha were fixed in both x- and y-axes, while the remaining nodes were fixed only in the y-axis direction. These boundary conditions were established following previous studies on FEA of post-retained teeth, which analyzed the effects of different post designs and loading directions on stress distribution in root and periodontal structures. Additionally, the general principles for defining boundary conditions in finite element modeling were applied based on established computational biomechanics guidelines [29,30]. A load of 100 N (≈10 kg) was applied at a 45° angle to the long axis of the tooth on the concave central lingual surface (right side of the model). The analysis was performed using the commercial software ANSYS 14.0. The analysis was conducted for two types of posts, Ti and FRC, each with a diameter of ϕ1.4 mm and a total length of 13 mm. In all cases, 1.6 mm of the post was embedded and fixed in the core, with the remaining portion of 11.4 mm implanted in the dentin part of the root. The core, dentin, and gutta-percha in contact with the posts were analyzed under bonded and non-bonded conditions for both Ti and FRC posts. However, Ti posts are generally used in a non-bonded state in practice, so the analysis was conducted under both fully bonded and

Table 2. Number of elements on used meshes

Material	Number of elements	Number of nodes
Crown		
Ceramic	638	2,125
Ingot	617	2,062
Core composite	505	1,650
Dentin	3,730	11,692
Post (FRC, titanium)	950	3,061
Ligament	603	2,214
Cortical bone	1,396	5,109
Gutta-percha	33	158
Cancellous bone	3,645	11,306
Total elements	12,117	

FRC, fiber-reinforced composite.

Table 1. Material properties used in Finite element models

Material	Young's modulus (E) (MPa)	Poisson's ratio (υ)	Note
Crown	100,000	0.25	
IPS-Empress-2 layering ceramic [28]	65,000	0.19	
IPS-Empress-2 layering ingot [28]	12,000	0.30	
Core composite [27]	18,600	0.31	
Dentin [29]			
Post	112,000	0.33	Bonded or non-bonded
Titanium [27]	15,000	0.29	
FRC	68.9	0.45	
Periodontal ligament [29]	13,700	0.30	
Cortical bone [29]	0.69	0.45	
Gutta-percha [29]	1,370	0.30	
Cancellous bone [29]			

FRC, fiber-reinforced composite.
IPS-Empress-2: Ivoclar Vivadent, Schaan, Liechtenstein. FRC: D.T. Light-Post, BISCO Inc., Schaumburg, IL, USA (information given by the manufacturers).

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non-bonded assumptions. For FRC posts, although they are initially bonded during implantation, continuous repeated loading during use can lead to partial or complete non-bonding. Therefore, analyses were performed under both fully bonded and non-bonded assumptions.

Based on the boundary conditions, the analysis was performed under single compressive loading conditions by applying loads. The stress distribution of maximum principal stress for each material was analyzed to understand stress concentration and characteristics. Finally, by examining the stress concentration in posts and dentin under bonded and non-bonded conditions of different post materials, the characteristics based on the material and bonding conditions were identified. The analysis was conducted using the FEA tool ANSYS 14.0 Workbench under plane strain conditions for a 2D analysis.

RESULTS

In a model sectioned parallel to the tooth's long axis, the applied load of 100 N (≈10 kg) at a 45° angle to the long axis at the central part of the lingual surface was analyzed for stress distribution using FRC and Ti posts, both with a length of 11.4 mm implanted in the root and a total length of 13 mm. The maximum principal stress distribution patterns were analyzed to confirm stress concentration and distribution trends under bonded and non-bonded conditions with surrounding materials.

The maximum principal stress values for the entire model, dentin, posts, and core composite under load, applied at the central concave part of the lingual surface at a 45° angle to the x-axis, are shown in Table 3. In all four conditions (bonded and non-bonded states for FRC and Ti posts), the maximum stress values in the entire model were similar, with slightly higher values in non-bonded conditions. This trend was also observed in the dentin.

However, in posts, the maximum stress concentration values in non-bonded states were significantly higher than in bonded states for both post materials. The FRC posts showed about a 27-fold increase, while the Ti posts showed about a 14-fold increase, indicating a significant increase in stress concentration in FRC posts. This is because the strength of FRC posts is approximately one-sixth that of Ti posts. Both FRC and Ti posts in bonded conditions and FRC posts in non-bonded conditions exhibited high stress concentration values in the dentin. In contrast, Ti posts in non-bonded conditions showed higher stress concentration values in the posts.

The stress distribution patterns under different bonding conditions for FRC and Ti posts are presented in Figure 2. The maximum principal stress was concentrated at the upper outer dentin near the contact area with the ceramic. A force applied at a 45° angle to the long axis is similar to a bending force. The slightly higher maximum value of the FRC posts compared to the Ti posts is attributed to the stronger material properties of the Ti posts under bending loads.

The stress concentration in posts and dentin under bonded and non-bonded conditions is illustrated in Figure 3. Only the non-bonded Ti post showed maximum stress concentration at the upper buccal corner, while the other three conditions showed stress concentration at the upper outer dentin (Figure 3D). The maximum stress concentration values in dentin were similar under bonded and non-bonded conditions, with slightly higher values in non-bonded states. Both post materials

Table 3. Maximum of von Mises stress in all body, dentin, post, and crown under load

Variable	Maximum principal stress (MPa)			
	FRC		Titanium	
	Bonded	Non-bonded	Bonded	Non-bonded
All body	996.90	1,043.60	986.74	1,019.70
Post	14.797	399.60	46.01	666.64
Dentin	429.91	438.89	426.06	431.03
Core composite	15.67	203.39	14.06	196.82

FRC, fiber-reinforced composite.

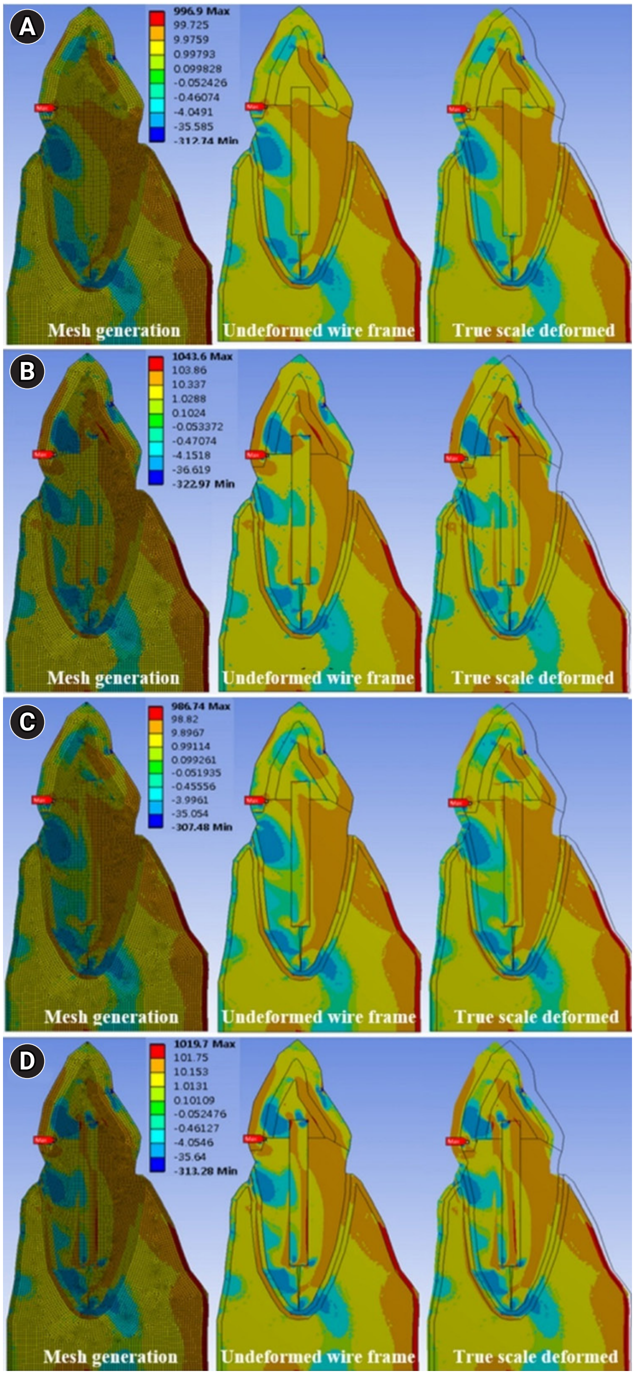

Figure 2. Maximum principal stress distribution across the tooth model under load conditions. (A) Maximum stress of tooth model with bonded fiber-reinforced composite (FRC) post under load. (B) Maximum stress of tooth model with non-bonded FRC post under load. (C) Maximum stress of tooth model with bonded titanium (Ti) post under load. (D) Maximum stress of tooth model with non-bonded Ti post under load.

showed increased stress concentration in posts and dentin under non-bonded conditions. Non-bonded FRC posts showed lower stress concentration values than dentin, while non-bonded Ti posts showed 1.6 times higher stress concentration values than dentin, with significant stress at the edges in contact with dentin. This indicates that non-bonded posts have reduced resistance to bending loads, leading to increased stress concentration in the posts and surrounding materials.

Stress concentration was observed in the lingual cancellous bone and dentin area, with stress also concentrated at the lingual dentin and post areas. In non-bonded states, stress was concentrated at the upper and lower ends of the post, and at the upper lingual dentin edge in contact with the post. Stress concentration was mainly in the lingual dentin, not the posts. FRC posts showed maximum stress values in dentin 36 times higher than in posts, while Ti posts showed 13 times higher stress values in dentin, with a three-fold greater increase in FRC posts than Ti posts.

Figure 4 shows the detailed stress distribution in the core composite, post, and dentin under bonded and non-bonded conditions. Bonded posts had lower stress concentration values than dentin, while non-bonded posts showed significantly higher stress concentration than bonded states (Figure 4B). Bonded FRC posts showed maximum stress concentration at the right edge in contact with dentin and core, while non-bonded FRC posts showed maximum stress concentration at the upper buccal edge and high stress at the boundary with dentin. Ti posts showed stress concentration at the lower part and upper contact edges, with maximum stress concentration at the lower buccal edge in bonded states and upper buccal edge in non-bonded states. Under load, non-bonded posts showed several-fold increases in maximum stress concentration values, with more complex stress distribution. Posts may transition from bonded to non-bonded states under repeated loads, leading to increased stress concentration and potential damage to surrounding tissues, emphasizing the importance of post adhesion in tooth restoration.

Figure 4C shows stress distribution in dentin under bonded and non-bonded conditions, with similar patterns and slightly higher stress concentration values in non-bonded states, concentrated at the upper buccal

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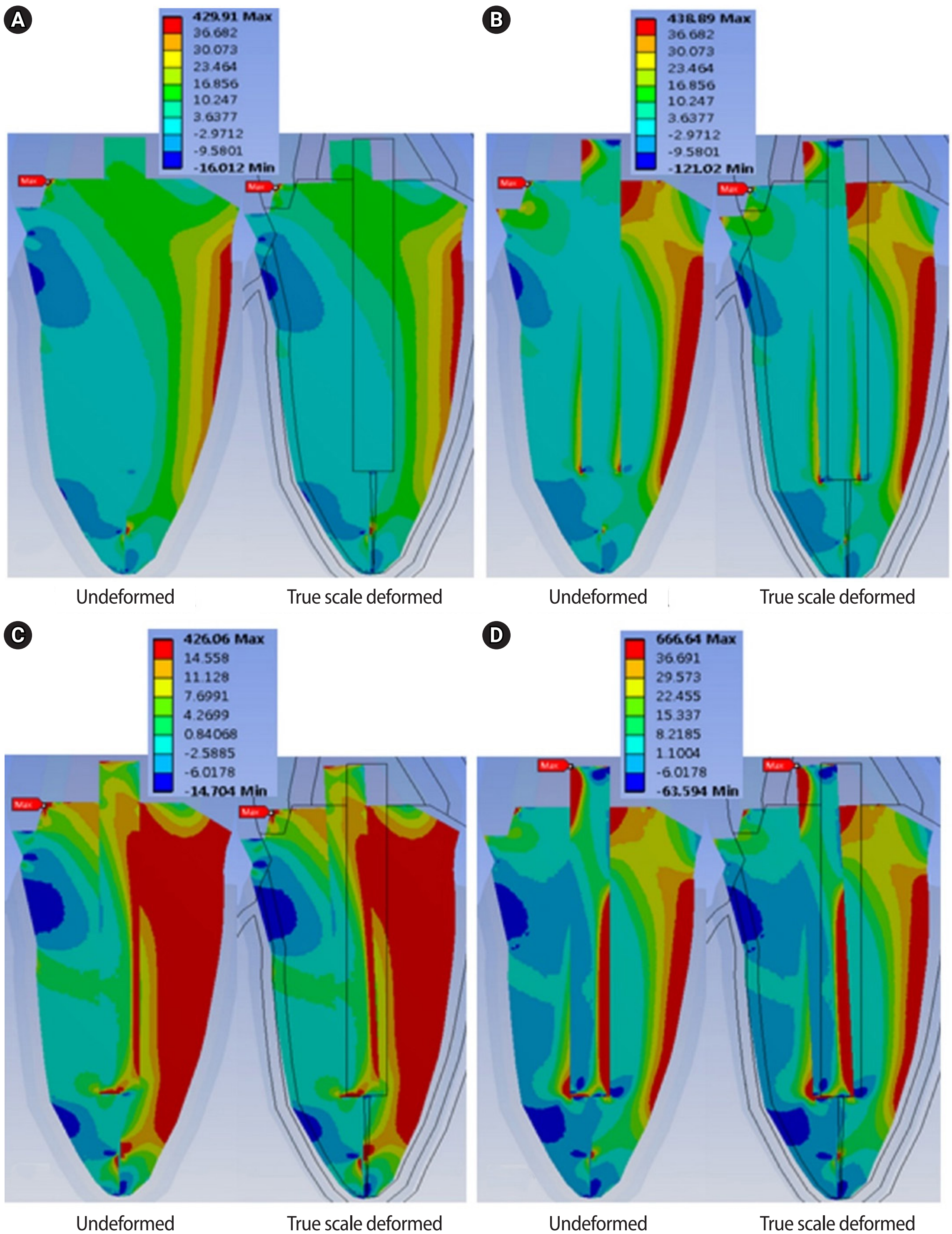

Figure 3. Maximum stress distribution of maximum principal stress in post and dentin of tooth model under load: (A) bonded fiber-reinforced composite (FRC), (B) non-bonded FRC, (C) bonded titanium (Ti), and (D) non-bonded Ti.

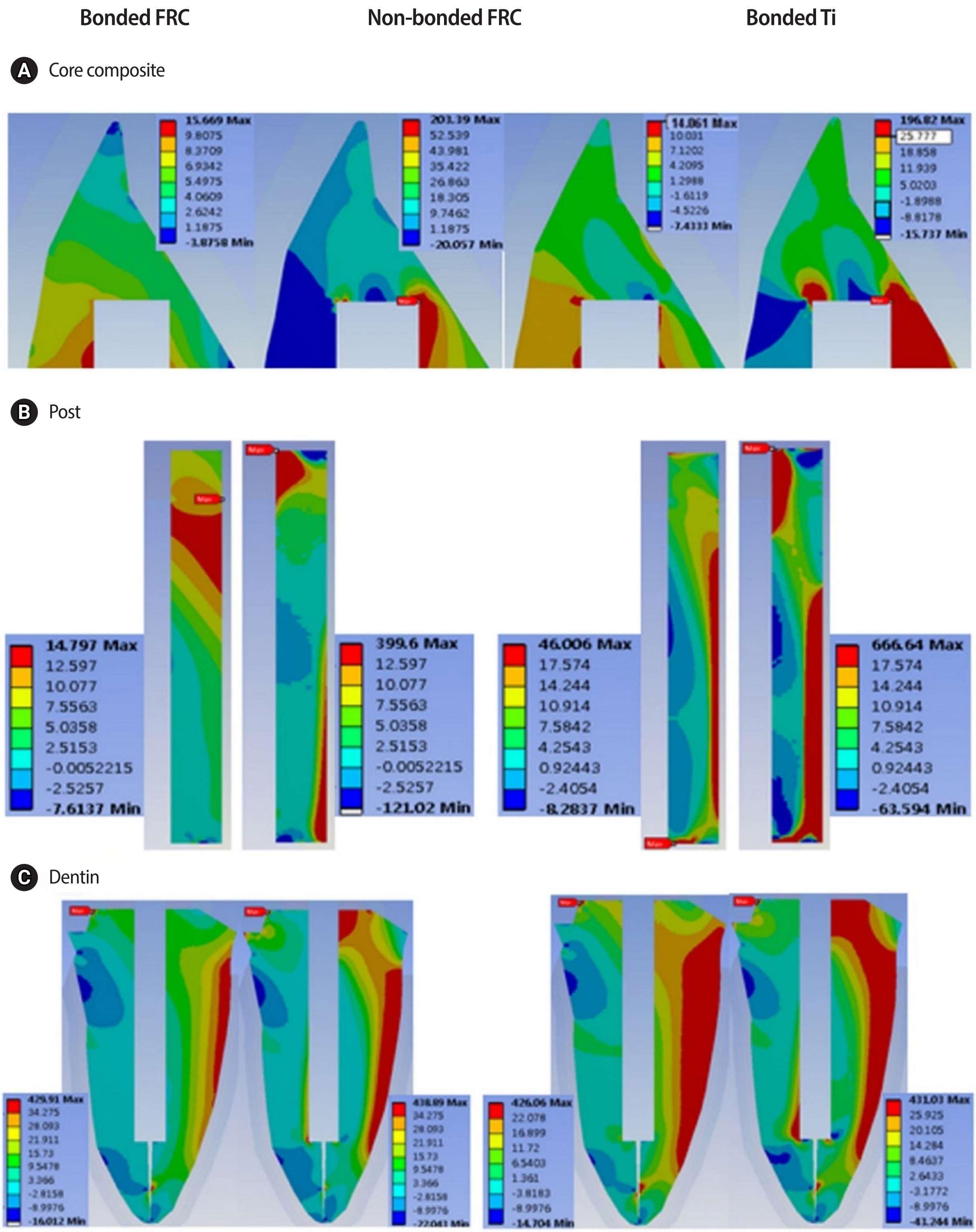

Figure 4. Maximum stress distribution of maximum principal stress in tooth model under load: (A) core composite, (B) post, and (C) dentin. FRC, fiber-reinforced composite; Ti, titanium.

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corner. Non-bonded conditions also showed stress concentration at the dentin in contact with the post lower edges, indicating the potential for internal fractures due to stress concentration.

Figure 4A shows the maximum principal stress distribution in the core composite. Bonded FRC posts showed stress concentration away from post contact areas, while non-bonded conditions in both posts showed stress concentration at the upper post and lower core edges, significantly increasing stress concentration values by 13-fold in non-bonded states. This highlights the importance of effective load distribution in bonded states to prevent stress concentration and potential tooth damage.

DISCUSSION

This study employed a 2D FEA method that provides easily interpretable results compared to three-dimensional (3D) FEA and excluded the cement layer between the root dentin and the post. While 3D models offer a more comprehensive simulation of complex anatomical structures and occlusal forces, they require significantly higher computational resources and more complex meshing processes. In contrast, 2D FEA allows for efficient analysis with well-controlled boundary conditions and has been widely used in previous studies for evaluating stress distribution in post-retained restorations [27–30]. Although the 2D model has limitations in fully replicating the 3D biomechanical behavior of teeth and surrounding tissues, it is a widely accepted approach for comparative stress analysis and remains a valuable tool for preliminary evaluations in dental biomechanics research. This is because the elastic modulus of resin cement is not significantly higher than that of dentin, and there is limited information on the thickness of the cement layer encountered in clinical practice.

Posts used clinically are made from various materials, including gold alloys, Ti, stainless steel, ceramics, zirconia, and FRC. FRC posts are manufactured by embedding carbon fibers, quartz, or glass fibers in epoxy resin or methacrylate resin [3,9]. The fibers are aligned parallel to the post's long axis, with diameters of 6 to 15 μm. The number of fibers in the post's cross-section varies by type, ranging from 25 to 30 fibers, occupying 30% to 50% of the area. Adhesion between the fibers and resin matrix is enhanced by silanization before embedding. Strong interfacial adhesion between fibers and the resin matrix allows stress transfer from the matrix to the fibers, essential for effective reinforcement properties [9,31].

Previous FEA studies related to stress distribution in posts did not consider different interface conditions, implying that both metal and FRC posts were bonded to the dentin. However, metal posts are not actually bonded to the cement, and FRC posts can become non-bonded over time due to increased fatigue stress. In this study, models of both bonded and non-bonded states of Ti and FRC posts were created and analyzed, considering actual usage conditions. Unlike previous studies, which assumed complete bonding of posts to the root, dentin, and composite resin core, this study accounted for the realistic conditions of usage [11]. Ti posts generally remain in a non-bonded state upon implantation, whereas FRC posts maintain a bonded state due to silanization. However, some may mistakenly believe that metal posts are bonded to surrounding tissues due to their excellent mechanical properties, expecting superior performance in use [9]. From an engineering perspective, repeated loading on a non-bonded contact state leads to fretting, which can damage surrounding tissues due to the post material's excellent mechanical properties [11]. FRC posts, despite being bonded initially, may also become non-bonded due to repeated masticatory loads and moisture absorption by the cement [24]. Therefore, it is necessary to predict potential non-bonding scenarios. Consequently, the analysis included not only the bonded and non-bonded states of the materials but also the opposite conditions.

Ti posts, regardless of bonding, cannot avoid stress concentration due to their higher elastic modulus compared to dentin. However, if Ti posts could be implanted in a bonded state, they might demonstrate better characteristics despite the unavoidable risk of root fractures from stress concentration. Practically, bonding Ti posts during implantation is difficult. Thus, higher stress concentration in the post than dentin during non-bonded state loads may increase the risk of surrounding tissue damage. Conversely, FRC posts, while showing increased maximum stress concentration in non-bonded states, exhibit stress concentration values similar to those of dentin in both bonded and non-bonded states. Despite the limitations of this study, our findings suggest that FRC posts may have less impact on surrounding tissue damage from stress concentration compared to metal posts.

Compared to bonded posts, non-bonded posts showed an increase in stress concentration. Our findings underscore the critical role of adhesion in stress distribution. Non-bonded posts exhibited significantly higher stress concentrations compared to bonded posts, particularly for Ti posts due to their high elastic modulus. This aligns with clinical observations where non-bonded posts increase the likelihood of mechanical failures such as root fractures [11,16,28]. While FRC posts maintained more favorable stress distributions even in non-bonded states, their adhesion degradation over time cannot be overlooked [3]. In clinical practice, adhesive failure is a significant concern for FRC posts due to moisture absorption and fatigue stress [23,24]. This highlights the necessity of robust bonding techniques and periodic assessment of bonded restorations. Future studies should explore the long-term effects of cyclic loading on adhesion degradation in FRC posts and investigate various materials or surface treatments to improve the durability of bonded restorations. Additionally, clinical trials comparing the failure modes and survival rates of bonded and non-bonded posts in various patient populations are necessary to validate these findings in real-world scenarios. Importantly, previous FEA studies assumed ideal bonding conditions, which do not align with clinical realities, particularly for metal posts. Our study, by incorporating both bonded and non-bonded scenarios, bridges this research gap and provides a more accurate representation of post-restored teeth under functional loads [11,16,23,29]. Additionally, Ti posts in non-bonded states exhibited higher stress concentration in the post compared to dentin under loads, whereas FRC posts showed lower values compared to dentin under loads. The load caused significantly greater stress concentration and impact on posts and surrounding tissues, especially in non-bonded states. FRC posts bonded to root canal dentin distributed stress uniformly to the dentin. While non-bonded FRC posts showed slight stress concentration at the post-dentin interface and root tip, the stress magnitude was not significantly higher than in dentin. This supports the conclusion of other studies that the primary failure cause of restorations with FRC posts is not root fracture but post non-bonding [11,12,23].

Therefore, ensuring the adhesion of FRC posts with resin cement to both the post and dentin is crucial for maintaining restorations. This includes proper surface treatment of the post, adhesion process, appropriate use of resin cement, and effective removal of gutta-percha, sealers, and other materials previously applied in the root canal during post hole preparation.

CONCLUSIONS

Considering all the limitations of this study, we can conclude that bonded FRC posts demonstrate a more favorable stress distribution compared to Ti posts, which exhibited higher stress concentration, particularly in non-bonded conditions. The results suggest that post adhesion plays a crucial role in minimizing mechanical complications and reducing the risk of surrounding tissue damage.

Furthermore, our findings emphasize the importance of selecting appropriate post materials and ensuring proper bonding techniques to improve long-term clinical outcomes. Clinicians should carefully consider the mechanical behavior of different post materials and the effects of bonding conditions when restoring endodontically treated teeth. Future studies with 3D models and *in vivo* validation are needed to further explore the biomechanical performance of post-retained restorations.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization: Hwang IN, Cho YT; Formal analysis: Cho YT; Investigation: Choi JY, Cho YT, Hwang IN; Methodology: Oh WM, Hwang YC; Visualization: Bae KB, Choi JY; Supervision: Lee BN, Chang HS, Hwang IN; Writing - original draft: Bae KB, Choi JY; Writing - review & editing: Bae KB, Hwang IN.

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All authors read and approved the final manuscript.

DATA SHARING STATEMENT

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. Requests for access to the data should include a clear description of the intended use and the conditions under which reuse is permitted.

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Cleaning protocols to enhance bond strength of fiberglass posts on root canals filled with bioceramic sealer: an *in vitro* comparative study

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ABSTRACT

Objectives: This study aimed to evaluate whether the agitation protocols using ultrasonic inserts or the XP-endo Finisher R file improved the removal of two different endodontic sealer remnants and the bond strength of fiberglass posts to dentin.

Methods: Seventy-two human teeth were selected. The canals were prepared with Reciproc 50 and Easy ProDesign 30/.10 and root filled according to the endodontic sealer groups: AH Plus or EndoSequence BC Sealer HiFlow. The samples were kept at 37ºC and 95% humidity for 28 days. During the post space preparation, the obturation was removed with Largo burs, and the groups were divided according to the irrigant agitation protocols ($n = 12$): no agitation, agitation with R1-Clearsonic associated with E1-Irrisonic ultrasonic inserts, or agitation with XP-endo Finisher R file. The fiberglass posts were cemented with RelyX ARC. The roots were sectioned into slices and submitted to the push-out test. Micro-computed tomography analysis was used to check the effectiveness of irrigating solution agitation in the elimination of remnants.

Results: The cleaning protocols with agitation were more effective in increasing the bond strength of posts to dentin for both sealer groups compared to non-agitation ($p < 0.05$). There was no difference between the same cleaning protocols for the different sealers. Among the different thirds, there was no statistical difference for the same sealer in the different cleaning protocols ($p > 0.05$).

Conclusions: Both agitation protocols effectively clean root-filled canals sealed with resin-based and calcium silicate-based sealers during fiberglass post space preparation. These protocols result in improved bond strength compared to non-agitation methods.

Keywords: Calcium silicate; Endodontics; Fiberglass; Root canal obturation

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INTRODUCTION

Endodontically treated teeth often exhibit significant coronal destruction, requiring intraradicular retainers before coronal reconstruction [1]. Fiberglass posts are widely used due to their esthetic properties and favorable mechanical characteristics, such as an elastic modulus (18 GPa) similar to dentin (20 GPa). Additionally, their translucency allows light transmission into the canal, enhancing resin cement polymerization [2].

However, the bond strength of fiberglass posts can be affected by the type of endodontic sealer used for root canal filling. Some studies suggest that bioceramic sealers may compromise adhesion, advising against their use when post placement is required [3–8]. Research consistently reports that canals filled with bioceramic sealers exhibit lower bond strength compared to those obturated with epoxy resin-based sealers. This reduced adhesion is attributed to the interaction between calcium ions released by bioceramic sealers and phosphate ions in dentin, leading to the formation of apatite crystals and tag-like structures [9–11]. These mineral precipitates obstruct dentinal tubules, making their removal challenging using conventional endodontic techniques [12].

EndoSequence BC Sealer HiFlow (Brasseler USA, Savannah, GA, USA) is a ready-to-use bioceramic sealer that, according to the manufacturer, has low viscosity and greater radiopacity compared to its predecessor, BC Sealer. AH Plus (Dentsply Maillefer, Ballaigues, Switzerland), on the other hand, is a well-established epoxy resin-based sealer widely recognized for its excellent physicochemical properties [13]. Comparative studies indicate that BC HiFlow leaves fewer remnants after retreatment [14] and exhibits higher cell viability [15]. However, AH Plus has lower solubility compared to BC HiFlow [15].

To enhance fiberglass post retention after removal of root canal filling, ultrasonic agitation has been proposed as a cleaning strategy to eliminate residual sealer and improve dentin adhesion. The R2-Flatsonic ultrasonic insert (Helse Ultrasonic, Santa Rosa de Viterbo, Brazil) has shown promising results in increasing bond strength when resin-based sealers are used. However, its efficacy in removing bioceramic sealers remains uncertain [16]. Other instruments frequently used in obturation removal include the R1-Clearsonic and E1-Irrisonic ultrasonic inserts (Helse Ultrasonic), and the XP-endo Finisher R file (FKG Dentaire, La Chaux-de-Fonds, Switzerland), which will be evaluated in this study.

The R1-Clearsonic ultrasonic insert provides mechanical action, scraping dentin walls to remove residual sealer [17]. The E1-Irrisonic insert facilitates irrigant agitation, enhancing fluid penetration into dentinal tubules [18]. Both inserts generate acoustic energy and vibration to break down mineral residues, potentially improving smear layer removal and hybrid layer formation for resin cement penetration.

The XP-endo Finisher R file is another promising alternative for removing residual root canal filling. This file assumes a serpentine shape upon activation, allowing it to stir the irrigating solution and reach complex anatomical areas. Studies indicate that it is more effective than ultrasonic inserts in removing bioceramic sealer [18–20]. Its MaxWire alloy composition enables an 8% taper expansion when transitioning from martensitic to austenitic phase at body temperature, improving its adaptability to irregular canal anatomy [18]. However, its impact on fiberglass post bond strength after sealer removal remains unclear.

Given these uncertainties, this study aimed to evaluate whether agitation protocols using ultrasonic inserts (R1-Clearsonic and E1-Irrisonic) or the XP-endo Finisher R file improve the removal of residual endodontic sealers (bioceramic and resin-based) and enhance the bond strength of fiberglass posts to dentin after cementation.

METHODS

Sample size

The sample size was justified through the sample calculation based on the previous methodologies by Özcan *et al.* [21] and Soares *et al.* [7]. The G*Power ver. 3.1 program for Mac (Heinrich Heine University Dusseldorf, Germany) was used to compare more than two means with independent groups (analysis of variance, ANOVA), with a total of three groups, with an alpha error (α) of 0.05, a beta power (β) of 0.80, a standard deviation estimates of 2.53, and a minimum difference to be detect-

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ed at the value of 6.90. Twelve samples per group were indicated as the ideal size required.

Sample preparation

The approval of the Human Ethics Committee of the Piracicaba Dental School (FOP/Unicamp) (CAAE: 30059020.9.0000.5418) was obtained before starting the research. This study used 72 single-rooted maxillary incisor teeth. The teeth were radiographed using a digital sensor on the mesiobuccal and buccolingual planes to check the degree of curvature. Inclusion criteria: teeth with a curvature of at most 5° according to Schneider's classification, single-rooted teeth with a single canal according to Vertucci's classification, and teeth with fully formed apices. Teeth with endodontic treatment, internal or external reabsorptions, root caries, cracks, and/or calcifications were excluded from the research [22].

The teeth were cleaned, and the crown was removed from the cementoenamel junction using a water-cooled diamond disc (Isomet100 PrecisionSaw; Buehler Ltd., Lake Bluff, IL, USA), leaving approximately 15 mm of root. The root canal cervical preparation was carried out with a 30./10 file at 6 mm from the apex (Easy ProDesign S; Easy Equipamentos Odontológicos, Belo Horizonte, Brazil) in continuous rotation at a speed of 950 revolutions/min (rpm) and torque of 4 Ncm mounted on a VDW Silver motor (VDW GmbH, Munich, Germany). The Reciproc file system in sequence R25, R40, and R50 instrumented the entire canal length at the foramen level and operated in "Reciproc all" mode using the same motor. During instrumentation, the canals were irrigated with a solution of 2.5% sodium hypochlorite (NaOCl) using a 30-gauge needle (NaviTip; Ultradent Products Inc., South Jordan, UT, USA) for a total of 10 mL in the whole irrigation. For this purpose, a layer of sticky wax was applied to the apical foramen to prevent liquid from leaking out of the canal. At the end of the instrumentation, passive ultrasonic irrigation was performed using the E1-Irrisonic insert mounted on a Newtron Booster ultrasonic device (Acteon North America, Mount Laurel, NJ, USA) at 30% power. The agitation was carried out at 2 mm short of the working length, where it was applied 2 mL of 2.5% NaOCl was applied into the root canal for three cycles of 20 seconds, totaling 6 mL and 1 minute. Soon after that, the same process was performed for ethylenediaminetetraacetic acid (EDTA) 17% and then with hypochlorite again. Finally, 5 mL of distilled water was introduced into the root canal for the final wash, and the canal was dried with absorbent Reciproc R50 paper points (VDW GmbH).

Root canal filling

The root was randomized and distributed in two groups (n = 36) according to the sealer used in the canal filling, either EndoSequence BC Sealer HiFlow or AH Plus. Table 1 displays the components of the endodontic sealers.

Single cone was the technique used for the obturation, and the sealers were prepared according to the manufacturer's instructions. R50 gutta-percha points were coated with the sealer and inserted into the canal with apical pressure until reaching the working length. Posteriorly, the heated condenser cut the gutta-percha, and other cold condensers vertically condensed the filling material. The roots were kept at 37°C and 95% humidity for 28 days to ensure a complete bioceramic set.

Root canal filling removal

After this period, the filling material was removed from the 15 mm-long canals using Largo burs corresponding to No. 1 Exact Pin Kit (Angelus, Londrina, Brazil), leaving 4 mm of gutta-percha in the apical third. A periapical radiograph was taken to confirm the complete removal of the filling material from the dentinal walls.

Table 1. Composition of AH Plus and EndoSequence HiFlow sealers

Cement	Batch	Composition
EndoSequence BC Sealer HiFlow (Brasseler USA, Savannah, GA, USA)	1901SPWF	Tricalcium silicate, dicalcium silicate, calcium hydroxide, zirconium oxide, and fillers
AH Plus (Dentsply Maillefer, Ballaigues, Switzerland)	1810000183	Paste A: Epoxide paste: bisphenol-A epoxy resin, bisphenol-F epoxy resin, calcium tungstate, zirconium oxide, aerosol, and pigment
		Paste B: 1-adamantane amine N, N'-dibenzyl-5-oxa-nonandiamine-1,9TCD-Diamine, calcium tungstate, zirconium oxide, aerosol, and silicone

Root canal cleaning

At this time, the root was randomized and subdivided into three groups ($n = 20$) corresponding to the cleaning protocol after root filling removal: group 1, ultrasonic agitation using R1-Clearsonic followed by E1-Irrisonic; group 2, agitation with XP-endo Finisher R; and group 3, no agitation. The cleaning sequence for each group was the following [18]:

Group 1 (US): The R1-Clearsonic tip mounted on a Newtron Booster ultrasonic device was used to remove and scrape clinging filling material in the dentinal wall of canals immersed with 2.5% NaOCl. After this process, the E1-Irrisonic tip, inserted 0.5 mm from the apical gutta-percha filling, and agitated 1 mL of this same solution for 30 seconds. Both the tips were set at power 1. Then, 5 mL of NaOCl washed the entire canal. After this, E1-Irrisonic agitated 1 mL of 17% EDTA for 30 seconds, and then the canal was washed with 5 mL of the same solution. In the next step, 1 mL of 2.5% NaOCl was agitated for 30 seconds according to the previous protocol. Finally, irrigation with 5 mL of distilled water concluded the cleaning of the canal.

Group 2 (XP): The XP-endo Finisher R file was coupled to a VDW Silver motor and operated in continuous rotation at a speed of 800 rpm with a torque of 1 Ncm inserted 0.5 mm from the apical gutta-percha filling. The file was agitated with 1 mL of 2.5% NaOCl, which was inserted into the root canal for 30 seconds. Then, 5 mL of NaOCl washed the entire canal. After this, the file was agitated with 1 mL of 17% EDTA for 30 seconds, and then the canal was washed with 5 mL of the same solution. In the next step, 1 mL of 2.5% NaOCl was agitated for 30 seconds according to the previous protocol. Finally, irrigation with 5 mL of distilled water concluded the cleaning of the canal.

Group 3 (control): A volume of 5 mL of 0.9% saline solution irrigated the canals without any agitation protocol using a 5 mL irrigation syringe and a 30-gauge NaviTip at 0.5 mm from the apical gutta-percha filling.

Quantitative analysis of the filling remnant

Cleaning efficiency was evaluated by micro-computed tomographic (micro-CT) images. For this quantitative analysis, five teeth from each group were selected and scanned after root filling removal and after the established cleaning protocols using a micro-CT device, the SkyScan 1174 (Bruker microCT, Kontich, Belgium). The scanning parameters were standardized as follows: 50 kV, 800 μA, 23.2-μm voxel side, 0.5-mm aluminum filter, and rotation steps of 0.7 and 3 frames. All scans were reconstructed with NRecon software (ver. 1.6.9; Bruker microCT) using the following parameters: smoothing level of 5, ring artifact correction of 6, and 30% of beam-hardening correction. Afterward, the alignment of the scans of each tooth acquired after root filling removal and after the cleaning protocol was performed using the 3D registration tool in Data Viewer software (Data Viewer ver. 1.5.1; Bruker microCT). Finally, the volume (mm^3) of the filling remnant was quantified with the CTAn software (ver. 1.13; Bruker microCT) using a standardized threshold of gray values that allowed to distinguish of the root dentin from the filling remnant material.

Fiberglass post cementation

For the post cementation, 37% phosphoric acid etched the post space for 15 seconds, and 5 mL of distilled water rinsed the canal for 30 seconds. Then, absorbent paper points dried the entire dentinal walls. The adhesion was performed using the Scotch Bond Multipurpose system (3M ESPE, St. Paul, MN, USA). Initially, the activator was applied into the canal with a microbrush, followed by the removal of excess with a paper point. The same process was carried out with the primer and catalyst. For the fiberglass post conditioning, 37% phosphoric acid was applied to the fiberglass post for 15 seconds and rinsed with distilled water. Sequentially, the post received a silane layer (Ultradent Products Inc.) using a microbrush. The RelyX ARC dual resin cement (3M ESPE) was handled, following the manufacturer's instructions, and taken to the Centrix-type syringe system (DFL, Rio de Janeiro, Brazil) to be applied inside the canal. Then, the post was inserted, adapted, and pressed for 20 seconds into the canal. The excess material on the root surface was removed. At the end, a Valo light curing unit (Ultradent Products Inc.) photopolymerized the system for 40 seconds. Each root was inserted into an individual Eppendorf tube containing moistened cotton at the base and labeled according to the corresponding group. The moistened cotton was used to maintain

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humidity and prevent dentin dehydration, avoiding potential bias in the push-out bond strength tests. The Eppendorf tubes were kept at 37ºC for 5 days. Table 2 summarizes the cleaning and cementation protocol for the posts.

Push-out bond strengths

The 5-day-old samples were cut into three slices with a 1-mm thickness, each corresponding to one-third of the root canal (cervical, middle, and apical), using a water-cooled diamond disc. In sequence, the sample slice was positioned on the universal testing machine (Instron 4411; Instron, Norwood, MA, USA) with a 0.5-mm diameter metal rod positioned in the center of the fiberglass post, applying mechanical load in a crown-to-apex direction at a speed of 0.5 mm/min until the post displacement from the root slice. This loading was quantified in newtons (N). To calculate the area of the truncated cone, the following formula was used: $A = \pi (R + r) \sqrt{h^2 + (R - r)^2}$. R is the radius of the coronal portion; r is the radius of the apical portion; and h is the height of the slice. The bond strength was calculated by dividing the force in N by the area in mm^2 and expressed in megapascals (MPa).

Table 2. Summary of the cleaning and cementation protocol

Group	Cleaning protocol	Fiber post cementation
Control	• 5 mL of 0.9% saline solution irrigated the canals without any agitation protocol using a 5-mL irrigation syringe and a 30-gauge NaviTip at 0.5 mm from the apical gutta-percha filling.	• Step 1: 37% phosphoric acid etched the post space for 15 seconds, and 5 mL of distilled water rinsed the canal for 30 seconds. • Step 2: absorbent paper points dried the entire dentinal walls. • Step 3: The activator (Scotch Bond Multipurpose system) was applied into the canal with a microbrush, followed by the removal of excess with a paper point. • Step 4: The same process (step 3) was carried out with the primer and catalyst. • Step 5: 37% phosphoric acid was applied to the fiberglass post for 15 seconds and rinsed with distilled water. • Step 6: the post received a silane layer.
US	• Step 1: R1-Clearsonic tip was used to remove and scrape clinging filling material in the dentinal wall of canals immersed with 2.5% NaOCl. • Step 2: E1-Irrisonic tip, inserted 0.5 mm from the apical gutta-percha filling, agitated 1 mL of this same solution for 30 seconds. Then, 5 mL of NaOCl washed the entire canal. • Step 3: E1-Irrisonic agitated 1 mL of 17% EDTA for 30 seconds, and then the canal was washed with 5 ml of the same solution. • Step 4: E1-Irrisonic agitated 1 mL of 2.5% NaOCl for 30 seconds according to the previous protocol. • Step 5: irrigation with 5 mL of distilled water concluded the cleaning of the canal.	• Step 7: The RelyX ARC dual resin cement was handled and taken to the Centrix syringe system to be applied inside the canal. • Step 8: the post was inserted, adapted, and pressed for 20 seconds into the canal. The excess material on the root surface was removed. At the end, a Valo light curing unit (Ultradent Products) photopolymerized the system for 40 seconds.
XP	• Step 1: XP-endo Finisher R file agitated 1 mL of 2.5% NaOCl inserted into the root canal for 30 seconds. Then, 5 mL of NaOCl washed the entire canal. • Step 2: XP-endo Finisher R agitated with 1 mL of 17% EDTA for 30 seconds, and then the canal was washed with 5 mL of the same solution. • Step 3: XP-endo Finisher R agitated 1 mL of 2.5% NaOCl for 30 seconds according to the previous protocol. • Step 4: irrigation with 5 mL of distilled water concluded the cleaning of the canal.	

EDTA, ethylenediaminetetraacetic acid; NaOCl, sodium hypochlorite; US, experimental group using an ultrasonic irrigation protocol; XP, experimental group based on the XP-endo Finisher R file.
Centrix-type syringe system: DFL, Rio de Janeiro, Brazil. E1-Irrisonic and R1-Clearsonic tips: Helse Ultrasonic, Santa Rosa de Viterbo, Brazil. NaviTip and Valo curing light: Ultradent Products Inc., South Jordan, UT, USA. RelyX ARC and Scotchbond Multipurpose: 3M ESPE, St. Paul, MN, USA. XP-endo Finisher R file: FKG Dentaire, La Chaux-de-Fonds, Switzerland.

Failure mode

The failure mode after the push-out test was evaluated using a stereomicroscope (LEICA MZ7.5; Leica Microsystems, Wetzlar, Germany) under 50× magnification. The fractures were classified as adhesive between dentin and cement, adhesive between post and cement, cohesive into dentin, cohesive into fiberglass post, cohesive into cement, or mixed failure.

Adhesive interface and nanoleakage with ammoniacal silver nitrate analysis

A root from each group was selected to obtain an extra slice to analyze the adhesive interface and nanoleakage. For this test, the slice of each group was immersed in ammoniacal silver nitrate solution in an Eppendorf tube covered with aluminum foil for 24 hours at 37ºC. After this time, the slices were rinsed with distilled water for 1 minute. Then, in other labeled Eppendorf tubes, containing 1 mL of developer solution, the sections were immersed and kept under fluorescent light for 8 hours. Next, the slices were rinsed with distilled water irrigation for 1 minute and embedded in epoxy resin to make stubs. After inclusion and resin polymerization, the stubs were polished with constant irrigation in the order of sandpaper 600 for 4 minutes, 1000 for 5 minutes, and 2000 for 5 minutes, respectively. At each sandpaper change, the stubs were cleaned in an ultrasonic vat with distilled water for 5 minutes. Sequentially, the stubs were polished with a felt disk, applying a small proportion of 1-µm diamond paste for 2 minutes. Finally, the stub was cleaned in an ultrasonic vat for 10 minutes. After polishing and dehydration, double-sided carbon tapes were glued to one side of the stubs, which were then subjected to carbon coverage and evaluated in a scanning electron microscope (SEM; JSM-5600LV, JEOL Ltd., Tokyo, Japan) at magnifications of ×270.

Statistical analysis

Statistical analyses were performed using JASP software (University of Amsterdam, Amsterdam, The Netherlands), ver. 0.14.1.0 (2021). A mixed ANOVA (considering both within- and between-subject effects) was conducted. The assumptions of normality and sphericity were assessed using the Shapiro-Wilk and Levene tests, respectively. When significant differences were found, the Tukey *post-hoc* test was applied for multiple comparisons. A significance level of 5% ($p < 0.05$) was adopted for all statistical tests.

RESULTS

There was no statistical difference between HiFlow and AH Plus sealers for the same cleaning protocols ($p > 0.05$). The ultrasonic and XP agitation groups did not show a statistical difference for canals obturated with AH Plus ($p > 0.05$). However, in the AH Plus group, both ultrasonic and XP agitation achieved higher bond strength than irrigation with saline solution during post preparation ($p < 0.05$). The ultrasonic and XP agitation groups did not show a statistical difference for canals obturated with HiFlow ($p > 0.05$). Both the US and XP groups achieved higher bond strengths compared to the saline irrigation group in the canals obturated with HiFlow ($p < 0.05$) (Table 3).

In micro-CT, there was no statistical difference between the different types of sealers for the same clean-

Table 3. The bond strength (Mpa) of the total of all thirds for each cleaning protocol and sealer type

Cleaning	AH Plus			HiFlow			AH Plus	HiFlow
	Cervical	Middle	Apical	Cervical	Middle	Apical	Total	Total
No agitation	8.35 ± 1.86	8.80 ± 2.66	7.91 ± 2.84	7.46 ± 2.20	7.71 ± 2.18	6.41 ± 2.28	8.35 ± 0.57^{Aa}	7.19 ± 0.05^{Aa}
US	13.49 ± 3.27	11.31 ± 2.14	10.37 ± 2.86	12.22 ± 6.18	11.12 ± 5.59	8.10 ± 3.40	11.72 ± 0.44^{Ba}	10.48 ± 1.40^{Ba}
XP	13.22 ± 5.16	13.37 ± 8.17	10.92 ± 5.94	13.25 ± 5.04	11.41 ± 3.76	9.80 ± 3.80	12.50 ± 1.19^{Ba}	11.49 ± 0.70^{Ba}

Values are presented as mean ± standard deviation.

US, experimental group using an ultrasonic irrigation protocol; XP, experimental group based on the XP-endo Finisher R file (FKG Dentaire, La Chaux-de-Fonds, Switzerland).

AH Plus: Dentsply Maillefer, Ballaigues, Switzerland. HiFlow: EndoSequence BC Sealer HiFlow; Brasseler USA, Savannah, GA, USA.

Different capital letters in the same column indicate statistical differences for the same sealer among different cleaning protocols ($p < 0.05$). Different lowercase letters in the same line indicate the absence of statistical differences among different sealers for the same type of cleaning protocol ($p > 0.05$).

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ing protocol. Only for the HiFlow group was a statistical difference observed in the removal of remnants after the cleaning protocol with ultrasonic tips ($p = 0.03$) (Table 4). The failure mode analysis indicated mostly mixed failures after the push-out analysis (Figure 1).

SEM images showing the post-cement dentin-cement line of the AH Plus and HiFlow groups and their respective cleaning subgroups are shown in Figure 2.

The agitation effect in cleaning the remnants adhered to the dentin wall after the root canal filling removal protocol is represented in Figure 3.

DISCUSSION

Endodontic sealer type has been found to influence the bond strength of fiberglass posts to root dentin [6,21,23]. Based on that, this study assessed the agitation effect of the irrigating solution after post space preparation on bond strength. This is the first study in the literature to assess this objective using the HiFlow bioceramic sealer and agitating with the Clerasonic/Irrisonic inserts and XP-endo Finisher R file.

The push-out test was used to evaluate bond strength. This test is frequently used in endodontics to evaluate the bond strength of root canal posts. The key advantage over different tests, such as the microtensile technique, is the presence of material within the canal surrounded by dentin [24]. Furthermore, the push-out test evaluates bonding throughout different canal regions and thirds [21].

Table 4. The remaining material volume (mm^3) in the root canals after obturation and after cleaning

Cleaning	AH Plus		HiFlow	
	After filling removal	After cleaning	After filling removal	After cleaning
US	0.95 ± 0.71^{Aa}	0.03 ± 0.03^{Aa}	1.56 ± 0.43^{Aa}	0.16 ± 0.36^{Ba}
XP	1.9 ± 1.89^{Aa}	1.12 ± 1.12^{Aa}	3.0 ± 1.53^{Aa}	2.2 ± 1.58^{Ab}

Values are presented as mean ± standard deviation.
US, experimental group using an ultrasonic irrigation protocol; XP, experimental group based on the XP-endo Finisher R file (FKG Dentaire, La Chaux-de-Fonds, Switzerland).
AH Plus: Dentsply Maillefer, Ballaigues, Switzerland. HiFlow: EndoSequence BC Sealer HiFlow; Brasseler USA, Savannah, GA, USA.
Different uppercase letters mean statistical differences for the same type of sealer and cleaning protocol ($p < 0.05$). Different lowercase letters indicate a statistically significant difference for the same sealer among the different cleaning protocols ($p < 0.05$).

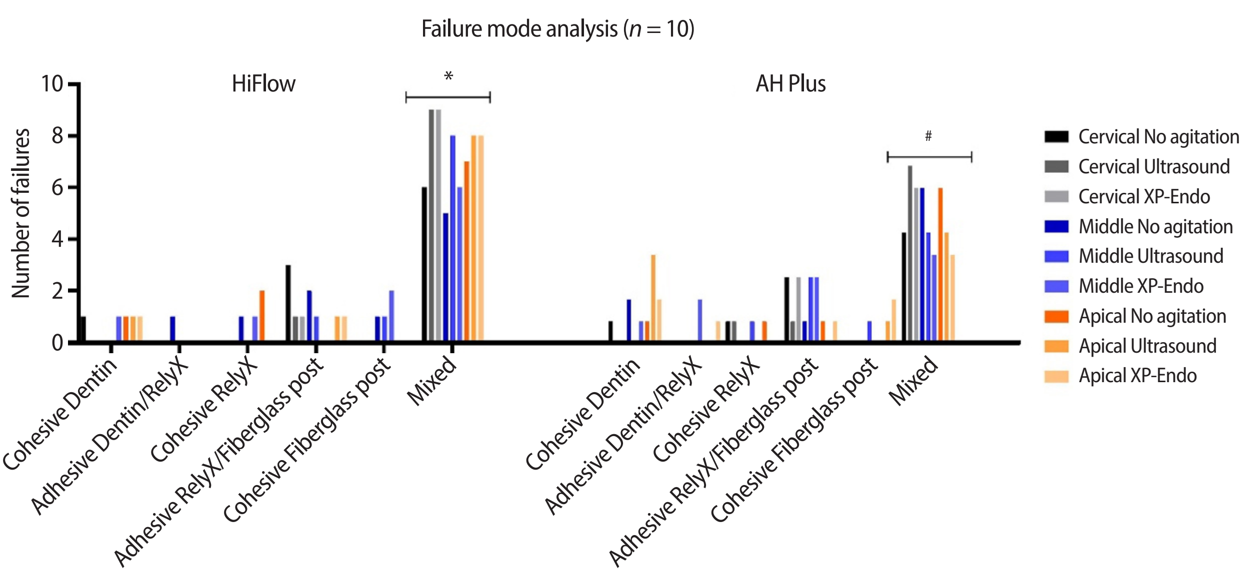

Figure 1. Failure mode analysis indicating mostly mixed failures after the push-out analysis. Symbols (*, #) indicate the significance between failures within the tested sealer. AH Plus: Dentsply Maillefer, Ballaigues, Switzerland. HiFlow: EndoSequence BC Sealer HiFlow; Brasseler USA, Savannah, GA, USA. RelyX: RelyX ARC; 3M ESPE, St. Paul, MN, USA. XP-endo: XP-endo Finisher R file; FKG Dentaire, La Chaux-de-Fonds, Switzerland.

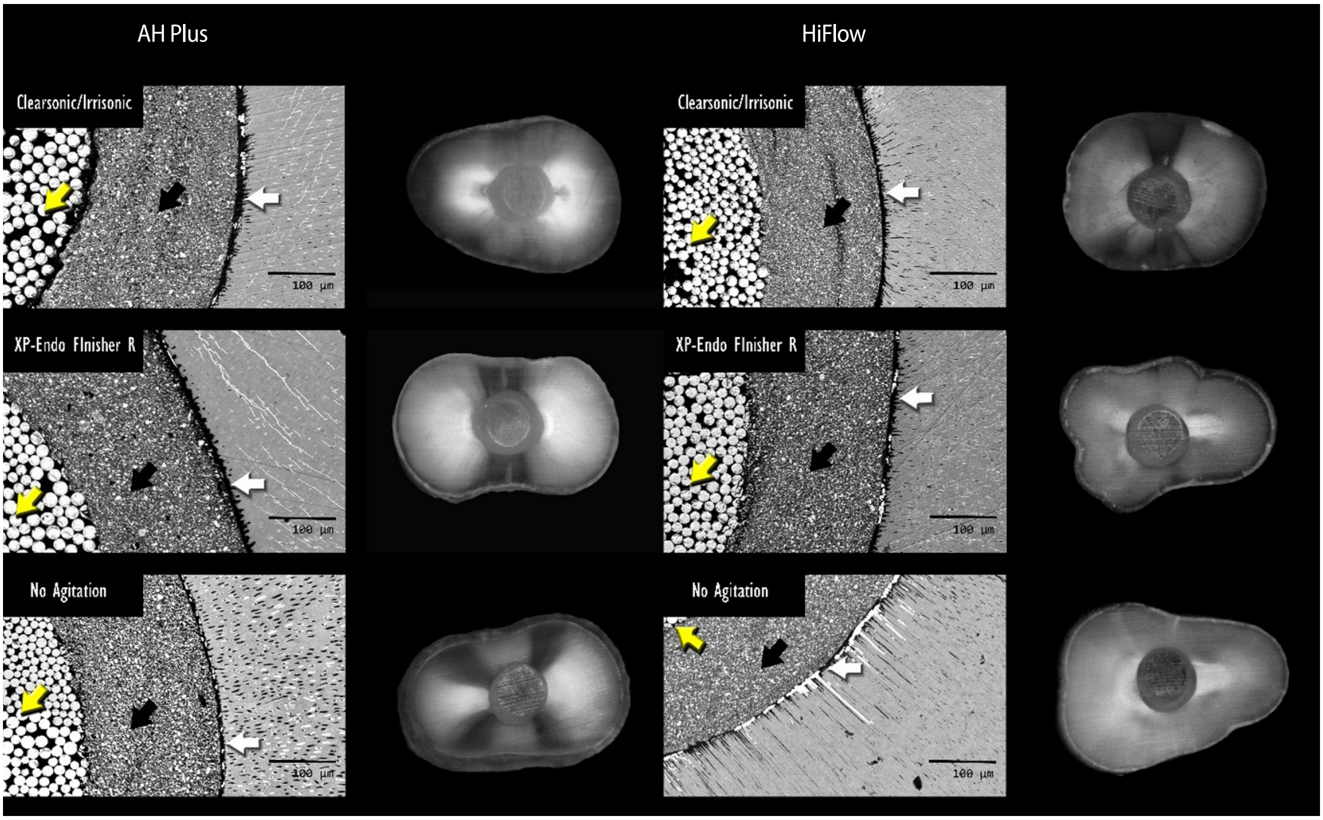

Figure 2. Scanning electron microscope images (250× and 15 kV) indicating the middle third adhesive interface of each sealer group and agitation subgroup. Yellow arrows indicate the glass fibers around the epoxy resin. Black arrows indicate the cement line. White arrows indicate adhesive penetration into the dentin. AH Plus: Dentsply Maillefer, Ballaigues, Switzerland. HiFlow: EndoSequence BC Sealer HiFlow; Brasseler USA, Savannah, GA, USA. Clearsonic and Irrisonic: Helse Ultrasonic, Santa Rosa de Viterbo, Brazil. XP-endo Finisher R: FKG Dentaire, La Chaux-de-Fonds, Switzerland.

In the current investigation, cleaning the root canals using an ultrasonic tip or an XP-endo Finisher R file resulted in a stronger bond strength than the control group in both canals filled with AH Plus and HiFlow. The XP-endo Finisher R file is extremely flexible and whips when inserted into the canals and exposed to body temperature. The file forms a sickle shape and presses against the dentin walls, causing the irrigation solution to spout into the dentinal tubules. This technique allows the tip file to whip to scrape the dentin wall, displacing adherent fragments [18,20,23]. Because of the agitation during cleaning, the XP file allowed for deep penetration of the resin cement into the dentin, resulting in a high bond strength. There were no statistical differences in bonding strength between canal thirds.

Cleaning with ultrasonic inserts also resulted in greater bond strength values and effective agitation and cleaning, which differed significantly from the control group. The Irrisonic does not come into contact with the canal walls; instead, it works through vibration and acoustic transmission to spout the solution into the canal wall by cavitation and acoustic flow, which splits material off the walls [23]. However, the Clearsonic tip works directly and mechanically, scraping the remaining material from the dentin wall with its arrow-shaped tip [17]. The combination of Irrisonic and Clearsonic was shown to improve cleaning while also allowing resin cement to adhere to and penetrate dentin more effectively.

Although there was no statistical difference, HiFlow sealer had lower bond strength values than AH Plus. The literature [21,25,26] found similar results. Other studies that did not use ultrasonic cleaning found lower bioceramic sealer bond strength values than AH Plus

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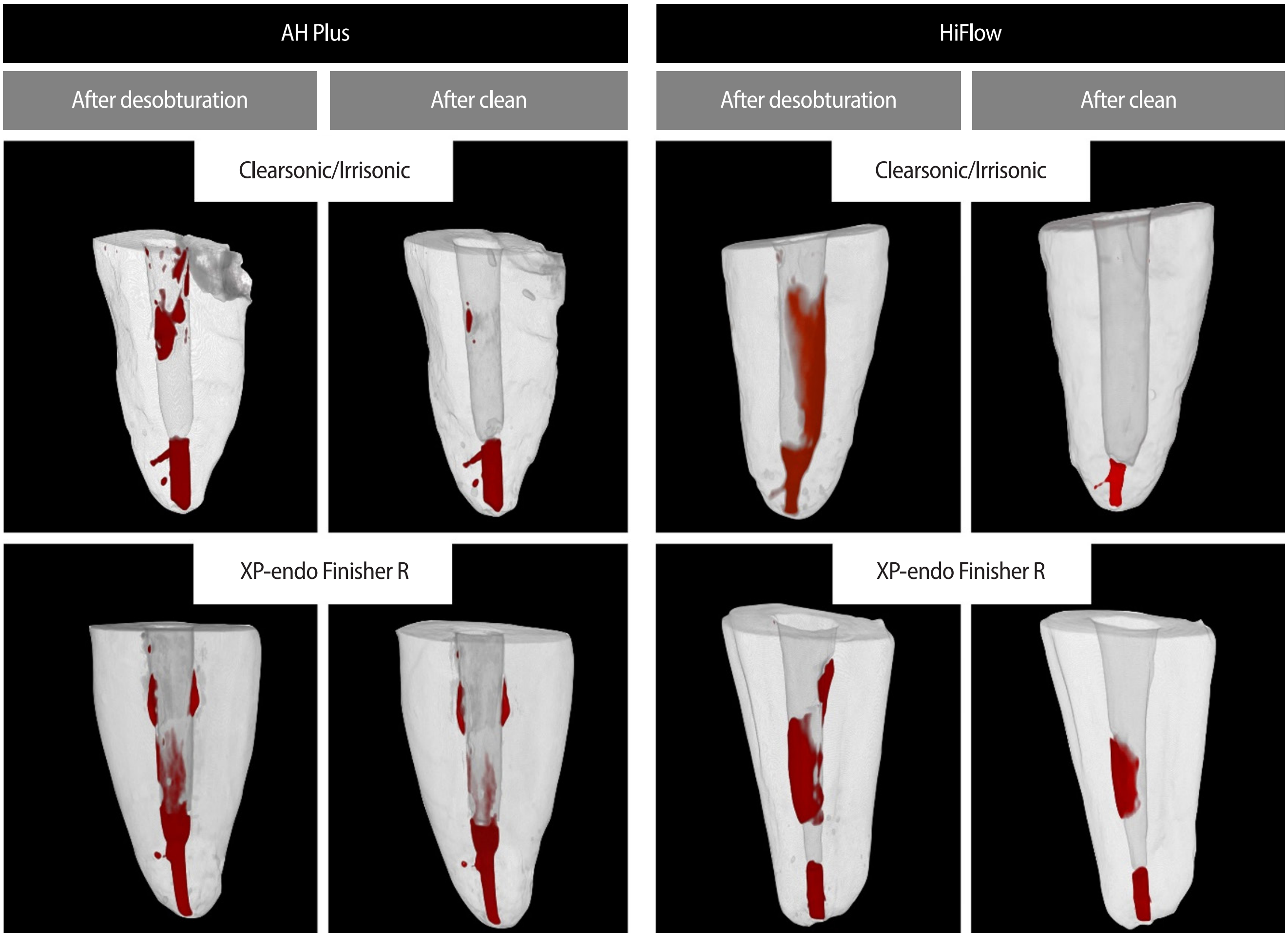

Figure 3. Representative micro-computed tomographic images showing remaining materials before and after cleaning with ultrasonics and the XP-endo Finisher R (FKG Dentaire, La Chaux-de-Fonds, Switzerland). AH Plus: Dentsply Maillefer, Ballaigues, Switzerland. HiFlow: EndoSequence BC Sealer HiFlow; Brasseler USA, Savannah, GA, USA. Clearsonic and Irrisonic: Helse Ultrasonic, Santa Rosa de Viterbo, Brazil.

[3,5,6,8]. Furthermore, similar experiments employing an ultrasonic insert to clean the post area demonstrated that AH Plus had a stronger bond strength than a bioceramic sealer [16]. Except for one study [27], which reported a greater result for iRoot SP (Innovative BioCeramix Inc., Vancouver, BC, Canada) in comparison to AH Plus.

While there was no statistical difference between AH Plus and HiFlow in this study, the literature indicates that resin-based cements have superior bond strength due to their similar composition to resin and the absence of components that affect polymerization [28]. Additionally, epoxy resin does not interfere with the free radicals that initiate the polymerization of composite resins [7].

HiFlow was chosen because it is a bioceramic sealer with a higher flow rate, which could show the effectiveness of agitation protocols to remove them from the dentinal tubules. Bioceramic sealers are harder to remove from canals [12]. In contact with dentin moisture, they release calcium hydroxide that binds to phosphates in the dentinal fluid and forms lath-like apatite crystals [9–11], which adhere to the dentin mineral and precipitate in the dentinal tubule [9,29], making removal difficult. In addition to crystal formation, the calcium hydroxide release creates an alkaline environment that reduces the effectiveness of acid etching, resulting in a weak hybrid layer with a resinous tag [6,7].

According to micro-CT analysis, the HiFlow ultrasonic group showed greater remaining removal after cleaning protocols than the XP group, owing to the combined efficiency of the two inserts, making it an alternative to removing bioceramic sealers from the wall canal. This is consistent with the literature [23], which demonstrated that the ultrasonic insert removed the remaining material from the canal better than the XP instrument. Both agitation groups for HiFlow and AH Plus sealers showed a significant reduction in remnants, demonstrating that the ultrasonic group had a higher cleaning percentage. This micro-CT analysis allowed us to conclude that agitation of the irrigant solution is suggested for post space preparation. In root canal retreatment, some authors [18–20] found that the Irrisonic insert eliminated fewer remains from the canal than the XP file. In contrast, another study [23] showed that the ultrasonic insert removed the most remains when compared to the XP file.

Our study was the first to apply the nanoleakage methodology with an ammoniacal silver nitrate solution to measure cementation density in SEM using backscattered electrons (BSE), which is more accurate than secondary electrons. In SEM, the post-cement-dentin interface cementation is shown hermetically, with no bubbles evident. The round bundles illustrate fiberglass that has been wrapped in epoxy resin (black). The cement line depicts the inorganic zirconia and silica particles that are covered by the bisphenol A-glycidyl methacrylate (Bis-GMA) and triethylene glycol dimethacrylate (TEGDMA) organic matrix. The black rays from the cement show the adhesive that has penetrated the dentinal tubules, indicating a high level of adhesion. White spots in the cement-dentin interface indicate gaps filled with silver particles. All groups show good adherence. However, there is a thicker adhesive layer for groups with agitation, particularly the AH Plus group. Furthermore, the HiFlow sealer no-agitation group contains voids filled with silver particles, represented by white rays, indicating a failure in adhesive adherence and penetration.

Regarding the failure mode, the highest frequency was the mixed type. This can be explained by the sum of the failure types. Cohesive failures could be invisible during push-out test execution, and the remaining endodontic sealer influences adhesive failures, especially those of cement-dentin. Adhesive failure between cement and dentin, only, was the least observed. The post-cement adhesive failure was the second most observed failure type and was the most frequent in other work [6]. The difference from the literature may be attributed to the use of silane in our study, which the authors did not use.

The limitation of this study includes the variability in root canal anatomy, with some being more flattened and others being more irregular. Besides the attempt to standardize as closely as possible to each other, this was not totally possible. Furthermore, despite the advantages of the push-out test, it does not show the true clinical situation, making it difficult to draw definitive conclusions from the study [30].

The findings of this study have significant clinical implications for root canal cleaning after the removal of filling material for fiber post preparation. The use of ultrasonic instruments and the XP-endo Finisher R proved effective in reducing intracanal residues, creating a cleaner and more suitable surface for adhesion, which may enhance the cementation of resin-based cements.

CONCLUSIONS

Both agitation protocols using the XP-endo Finisher file or Clearsonic combined with Irrisonic ultrasonic inserts effectively clean root-filled canals sealed with resin-based and calcium silicate-based sealers during fiberglass post space preparation. These protocols result in improved bond strength compared to non-agitation methods.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization: Marciano MA, Antunes TBM. Data curation: Antunes TBM, Fontenele RC. Formal analysis: Bronzato JD, Marciano MA, Janini ACP. Funding acquisition, Supervision: Marciano MA. Investigation: Graciani J. Methodology:

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DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

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Stress distribution of restorations in external cervical root resorption under occlusal and traumatic loads: a finite element analysis

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ABSTRACT

Objectives: This study analyzed the stress distribution in a maxillary central incisor with external cervical resorptive defect restored with different restorative materials under normal masticatory and traumatic loading conditions using finite element analysis.
Methods: Cone-beam computed tomography of an extracted intact incisor and created resorptive models (Patel's 3D classification-2Bd and 2Bp) in the maxillary central incisor was performed for finite element models. The 2Bd models were restored either with glass ionomer cement (GIC)/Biodentine (Septodont) or a combination of both with composite resin. 2Bp models were restored externally with a combination technique and internally with root canal treatment. The other model was external restoration with GIC and internal with fiber post. Two masticatory loads were applied at 45˚ to the palatal aspect, and two traumatic loads were applied at 90˚ to the buccal aspect. Maximum von Mises stresses were calculated, and stress distribution patterns were studied.
Results: In 2Bd models, all restorative strategies decreased stress considerably, similar to the control model under all loads. In 2Bp models, the dentin component showed maximum stress at the deepest portion of the resorptive defect, which transfers into the adjacent pulp space. In 2Bp defects, a multilayered restoration externally and root canal treatment internally provides better stress distribution compared to the placement of a fiber post.
Conclusions: Increase in load, proportionally increased von Mises stress, despite the direction or angulation of the load. Multilayered restoration is preferred for 2Bd defects, and using an internal approach of root canal treatment is suggested to restore 2Bp defects.

Keywords: Biodentine; Cone-beam computed tomography; Dental stress analysis; Finite element analysis; Glass ionomer cements; Root resorption

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INTRODUCTION

External cervical resorption (ECR) is a complex process with dynamic pathogenesis occurring in the cervical area of the tooth due to clastic cell activity [1]. Tissue injuries, such as pre-cemental or periodontal damage associated with inflammation, are most likely the reasons for the initiation of ECR [2]. ECR has varied predisposing factors, with orthodontic treatment being considered the most common factor, attributing up to an incidence of 45.7% [3]. Among the other risk factors, trauma and hypoxia play a major role in the initiation and progression of resorptive lesions [4]. The incidence of ECR is most common in maxillary central incisors, accounting for up to 29.24% [5]. Clinical characteristics of ECR range from being minimally restricted to dentin in the cervical region to being invasive and extensive, involving the full length of the roots. Based on two-dimensional and three-dimensional (3D) assessments of depth and extension, various classifications are available [6,7].

The treatment strategy of ECR depends on various factors such as clinical signs and symptoms, the ability to probe the point of entry, and the presence of bone-like tissue at the point of entry. Based on these parameters, three treatment options, such as extraction, monitoring, or a therapeutic restorative approach, are suggested [8]. Restoration of ECR can be performed by an external, internal, or combined approach depending on lesion access and debridement [9]. Over ten-year follow-ups of 274 teeth, the overall survival rate of treated ECR was found to be 84.6% in the first 3 years and gradually reduced to 28.6% in 10 years. This reduction in success rate drastically reduced after 5 years, with vertical root fracture being attributed as the main reason for failure [8]. Occlusal forces (centric and eccentric) could play a major role in the biomechanics of the tooth. As eccentric forces flex the tooth and the highest stress concentration is seen in the cervical region [10], managing resorptive defects involving the cervical region of the tooth becomes challenging for clinicians. Thus, treatment strategies for ECR should focus on materials capable of resisting occlusal load and rehabilitating the tooth by compensating for the lost structural integrity.

Currently, it is observed that 61% of ECR lesions have been treated by external surgical methods using bioactive endodontic cements and glass ionomer cement (GIC) [11]. Heithersay's class II and class III lesions were restored mostly with bioactive endodontic cements alone (41%) or along with composite resin, while class IV lesions were completely restored with bioactive endodontic cements (57%) following root canal treatment [11]. Rajawat and Kaushik [12] have observed that the stress distribution in smaller resorptive lesions extending into the dentin (1Bd) when restored with mineral trioxide aggregate was better. However, restoring larger and deeper ECR lesions (2Bd and 3Bd) with BioAggregate (Innovative BioCeramix Inc., Vancouver, BC, Canada) and Biodentine (Septodont, Saint-Maur-des-Fossés, France) distributed the stress similar to that observed in intact teeth [12]. Askerbeyli Örs and Küçükkaya Eren [13] have shown that, for resorptive lesions involving pulp with less than 90˚ of circumferential spread, restoring with Biodentine distributes stress better than GIC or composite resin. For resorptive lesions involving pulp and with more than 90˚ of circumferential spread, GIC yielded favorable results [13]. A recent finite element study by Manaktala *et al.* [14] concluded that for resorptive lesions involving the pulp, irrespective of the location and size of the lesion, restoring with both mineral trioxide aggregate and Biodentine exhibited similar biomechanical performance. It would be interesting to see if restoring the ECR defect with multilayered restorations and the addition of post inside root canal to check if it would distribute the stress and reinforce the tooth.

Finite element simulations of ECR lesions and their restorations under various forces, such as normal occlusal and traumatic loads, are essential. Normal occlusal forces on the anterior could vary in a range between 50 N and 370 N [15], and the traumatic load reported in the literature ranges between 300 N and 2,000 N [16–18]. Thus, the aim of the current study is to understand the stress distribution in a maxillary central incisor with an external cervical resorptive defect restored with different restorative materials under normal masticatory and impact loading conditions using finite element analysis (FEA).

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METHODS

Generation of geometric finite element models

Following approval by the Institutional Ethical Committee of Meenakshi Ammal Dental College and Hospital (MADC/IECI/031/2021), five freshly extracted intact, sound, mature human maxillary right central incisors with a regular crown and root morphology were scanned using high-resolution cone-beam computed tomography (CBCT) CS 9600 3D machine (Carestream Dental LLC, Atlanta, GA, USA) at 10 × 10 micron voxel size, 120 kV and 3.20 mA and viewed using software CS 3D Imaging ver. 3.5.18 (Carestream Dental LLC).

ECR defect 2Bd was then created in the teeth using diamond points TF13 and TF15 (Mani Medical India, Pvt. Ltd., Delhi, India) with a high-speed airotor handpiece (NSK; Nakanishi Inc., Kanuma, Japan) under water coolant. The resorption cavity was extended from the mid-labial to distal to mid-palatal region circumferentially (approximately 160˚–170˚), involving the enamel, cementum, and dentin in the cervical third of the crown and root longitudinally, with a depth of 1.2 to 1.5 mm into the dentin, and verified using multiple angled intraoral periapical radiographs. One of the five simulated defects was then subjected to a second CBCT scan using the same device settings as in the first scan. The simulated 2Bd defect was then modified using the same armamentarium by extending its depth by 0.5 mm in its deepest portion to involve the pulp in order to create a 2Bp defect, which was similarly verified, validated, and scanned.

The DICOM (Digital Imaging and Communications in Medicine) files generated by the CBCT scans were converted to STL (stereolithography) files using MIMICS CS ver. 18.0 (Materialise, Leuven, Belgium), which were further utilized to generate 3D models with delineated boundaries of enamel, dentin, pulp, and cementum using Geomagic studio and control version 2014. The models were then imported into SolidWorks (Dassault Systèmes, Cedex, France) for further work. The 3D models of the control tooth, tooth with 2Bd resorptive defect, and tooth with 2Bp resorptive defect are illustrated in Figure 1A–C.

Experimental models with simulation of various restorative strategies

The 2Bd models were restored using external approaches as follows: (a) completely restored with GIC (R1) (Figure 2A), (b) completely restored with Biodentine (R2) (Figure 2B), and (c) layered restorations of Biodentine and GIC subgingivally and Biodentine and composite supragingivally (R3) (Figure 2C).

Combined therapeutic options for the 2Bp models were simulated as follows: the internal approach—endodontic treatment with incisal access was simulated corresponding to a no. 7 round bur. A conical canal

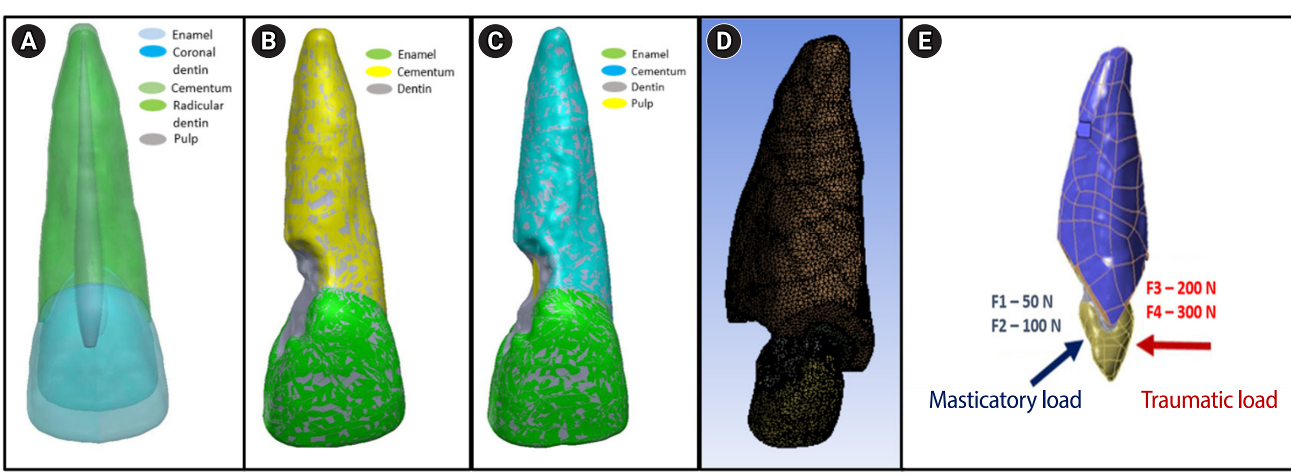

Figure 1. Virtually created three-dimensional (3D) model of an intact tooth (control) (A), 2Bd unrestored tooth (B), 2Bp unrestored tooth (C), representation of the 3D meshed model (D), and loading conditions (E).

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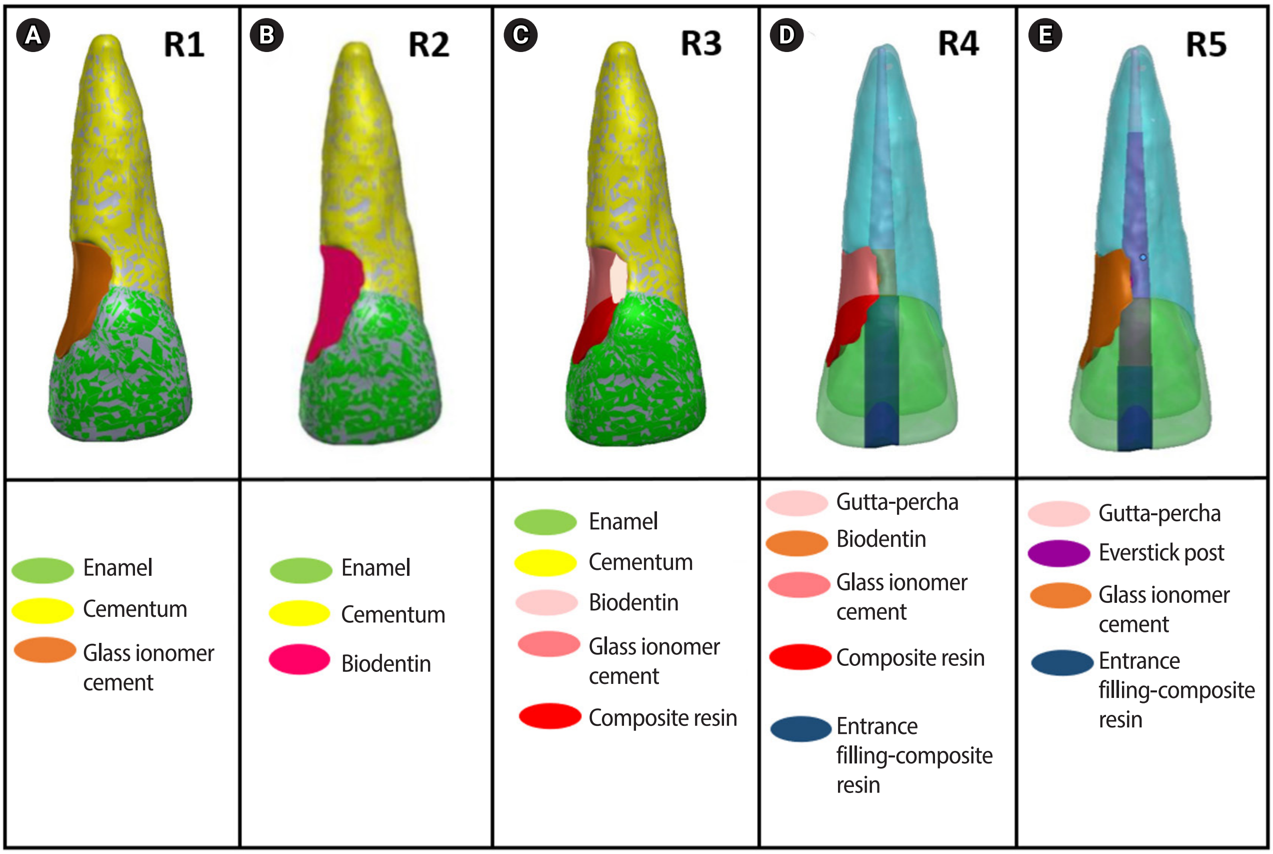

Figure 2. Virtually created three-dimensional models of five restoration types based on material combinations. (A) R1: restoration with glass ionomer cement (GIC) alone. (B) R2: restoration with Biodentine (Septodont, Saint-Maur-des-Fossés, France) alone. (C) R3: restoration with Biodentine, GIC, and composite resin. (D) R4: internal restoration with gutta-percha and composite resin, and external restoration with Biodentine, GIC, and composite resin. (E) R5: internal restoration with fiber-reinforced composite (Everstick post, GC Corp., Tokyo, Japan), gutta-percha, and composite resin, and external restoration with GIC.

preparation was simulated with an apical diameter of #50 with a 2% taper. This simulation was further restored as follows: (a) internally obturated with gutta-percha and externally restored with Biodentine and GIC subgingivally and Biodentine and resin composite supragingivally (R4) (Figure 2D), and (b) internally obturated with 5-mm gutta-percha (GP) and fiber-reinforced composite (FRC) post placed in the canal coronally and externally restored with GIC completely (R5) (Figure 2E).

Finite element meshing details

The 3D meshes were generated with 10-node tetrahedral elements and quadratic displacement shape functions with three degrees of freedom per node (Figure 1D). The average mesh size was about 0.5 mm, and the number of elements and nodes of each model is tabulated (Table 1).

Properties of the materials used

The generated models were transferred to Ansys software (Ansys 2022, R1 student version; Ansys, Inc., Canonsburg, PA, USA) for subsequent stress analysis. All tissues were presumed to be linearly elastic, homogeneous, and isotropic, with the bonding between the tissues considered ideal. The needed properties are presented in Table 2 [19–24].

Boundary and loading conditions

A thickness of 0.25 mm of periodontal ligament, 2 mm each of cancellous and cortical bone were simulated around all the models, starting 1.5 mm apical to the ce-

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Table 1. Number of elements and nodes for control, unrestored, and restored models

Model	Number of elements	Number of nodes
Control	123,720	719,037
2Bd unrestored	69,710	365,522
2Bd restored (R1, R2, R3)	72,405	381,505
2Bp unrestored	198,591	1,121,134
2Bp restored (R4, R5)	284,308	1,156,977

Table 2. Properties of materials used in finite element models

Material	Young's modulus (GPa)	Poisson's ratio
Enamel [19]	41	0.31
Dentin [19]	18.6	0.31
Cementum [20,21]	6.8	0.31
Pulp [19]	0.003	0.45
Periodontal ligament [19]	0.0000689	0.45
Cancellous bone [19]	1.37	0.30
Cortical bone [19]	13.7	0.30
Gutta-percha [19]	0.14	0.45
Glass ionomer cement [22]	10.8	0.30
Biodentine [23]	22	0.33
Glass fiber post [24]	29.2	0.30
Composite resin [19]	12	0.30

Biodentine: Septodont, Saint-Maur-des-Fossés, France.

mentoenamel junction and uniformly wrapped around the root [25,26], except for at the site of resorptive defect. Under all loading conditions, it was assumed that the simulated cortical bone was fixed.

Four loading conditions were applied: F1 and F2, masticatory load of 50 N [15,27] and 100 N [28,29], respectively, applied at 45° to the long axis of the tooth, palatally and incisal to the cingulum; F3 and F4, impact forces of 200 N and 300 N [16,17], respectively, applied to the middle third of the buccal surface of the crown at 90˚ to the long axis of the tooth (Figure 1E).

Von Mises stress evaluations were carried out using Ansys software, and the highest equivalent stresses in the entire tooth structure and resorptive areas for each model were visualized and noted from the color scale.

RESULTS

The number of elements and nodes for control, unrestored, and restored models is presented in Table 1. The overall maximum stress was always found to be in enamel at the point of force application. Von Mises stresses of control, unrestored, and restored models for 2Bd and 2Bp are presented in Tables 3 and 4, respectively.

2Bd models

In 2Bd models, on application of forces (F1, F2, F3, and F4), the highest stress was observed in experimental models with resorptive defects without any restoration. The dentin component showed maximum stress at the deepest portion of the resorptive defect. On F1 and F2 applications, the stress gets distributed to the mid root region on the buccal side and the buccal and palatal sides for F3 and F4. In the dentin component, R1, R2, and R3 have been found to reduce stresses equally and considerably similar to control under F1, F2, F3, and F4. The maximum stress concentration gets transferred to the mid root region on the buccal aspect on application of F1, F2, and to the mid root region on both buccal and palatal aspects, with more concentration on the palatal aspect with F3 and F4. The stresses exponentially increase from F1 to F2 (2 times) and from F3 to F4 (1.5 times) in all models. The stresses increase by 1.9 times from F2 to F3 in all models. With respect to dentin, the control model, unrestored model, and restored models show an increase of 5.4, 3.5, and 4.5 times, respectively. The maximum stresses of the periodontal ligament and cementum components of 2Bd unrestored were observed to be adjacent to the deepest part of the resorptive site. In cementum, von Mises stress after restoration in 2Bd models (R1 and R3) under F1, F2, F3, and F4 was closer to the range of stress in the intact tooth model. However, in R2, the stress was greater than the unrestored defect model. Within the restorations, Biodentine takes up the maximum stress concentration compared to GIC and composite. Multilayered restorations are attributed to more stress concentration compared to single restorations. The distribution of von Mises stresses in dentin and cementum in the 2Bd models is given in Figure 3.

2Bp models

In 2Bp models, on application of F1 and F2, the highest stress was observed in the control model. On application of F2, the maximum stress concentrations observed for R4 and R5 were greater than the unrestored model.

Table 3. Maximum von Mises stresses in Patel's three-dimensional classification 2Bd models

Component	Control				2Bd unrestored				R1				R2				R3			
	50 N	100 N	200 N	300 N	50 N	100 N	200 N	300 N	50 N	100 N	200 N	300 N	50 N	100 N	200 N	300 N	50 N	100 N	200 N	300 N
Enamel	32.27	63.86	115.80	173.69	38.002	76.009	144.48	216.73	37.66	75.32	143.73	215.59	37.53	75.06	143.47	215.21	37.61	75.22	143.63	215.44
Dentin	6.90	13.92	75.41	113.12	12.61	25.22	89.60	134.40	7.77	15.54	71.48	107.22	7.90	15.80	70.46	105.69	7.82	15.64	71.00	106.50
Pulp	0.0010	0.0023	0.007	0.011	0.0013	0.0027	0.009	0.013	0.0011	0.0020	0.007	0.010	0.0010	0.0021	0.006	0.010	0.0011	0.0022	0.007	0.010
Cementum	2.28	4.56	30.00	45.01	5.23	10.46	43.02	64.54	4.47	8.95	35.78	53.67	6.47	12.95	50.17	75.25	5.15	10.30	39.63	59.45
PDL	0.62	1.25	3.39	5.09	0.67	1.35	3.81	5.71	0.67	1.35	3.81	5.71	0.67	1.35	3.81	5.71	0.67	1.35	3.81	5.71
Cortical bone	4.72	5.78	36.32	54.49	7.81	8.64	57.43	86.15	7.81	8.64	57.43	86.14	7.81	8.64	57.42	86.14	7.81	8.64	57.42	86.14
Cancellous bone	2.89	9.43	20.82	31.23	4.32	15.62	31.35	47.03	4.32	15.62	31.35	47.03	4.32	15.62	31.35	47.03	4.32	15.62	31.35	47.03
Restoration	-	-	-	-	-	-	-	-	5.33	10.67	51.89	77.83	8.64	17.92	83.38	125.07	BD 9.23 CR 3.85 GIC 5.46	BD 18.47 BD 7.70 GIC 10.93	BD 86.42 BD 22.24 GIC 45.79	BD 130.02 CR 33.36 GIC 68.90

BD, Biodentine (Septodont, Saint-Maur-des-Fossés, France); CR, composite resin; GIC, glass ionomer cement; PDL, periodontal ligament.
Please refer to Figure 2 for the description of R1 to R3.

Table 4. Maximum von Mises stresses in Patel's three-dimensional classification 2Bp models

Component	Control				2Bp unrestored				R4				R5			
	50 N	100 N	200 N	300 N	50 N	100 N	200 N	300 N	50 N	100 N	200 N	300 N	50 N	100 N	200 N	300 N
Enamel	32.27	63.86	115.80	173.69	26.97	53.98	164.86	247.30	27.48	54.98	159.30	238.95	27.46	54.95	159.39	239.09
Dentin	6.90	13.92	75.41	113.12	25.46	50.94	135.73	203.59	8.92	17.85	60.57	90.86	8.64	17.30	61.63	92.45
Pulp	0.0010	0.0023	0.007	0.011	0.0069	0.13	0.036	0.054	-	-	-	-	-	-	-	-
Cementum	2.28	4.56	30.00	45.01	5.20	10.42	39.56	59.34	4.23	8.48	28.11	42.16	4.15	8.32	28.09	42.14
PDL	0.62	1.25	3.39	5.09	0.82	1.65	4.52	6.78	0.82	1.65	4.52	6.78	0.82	1.65	4.52	6.78
Cortical bone	4.72	5.78	36.32	54.49	10.70	21.41	75.51	113.27	10.70	21.41	75.48	113.23	10.69	21.40	75.48	113.23
Cancellous bone	2.89	9.43	20.82	31.23	7.78	15.58	52.23	78.35	7.78	15.58	52.23	78.34	7.78	15.58	52.23	78.34
Restoration (external)	-	-	-	-					Full 7.90 BD 8.50 CR 2.84 GIC 5.80	Full 15.80 BD 17.02 CR 5.69 GIC 11.61	Full 57.94 BD 64.44 CR 15.31 GIC 44.69	Full 86.91 BD 96.66 CR 22.96 GIC 67.04	5.73	11.47	45.94	68.91
Restoration (internal)	-	-	-	-	-	-	-	-	Full 5.06	Full 10.13	Full 28.67	Full 43.01	Full 6.39 FRC 8.85	Full 12.80 FRC 17.72	Full 39.3 FRC 51.18	Full 58.95 FRC 76.77
Restoration (internal + external)	-	-	-	-	-	-	-	-	7.90	15.80	57.94	86.91	6.23	12.46	45.94	68.91

BD, Biodentine (Septodont, Saint-Maur-des-Fossés, France); CR, composite resin; FRC, fiber-reinforced composite; GIC, glass ionomer cement; PDL, periodontal ligament.
Please refer to Figure 2 for the description of R4 and R5.

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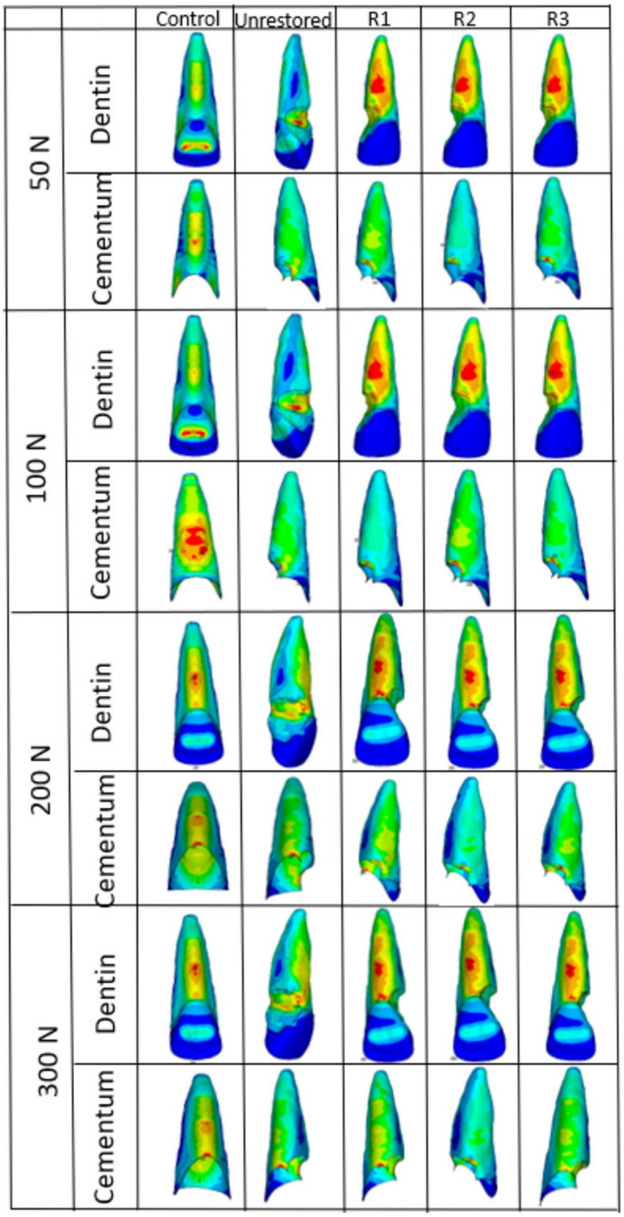

Figure 3. Distribution of von Mises stresses in dentin and cementum in the Patel's three-dimensional classification 2Bd models (control, unrestored, and restored). Please refer to Figure 2 for the description of R1 to R3.

On application of F3 and F4, the maximum stress was observed in the unrestored model. In the 2Bp unrestored model, the dentin component showed maximum stress at the deepest portion of the resorptive defect, which gets transferred into the pulp space adjacent to it. In the dentin component, R4 and R5 have been found to reduce stresses equally and considerably similar to control under F1, F2, F3, and F4. Also, the maximum stress concentration gets transferred to the mid root region on the buccal aspect upon application of F1 and F2, and to the mid root region on both buccal and palatal aspects, with more concentration on the palatal aspect on application of F3 and F4. The stresses increase by 1.8, 3.1, and 2.9 times from F2 to F3 in control, unrestored, and restored models, respectively. With respect to dentin, the control model, unrestored model, and restored models show an increase of 5.4, 2.6, and 3.5 times, respectively. The maximum stress of the cementum component of 2Bp unrestored was observed to be adjacent to the deepest part of the resorptive defect extending buccally on the application of F1 and F2, and palatally on the application of F3 and F4. The maximum stress of the periodontal ligament component was found to be at the apex on the application of all four loads. In 2Bp models, under F1 and F2, von Mises stress was closer to the intact tooth model, while it got reduced below it under F3 and F4. Considering the stress on restorations exclusively, R4 has more stress concentration than R5. The external part that is restored with multilayered restorations is subject to more stress concentration than single-layer restorations, as observed in 2Bd models. On the contrary, R5 has more stress concentration than R4 when the internal part is considered in particular, because FRC takes up more stress. The distribution of von Mises stresses in dentin and cementum in the 2Bd models is given in Figure 4.

DISCUSSION

The strategies in the management of ECR have evolved over the years. However, the loss of structural integrity of the tooth due to chemical, mechanical, and physical reasons could result in a massive drop in success and survival rates after 5 years [8,30–33]. In previous endodontic literature, the impact of traumatic loads on ECR has not been studied. It is observed that the incidence of recurrent trauma ranges from 8% to 45%, and patients under 9 years of age have an eightfold increased risk of re-trauma in comparison to 12-year-olds [34]. Thus, in our study, other than the two normal occlusal loads, two traumatic loads of 200 N and 300 N were chosen. Unlike normal occlusal load, a specific force cannot be attribut-

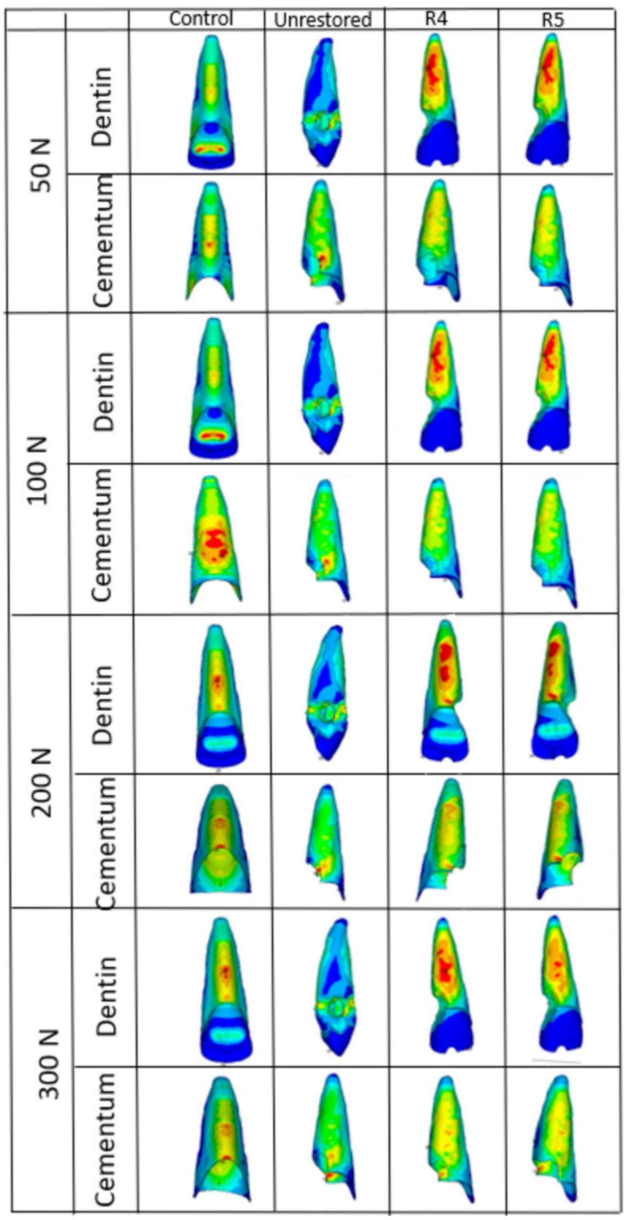

Figure 4. Distribution of von Mises stresses in dentin and cementum in the Patel's three-dimensional classification 2Bp models (control, unrestored, and restored). Please refer to Figure 2 for the description of R4 and R5.

ed to traumatic clinical situations [15,27–29]. Thus, a traumatic load of 200 N was chosen as double the normal masticatory load, and 300 N was chosen based on previous literature [16,17].

Von Mises stress in dentin in the 2Bd unrestored model was 1.8 and 1.2 times more as compared to that of the respective control models under masticatory and traumatic loads. Amongst the 2Bd models, all the restorative strategies resulted in von Mises stress closer to the range of stress in the intact tooth model in the dentin component under masticatory load. It was interesting to note that after being restored, the stress values decreased below the intact tooth model under traumatic load in R1, R2, and R3. In our study, 2Bd models that were completely restored with GIC or Biodentine showed similar von Mises stresses to those of the normal dentin. This was in concurrence with the previous literature where a 2Bd defect in the buccal aspect was restored with Biodentine and Bioaggregate [12,13]. Biodentine and GIC are considered excellent dentin replacement materials due to properties such as tensile stress, modulus of elasticity, Poisson's ratio, and resilience being similar to that of dentin [35,36]. These properties could aid in the uniform distribution of stresses in R1 and R2 in a similar pattern to that of the intact tooth. A recent systematic review has shown that bioactive endodontic cements exclusively are preferred for restoring ECR in approximately 32% of cases [11]. However, a combination of bioactive cements with composites is preferred in 42% of cases [11]. Low wear resistance and non-esthetic properties of these materials restrict the placement to the crestal bone level and layering composite over them in a clinical situation [37,38]. Thus, a combination of various materials (R3) has been considered in this study. R3 has also been shown to reduce von Mises stress similar to normal dentin and hence will be preferred over R1 and R2.

Von Mises stress in dentin in the 2Bp unrestored model was 3.7 and 1.8 times more as compared to the respective control models under masticatory and traumatic loads. It is interesting to note that the masticatory loads showed more stresses than traumatic loads, and this could possibly be because of the change in the angle of load application and the involvement of pulp. In comparison to 2Bd models, when the resorptive lesion involves the pulp, von Mises stresses increase by approximately 2 and 1.5 times under both normal and traumatic load. A previous study has compared various treatment options in multiple resorptive defects depicting dentin and pulpal involvement [13]. However, the increase in stress in pulpal models is not mentioned elaborately.

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In our study, amongst the 2Bp models, internal approaches with or without FRC post resulted in von Mises stress closer to the range of stress in the intact tooth model in the dentin component under masticatory load. In the recent systematic review, it was observed that nearly 34% of ECRs were treated with root canal treatment (internal approach) and only 5% of cases were managed with a combined approach [11]. It was interesting to note that after being restored, the stress values decreased below the intact tooth model under traumatic load in R4 and R5. The use of GIC externally and GP internally has generated the lowest von Mises stress for the 2Bp models in this study, which is similar to that of a previous study [13]. This is the first study to evaluate the role of placing an FRC post and the stress distribution caused thereby in teeth with ECR. It is observed that the placement of an FRC post does not improve the stress distribution when restoring an ECR lesion. Thus, the R4 therapeutic option is preferable as it will reduce multiple interfaces and thereby the bonding difficulties inside the root canal.

In all restorative strategies, the stress gets transferred from the defect to the buccal aspect extending from the middle to the apical third in the root under 50 N and 100 N. These results are similar to the previous FEA studies on ECR [12,13]. In one study, the stress distribution in the root dentin was on the palatal aspect as the defect was on the palatal aspect [14]. In our study under 200 N and 300 N, the stress gets transferred to the cervical to the middle 3rd on the palatal aspect and the middle 3rd on the buccal aspect. This might be due to an increase in the force and the point of application (90˚ to the long axis of the tooth).

In our study, Biodentine, which has a similar Young's modulus (22 GPa) [23] to that of dentin (18.6 GPa) [19], was found to have decreased the stress towards GIC and composite resin. Thus, future research can aim at constructing models with undermining resorptive lesions as well as increasing the thickness of Biodentine in combination with restorations.

The strengths of the current study are the non-invasive, standardized methodology possible with FEA, and that two classes of ECR being repaired with different restorative strategies, including a multilayered restoration for 2Bd models and the combination of GP with FRC post for 2Bp models under a wide range of loading conditions, were evaluated.

However, the limitations include that only a single representative model of each of the 2Bd and 2Bp classes was studied, though clinically, many such patterns of resorption can occur. Secondly, the resorptive defect was created with drills, which might not be as precise as the clinical situation. This was performed to standardize the models (2Bd and 2Bp) at baseline in all dimensions with the exception of pulpal involvement. It is also not very definite if the influence of the surrounding tissue architecture would influence the restorations in the real resorptive defects, as this cannot be replicated in this scenario. The assumption that all tissues and materials were homogenous, isotropic, and elastic, and all surfaces were considered to be ideally bonded, is an inherent disadvantage of FEA, which should be considered while clinically translating the results.

CONCLUSIONS

Within the limitations of the study, it can be concluded that restoring with a single restorative material or multiple layers decreases the stress concentration; multilayered restorations are preferred in 2Bd defects. Placement of the FRC post does not add a significant difference in stress distribution compared to GP alone, and therefore, the use of GP alone is suggested for the internal approach restoration of 2Bp defects.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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AUTHOR CONTRIBUTIONS

Conceptualization: All authors. Data curation, Resources: Ramanujam P, Karthikeyan PVA. Formal analysis, Investigation, Methodology, Visualization: Ramanujam P, Karthikeyan PVA, Suresh N, Srinivasan V, Ulaganathan S. Project administration, Supervision, Validation: Suresh N, Srinivasan V, Ulaganathan S, Natanasabapathy V. Software: Karthikeyan PVA, Ulaganathan S. Writing - original draft: Suresh N, Karthikeyan PVA. Writing - review & editing: Suresh N, Srinivasan V, Ulaganathan S, Natanasabapathy V. All authors read and approved the final manuscript.

DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

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Case Report

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Surgical management of maxillary sinusitis of endodontic origin after reestablishing maxillary sinus floor healing through a nonsurgical approach: a case report

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ABSTRACT

When root canal infections breach the maxillary sinus floor (MSF), maxillary sinusitis of endodontic origin (MSEO) can result. This case illustrates the surgical management of MSEO following the nonsurgical reestablishment of the MSF. A 55-year-old woman presented with left facial pain and was diagnosed with MSEO originating from the left upper first molar. Despite undergoing nonsurgical root canal treatment, there was no evidence of bony healing after 6 months. However, cone-beam computed tomographic (CBCT) scans revealed the reestablishment of MSF. Subsequently, surgical intervention was carried out using a dental operating microscope. Two years after surgery, CBCT images indicated that the mucosal edema had resolved, and the MSF was well reestablished. Preserving the MSF is crucial for the success of endodontic surgery. When MSEO is present, the integrity of the MSF must be assessed to determine appropriate treatment options.

Keywords: Cone-beam computed tomography; Endodontics; Maxillary sinusitis

INTRODUCTION

Endodontic microsurgery has a high success rate and a favorable prognosis [1], making it a reliable treatment option for periradicular pathosis that does not respond to nonsurgical endodontic treatment. However, when this surgical approach is performed on maxillary posterior teeth, there is an increased risk of maxillary sinus

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perforation due to the close proximity of the tooth root apices to the maxillary sinus floor (MSF) [2]. Maxillary sinusitis can occur when the Schneiderian membrane on the MSF is violated by root canal infections originating from the maxillary teeth. This condition is often referred to as maxillary sinusitis of endodontic origin (MSEO) [3], which was previously known as 'endo-antral syndrome' [4]. Additionally, in some instances, the MSF may be extensively damaged by the expansion of pathological tissue. If endodontic surgical procedures are carried out under these circumstances, the roots of the maxillary teeth may become directly exposed to the sinus, potentially leading to unfavorable healing outcomes. Therefore, it is important to consider the proactive healing of the MSF prior to surgical intervention by first performing nonsurgical endodontic treatment. However, to our knowledge, there are no case reports demonstrating the healing of the MSF that facilitates subsequent surgical intervention.

In this context, this case report presents the surgical management of MSEO following the reestablishment of the MSF through a nonsurgical approach.

CASE REPORT

Dental history and diagnosis

A 55-year-old Asian woman presented with complaints of left facial pain. Her medical history was unremarkable. Approximately 3 years prior, she underwent nonsurgical root canal treatment on her maxillary first molar (#26) and second molar (#27) at a private clinic. Examination of the molars in the left upper quadrant revealed normal probing depths, no visible buccal gingival swelling, and no sensitivity to percussion. A periapical radiograph displayed root canal fillings in #26 and #27, along with periradicular radiolucency around the buccal root apexes of #26 (Figure 1A). Sagittal and coronal cone-beam computed tomography (CBCT) images showed a significant periradicular lesion with mucosal edema in the left maxillary sinus (Figure 1B, C). Notably, the MSF between the root apexes of #26 and the maxillary sinus was almost indiscernible.

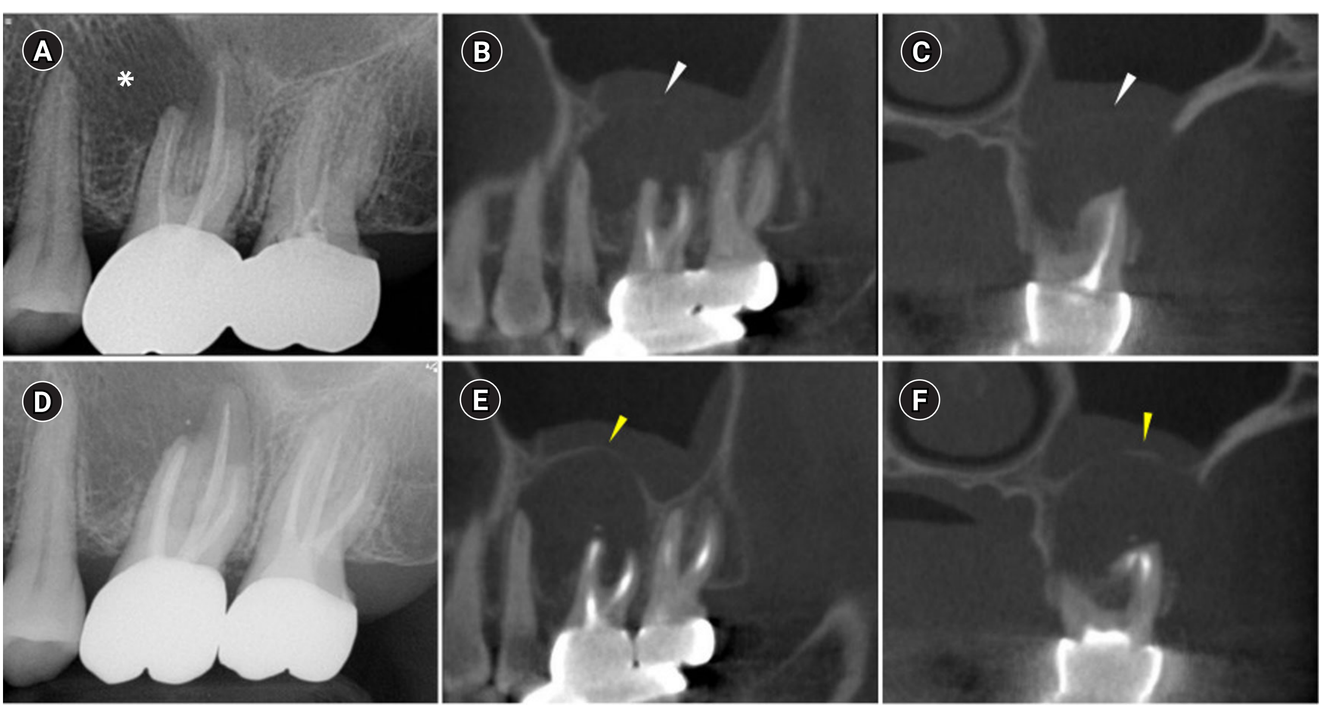

Figure 1. Nonsurgical endodontic treatment. (A) Diagnostic X-ray image. An asterisk indicates periapical radiolucency around the mesiobuccal root. Sagittal (B) and coronal (C) views of diagnostic cone-beam computed tomography (CBCT) images show the destroyed maxillary sinus floor (MSF; white arrowheads) and mucosal edema on the MSF. (D) Periapical X-ray image taken after 6 months. Sagittal (E) and coronal (F) views of CBCT images demonstrate the reestablished MSF (yellow arrowheads).

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Based on these findings, a diagnosis of MSEO with a periapical abscess originating from tooth #26 was made. Due to the risk of unfavorable outcomes, such as endo-antral communication, a surgical approach was ruled out. Instead, nonsurgical root canal treatment was planned. Written informed consent was obtained from the patient.

Nonsurgical and surgical procedures and follow-up visits

Tooth #26 was anesthetized with a 2% lidocaine solution containing 1:100,000 epinephrine by infiltration. The root canal filling material was removed using a reciprocating nickel-titanium instrument (Reciproc R25; VDW, Munich, Germany). Copious irrigation with 5% sodium hypochlorite was performed, and a calcium hydroxide-based intracanal medicament (Calcipex II; Nippon Shika Yakuhin, Shimonoseki, Japan) was placed into the root canals. At the subsequent visit, the patient's symptoms had significantly decreased, and the canals were filled with gutta-percha and a bioceramic sealer (White Endoseal MTA; Maruchi, Wonju, Korea). The access cavities were restored with a light-cure resin composite (Filtek Z350 XT; 3M ESPE, St. Paul, MN, USA). Additionally, root canal treatment on tooth #27 was performed using the same protocols as for #26. Two months later, the patient's symptoms had resolved, and full zirconia crowns were placed on teeth #26 and #27.

At the 6-month follow-up, the patient reported a sensation of fullness in the left facial area. A periapical radiograph revealed no evidence of bony healing (Figure 1D). Interestingly, the sagittal and coronal views from CBCT scans showed a remarkable reestablishment of the cortical MSF, although the size of the mucosal edema and periradicular bony lesion remained unchanged (Figure 1E, F). Consequently, surgical intervention was planned. After informed consent for the surgical procedures was obtained, the procedure began with the reflection of the mucoperiosteal flap, followed by enucleation of the inflamed tissue and resection of the buccal roots-ends (Figure 2A–C). Then, root-end cavities were then prepared with an ultrasonic tip (KiS tip, Young Specialties, Algonquin, IL, USA) and filled with mineral trioxide aggregate (Endocem MTA; Maruchi)

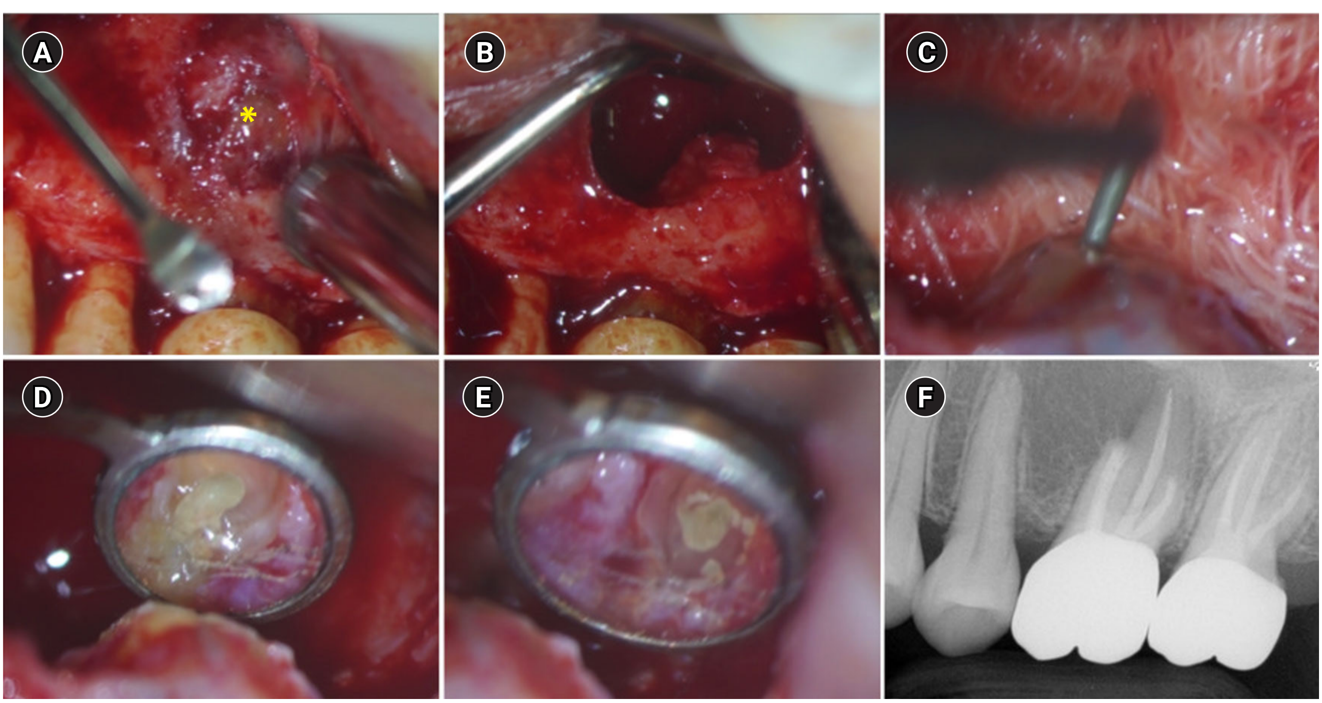

Figure 2. Surgical endodontic treatment procedure. (A) Clinical appearance of the cystic capsule (yellow asterisk). (B) Mesiobuccal root apex within the bony cavity. (C) Preparation of the retrograde cavity using an ultrasonic tip. (D, E) Root-end cavities filled with mineral trioxide aggregate. (F) Postoperative periapical radiographs.

(Figure 2D–F). The excised tissue was sent for pathological examination and was diagnosed as a radicular cyst characterized by stratified squamous epithelium and infiltration of chronic inflammatory cells (Figure 3A, B). Additionally, numerous cholesterol crystals were identified (Figure 3C).

Two years post-surgery, the patient exhibited no symptoms. Additionally, the periapical radiograph and CBCT images indicated bony healing around the roots of tooth #26, and mucosal edema had resolved with a well-reestablished MSF (Figure 4). However, on the coronal view of the CBCT, a well-demarcated radiolucency

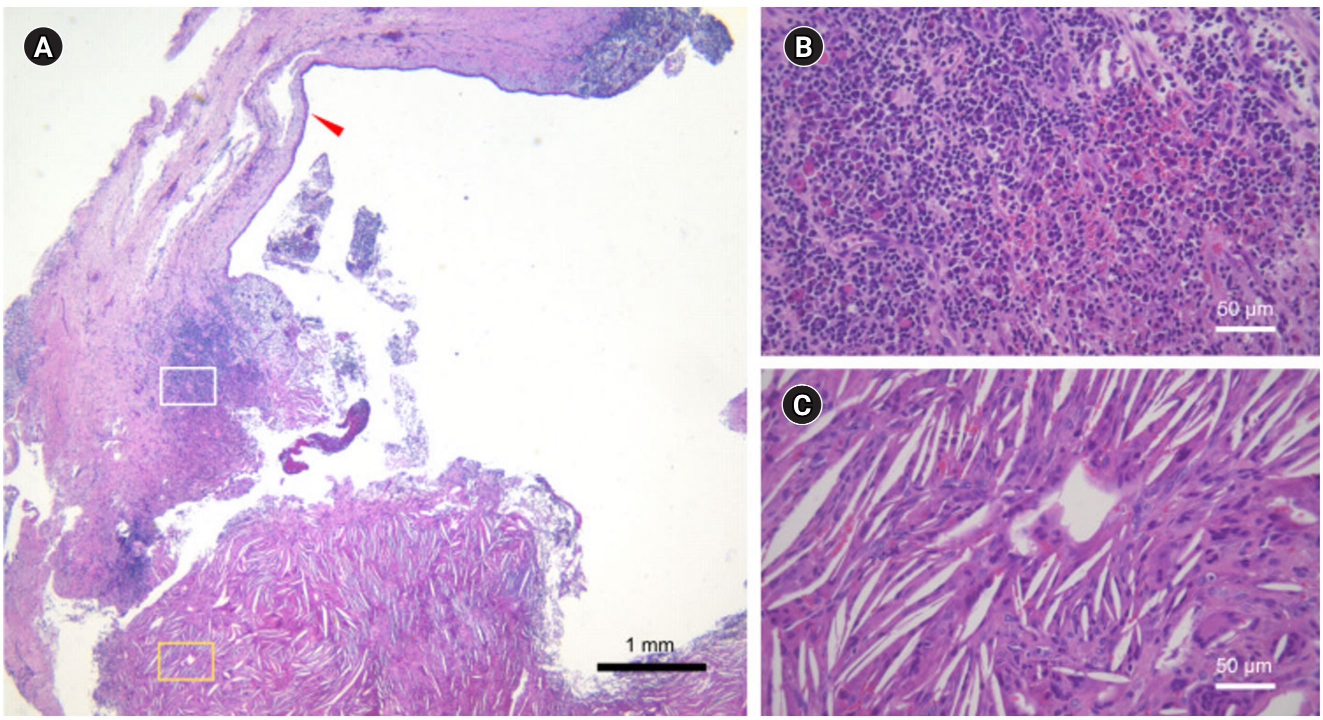

Figure 3. Histological features of the cystic tissue (hematoxylin and eosin staining). (A) The cyst was lined with fibrous connective tissue and stratified squamous epithelium (red arrowhead) (×40). (B) A dense infiltration of chronic inflammatory cells is evident (highlighted within the wihte rectangular box in A). (C) Cholesterol clefts were observed within the cystic wall (indicated by the yellow rectangular box in A).

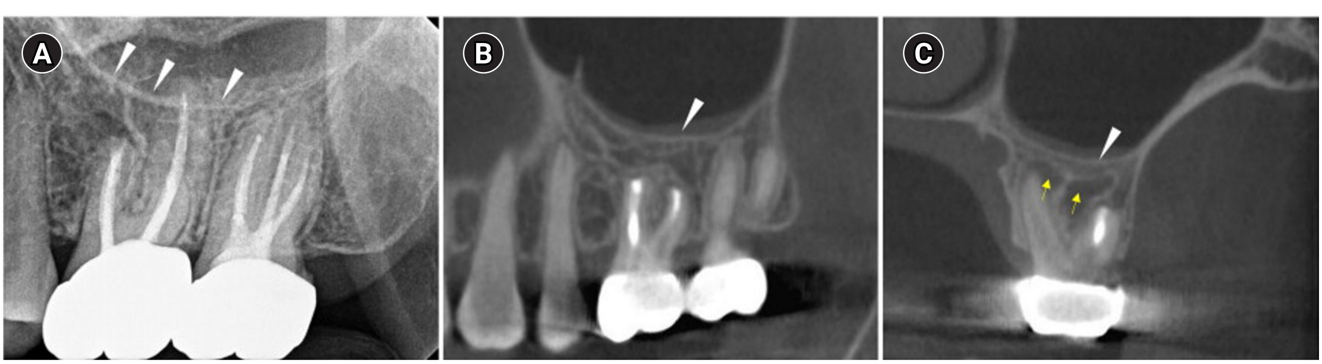

Figure 4. Two-year follow-up radiographs. (A) The periapical radiograph demonstrates bony healing and maxillary sinus floor (MSF) around the root apices. (B, C) Cone-beam computed tomography images reveal favorable bony healing and normal mucosa with a well-defined MSF. The MSF depicted in the radiographs is marked with white arrowheads. Well-demarcated radiolucent areas around the palatal root are indicated with yellow arrows.

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was observed around the buccal aspect of the palatal root (Figure 4C).

DISCUSSION

In this case, we opted to perform nonsurgical endodontic treatment to remove the microorganisms within the root canals and to promote the healing of the lesion. At the 6-month follow-up, we confirmed the remarkable reestablishment of cortical MSF integrity, despite the recurrence of the patient's symptoms and the absence of radiographic changes in the size of the mucosal edema and the bony lesion itself (Figure 1E, F). This phenomenon may have occurred because the overall bacterial load was reduced by nonsurgical endodontic treatment, leading to a decrease in cystic pressure on the MSF. The periradicular lesion in this case was likely a bay cyst, as it was associated with failed root canal treatment and responded to a nonsurgical approach [5]. It is also postulated that the reduction in cystic pressure resulted in less force exerted on the maxillary sinus, particularly under the influence of gravity, thus facilitating the healing of the MSF.

Despite reestablishing the MSF after 6 months, the patient experienced a recurrence of symptoms associated with maxillary sinusitis, and there was no reduction in lesion size. Siqueira noted that there are instances where nonsurgical endodontic treatment adheres to the highest technical standards but still results in failure [6]. Research suggests that certain factors, both microbial and nonmicrobial, may contribute to the unsatisfactory outcomes of cases that have been adequately treated [7,8]. In this case, the periapical lesion was histologically diagnosed as a periapical cyst, associated with failed endodontic treatment. As a result, the cystic cavity is exposed to the infected root canal, increasing the risk of microorganisms egressing into the cavity. Persistent microorganisms and their by-products within the cystic lumen can sustain inflammation, potentially leading to treatment failure due to extraradicular infection. Additionally, the tissue removed during this case was histologically examined, revealing cholesterol crystals and chronic inflammatory cell infiltration (Figure 3). Cholesterol, being water-insoluble, forms thin, flat rhomboid plates, as observed in the cystic lesion [9]. Cholesterol crystals have been implicated as a causative factor in persistent chronic inflammation and are also suggested to hinder the healing of apical periodontitis lesions because macrophages are unable to phagocytize and degrade them [7,10]. Given that cholesterol forms similar crystals in apical periodontitis lesions, it is hypothesized that both extraradicular microbial factors (microorganisms within the cystic lumen) and nonmicrobial factors (cholesterol crystals) may have influenced the failure of the nonsurgical endodontic treatment in this case.

Two years after surgery, the patient exhibited no symptoms, and no radiographic pathosis was evident on periapical radiography. However, coronal views from CBCT scans revealed that a well-demarcated radiolucent area persisted around the buccal aspect of the palatal root (Figure 4C). This suggests that the lesion may be healing, or that an irritant might remain in or around the palatal root, which was not addressed surgically. The fact that we did not perform root-end surgery on the palatal roots, which could have precluded any issues, warrants discussion. Surgical management of the palatal root of the maxillary first molar presents technical challenges. Two approaches are suggested: the buccal or trans-antral approach [11], and the palatal approach, which involves raising a palatal flap to access the root [12]. In this case, we opted against root-end surgery on the palatal root for several reasons. Initially, the trans-antral approach was dismissed as it would render the regenerated MSF inconsequential. Moreover, combining the palatal approach with the buccal approach for managing the buccal roots could lead to a "through-and-through" or "transosseous" lesion, potentially necessitating additional procedures such as guided tissue regeneration with graft material and a barrier membrane. Beyond the surgical management of the palatal root, it is important to determine whether the lesion represents a chronic periapical lesion that has not resolved or is merely scar tissue, especially given the patient's asymptomatic status for two years. Such determination requires histological examination, and it is important to note that radiological and histological findings do not always correlate. The criteria for evaluating the success or failure of root canal treatment include clinical and radiological assessments, as well as the passage of time [13]. Therefore, ongoing follow-up is necessary.

CONCLUSIONS

Preservation of the MSF is another important factor for successful endodontic surgery, and the integrity of the MSF must be assessed to determine appropriate treatment options, especially when MSEO occurs.

CONFLICT OF INTEREST

Kyung-San Min is the Editor-in-Chief of *Restorative Dentistry and Endodontics* and was not involved in the review process of this article. The authors declare no other conflicts of interest.

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None.

AUTHOR CONTRIBUTIONS

Conceptualization, Resources, Supervision: Yu MK, Min KS. Formal analysis, Visualization: Kang ES. Investigation: Kang ES, Kim MK. Methodology: Kang ES, Min KS. Validation: Yu MK, Kim MK. Writing - original draft: Kang ES. Writing - review & editing: Kim MK, Yu MK, Min KS.

DATA SHARING STATEMENT

The datasets are not publicly available but are available from the corresponding author upon reasonable request.

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