The Saudi Dental Journal 36 (2024) 1278–1294

Contents lists available at ScienceDirect

The Saudi Dental Journal

journal homepage: www.ksu.edu.sa
www.sciencedirect.com

Review Article

Retreatability of calcium silicate-based sealers based on micro-computed tomographic evaluation – A systematic review

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ARTICLE INFO

Keywords:
Endosealers
Calcium silicate based sealers
Micro-CT
Retreatment

ABSTRACT

Introduction: Endodontic retreatment procedures with calcium silicate-based sealers (CSS) have been receiving greater credibility in clinically challenging situations. The objective of this systematic review was to analyze the published *in vitro* studies for the retrievability of CSS in comparison to resin-based sealers evaluated using micro-computed tomography (micro-CT) in terms of the volume of the residual root canal filling materials, time taken, efficacy of the solvent, and different systems used during the retreatment procedure.

Methods: The study protocol was registered in the International Prospective Register of Systematic Reviews and conducted in adherence to PRISMA 2020 checklist. Accordingly, an electronic literature search was done to identify studies published in English language, within the time frame from January 2004 to June 2024. The search was conducted through popular databases including PubMed (Medline – National Library of Medicine), Scopus (Science Direct), EMBASE and Google Scholar following the inclusion and exclusion criteria answering the research question in focus.

Results: After thorough scrutiny, 15 studies qualified for the systematic review. Following retreatment, in all of the studies pre-treatment working length was achieved, with both the types of endodontic sealers. However, none of the micro-CT studies reported complete removal of endodontic filling material from the root canals. Irrespective of the sealer type used, within each root canal, apical third had the greatest amount of remaining filling material, followed by the middle and coronal thirds.

Conclusions: Retreatment of canals obturated with bioceramic sealers is feasible in most cases using traditional instruments and techniques. Active irrigation and supplemental mechanical removal, which employs lasers, XP-Finisher, and ultrasonics, adds advantage to maximize material removal.

1. Introduction

Calcium silicate-based sealers (CSS), have gained more preference over other endodontic sealers in the recent times. Choice of the endodontic sealer, is a critical factor for the success of non-surgical endodontics (Zhou, Shen et al. 2013). The application of these sealers as a slender, adhesive paste during obturation, satisfies the dual purpose of cementing the gutta percha and as lubrication (Camilleri 2015). An additional advantage of sealers is filling up of auxiliary canals, lateral canals and cavities inaccessible to the core obturation materials. (Fernández, Restrepo et al. 2016).

Based on their setting reaction & composition, the endodontic sealers are categorized into epoxy resin, glass ionomer, silicon, calcium silicate (bioceramics sealers) and zinc systems (Lim, Jung et al. 2020). Calcium silicate based sealers have proven biocompatibility, high levels of hermetic seal, radiopacity and chemical bonding with the tooth structure (Prati and Gandolfi 2015; Raghavendra, Jadhav et al. 2017). In addition, these bioceramic sealers being porous and containing nanocrystals of 1–3 nm also demonstrate commendable antibacterial properties through bacterial sequestration and prevention of microbial adhesion (Jitaru, Hodisan et al. 2016). In comparison, epoxy resin sealers have also found widespread usage due to their attributes of apical sealing capability, low solubility and favorable handling properties (Baldi, Bernardes et al. 2012).

Effective debridement of the canal space along with the adequate bioseal ensures the long term success of the root canal treatment (Iandolo, Abdellatif et al. 2020). However, more often, this is not completely achieved due to the complexities in the root canal system

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https://doi.org/10.1016/j.sdentj.2024.09.011
Received 19 August 2024; Received in revised form 8 September 2024; Accepted 8 September 2024
Available online 10 September 2024

thus leading to persistence of infected endodontic microbiota (Dioguardi, Di Gioia et al. 2019). Bio mechanical root preparation in endodontic retreatments focus on appropriate removal of the residual filling material and secondary smear layer with effective microbial reduction (Jayakodi, Kailasam et al. 2012). This further enables, intact adaptation of the guttapercha followed by a possible resin post to the dentin in the canal space (Nair, Sjögren et al. 1999; Haapasalo, Shen et al. 2008).

In clinical scenarios, the concerns raised over retrievability of CSS during retreatments is due to its hard setting and insolubility in commonly used solvents like chloroform (Guivarc'h, Jeanneau et al. 2020). Evidence-based studies have debated the nature of the bonding between CSS and dentin which is effective as a result of mechanical interlocking by tubular (dentinal tubule) diffusion (Zhang, Li et al. 2009) or development of a mineral infiltration zone (Raghavendra, Jadhav et al. 2017; Aminoshariae, Primus et al. 2022) or formation of hydroxyapatite through reaction of calcium silicates and moisture in dentin (Zhang, Shen et al. 2009). Nevertheless, the adversity in retreatment of root canals filled with CSS from the apical third of the root, thermal compaction incompatibility, unfavorable resorption time, interactions with rinsing solutions like EDTA are also reported as some of the major disadvantages (Massi, Tanomaru-Filho et al. 2011; Formosa, Mallia et al. 2012; Parirokh and Torabinejad 2014).

Several approaches have been used for retreatment procedure such as; ProTaper universal retreatment system, ProFile ISO rotary instrumentation system, or nickel-titanium or reciprocating stainless steel filing systems. In addition, several of the recent supplemental methods like XP-endo finisher (Aksel, Küçükkaya Eren et al. 2019), ultrasonic tips (Crozeta, Lopes et al. 2021), Gentlewave systems (Wright, Glickman et al. 2019), photo-initiated photon acoustic streaming (PIPS) (Suk, Bago et al. 2017), and passive ultrasonic irrigation (Alsubait, Alhathlol et al. 2021) have enhanced the obturation material removal procedures. Nonetheless, total removal of the filling material is not achieved by any of these retreatment methods (Rossi-Fedele and Ahmed 2017).

Effective cleaning of the canal space during retreatment should result in 0.5 % of the residual obturation material (Solomonov, Paqué et al. 2012). Retrievability of the CSS during retreatment pose serious challenges due to the strong chemical bonding with the dentin (Alves, Rôças et al. 2022). The level of difficulty is often compared in terms of volume of the remaining filling material, retreatment time, working length and apical patency between the various commercially available endodontic sealers (de Mello Junior, Cunha et al. 2009). Currently AH plus sealers are the most popularly used epoxy resin-based sealers and hence used as golden standard for comparison to ascertain the efficacy of the studied sealer material (Akcay, Arslan et al. 2016).

In previous published reports, volume of remaining filling material was quantified using direct visualization, camera or stereomicroscope which were considered inaccurate as they were two dimensional interpretations of the three dimensional canal space (Betti and Bramante 2001; Bodrumlu, Uzun et al. 2008; Ajina, Shah et al. 2022). Similar two dimensional observations were also made using conventional radiographs measuring only the area (mm^2) of the remaining filling material (Masiero and Barletta 2005). With recent advances in technology scanning electron microscopy, (Donyavi, Shokri et al. 2019) and micro-CT (Rossi-Fedele and Ahmed 2017) are being increasingly used for analyzing the samples obtained through longitudinal sectioning and clearing (Hess, Solomon et al. 2011) subsequent to retreatment.

In recent times, micro-CT is the most commonly used evaluation method to compare the quantified root canal filling material before and after the retreatment. Micro-CT is a nondestructive, high-resolution, three- dimensional imaging technology which enables repeated exposures, for accurate acquisition of information (Al-Hezaimi, Ramalingam et al. 2016; Versiani, Ordinola-Zapata et al. 2016). Unlike clearing or sectioning techniques micro-CT evaluation is advantageous in facilitating sequential analysis of the samples.

Although, a large number of research conducted earlier have adopted similar methodology, no efforts have been made to conduct a qualitative analysis of their study findings. Accordingly, the objective of the current systematic review was to analyze the published literature on *in vitro* researches, for retrievability of calcium silicate-based sealers evaluated using micro-CT. The primary objectives was to compare the volume (%) of the residual root canal filling materials following retreatment. The secondary objectives included assessment of the time taken, efficacy of the solvent and different systems used during the retreatment procedure.

2. Materials and Methods

2.1. Focused question and search strategy

The present systematic review was conducted to address the focused question, "What is the retreatability of root canals treated with calcium-silicate based endodontic sealers as compared to resin based sealers?" In order to answer the above question, the review focused on identifying studies comparing retreatability of root canals after treatment with both types of sealers, and with their respective outcomes measured using micro-CT.

Following registration of the study protocol in the International Prospective Register of Systematic Reviews (PROSPERO ID – CRD42024524196), the review was conducted in adherence to the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) checklist". Accordingly, an electronic literature search was done to identify studies published in English language, within a time frame from January 2004 to June 2024. The search was conducted through popular databases including PubMed (Medline – National Library of Medicine), Scopus (Science Direct), EMBASE and Google Scholar. In addition, registries such as the Cochrane CENTRAL registry of trials, ProQuest and OATD.org (registries for theses and dissertations) were also searched.

The literature search was carried out using a combination of MeSH (Medical Subject Headings) terms and keywords including but not limited to: "endodontic treatment", "root canal treatment", "retreatment", "endodontic sealer", "calcium-silicate sealer", "bioceramic sealer", "endodontic sealer removal", "root canal sealer removal", "remaining endodontic sealer", "root canal patency", and "radiographic assessment", along with "AND", "OR", "NOT" (Boolean operators).

2.2. Eligibility, inclusion and exclusion criteria

In order to answer the focused review question, the study eligibility criteria were formulated using PICOS (Population, Intervention, Comparison, Outcome and Study setting), and accordingly only studies meeting the following (PICOS) conditions were included in the review.

P – Studies conducted on extracted human permanent teeth, with roots that were complete and mature.

I – Use of calcium-silicate based sealers for obturation following endodontic treatment.

C – Use of epoxy-resin based sealers for obturation following endodontic treatment.

O – Endodontic retreatability to achieve root canal patency and assessed in terms of either remaining volume or reduction in volume of root canal filling material, retreatment time and any additional procedures performed (irrigation techniques, solvent use…etc.) during retreatment.

S – In vitro studies wherein micro-CT was used as the method of outcome assessment.

Clinical studies, studies performed in animals, artificial teeth, narrative reviews, book chapters, conference abstracts, and expert opinion were explicitly excluded from this review. In addition, non-English articles, studies reporting about retreatability only after using calcium-silicate based sealers or epoxy-resin based sealers, and those studies not reporting outcomes based on micro-CT were selectively

excluded.

2.3. Study selection

The selection of studies for inclusion in the review followed a two-phase process. In both phases, study selection was carried out by two independent reviewers, who were previously scored for inter-reviewer agreement based on a pilot sample of 10 articles (Cohen's kappa score – 0.87). In the initial phase, the reviewers carefully identified studies from electronic databases and examined their titles and abstracts. In addition to articles with titles and abstracts meeting the predetermined inclusion criteria, studies lacking abstracts yet appearing relevant based on their titles were also selected. In the second phase, the identified studies were screened for eligibility and any duplicates or reports with similar datasets were removed. This was followed by retrieval of full-text articles, which were thoroughly read by both reviewers and any study was accepted for final review only when it was accepted by both. In cases where there were differences of opinion regarding the eligibility of a particular study, the reviewers engaged in discussions until a consensus was arrived at. These discussions aimed to address any discrepancies and resolve disagreements regarding a study's eligibility, thereby ensuring an objective evaluation and resolution of conflicts in a fair and systematic manner.

2.4. Assessment for risk-of-bias

The selected studies were subjected to assessment for quality and risk-of-bias using the "Quality Assessment Tool for In vitro Studies" (QUIN Tool) (Sheth, Shah et al. 2024). This particular tool was selected for quality assessment, as it was specifically designed and tested for evaluating risk-of-bias among *in vitro* studies, conducted in the field of dentistry. Furthermore, the QUIN tool uses a 3-point scoring scale based on 12 items, which is used to determine if a particular study has low, medium or high risk-of-bias, in reporting. This was followed by

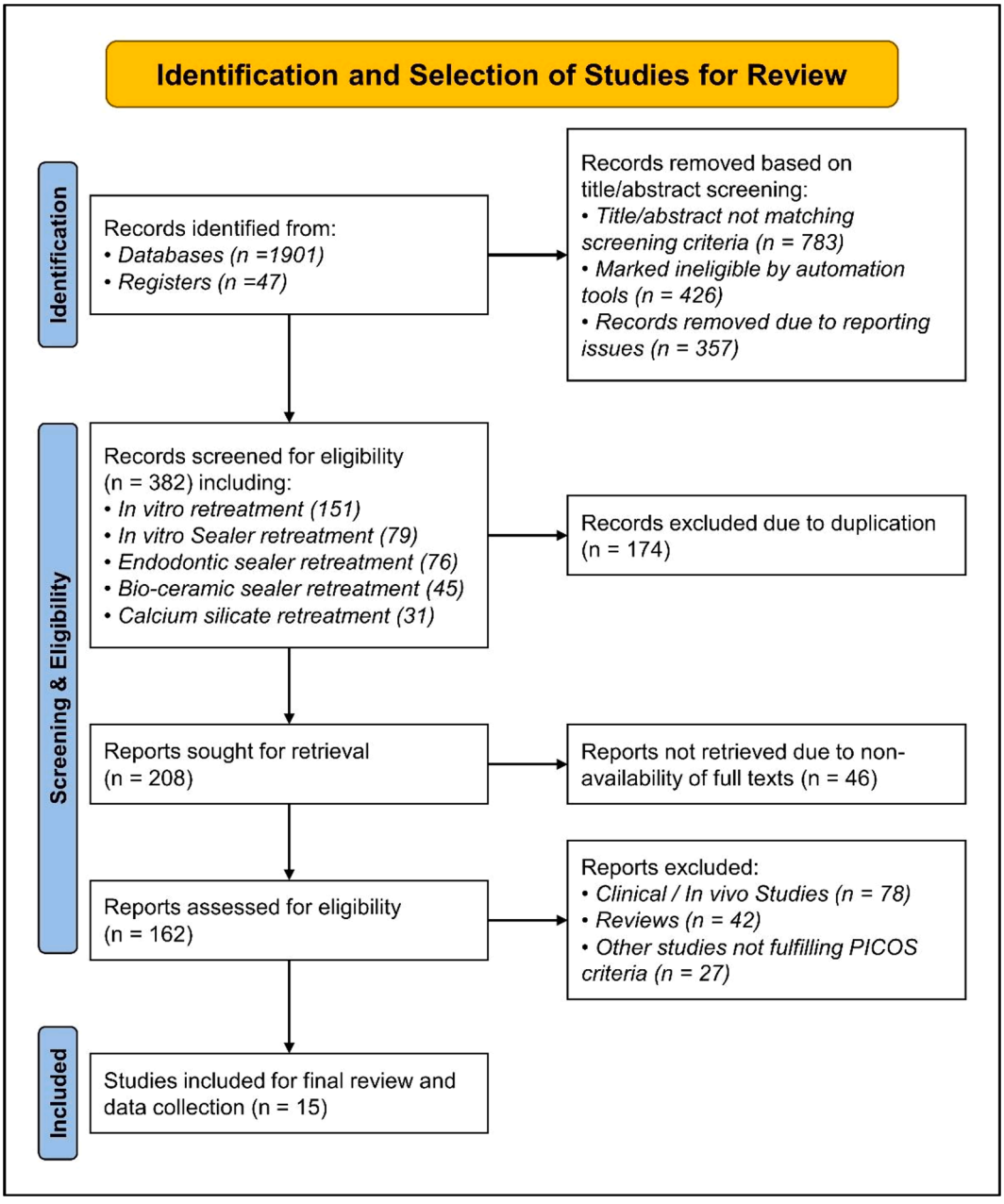

Fig. 1. Flow chart explaining the process of screening, eligibility and study selection.

tabulation of the final selected studies for data extraction, using MS-Excel spreadsheet software (Microsoft Office Excel 2019, Microsoft Corp., Redmond, VA, USA).

2.5. Data collection

Data extraction included name of the author(s), year of publication, study objective(s), sample size and characteristics, nature of calcium-silicate based sealer and comparison (epoxy-resin based) sealer, retreatment techniques, solvent, evaluation method, and outcomes reported. While retreatability was the overall qualitative outcome measured, specific quantitative outcomes such as remaining volume or reduction in volume of endodontic filling material, percentage re-establishment of canal patency and working length, and time taken for retreatment were also recorded.

3. Results

3.1. Study selection and study characteristics

A total of 1948 titles and abstracts were obtained through initial search conducted on databases and registries. Screening these titles and abstracts for eligibility based on matching criteria and reporting quality, 382 records were identified as eligible for further evaluation. Among these 382 records, only 208 were sought for full text retrieval and the remaining 174 records had to be excluded due to duplication. 162 eligible full-text articles were retrieved and reviewed, leading to the selection of 15 articles for the final systematic review. Reasons for exclusion at each level and the detailed study selection process are outlined as a flowchart in Fig. 1.

All the selected studies fulfilled the PICOS criteria of *in vitro* studies on extracted human teeth (P), compared retreatability following endodontic treatment with calcium-silicate based sealers (I) and epoxy-resin based sealers (C), evaluated outcomes qualitatively and quantitatively (O) and utilized micro-CT for evaluating endodontic retreatment (S). When the selected studies were subjected to assessment for quality and bias, based on the QUIN Tool, only three out of the 15 studies were found to have a medium risk-of-bias (Romeiro, de Almeida et al. 2020; Rajda, Miletić et al. 2021; Baraba, Rajda et al. 2023). All the other studies had a low risk-of-bias, thereby establishing transparency of collected evidence and quality of results and findings synthesized (Fig. 2). The detailed characteristics of each study and their respectively reported outcomes are elucidated in Table 1.

3.2. Sample sizes and their characteristics

Among all the reviewed studies, a total of 684 extracted human teeth/root canals underwent retreatment after obturation with either calcium-silicates based sealer (n = 371) or epoxy-resin based sealer (n = 313). This predominantly included mandibular molars (n = 239), followed by mandibular premolars (n = 139), maxillary incisors (n = 119), maxillary 2nd premolars (n = 79), mandibular incisors (n = 63) and maxillary molars (n = 45). In most of the reviewed studies, retreatment was evaluated based on root canal preparation and obturation of single canals, except for one study, which reported outcomes based on mandibular molars with 2 mesial canals and separate apical foramina (Romeiro, de Almeida et al. 2020). While most of the studies were based on endodontic treatment of straight or non-curved canals, four studies evaluated retreatability of curved root canals (Aksel, Küçükkaya Eren et al. 2019; Romeiro, de Almeida et al. 2020; Mavishna and Venkatesh 2021; Mufti and Al-Nazhan 2021). More specifically, (Mufti and Al-Nazhan 2021) classified root canals treated in their study based on Schneider's method, and compared between canals that had mild (≤15 degrees), moderate (16–30 degrees) or severe (≥31 degrees) curvature. In addition, one study reported outcomes based on retreatment of oval shaped root canals (Kim, Jang et al. 2024), and three studies evaluated retreatability of C-shaped root canals (Crozeta, Lopes et al. 2021; Rajda, Miletić et al. 2021; Jamleh, Nassar et al. 2023). With respect to the remaining studies wherein teeth with curved canals were excluded from the sample, there was considerable heterogeneity in terms of criteria for exclusion based on curvature, which ranged from 5 degrees to 20 degrees. Nevertheless, teeth with fractures, restorations, resorption and calcification were excluded from the sampling frame in all reviewed studies. (Table 1).

3.3. Types of sealers used

Within the presently reviewed studies, several types of bioceramic, calcium-silicate based sealers were compared against epoxy-resin based sealers. Although EndoSequence BC (Brasseler, Georgia, USA), was the

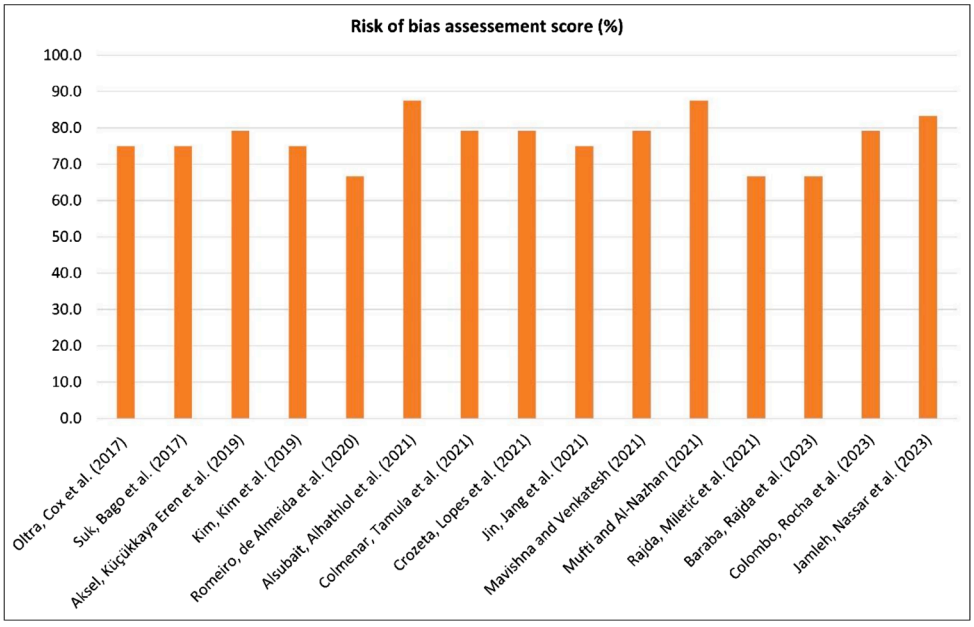

Fig. 2. Graph showing the overall score for each one of the selected studies after assessment for quality and risk-of-bias, based on "Quality Assessment Tool For *in vitro* Studies" – QUIN tool (Sheth et al., 2024).

Table 1

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
Oltra, Cox et al. (2017)	Compare retreatability of root canals filled with either calcium-silicate based sealer or resin-based sealer, and with or without the use of solvent chloroform.	56 maxillary incisors with single canals, divided into four groups (n = 14 per group). Teeth with canal curvature > 20 degrees, restorations or calcifications were excluded.	EndoSequence BC (Brasseler, Georgia, USA)	AH Plus (Dentsply, Konstanz, Germany)	Rotary instrumentation system until WL was reached. For each sealer type, one group underwent retreatment with solvent and no solvent used in other group. All root canals irrigated using 6 % NaOCl, 17 % EDTA and normal saline.	ProFile ISO (Dentsply Maillefer, Ballaigues, Switzerland)	Chloroform 0.2 ml per root canal	–	Retreatment done 30 days after initial obturation. *__Volume of remaining filling material__ Significantly lowest ($p < 0.05$) in AH Plus-Solvent group. EndoSequence BC had the highest volume of remaining filling material followed by AH Plus and EndoSequence BC-Solvent group. *__Re-establishment of WL and patency__ – AH Plus (with or without solvent) – 100 % Endosequence BC-Solvent – 93 % Endosequence BC – WL in 93 % teeth and Patency in 14 % teeth.		Skyscan 1067 Micro CT (Bruker, Kontich, Belgium). Operating at 65 kV, 10 W, 154 μA, 0.5 mm aluminiinium filtration, 160 ms exposure and 0.7 degree rotation step. Voxel size 35 μm.
Suk (2017)	Compare retreatability of oval root canals filled with either calcium-silicate based sealer or resin-based sealer, and to evaluate efficacy of photoacoustic streaming.	36 single-rooted teeth (maxillary and mandibular second premolars and incisors), divided into three groups (n = 12 per group). Teeth with caries, resorption, restorations or calcifications were excluded.	EndoSequence BC (Brasseler, Georgia, USA) MTA Fillapex (Angelus Dental, Londrina, Brazil)	AH Plus (Dentsply, Konstanz, Germany)	Rotary instrumentation system until WL was reached. All root canals irrigated using 2.5 % NaOCl, 15 % EDTA and normal saline.	ProTaper (Dentsply Maillefer, Ballaigues, Switzerland)	–	PIPS was done with Er:YAG laser at 2940 nm, with 2.5 % NaOCl and for 60 s.	Retreatment done 14 days after initial obturation. * **Volume of remaining filling material** Significantly reduced in all groups ($p < 0.05$), Highest reduction in MTA Fillapex group (97.73 %) followed by EndoSequence BC (78.55 %) and AH Plus (72.86 %) groups. Further significant reduction ($p < 0.05$) in volume of remaining filling material after PIPS in all groups (MTA Fillapex – 99.25 %; EndoSequence BC –	–	Nikon XT H 225 Micro CT (Nikon Industrial, USA). Operating at 80 kV, 60 μA, 1 s exposure, and 0.7 μm focal spot and 127 μm pixel size.

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Table 1 (*continued*)

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
									96.43 %; AH PLus – 74.16 %). ***Calcium silicate sealers were better removed after rotary instrumentation and PIPS.**		
Aksel, Küçükkaya Eren et al. (2019)	Compare retreatability of root canals filled with either calcium-slicate based sealer or resin-based sealer.	30 mandibular molars with moderately curved mesiobuccal root canals (20–30 degrees), divided into three groups (n = 10 per group). Teeth with fracture, restorations or calcifications were excluded.	NeoMTA Plus (Avalon Biomed Inc., Florida, USA) & EndoSequence BC (Brasseler, Georgia, USA)	AH Plus (Dentsply, Konstanz, Germany)	Rotary instrumentation system until WL was reached. Root canals were irrigated using 2.5 % NaOCl, 17 % EDTA and distilled water.	ProTaper (Dentsply Maillefer, Ballaigues, Switzerland)	–	XP-Endo finisher file (FKG Dentaire, Le Crêt-du-Locle, Switzerland) used at 800 RPM for 20 s, 2 mm short of WL and with 2.5 NaOCl irrigant solution.	Retreatment done 14 days after initial obturation. ***Volume of remaining filling material** No significant difference between the groups (NeoMTA Plus – 9.07 %; EndoSequence BC – 7.55 %; AH Plus – 18.1 %). Additional preparation with XP Endo finisher files resulted in further significant reduction in volume of remaining filling material (NeoMTA Plus – 4.87 %; EndoSequence BC – 3.5 %; AH Plus – 8.78 %), without any significant difference between the groups. ***Remaining root canal filling material, after retreatment, was highest with epoxy resin based sealer than with calcium silicate based sealers.**	–	Skyscan 1174 Micro CT (Bruker, Kontich, Belgium). Operating at 50 kV, 800 μA, 30 % beam hardening, 33 μm pixel size 2500 ms exposure and 0.7 degree rotation step.
Kim, Kim et al. (2019)	Compare retreatability of root canals filled with either calcium-silicate based sealer or resin-based sealer.	21 mandibular premolars (one root), 21 maxillary premolars (two roots) 15 mandibular molars with c-	EndoSeal MTA (Maruchi, Wonju,Korea) & EndoSequence BC (Brasseler, Georgia, USA)	AH Plus (Dentsply, Konstanz, Germany)	Rotary instrumentation system until WL was reached. Root canals were irrigated using 3 % NaOCl, 17 %	ProFile ISO (Dentsply Maillefer, Ballaigues, Switzerland)	–	–	Retreatment done 10 days after initial obturation. ***Volume (%) of remaining filling material** Significantly higher ($p < 0.05$) in C-	–	Skyscan 1172 Micro CT (Bruker, Kontich, Belgium). Operating at 100 kV, 100 μA, 0.5 mm

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Table 1 (*continued*)

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
		shaped root canals.			EDTA and normal saline.				shaped root canals, for all tested endodontic sealers. Highest in the apical third irrespective of the root configuration or type of sealer used. EndoSequence BC resulted in highest remaining filling material with single-rooted (3.92 %) and double-rooted (7.4 %) teeth **EndoSeal MTA had the highest remaining filling material in C-shaped canals (38.89 %).** AH Plus had the lowest remaining volume of filling material for single and double-rooted teeth.		aluminiinium filtration, and 0.83 degree rotation step for 180 degree rotation. Voxel size 23.86 μm.
Romeiro (2020)	Compare retreatability of severely curved root canals filled with calcium-silicate based sealer or resin based sealer, and treated using two types of reciprocating instrumentation systems	60 mandibular first or second molars with severe curvature (20—40 degrees) and two mesial canals with independent apical foramina, divided into four groups (n = 15 per group). Teeth with fracture, resorption, restorations or calcifications were excluded.	EndoSequence BC (Brasseler, Georgia, USA)	AH Plus (Dentsply, Konstanz, Germany)	Reciprocating instrumentation system until WL was reached. All root canals were irrigated with 2.5 % NaOCl, 17 % EDTA and normal saline.	Reciproc or ReciprocBlue (VDW, Munich, Germany)	–	–	Retreatment was done 30 days after intitial obturation. *__Volume (%) of remaining filling material__ Not significantly different between the groups. Greatest reduction was observed in Endosequence BC/ Reciproc group (91.71 ± 6.56 %), followed by AH Plus ReciprocBlue (86.82 ± 9.33 %), EndoSequence BC/ ReciprocBlue (86.51 ± 12.08 %) and AH Plus/Reciproc (84.64 ± 9.07 %) groups. *__In all groups, lowest reduction in remaining filling material__	Significantly different between the groups ($P<0.01$), Lowest time (minutes) taken for AH Plus groups (Reciproc − 1.39 ± 0.40; ReciprocBlue − 1.79 ± 0.53) followed by EndoSequence BC groups (Reciproc − 2.0 ± 0.75; ReciprocBlue − 2.40 ± 1.33).	Skyscan 1172 Micro CT (Bruker, Kontich, Belgium). Operating at 100 kV, 100 μA, 1 mm copper/ aluminiinium filtration, and 0.5 degree rotation step for 360 degree rotation. Voxel size 17.87 μm.

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Table 1 (*continued*)

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
									was seen in the apical thirds, followed by middle and coronal thirds.		
Alsubait, Alhathlol et al. (2021)	Compare retreatability of root canals filled with either calcium-slicate based sealer or resin-based sealer.	34 mandibular premolars, divided into two groups (n = 17 per group). Teeth with apical canal curvature > 5 degrees, restorations or calcifications were excluded.	BioRoot RCS (Septodont, Saint-Maur-des-Fosses, France)	AH Plus (Dentsply, Konstanz, Germany)	Rotary instrumentation system until WL was reached. Root canals were irrigated with 17 % EDTA, 2.5 % NaOCl and normal saline.	ProTaper (Dentsply Maillefer, Ballaigues, Switzerland)	–	Passive ultrasonic irrigation with NaOCl (2.5 %)	Retreatment was done 30 days after intitial obturation. ***Volume (%) of remaining filling material** **S**ignificantly lower ($p < 0.05$) in BioRoot RCS group (7.96 ± 8.18) than in AH Plus group (14.48 ± 11.92). Use of ultrasonic irrigation resulted in highly significant reduction ($p < 0.01$) in both groups (BioRoot RCS − 3.88 ± 4.9; AH Plus − 10.77 ± 9.18). ***Use of BioRoot RCS resulted in better retreatment outcomes**.	BioRoot RCS filled canals (135.28 ± 18.33 s) took significantly longer than AH Plus filled canals (113.29 ± 21.72 s) ($p < 0.01$)	Operating at 94 kV, 85 μA, 0.25 mm brass filtration, and 0.5 degree rotation step for 360 degree rotation. Voxel size 19 μm.
Colmenar, Tamula et al. (2021)	Compare retreatability of root canals filled with either calcium-slicate based sealer or resin-based sealer.	10 anterior teeth with single canals, divided into two groups (n = 5 per group). Teeth with fracture, restorations or calcifications were excluded.	EndoSequence BC (Brasseler, Georgia, USA)	AH Plus (Dentsply, Konstanz, Germany)	Rotary instrumentation system until WL was reached. No information mentioned about nature and type of irrigation.	ProTaper (Dentsply Maillefer, Ballaigues, Switzerland)	–	–	Retreatment was done 90 days after intitial obturation. ***Volume (%) of remaining filling material** No statistically significant difference was observed between the two groups, and between the different root sections within each group (EndoSequence BC − coronal 92.9 ± 7.3 % / middle 94.9 ± 8.5 % / apical 76.2 ± 27.9 %; AH Plus − coronal 93.2 ± 6.1 % / middle 96.5 ± 6.1 % / 70.1 ± 30.8 %).	–	Skyscan 1272 Micro CT (Bruker, Kontich, Belgium). Operating at 90 kV, 110 μA, and 1 mm copper/ alumininium filtration. Voxel size 6 μm.

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Table 1 (*continued*)

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
Crozeta (2021)	Compare retreatability of oval root canals filled with either calcium-silicate based sealer or resin-based sealer, and to evaluate efficacy of supplemental finishing techniques.	28 mandibular molars with oval and single distal root canals and mild curvature (0—–10 degrees), divided into four groups (n = 7 per group). Teeth with fracture, resorption, restorations or calcifications were excluded.	EndoSequence BC (Brasseler, Georgia, USA)	AH Plus (Dentsply, Konstanz, Germany)	Reciprocating instrumentation system until WL was reached. Root canals were irrigated using 2.5 % NaOCl and normal saline.	Reciproc R50 (VDW, Munich, Germany)	–	Ultrasonic irrigation (30 % power) and 2.5 % NaOCl or XP Endo finisher file at 1000 RPM and 2.5 % NaOCl	Retreatment was done 14 days after intitial obturation. ***Volume (%) of remaining filling material** Significantly different between the two groups. Lower with EndoSequence BC (24.9 ± 13.27 %) than with AH Plus (35.05 ± 10.26 %). Following, ultrasonic instrumentation, significantly reduced ($p < 0.05$) for both groups (EndoSequence BC − 11.6 ± 5.7 %; AH Plus − 27.0 ± 7.5 %). ***Reduction in filling material after XP Endo finisher was significant ($p < 0.05$) only for AH Plus (23.4 ± 8.3 %) and not for EndoSequence BC (22.9 ± 15.1 %; $p = 0.523$).**	–	Skyscan 1176 Micro CT (Bruker, Kontich, Belgium). Operating at 90 kV, 276 μA, 0.1 mm copper filtration, and 0.7 degree rotation step for 360 degree rotation.
Jin, Jang et al. (2021)	Compare retreatability of root canals filled with either calcium-silicate based sealer or resin-based sealer, and their post-retreatment obturation.	40 single-rooted maxillary premolars, divided into four groups (n = 10 per group). Based on (single cone or continuous wave) obturation, each group subdivided into two groups.	Endoseal TCS (Maruchi, Wonju,Korea)	AH Plus (Dentsply, Konstanz, Germany)	Removal of endodontic filling material was done using rotary instrumentation system until WL was reached. All root canals were irrigated with 2.5 % NaOCl.	ProTaper (Dentsply Maillefer, Ballaigues, Switzerland)	–	–	Retreatment was done 7 days after intitial obturation. ***Volume (%) of remaining filling material** **S**ignificantly ($p <$ 0.05) higher in the Endoseal TCS groups (2.54 ± 1.56) than in the AH Plus groups (1.74 ± 0.87), irrespective of obturation technique. During initial obturation, use of Endoseal TCS resulted in significantly ($p <$	–	Skyscan 1272 Micro CT (Bruker, Kontich, Belgium). Operating at 70 kV, 142 μA, 0.5 mm aluminium filtration, and 0.6 degree rotation step for 180 degree rotation. Voxel size 12 μm.

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Table 1 (*continued*)

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
									0.05) lower void volume than with AH Plus. *__Post-retreatment obturation the void volume was not significantly different.__		
Mavishna and Venkatesh (2021)	Compare retreatability of curved root canals filled with either calcium-silicate based sealer or resin-based sealer	45 maxillary first molars (with curved mesio-buccal root), divided into three groups (n = 15 per group). Canal curvature was confirmed by Schneiders test.	BioRoot RCS (Septodont, Saint-Maur-des-Fosses, France) & MTA Fillapex (Angelus Dental, Londrina, Brazil)	Dia-Proseal (DiaDent, Cheongju-si, Korea)	Rotary instrumentation system until WL was reached. All root canals were irrigated with 3 % NaOCl, 17 % EDTA and normal saline.	ProTaper (Dentsply Maillefer, Ballaigues, Switzerland)	–	–	Retreatment was done 120 days after intitial obturation. *__Volume (%) of remaining filling material__ Highest in BioRoot RCS group (0.11 cu.mm), followed by MTA Fillapex group (0.07 cu.mm) and Dia-Proseal group Differences were statistically significant ($p < 0.001$) between groups. In all groups, remaining root canal sealer volume was significantly ($p < 0.001$) higher in the apical third, followed by the middle and coronal thirds. Cross-sectional evaluation of the root canal walls showed more cracks in Dia-Proseal group followed by MTA Fillapex group. **No cracks were obsrved in BioRoot RCS group.**	–	Operating at 50 kV, 500 μA, 0.5 mm aluminium filtration, and 0.6 degree rotation step for 360 degree rotation.
Mufti and Al-Nazhan (2021)	Compare retreatability of root canals filled with either calcium-silicate based sealer or resin-based sealer, and with differing degrees of root canal curvature.	106 curved root canals (classified as mild ≤ 15 degrees; moderate 16–30 degrees; severe ≥ 31 degrees), in mandibular first molars, divided into two groups	EndoSequence BC (Brasseler, Georgia, USA) (n = 54)	AH Plus (Dentsply, Konstanz, Germany) (n = 52)	Rotary instrumentation system until WL was reached. All root canals were irrigated with 2.5 % NaOCl and normal saline.	OneCurve (Micro-Mega, Besançon, France)	–	–	Retreatment was done 14 days after intitial obturation. *__Volume (cu.mm) of remaining filling__ Not statistically significant between root canals filled with EndoSeqeunce	–	Skyscan 1172 Micro CT (Bruker, Kontich, Belgium). Operating at 100 kV, 10 W, 100 μA, 1475 ms exposure, and 0.4 degree

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Table 1 (*continued*)

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
		(n1 = 54 / n2 = 52).							BC sealer (0.85 ± 0.98 cu.mm) or AH Plus sealer (0.89 ± 0.78 cu.mm). No significant difference in remaining filling material between root canals of differing curvature. **Severely curved root canals filled with AH Plus sealer had the highest amount of remaining filling material.**		rotation step for 180 degree rotation. Voxel size 11.88 μm.
Rajda (2021)	Compare retreatability of oval root canals filled with either calcium-silicate based sealer or resin-based sealer.	40 single-rooted teeth with single canals, divided into two group (n = 20 per group). Teeth with fracture, resorption, restorations or calcifications were excluded.	TotalFill BC (FKG Dentaire, Le Crêt-du-Locle, Switzerland)	AH Plus (Dentsply, Konstanz, Germany)	Reciprocating instrumentation system until WL was reached. Root canals were irrigated with 2.5 % NaOCl, 17 % EDTA and normal saline.	Reciproc R25 (VDW, Munich, Germany)	–	–	Retreatment was done 7 days after intitial obturation. *__Volume of remaining filling material__ Not significantly different between the two groups. TotalFIll BC group had lower remaining filling material (4.01 ± 3.13 cu.mm; 28.5 %) than AH Plus group (6.96 ± 2.71 cu.mm; 45.5 %).	–	Nikon XT H 225 Micro CT (Nikon Industrial, USA). Operating at 110 kV and 240 μA. Voxel size 36 μm.
Baraba, Rajda et al. (2023)	Compare retreatability of root canals filled with either calcium-silicate based sealer or resin-based sealer, employing two different obturation techniques (single cone or carrier-based gutta percha) and with or without laser assisted photoacoustic streaming irrigation (SWEEPS).	76 single-rooted teeth, divided into four groups (n = 19 per group).	TotalFill BC (FKG Dentaire, Le Crêt-du-Locle, Switzerland) & MTA Fillapex (Angelus Dental, Londrina, Brazil)	AH Plus (Dentsply, Konstanz, Germany)	Reciprocating instrumentation system until WL was reached. All root canals were irrigated with 2.5 % NaOCl, 17 % EDTA and normal saline.	Reciproc R25 (VDW, Munich, Germany)	–	Root canal irrigation using laser-activated photoacoustic streaming (SWEEPS) with Er:YAG laser at 2940 nm and normal saline, for 60 s.	Retreatment was done 7 days after initial obturation. *__Volume of remaining root canal filling__ After mechanical retreatment and SWEEPS irrigation, there was significant reduction in root canal filling material in all groups, but there was no complete removal. No significant difference between the groups	–	Nikon XT H 225 Micro CT (Nikon Industrial, USA). Operating at 110 kV and 240 μA. Voxel size 36 μm.

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Table 1 (*continued*)

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
									Root canals obturated with epoxy resin based sealer and single-cone GP technique had significantly higher volume ($p < 0.05$) of remaining filling material (2.8 ± 1.5 cu.mm) than the other groups (TotalFill BC+single cone GP − 0.4 ± 1.1 cu.mm; AH Plus + carrier based GP − 1.0 ± 0.8 cu.mm; MTA Fillapex + carrier based GP − 0.8 ± 1.4 cu.mm)		
Colombo, Rocha et al. (2023)	Compare retreatability of root canals filled with either calcium-silicate based sealer or resin-based sealer.	42 single-rooted mandibular premolars, with oval root canals, divided into two groups (n = 21 per group). Teeth with canal curvature > 20 degrees, restorations or calcifications were excluded.	Bio C (Angelus Dental, Londrina, Brazil)	AH Plus (Dentsply, Konstanz, Germany)	Reciprocating instrumentation system until WL was reached. Root canals were irrigated using 2.5 % NaOCl, 17 % EDTA and normal saline.	Reciproc R40 (VDW, Munich, Germany)	–	Continuous ultrasonic (10 % power) irrigation with distilled water, for up to 60 s.	Retreatment was done 30 days after initial obturation. ***Volume (%) of remaining filling material N**ot significantly different between the Bio C group (21.08 %) and AH Plus group (14.63 %). After ultrasonic irrigation, volume of remaining filling material significantly decreased ($p < 0.001$) in both groups (Bio C − 8.29 %; AH Plus − 11.75 %), but without any statistical difference between groups.	–	Skyscan 1173 Micro CT (Bruker, Kontich, Belgium). Operating at 70 kV and 114 μA. Voxel size 8.4 μm.

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Table 1 (*continued*)

Author (year)	Study objective	Sample size and characteristics	Calcium silicate sealer	Comparison sealer	Retreatment technique	Instrument-ation system	Solvent used	Supplemental technique(s)	Outcome measures	Retreatment time (Mean)	Micro-CT parameters
Jamleh, Nassar et al. (2023)	Compare retreatability of oval root canals filled with either calcium-silicate based sealer or resin-based sealer.	24 single-rooted mandibular premolars, with oval root canals, divided into two group (n = 12 per group). Teeth with canal curvature > 5 degrees, restorations or calcifications were excluded.	TotalFill BC (FKG Dentaire, Le Crêt-du-Locle, Switzerland)	AH Plus (Dentsply, Konstanz, Germany)	Reciprocating instrumentation system until WL was reached. All root canals were irrigated with 2.5 % NaOCl, 17 % EDTA and normal saline.	Wave One Gold (Dentsply Sirona, Charlotte, NC, USA)	Chloroform	–	Retreatment was done 180 days after initial obturation. *__Volume (%) of remaining filling material__ Higher with TotalFill BC sealer (13.02 ± 8.12) than with AH Plus sealer (10.11 ± 8.46). Difference was not statistically significant Apical patency was difficult to achieve with AH Plus sealer. **Retreatment of root canals filled with calcium silicate based sealer required significantly higher number of strokes** ($p < 0.05$) with reciprocating instrumentation system.	Signficantly higher ($p < 0.01$) for AH Plus sealer (113.09 ± 33.10 s), than with TotalFill BC sealer (75.92 ± 20.93 s).	Skyscan 1172 Micro CT (Bruker, Kontich, Belgium). Operating at 70 kV, 139 μA, 0.5 mm aluminium filtration, 2 s exposure, and 0.8 degree rotation step for 180 degree rotation. Voxel size 13.6 μm.

WL – Working length; NaOCl – Sodium hypochlorite; EDTA – Ethylene diamine tetra-acetic acid; Micro CT – Micro computed tomography; PIPS – Photon initiated photoacoustic streaming; Cu.mm – Cubic millimeter; SWEEPS – Shock-wave enhanced emission photoacoustic streaming; Er:YAG – Erbium-doped yttrium aluminium garnet; GP – Gutta percha; RPM – Revolutions per minute;

commonest reported calcium-silicate based sealer, studies also evaluated MTA Fillapex (Angelus Dental, Londrina, Brazil), NeoMTA Plus (Avalon Biomed Inc., Florida, USA), EndoSeal MTA (Maruchi, Wonju, Korea), BioRoot RCS (Septodont, Saint-Maur-des-Fosses, France), Endoseal TCS (Maruchi, Wonju, Korea), TotalFill BC (FKG Dentaire, Le Crêt-du-Locle, Switzerland), and Bio C (Angelus Dental, Londrina, Brazil). On the contrary, AH Plus (Dentsply, Konstanz, Germany) epoxy-resin based sealer was comparatively evaluated for retreatability in all studies except one, wherein Dia-Proseal (DiaDent, Cheongju-si, Korea) was used (Mavishna and Venkatesh 2021) (Table 1).

3.4. Retreatment technique

There was considerable similarity among the reviewed studies in terms of the initiation of root canal retreatment, wherein a rotary Gates-Glidden drill was used for initial preparation followed by either rotary or reciprocating instrumentation, until pre-treatment working length was achieved. Out of the 15 reviewed studies, six studies used a reciprocating instrumentation system (Romeiro, de Almeida et al. 2020; Crozeta, Lopes et al. 2021; Rajda, Miletić et al. 2021; Baraba, Rajda et al. 2023; Jamleh, Nassar et al. 2023), and the other studies used rotary instrumentation. Following retreatment, all the studies reportedly achieved pre-treatment working length, with both types of endodontic sealers. However, none of the studies reported complete removal of endodontic filling material from the root canals. Irrespective of the sealer type used, within each root canal, the apical third had the greatest amount of remaining filling material, followed by the middle and coronal thirds.

In general, retreatment was considered complete when all gutta percha was removed and no remnants were observed on the last used instrument. Interestingly, most of the studies reviewed did not employ the use of a solvent for easing removal of root canal filling material. Among the two studies reporting use of chloroform solvent during retreatment (Oltra, Cox et al. 2017; Jamleh, Nassar et al. 2023), improved removal of endodontic filling material was reported only by Oltra, Cox et al. 2017). With the respect to the irrigation solutions used during retreatment, most of the studies reported using a combination of 17 % EDTA (Ethylene diamine tetra-acetic acid), 2.5 % or 6 % NaOCl (Sodium hypochlorite) and normal saline, at volumes ranging from 2 – 5 ml.

In addition to mechanical retreatment with either rotary or reciprocating instrumentation systems, studies also reported the use of supplemental techniques. These included the use of laser assisted photoacoustic streaming irrigation (PIPS – Photon initiated photoacoustic streaming / SWEEPS – Shock-wave emission enhance photoacoustic streaming) (Suk, Bago et al. 2017), and ultrasonic irrigation (passive or powered up to 10–30 %) (Alsubait, Alhathlol et al. 2021; Crozeta, Lopes et al. 2021; Colombo, Rocha et al. 2023). In the aforementioned scenarios, the irrigation solution used was either 2.5 % NaOCl or normal saline, for durations ranging up to 60 s. In addition, (Aksel, Küçükkaya Eren et al. 2019) reported the use of XP-Endo finisher file (FKG Dentaire, Le Crêt-du-Locle, Switzerland) as a supplemental technique during retreatment. The endo finisher file was used at 800 RPM for 20 s, 2 mm short of WL and with 2.5 % NaOCl. In all the studies reporting use of supplemental retreatment techniques, there was reduction in the volume of remaining filling material post-retreatment, irrespective of the type of endodontic sealer used. Lastly, in terms of the waiting time period between initial obturation and retreatment, extreme variation was observed among the reviewed studies and this ranged from as low as 7 days to as high as 6 months (Table 1).

3.4.1. Volume of the remaining root canal filling material

Based on individual comparison between the two types of sealers, four studies reported greater volume of remaining filling material after retreatment of root canals filled with calcium-silicate based sealers, than with epoxy-resin based sealers (Oltra, Cox et al. 2017; Jin, Jang et al. 2021; Mavishna and Venkatesh 2021; Jamleh, Nassar et al. 2023). In comparison, 7 out of the 15 reviewed studies reported better outcomes with calcium-silicate based sealers than with epoxy-resin sealers, both in terms of retreatability and efficiency of removal of root canal filling material (Suk, Bago et al. 2017; Aksel, Küçükkaya Eren et al. 2019; Romeiro, de Almeida et al. 2020; Alsubait, Alhathlol et al. 2021; Crozeta, Lopes et al. 2021; Rajda, Miletić et al. 2021; Kim, Jang et al. 2024). Among studies which reported no differences in the volume of remaining filling material between the two sealer types post-retreatment, (Baraba, Rajda et al. 2023; Colombo, Rocha et al. 2023) observed better retreatability with calcium-silicate sealers, after respectively using SWEEPS and ultrasonic irrigation as supplemental techniques to mechanical instrumentation.

Similarly, (Mufti and Al-Nazhan 2021) while observing no differences in volume of remaining root canal filling materials with calcium-silicate and epoxy-resin sealers within mild and moderately curved root canals, reported poorer outcomes with epoxy-resin sealers when used in severely curved canals. Although the study by (Colmenar, Tamula et al. 2021) was the only one reporting absolutely no differences in retreatability of root canals treated with either calcium-silicate or epoxy resin sealers, and showing similar volumes of remaining filling materials, between the two groups and in different parts of the root canal, their study findings were limited by the low sample size per group (n = 5).

3.4.2. Retreatment time

Out of the 15 reviewed studies, only three studies reported outcomes relating to time taken for retreatment with the different types of sealers. While retreatment time was significantly longer for root canals obturated with calcium-silicate based sealers as reported in two studies, (Romeiro, de Almeida et al. 2020; Alsubait, Alhathlol et al. 2021) it was significantly longer for epoxy-resin sealer in another study (Jamleh, Nassar et al. 2023). The individual outcome measures comparatively reported in each one of the reviewed studies are enumerated in Table 1.

4. Discussion

Calcium silicate-based sealers had proven efficacy in clinical use due to the formation of the hydroxyapatite with the root dentin, antibacterial property and the assured three dimensional seal (Aminoshariae, Primus et al. 2022). Previous studies have also reported a success rate of 84–90 % when adopting single cone technique with CSS in comparison to warm vertical condensation with epoxy resin based sealer (Zavattini, Knight et al. 2020).

Unfortunately, these favorable attributes of CSS has strewn challenges to regain patency of the canal space during retreatments (Santos, Coelho et al. 2021). However, there is lack of thorough investigation of the published literature with regards to the retrievability of CSS. Therefore, the objective of this study was to systematically analyze the reviewed articles with respect to the efficacy of the different retreatment techniques used for retrieving the obturation material, the time taken and the volume of the root filling material remaining, in the CSS filled canals evaluated through micro-CT.

In comparison with other evaluation methods, the advantage of micro-CT is its propensity to allow for a 3-dimensional quantification (Binsalah, Ramalingam et al. 2019) in a non-destructive manner of the filling material volume (Ghavami-Lahiji, Davalloo et al. 2021). In addition, micro-CT also gives a mathematically predicted calculation of the percentage volume of the remaining material, assessed post retreatment (Colmenar, Tamula et al. 2021). Further, this technology has been universally utilized as an analytical tool (Ramalingam, Al-Rasheed et al. 2016). for assessing the volume of remaining root

filling materials with great precision (Colombo, Rocha et al. 2023). By comparison of the micro-CT scanned reports in the pre- and post-operative periods, the volume of filling material remnants was calculated. The reconstructed raw data scans was converted into multiplanar images along with the computer program (NRecon) software for all the three tooth planes (coronal, trans-axial, sagittal) and viewed by Data viewer software to determine the volume of sealer (Mavishna and Venkatesh 2021).

Classically, Because of its ideal properties for clinical usage, AH Plus has long been considered a "gold standard" sealer with widespread usage in endodontics. Except Mavinsha et al., who used Dia-Proseal (DiaDent, Cheongju-si, Korea) (Mavishna and Venkatesh 2021) all the other studies compared their selected CSS with AH plus sealer. Majority of the articles under review used EndoSequence BC (Brasseler, Georgia, USA) for comparison (Colmenar, Tamula et al. 2021; Crozeta, Lopes et al. 2021; Jin, Jang et al. 2021).

Total removal of the residual filling material though often desired, remains unachievable by all the currently available retreatment techniques (Jamleh, Nassar et al. 2023; Madarati, Sammani et al. 2023). Retreatments in the early years were done with the Gates Glidden drills and hand instruments (Arul, Varghese et al. 2021). Later with the introduction of the rotary system and the reciprocating nickel titanium files, these were popularly used as part of the retreatment instrumentation (Ajina, Shah et al. 2022). The enhanced sealer penetration into the dentinal tubules during the initial treatment hinders the complete retrieval of the filling material (Akcay, Arslan et al. 2016). In addition, the removal of the smear layer consisting of the plasticized guttapercha and debris is also required during instrumentation (Al Akam, Kim et al. 2024). These challenges have sparked the necessity for the evolution of new retreatment strategies. Among the reviewed studies, majority of them used Protaper Universal and ProFile ISO Rotary instrumentation system (Dentsply Maillefer, Ballaigues, Switzerland), However, no difference was reported among the different systems in retrievability and complete removal was not ascertained.

The supplemental methods have increased the retrievability by 1.15–2.1 times (Arul, Varghese et al. 2021). The present review findings indicate enhanced filling removal by Passive Ultrasonic Irrigation in the AH Plus group (Crozeta, Lopes et al. 2021). The positive effect of PUI can be attributed to its 1vibration that results in the canal irrigant's continuous movement, augmenting filling removal. Enhanced removal of both calcium-silicate-containing and epoxy-resin-based sealers can be achieved with SWEEPS, along with the combination of carrier-based obturation and single-cone techniques. In both SWEEPS (Baraba, Rajda et al. 2023) & PIPS(Suk, Bago et al. 2017), there is characteristic placement of laser fiber in the pulp chamber instead of insertion into the canal (Razavi, Savadkouhi et al. 2023). The effective vibration, causes elevation of temperature and acoustic transmission with production of cavitation bubbles and hydrodynamic shear stresses (Wiesse, Silva-Sousa et al. 2018) which improves the retrievability of the filling material (Crozeta, Lopes et al. 2021).

The primary outcome on focus was the volume of remaining residue which ascertains the efficacy of the retreatment techniques. This necessitates the complete removal of the filling remnants to provide unhindered access for irrigation along with deposition of medicaments in all essential parts of the root canal system. Significantly higher quantities of residue were observed in the CSS groups in comparison to the AH Plus samples except in 6 studies, where no significant difference between the groups were found. (Aksel, Küçükkaya Eren et al. 2019; Romeiro, de Almeida et al. 2020; Crozeta, Lopes et al. 2021; Mufti and Al-Nazhan 2021; Rajda, Miletić et al. 2021; Colombo, Rocha et al. 2023). However, supplemental usage of ultrasonic irrigation, (Alsubait, Alhathlol et al. 2021) and PIPS (Suk, Bago et al. 2017) illustrated that the CSS groups had reduced volume(%) of the residue. Similarly, after SWEEPS irrigation, root canals obturated with epoxy resin based sealer and single cone technique had significantly higher volume ($p < 0.05$) of remaining filling material (Baraba, Rajda et al. 2023) than the CSS group.

Anatomy of the root canal is an important factor which determines the amount of remaining root filling material (Arul, Varghese et al. 2021). Although the radiographical image conveys the appearance of a straight root, curvatures are more common at the apical third. Hence, lack of complete removal of the filling material can lead to procedural failure. After retreatment, the volume (%) of remaining filling material was significantly higher ($p < 0.05$) in C-shaped root canals (Kim, Jang et al. 2024). Nevertheless, in all the articles under purview, the remaining root canal material was highest in the apical third irrespective of the root configuration or type of sealer used.

Three of the reviewed studies have reported the retreatment time with a chronometer as part of the parameters analyzed to evaluate the retrievability of the filling materials Endodontic retreatment time, expressed in seconds is reported as the measure of the net or total time to remove the CSS or AH Plus sealers from the beginning of the instrumentation until the working length is reached (Alakabani, Faus-Llácer et al. 2018). Mean retreatment time was significantly different between the groups ($P<0.01$), with the lowest time taken for AH Plus groups. Romeira et al., and Alsubait et al., enumerated that retreatment time for CSS filled canals (135.28 ± 18.33 s) was significantly longer than AH Plus filled canals ($p < 0.01$) (Romeiro, de Almeida et al. 2020; Alsubait, Alhathlol et al. 2021). In contrast, Jamleh, Nassar et al. (2023) found that the mean retreatment time was significantly higher ($p < 0.01$) for AH Plus sealer (113.09 ± 33.10 s), than with TotalFill BC sealer (75.92 ± 20.93 s) (Jamleh, Nassar et al. 2023). Interestingly, the retreatment time was measured to be significantly ($P<0.05$) less when solvents were used during instrumentation (Ma, Al-Ashaw et al. 2012). Among the two of the reviewed studies, Oltra et al. and Jamleh, Nassar et al. (2023) used chloroform as solvents and resulted in enhanced removal of the residual filling material (Oltra, Cox et al. 2017; Jamleh, Nassar et al. 2023).

4.1. Limitations

One major limitation of the present systematic review was the heterogeneity of collected data from the individual studies. Dissimilarities were observed in terms of the sampling frame, type of teeth/root canals selected for *in vitro* study, endodontic sealers used, retreatment techniques and outcome measures reported. As a result of which a *meta*-analysis based on quantitative data collected from the individual studies was not possible. Nevertheless, the present review comprehensively elaborates on the nature of endodontic retreatment outcomes with different sealer types, which to our knowledge is being uniquely reported.

5. Conclusion

In conclusion, there is no scientific or empirical data to support concerns about the retreatability of bioceramic sealers. Retreatment of canals obturated with bioceramic sealers is feasible in most cases using traditional instruments and techniques. Active irrigation and supplemental mechanical removal, which employ lasers, XP-Finisher, and ultrasonics, add advantage to maximize material removal. The various retreatment techniques currently in use are evaluated against the wide range of sealers to improve the outcomes. However, complete removal of the remnants have never been successful. The reviewed studies were all In-vitro researches and hence inconclusive about the complete removal of the CSS sealers irrespective of the retreatment techniques or supplemental methods. In future, more standardized protocols to assess retrievability could yield homogenous data and conclusive

proclamations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The author acknowledges Division of Endodontics, Department of Restorative Dental Science, College of Dentistry, King Saud University, and its Teaching Staff, Colleagues, and any member help to pursue and finish this study. The author expresses sincere gratitude to **Dr. Sarah Alkahtany** for supporting in the review process.

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