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Review Article

Impact of direct restorative dental materials on surface root caries treatment. Evidence based and current materials development: A systematic review

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ABSTRACT

This systematic review provides an update on the development and efficacy of direct restorative dental materials for root caries interventions from in vitro and clinical studies. PubMed, Embase, and Web of Science were searched using specific MeSH keywords. Full articles from September 1990 to October 2021 were collected. Additional articles were identified by reference retrieval and manual searching. Studies not related to restorative materials for root caries treatment, case reports, non-original articles, and/or articles not written in English were excluded. Bias risk assessment was performed for the clinical studies. Forty-two articles (eleven clinical studies and thirty-one in vitro studies) were included for analysis. Most in vitro studies indicated an excellent cariostatic effect of glass ionomer cement. Resin-modified glass ionomer restorations also presented reduced recurrent caries activity but had a lower efficacy than glass ionomer cement restorations. For composite resin restorations, the main material development strategies are to strengthen the tooth structure and integrate antimicrobial activity. The clinical studies offered limited data, so the most appropriate material for surface root caries treatment is still inconclusive. However, atraumatic restorative treatment (ART) is an alternative treatment for patients with limiting conditions. Further clinical studies are required to confirm the efficacy of bioactive materials.

1. Introduction

Due to increasing life expectancies, the World Health Organization has predicted that the elderly population will increase significantly by 2050 [1], with nearly 1.5 billion people—approximately 15%–20% of the world's population—aged 65 or older. The medical and dental status of elderly patients is a considerable factor in their quality of life [1]. In the field of dentistry, dental caries (particularly dental root caries) and periodontal diseases are considered the main problems in older adults. A systematic review demonstrated that the average incidence of root caries was approximately half of the population for older adults [2].

Multiple species of cariogenic bacteria, including streptococci, actinomyces, lactobacilli, and bifidobacteria have been indicated as having a strong association with dental caries [3]. After bacterial biofilm formation, these bacteria, which are tolerant of acidic environments, can produce acid via sugar metabolism, altering the mineral composition of the tooth structure [3]. However, caries formation at the tooth root differs from that at the crown due to the difference in composition, particularly regarding the inorganic components [3]. Approximately 90 wt% of enamel comprises inorganic minerals, whereas dentin has a lower inorganic composition of approximately 70 wt%. This leads to a faster degree of caries progression in root dentin, which means that the root area is particularly vulnerable to caries formation [4]. In addition, many individual factors associated with dental root caries have been identified, such as age, oral hygiene, gingival recession with root surface exposure, smoking, economic status, xerostomia, medication, and other drug use [5].

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When cavitated caries lesions form, restorative procedures with material replacement of the lesion are commonly used to address the problem. Many restorative materials such as glass ionomer cement (GIC), resin-modified glass ionomer (RMGI), and composite resin (CR) have been introduced and used for root caries restorations. However, difficulties associated with the cavity position, access of the restoration site, and moisture control [6], combined with the risk factors described above, mean that the proper selection of restorative materials is a critical challenge for dentistry. Moreover, a new generation of materials has been developed to enable more precise surface root caries treatment. However, their efficacies on root caries prevention remain controversial.

The objectives of this review are (1) to reveal the efficacy of direct restorative materials on root caries treatment in in vitro and clinical studies, and (2) to provide an update on the current and perspective concepts and development of direct restorative dental materials for root caries treatment.

2. Material and methods

2.1. Search and selection

One researcher performed the article selection process. The literature was electronically searched from three online databases: MEDLINE/PubMed, Cochrane Library/Embase, and Web of Science. The Medical Subject Headings (MeSH) database was used to select the search terms. The keyword search criteria for the different advanced searching systems were as follows:

- PubMed: (“Root Caries”[Mesh]) AND ((“Dental Materials”[Mesh] OR “Dental Atraumatic Restorative Treatment”[Mesh]))
- Embase: (Root caries):ti,ab,kw AND ((Dental materials):ti,ab,kw OR (Dental Atraumatic Restorative Treatment):ti,ab,kw)
- Web of Science: (“Root Caries”) AND ((“Dental Materials” OR “Dental Atraumatic Restorative Treatment”))

Publications from September 1990 to October 2021 were included (last search date: 17 October 2021). Duplicate articles were detected and excluded.

2.2. Inclusion and exclusion criteria

To conform with the objectives of the review, the identified articles were filtered using the following inclusion criteria:

- In vitro studies
- Clinical studies in humans
- Studies involving direct restorative materials for root caries
- Both abstract and full article available
- Written in English

For studies that fulfilled all the inclusion criteria, the abstract was then checked against the following exclusion criteria:

- Studies not involving dental root caries
- Studies not involving direct restorative materials (e.g., those involving indirect restorative materials, varnishes, coating materials, or other chemical agents)
- Articles of case reports
- Articles that were not of original studies

Articles that met at least one exclusion criteria were excluded. The full texts of the relevant articles were then retrieved and analyzed. Additional articles were added by checking the references from the final included articles and manual searching.

2.3. Risk of bias

The clinical studies were assessed for risk of bias. The studies were first identified as either randomized or nonrandomized controlled trials. The risk of bias in the randomized trials was assessed using the revised Cochrane risk-of-bias (RoB 2) tool [7], while the risk of bias in the non-randomized trials was assessed using the risk of bias in non-randomized studies of interventions (ROBINS-I) tool [8]. Eight risk categories were considered, with several criteria in each category (see Refs. [7,8] for details of the criteria). Both randomized and non-randomized studies were assessed against the risk categories of “bias due to deviations from intended interventions”, “bias due to missing outcome data”, “bias in measurement of the outcome”, and “bias in selection of the reported result”. The randomized trials were also assessed against the risk category of “bias in randomization process”, while the non-randomized studies were also assessed against “confounding bias”, “bias in selection of participants”, and “bias in classification of interventions”. The overall bias score was then classified using the following criteria:

- If the study had a “high risk” score in two or more risk categories, the overall bias was classified as “high risk”.
- If the study had a “low risk” score in more than half the risk categories, the overall bias was classified as “low risk”.
- If the study did not meet either of the above criteria, the overall bias was classified as “moderate risk”.

3. Results

3.1. Data selection

Fig. 1 presents a schematic diagram of the process and results of the search. After duplicate articles were excluded, a total of 197 articles were identified from the keywords search. An additional 8 articles were identified from the manual search and reference retrieval. A total of 38 studies were excluded as only the abstract was available (19 of these were published prior to 2001). A number of studies met the exclusion criteria: 44 articles did not relate to dental root caries; 61 did not relate to direct restorative materials; 3 were case reports; and 17 were not of original studies. In total, 42 studies were included in this study, of which 11 were clinical studies and 31 were in vitro studies.

3.2. Quality of evidence

The results of the bias risk analysis for the included clinical studies are summarized in Fig. 2. Overall, of the eleven clinical studies, nine were classified as having “low risk” of bias (Refs. [9–17]), while two were classified as having “moderate risk” (Refs. [18,19]). None of the clinical trials were classified as having “high risk” of bias. Many of the randomized controlled trials had a “moderate risk” of bias for the “bias in randomization process” category because of “unclear concealment” in their articles [13,15,16,19]. The “bias due to deviations from intended interventions” category was a common risk of bias for both randomized and non-randomized trials, as only three articles [10,14,17] reported the safety of the materials used in their trials. All others [9,11–13,15,16,18,19] were therefore classified as having “moderate risk” of bias for this category. For the “bias due to missing outcome data” risk category, only two studies [18,19] were classified as having “moderate” or “high risk”. For the “bias in the measurement of the outcome” risk category, two studies [9,18] were unclear about whether a blinded examiner was used, while one study [10] used a non-blinded examiner; thus, all three were classified as having “moderate risk” of bias for this category. For the non-randomized studies, concerns about “con-

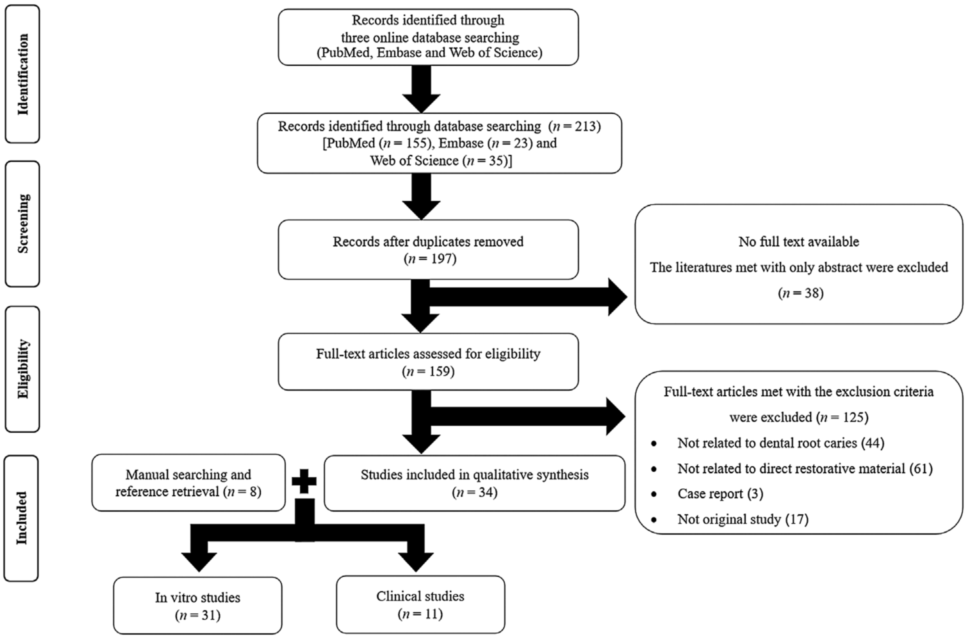
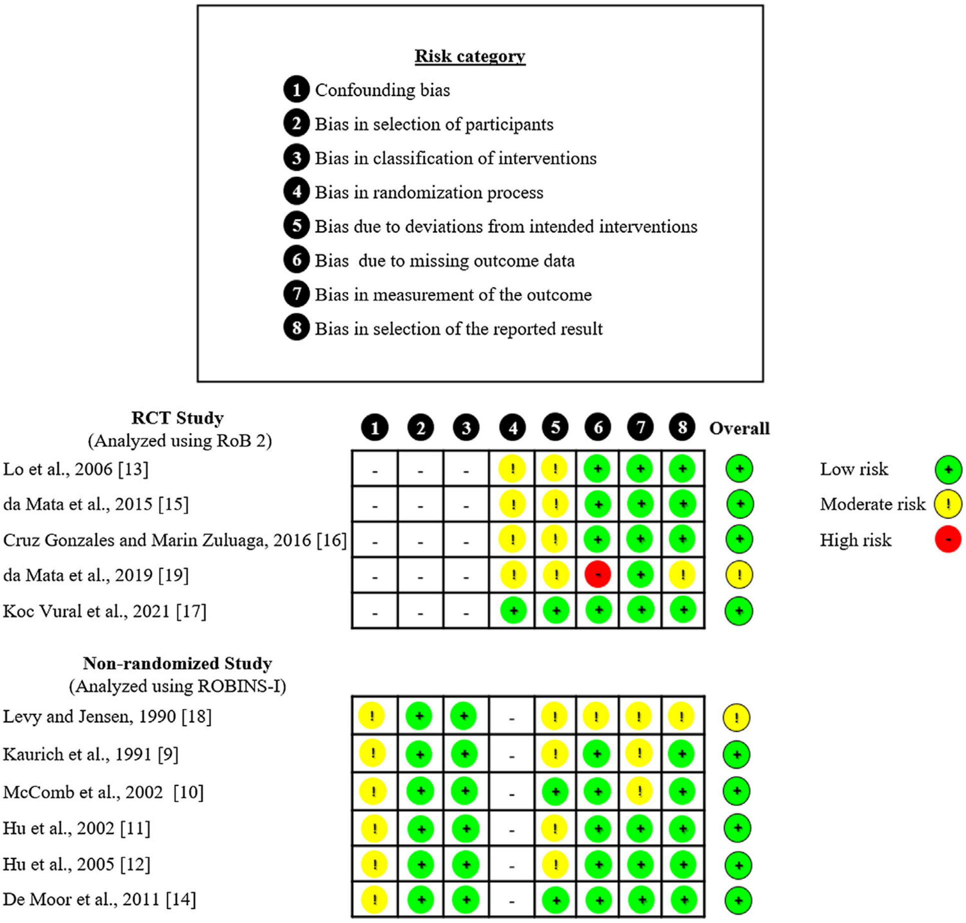


Fig. 1. Modified PRISMA scheme of the process and results of literature searching.



Risk category

1. Confounding bias
2. Bias in selection of participants
3. Bias in classification of interventions
4. Bias in randomization process
5. Bias due to deviations from intended interventions
6. Bias due to missing outcome data
7. Bias in measurement of the outcome
8. Bias in selection of the reported result

RCT Study (Analyzed using RoB 2)	1	2	3	4	5	6	7	8	Overall
Lo et al., 2006 [13]	-	-	-	!	!	+	+	+	+
da Mata et al., 2015 [15]	-	-	-	!	!	+	+	+	+
Cruz Gonzales and Marin Zuluaga, 2016 [16]	-	-	-	!	!	+	+	+	+
da Mata et al., 2019 [19]	-	-	-	!	!	🔴	+	!	!
Koc Vural et al., 2021 [17]	-	-	-	+	+	+	+	+	+

Non-randomized Study (Analyzed using ROBINS-I)	1	2	3	4	5	6	7	8	Overall
Levy and Jensen, 1990 [18]	!	+	+	-	!	!	!	!	!
Kaurich et al., 1991 [9]	!	+	+	-	!	+	!	+	+
McComb et al., 2002 [10]	!	+	+	-	+	+	!	+	+
Hu et al., 2002 [11]	!	+	+	-	!	+	+	+	+
Hu et al., 2005 [12]	!	+	+	-	!	+	+	+	+
De Moor et al., 2011 [14]	!	+	+	-	+	+	+	+	+

Low risk	+
Moderate risk	!
High risk	🔴

Fig. 2. Summary of the bias risk analysis of the included clinical studies. Randomized controlled trials (RCTs) were assessed using RoB2 with five risk categories; non-randomized studies were evaluated using ROBINS-I with seven risk categories.

founding bias" were identified for all studies. Confounding bias may be of concern because the treatment outcome may be affected by multifactorial factors, such as routine life behavior of the patient, diet, cleaning, and so on.

3.3. Summary of the results

3.3.1. Glass ionomer cement (GIC)

Since Wilson and Kent introduced GIC as a new material in 1972 [20], it has become one of the most popular materials in restorative dentistry. This "acid–base cement" [21] is produced by mixing a polymeric acid aqueous solution with glass powder for 2–5 min, which triggers a setting reaction. This material introduces a therapeutic effect on the surrounding tooth structure via the release of fluoride ions [21]. For this reason, GIC has been used for clinical applications such as restorations and luting cements, bases, and liners. In this review, we focus solely on its restorative function for dental root caries.

A list of in vitro studies of GIC restorations for root caries treatment is shown in Table 1. The properties of GIC restorations have been widely analyzed, with a particular focus on the interesting cariostatic efficacy of GIC restorations on the root surface. Many studies have confirmed that GIC has the ability to reduce outer lesion depth [22–24]. In addition, the surrounding structure contacting the restoration, extending to 20 μm, has been shown to be protected from demineralization by the remaining calcium and phosphate content [25]. Moreover, the surrounding dentin showed less exposure of the collagen and organic matrix, which presented as a low degree of log[amide I: HPO_4^{2-}] [13]. Hara et al. [26] reported that the cariostatic effect of GIC extended to 300 μm on root dentin using a microhardness assessment. Recently, micro-computed tomography (micro-CT), which can observe the tooth cross-section and mineral content at the same time, has been modified for observing the surrounding structure in experimental studies. Zan et al. [24] reported that GIC restorations had a protective effect on contacting dentin and maintained a higher subsurface mineral density compared to conventional CR and multi-ion-releasing composite restorations. Moreover, an acid-resistant zone was found between the interphase of the GIC restoration and the tooth structure by scanning electron microscopy (SEM) [27]. Based on the evidence of in vitro studies, it has been implied that conventional GIC restorations have a great ability to prevent caries on the root surface. However, few in vitro studies have investigated the mechanical properties of GIC, instead of focusing on the sealing ability of the material. Sidhu et al. [28] compared the microleakage values of GIC and CR restorations after treatment with and without thermocycling. They found that GIC restorations showed a greater sealing ability than CR restorations. Recently, experimental studies that combine intervention and chemical agents have been used to modify GIC restorations to enhance the therapeutic effect. Zhao et al. [29] applied 38% silver diamine fluoride (SDF) for 3 min to a GIC restoration containing 3% casein phosphopeptide amorphous calcium phosphate (CPP-ACP), which had a synergistic effect on the prevention of secondary caries by increasing the calcium and phosphorus contents around the root dentin. Moreover, Zhao et al. [30] found that the combined application of potassium iodide (KI) and SDF before GIC restoration improved the anticariogenic effect and reduced the degree of discoloration compared to SDF application alone.

The clinical trials of GIC restorations for root caries treatment included in the review are listed in Table 2, along with the study designs and outcomes. The criteria for restorative and surrounding structure follow-up, such as the presence of restorations, marginal integrity, marginal discoloration, anatomical form, and secondary caries, must be observed in many clinical manifestations. In this review, we categorized the criteria that were used in previous studies into three parts: restoration condition, tooth condition, and surrounding condition, as shown in Table 3. Comparing the clinical efficacies of different materials has been the focus of many studies. McComb et al. [10] compared the incidence of recurrent caries in Class V restorations comprising GIC, RMGI, and CR in radiation-treated patients. The results showed that the restorative failure rate caused by anatomical deformation and marginal leakage of GIC restorations was higher than that of CR restorations in patients using daily fluoride tray application. Moreover, GIC restorations showed a lower incidence of recurrent caries in non-fluoride use patients [10]. Kaurich et al. [9] compared the failure rate after two years between GIC and CR restorations using the United States Public Health Service (USPHS) criteria. Most of the clinical features, including color match, marginal adaptation, and marginal discoloration were clinically comparable, except for the anatomical form of GIC, which had a higher incidence of degradation than that of CR. Similarly, Levy et al. [18] found that the clinically acceptable rates of GIC and CR restorations were comparable. De Moor et al. [14] showed that the marginal adaptation of CR restorations after a two-year postoperative follow-up was greater than that of GIC restorations, whereas the cariostatic effect from GIC restorations was higher than that of CR restorations. They recommended that the sandwich technique could be an alternative procedure for utilizing the beneficial effects of both materials [14]. Owing to the limited data of clinical studies, the clinical success rate of GIC restorations compared to CR restorations remains controversial. However, many studies have shown that the mechanical properties of GIC restorations are lower than those of CR restorations after long-term clinical use.

In addition to conventional restoration techniques, atraumatic restorative treatment (ART) has become popular in dentistry because it does not require local anesthesia, instead using low pressure, vibration, and noise [31]. Owing to the advantages of this technique, it has been used as a clinical treatment option in patients with limitations including children, patients with special needs, patients with anxiety, and patients in rural areas who cannot visit dental clinics. Briefly, after the soft cavitated carious lesion is removed using a hand instrument, an adhesive dental material such as high viscosity glass ionomer cement is used for restoration. Five studies have compared the clinical efficacies of conventional and ART techniques for root caries treatment. Cruz and Marin [16] compared the six-month postoperative success rate between ART and conventional restoration in 64 elderly patients. They found that the success rate of conventional restorations (92.9%) was significantly higher than that of ART (81.3%). In contrast, four clinical studies with follow up period of more than six months presented the success rates of these techniques as not significantly different [12,13,15,19]. Moreover, after five years of clinical observation, the survival rate of ART (85%) was comparable with that of conventional techniques (79%) [19].

3.3.2. Composite resin (CR) and dental adhesive

Since CR has been clinically used as a restorative dental material, it has become popular in the dental field due to its advantages including good mechanical properties, ease of color matching with natural teeth, and ease of clinical application. However, when compared with other commercial materials, conventional CR has no cariostatic effect on dental root structure [27], which is an important property for successful root caries restorations. Many studies have been conducted based on the addition of bioactive agents into CR to improve its therapeutic effect. In addition, a CR-based dental adhesive system has been developed that boosts the antimicrobial activity, strengthens the surrounding structure, and prevents demineralization.

Table 1
List of in vitro studies related to glass ionomer cement (GIC) restorations for root caries treatment and their details.

Study	Study design	Parameter	Evaluation	Finding
Zan et al., 2018 [24]	Restored root bovine dentin using different restorative materials. Experimentally tested demineralization and remineralization cycles. Evaluated mineral density and mineral loss using micro-CT.	Mineral volume,Mean mineral profile,Mean mineral loss	Micro-CT,SEM	Mineral profiles of restoration using two-step self-etch adhesive (FL-Bond II) with CR restoration (Beautifil Flow F10) was greater than that for fluoride-free self-etch adhesive (Clearfil SE Bond) and CR (Clearfil Majesty ES Flow High) but lower than that for GIC restoration (Fuji-VII).
Zhao et al., 2017 [29]	Determined effect of SDF and CPP-ACP in GIC on root caries prevention. Prepared and restored specimens in difference conditions then exposed them to thermocycling and cariogenic bacteria.	Outer lesion depth,Mineral content,Inorganic profile in dentin	Micro-CT,SEM/EDS, FTIR	SDF application combined with CPP-ACP containing GIC restoration had a synergistic effect on root caries prevention. Both SDF and CPP-ACP had a significant effect for reducing the outer lesion depth and collagen exposure. Calcium and phosphate content increased in GIC restoration containing CPP-ACP.
Zhao et al., 2017 [30]	Determined effect of SDF and KI in GIC on secondary caries prevention. Prepared and restored specimens in different conditions then exposed them to cariogenic biofilm.	Outer lesion depth, Inorganic profile in dentin, Total color change	Micro-CT,FTIR, Spectrophotometry	SDF + KI application combined with GIC restoration had a synergistic effect on root caries prevention. This combination significantly reduced the outer lesion depth, collagen exposure, and degree of discoloration.
Yip et al., 2007 [25]	Tested protective effect of GIC (Ketac-Molar Applicap), RMGI (Photac-Fil), and CR (Filtek Supreme) restorations against multispecies oral biofilm.	Mineral content,Inorganic profile in dentin	SEM/EDS,FTIR	GIC showed higher mineral content at depth of 20 µm (higher log Ca: P) and lower collagen and organic matrix exposure (low degree of log[amide I: HPO_4^{2-}]) when compared to the other materials.
Hara et al., 2006 [67]	Loaded GIC (Ketac-fil plus) or RC (Filtek Z250) restorations into intra-oral appliances in 16 human volunteers to restore bovine root specimens. Measured fluoride levels from restoration, fluoride concentration in the biofilm, and mineral loss.	Fluoride level,Fluoride concentration in the biofilm, Mineral loss	Fluoride electrode, X-ray imaging and computer software	GIC restoration did not provide protective effect against secondary root caries, although the level of released fluoride ions was higher than that for the RC restoration.
Hara et al., 2002 [26]	Tested the cariostatic effect of five fluoride containing restorative materials (Ketac-Fil plus, Fuji II LC, Dyract AP, SureFil/Prime & Bond NT, and Filtek Z250/Single Bond) using artificial caries formation and measured surface microhardness.	Microhardness	Microhardness testing (Knoop diamond indenter)	GIC (Ketac-Fil) and RMGI (Fuji II LC) extended the cariostatic effect to 300 and 150 µm on the subsurface, respectively, but no effect was observed for the other materials.
Dionysopoulos et al., 1998 [22]	Determined lesion depth of difference restorative materials after artificial acidic challenge for five weeks.	Mean lesion depth	Polarized light microscopy	Lesion depth of GIC (Fuji) restoration was lower than that of other fluoride-releasing restorations.
Pereira et al., 1998 [27]	Measured inhibition zone and lesion formation with different restorative materials after artificial caries formation.	Outer lesion depth,Height and width of inhibition zone, Wall lesion formation	Polarized light microscopy	No significant difference in outer lesion depth with different restorative materials. An inhibition zone was found with GIC (Fuji II) and RMGI (Fuji II LC and Vitremer) restorations but not with fluoride-releasing adhesive or CR restorations (Clear Fill Liner Bond II and Clear Fill AP-X).
Gilmour et al., 1997 [23]	Evaluated outer lesion depth and wall lesion formation of different restorative materials after treatment with *S mutans* acidic challenge for 15 days.	Outer lesion depth, Wall lesion formation	Polarized light microscopy	GIC restoration (Chemfil II Compules) presented caries preventive effect via less outer lesion depth and wall lesion formation compared to CR restoration (Mirage-Bond and Heliomolar RO cavifil).
Sidhu and Henderson, 1992 [28]	Prepared and restored Class V cavities using difference restorative materials. Treated half of specimens by thermocycling (1500 cycles) and the other half used as control. Determined microleakage by degree of dye penetration.	Microleakage	Stereomicroscopy	GIC (Fuji II) presented the most effective sealing. In addition, the acid etching technique reduced microleakage of occlusal margin in composite material but did not completely seal at the gingival margin. There was no significant difference of microleakage between the groups treated with/without thermocycling.

Abbreviations: CPP-ACP: Casein phosphopeptide–amorphous calcium phosphate complexes; CR: Composite resin; GIC: Glass ionomer cement; KI: Potassium iodide; Micro-CT: Micro-computed tomography; RMGI: Resin-modified glass-ionomer; SDF: Silver diamine fluoride; SEM: Scanning electron microscopy, SEM/EDS: Scanning electron microscopy with energy dispersive spectroscopy; FTIR: Fourier-transform infrared spectroscopy.

Table 2

List of clinical studies related to direct restoration for root caries and their details.

Author	Study design	Material	Participant				Post-operative evaluation		
			Target	Number of participants(beginning/ final)	Subject's age in mean ± SD [range] (years)	Number of restorations (beginning/final)	Follow up (month)	Criteria	Clinical outcome
Levy and Jensen, 1990 [18]	**Non-RCT**[a]	**GIC** (Ketac-Fil) vs **CR** (Silux Microfill Composite)	Nonspecific	50/34	52.4 [25–7]	GIC (59/44) CR (45/33)	24	USPHS	**Clinically acceptable: GI (45%) = CR (73%)** Full retention: GI (39%) = CR (73%) Caries formation: GI (0%) = CR (2%) Marginal integrity: GI (45%) = CR (38%) **[Not statistically significant (Chi-square test: $p > 0.05$)]**
Kaurich et al., 1991 [9]	**Non-RCT (Matched-pair study)**	**GIC** (Ketac-Fil) vs **CR** (Silux Microfill Composite)	Excluded participants with symptoms of xerostomia, physical disabilities that prevented bilateral oral hygiene, or severe medical problems	9/8	40.3 ± 41 [27–63]	GIC (27/23) CR (27/23)	12, 24	USPHS	**At 24 months** Caries formation: GI (4.3%) = CR (4.3%) Plaque score: GI (54.6%) = CR (52.2%) Color match: GI (20.3%) = CR (30.4%) Gingival inflammation: GI (13.6%) = CR (13.0%) Marginal adaptation: GI (54.6%) = CR (56.5%) Marginal discoloration: GI (73.3%) = CR (87.0%) **[Not statistically significant using Chi-square test: $p > 0.05$]** Anatomical form: GI (68.2%) < CR (100.0%) **[Statistically significant (Chi-square test: $p < 0.05$)]**
McComb et al., 2002 [10]	**Non- RCT**[a]	**GIC** (Ketac-Fil) vs **RMGI** (Vitremer) vs **CR** (Z100)	Head and neck radiotherapy patients	50/44	18 years age or older	GIC (50/28) RMGI (50/21) CR (50/20)	6, 12, 18, 24	Marginal adaptation, Anatomical form, Recurrent caries	**In fluoride users** There was no recurrent caries were observed in any restorative materials all the time. **In non-fluoride users (**24 months) Marginal caries: GI (0%), RMGI (12.5%), CR (67%) **Mechanical failure, independent of fluoride use (**24 months) GI (89%), RMGI (67%), CR (41%)
Hu et al., 2002 [11]	**Non-RCT**[a]	**GIC** (Ketac-Molar Aplicap) vs **GIC** (Fuji IX GP)	Head and neck radiotherapy patients	15/13	[37–76]	Ketac-Molar Apicap (73) Fuji IX GP (73)	6, 12, 24	Secondary caries, Anatomic form, Marginal integrity retention, Marginal discoloration, Surface texture	Both materials presented 0% secondary caries and anatomical failure all the observational periods. **At 12 months** Overall failure: Ketac-Molar Apicap (20.5%), Fuji IX GP (2.7%) **At 24 months** Overall failure: Ketac-Molar Apicap (33.3%), Fuji IX GP (13.8%)
Hu et al., 2005 [12]	**Non-RCT**[a]	**GIC** (Ketac-Molar Aplicap) vs **GIC** (Fuji IX GP)ART vs conventional technique	Head and neck radiotherapy patients	15/13	63 [37–76]	Art (74) Conventional technique (72)	6, 12, 24	Phantumvanit et al., 1996	**At 24 months** Success rate; ART (65.2%) = conventional (66.2%) **[Not statistically significant (Fisher's exact test, $p = 0.62\text{-}1.00$)]**
Lo et al., 2006 [13]	**RCT**[a]	**GIC** (Ketac Molar) ART vs conventional technique	Elderly patients (>60 years)	103/77	78.6	ART (78/59) Conventional technique (84/63)	6, 12	USPHS and Francken et al., 1998	**At 12 months** Survival rate**:** ART (87.0%) = Conventional technique (91.7%) **[Not statistically significant (Gehan's Wilcoxon test, $p = 0.30$)]**

Table 2 (*Continued*)

Author	**Study design**	**Material**	**Participant**				**Post-operative evaluation**		
			Target	**Number of participants(beginning/ final)**	**Subject's age in mean ± SD [range] (years)**	**Number of restorations (beginning/final)**	**Follow up (month)**	**Criteria**	**Clinical outcome**
De Moor et al., 2011 [14]	**Non-RCT**[a]	**GIC** (KetacFil) vs **RMGI** (PhotacFil) vs **CR** (Herculite XRV)	Head and neck radiotherapy patients with xerostomia	35/27	Not mentioned	GIC (35) RMGI (35) CR (35)	6, 12, 18, 24	Marginal adaptation, Loss of material, Recurrent caries [18]	**In non-fluoride user** Recurrent caries at 6, 12,18 and 24 months: GI<CF **Marginal and anatomical failure form independent of fluoride use** At 6 months: GI > CR At 12 months: GI > RMGI = CR At 18 and 24 months: GI > RMGI > CR **[Statistically significant (Pearson's Chi-square and Fisher's exact tests)]**
da Mata et al., 2015 [15]	**RCT**	**GIC** (GC Fuji IX) ART vs conventional technique	Elderly patients (>65 years)	99/71	73.2 ± 6.8 [65–90]	ART (101) Conventional technique (73)	6, 12, 24	Presence of restoration, Marginal adaptation, Anatomical form, Recurrent caries	**At 24 months** Survival rate: ART (85.4%) = Conventional technique (90.9%) **[Not statistically significant (Cox pH model, p = 0.8095)]**
Cruz Gonzalez and Marin Zuluaga, 2016 [16]	**RCT**[a]	**RMGI** (Vitremer) ART vs conventional technique	Elderly patients (>60 years)	75/64	74.9 [60–101]	ART (101) Conventional technique (73)	6	Presence of restoration, Condition of restoration, Secondary caries, Antagonist, Oral hygiene	Clinical successful: ART (81.3%) < Conventional technique (92.9%) Secondary caries: ART (17/64) > Conventional technique (1/84) **[Statistically significant (chi-square tests, p < 0.01)]**
da Mata et al., 2019 [19]	**RCT**	**GIC** (GC Fuji IX) ART vs conventional technique	Elderly patients (>65 years)	99/28	73.2 ± 6.8 [65–90]	ART (142) Conventional technique (158)	6, 12, 18, 24, 60	Presence of restoration, Marginal adaptation, Anatomical form, recurrent caries	**At 60 months** Survival rate: ART (85%) = Conventional technique (79%) **[Not statistically significant (Cox pH model, p = 0.8095)]**
Koc Vural et al., 2021 [17]	**RCT (Split-mouth)**	**RMGI** (Riva Light Cure) vs **RC** (Spectrum TPH3)	Elderly patients (>60 years)	33/30	52.69 ± 9.7 [37–89]	RMGI (47) RC (43)	6, 12, 18, 24, 36	modified USPHS	**At 36 months** Retention: RMGI = RC (p = 0.219) Marginal adaptation: RMGI = RC (p = 0.16) **[Not statistically significant, Pearson's Chi-square test]** Marginal discoloration: RMGI > RC (p < 0.001) **[Statistically significant, Pearson's Chi-square test]** Both materials presented 0% secondary caries all the observational periods

Abbreviations: CR: Composite resin; GIC: Glass ionomer cement; Non-RCT: Non-randomized controlled trial; RCT: Randomized controlled trial; RMGI: Resin-modified glass-ionomer; USPHS: United States Public Health Service.

[a] Classification based on the reported study design as the type of study was not clearly indicated in the original article.

Table 3
Clinical follow up criteria for dental restorative materials on root caries and surrounding structure.

	Criteria	Modified Ryge criteria 1971	Phantumvanit et al., 1996	Francken et al., 1998	Mccomb et al., 2002	Francken et al., 2006	Cruz Gonzalez and Marin Zuluaga, 2016	USPHS	Modified USPHS
	Hu et al., 2002 [11]	Hu et al., 2005 [12]	Lo et al., 2006 [13]	De Moor et al., 2011 [14], McComb et al., 2002 [10]	da Mata et al., 2015 [15], da Mata et al., 2019 [19]	Cruz Gonzalez and Marin Zuluaga, 2016 [16]	Kaurich et al., 1991 [9], Levy and Jensen, 1990 [18], Lo et al., 2006 [13]	Koc Vural et al., 2021 [17]	
1. Restorative conditions	1.1 Presence of restoration	√	√	√	√	√	√	√	√
	1.2 Color matching	–	–	–	–	–	√	√	–
	1.3 Marginal integrity	√	√	√	√	√	√	√	√
	1.4 Marginal discoloration	√	√	–	–	–	√	√	√
	1.5 Anatomical form/wear	√	√	√	√	√	√	√	–
	1.6 Surface texture	√	√	√	–	–	√	–	–
2. Tooth conditions	2.1 Tooth presence	–	√	√	–	√	√	–	–
	2.2 Presence secondary caries	√	√	√	√	√	√	√	√
	2.3 Post-operative sensitivity	–	–	–	–	–	–	–	√
	2.4 Prosthodontic replacement	–	–	–	–	–	√	–	–
3. Surrounding conditions	3.1 Oral hygiene	–	–	–	–	–	√	–	–
	3.2 Periodontal status	–	–	–	–	–	√	–	–

Abbreviations: USPHS: United States Public Health Service.
[a]The symbol "√" means the clinical manifestation was included in the clinical follow-up criteria of root surface restoration.

Table 4
List of In vitro studies related to dental adhesive system and composite resin (CR) restoration for root caries treatment.

Authors	Material	Bioactive agents	Study design	Parameter	Evaluation	Finding
Balhaddad et al., 2020 [44]	CR	DMAHDM, NACP	Experimentally created new bioactive CR. Added DMAHDM and NACP into CR. Evaluated mechanical properties and antibacterial response.	Flexural strength, Elastic modulus, Surface roughness, Surface charge density, Bacterial response	Universal Testing Machine, Surface roughness testing, Fluorescein staining, CFU count, MTT assay, Live/Dead staining, Lactic acid production	The interaction of DMAHDM and NACP significantly reduced the flexural strength. Clinically acceptable roughness values of less than 0.2 μm were found in all groups. DMAHDM and NACP increased charge density. Artificial biofilm formation can be reduced by presence of DMAHDM with concentration dependent manner.
Zhou et al., 2020 [46]	CR	DMAHDM, NACP	Synthesized antibacterial and demineralizing CR. Added DMAHDM and NACP into CR. Evaluated mechanical properties and antibacterial response.	Surface hardness, Flexural strength, Elastic modulus, Calcium and phosphate release, Bacterial response	Vickers hardness testing, Universal Testing Machine, Spectrophotometric methodCFU count, MTT assay, Live/Dead staining, Lactic acid production, Polysaccharide production	30% NACP and 3% DMAHDM had no negative effect on the flexural strength or elastic modulus of the composite when compared to commercial product. After acidic challenge, CR incorporating DMAHDM and NACP showed protective effect via root dentin hardness at 100, 200, and 300 μm. New material could release calcium and phosphate ions. Antimicrobial properties shown through the suppression of microbial metabolic activity, lactic acid production, and biofilm formation (*S. mutans*, *L. acidophilus*, *C. albicans*, and multispecies model).
Wang et al., 2019 [41]	CR	DMAHDM, MPC NACP	Synthesized new prototype of CR to prevent periodontal biofilm formation by adding DMAHDM, MPC, and NACP. Evaluated mechanical properties and antibacterial response.	Surface roughness and topography, Charge density, Protein adsorption, Response to periodontal bacteria	Atomic force microscopy,Fluorescein staining,Micro bicinchoninic acid method,CFU count, MTT assay, Live/Dead staining, Lactic acid production, Polysaccharide production	The new CR had no negative effect on surface roughness. DMAHDM can increase the charge on the surface. 3% MPC in composite decreased protein adsorption. The new CR had suppressive effect on multispecies periodontal biofilm.
Xiao et al., 2019 [42]	CR	AgNPs, MPC, DMAHDM, NACP	Created novel multifunctional composite for root caries treatment. Added AgNPs, MPC, DMAHDM, NACP into new material. Evaluated mechanical properties and antibacterial response.	Flexural strength, Elastic modulus, Dentin shear bond strength, Protein adsorption, Response to periodontal bacteria	Universal Testing Machine, Micro bicinchoninic acid method, CFU count, MTT assay, Polysaccharide production for biofilm, Live/Dead staining	The novel multifunctional nanocomposite containing 0.12% AgNPs reduced metabolic activity, polysaccharide production, and biofilm growth of three periodontal pathogens without negatively affecting the mechanical properties.
Wang et al., 2016 [45]	CR	DMAHDM, NACP	Created novel multifunctional composite for root caries treatment. Added DMAHDM, NACP into new material. Evaluated mechanical properties and antibacterial response.	Flexural strength, Elastic modulus, Response to periodontal bacteria	Universal Testing Machine, Live/Dead staining, CFU count, Crystal violet biofilm biomass assay, Polysaccharide production	3% DMAHDM + 20% NACP + CR had no negative effect on flexural strength and elastic modulus compared to Heliomolar (commercial product). Strong suppression of the activity of periodontal bacteria was observed.

Table 4 (*Continued*)

Authors	Material	Bioactive agents	Study design	Parameter	Evaluation	Finding
Zhang et al., 2015 [43]	Dental adhesive	MPC, DMAHDM, NACP	Created novel multifunctional adhesive system for root caries treatment. Added MPC, DMAHDM, NACP into new material. Evaluated mechanical properties and antibacterial response.	Dentin bonding strength,Protein adsorption,Adhesive surface texture,Response to periodontal bacteria	Universal Testing MachineMicro bicinchoninic acid method,SEM, Live/Dead staining, MTT assay, Lactic acid production, CFU count	7.5% MPC + 5% DMAHDM + 30% NACP had no effect on dentin shear bonding strength. Low protein adsorption was observed when compared to the control. Strong suppression on the bacterial activities was represented.
Rolland et al., 2011 [36]	Dental adhesive	MDPB	Applied Clearfil SE Bond and Clearfil Protect Bond containing MDPB to 36 volunteers. Tested antimicrobial properties using CFU method. Calculated percentage reduction in CFU.	Antimicrobial effects	CFU count	Clearfil Protect Bond containing MDPB had a significantly higher inhibitory effect on streptococci than that of Clearfil SE Bond. For other species (lactobacilli, yeasts, and gram-positive pleomorphic rods), there were no significant differences between the materials.
Espejo et al., 2010 [63]	Dental adhesive	–	Formed artificial caries and tested anticaries behavior of three dental adhesives: Clearfil SE Bond, Xeno III, and Scotchbond Multi-Purpose Plus, using light microscopy and SEM.	Outer lesion depth, Wall lesion depth, Wall lesion extension	Light microscopy with computer software, SEM	Clearfil SE Bond showed the smallest caries formation. In addition, an interdiffusion zone, which may protect the dental structure from dental caries, was formed by Clearfil SE Bond.
Thome et al., 2009 [35]	Dental adhesive, CR	MDPB	Determined root caries progression in dental adhesives and CR containing MDPB after 15 days artificial carious challenge.	Outer lesion depth	Polarized light microscopy	MDPB-containing CR presented an inhibitory effect on artificial root caries formation regardless of adhesive systems.
Walter et al., 2008 [64]	Dental adhesive	Fluoroalumino-silicate glass, glutaraldehyde	Determined root caries progression in four dental adhesives using confocal laser microscopy after a week's artificial carious challenge.	Mean lesion depth	Confocal laser microscopy with ImageJ software	Fluoride- and glutaraldehyde-containing adhesive systems had a potential to prevent caries formation.
Hara et al., 2005 [65]	Dental adhesive	Strontium fluorosilicate glass, Fluoroalumino-silicate glass	After artificial caries formation, observed the fluoride release level, demineralization areas, wall lesions, and inhibition zone of restorations using fluoride-releasing dental adhesive.	Amount of fluoride release,Demineralization areas, Wall lesion formation, Inhibition zone	Ion-selective electrode,Polarized light microscopy	Fluoride-releasing dental adhesive could not prevent caries formation when compared to GIC, although some could release fluoride.
Kuramoto et al., 2005 [34]	Dental adhesive	MDPB	Evaluated anti-caries behavior of dental adhesive containing MDPB and three commercial dental adhesives after immersion in acid-gel or acid-producing *S. mutans*.	Outer lesion depth	X-ray with image-analyzing software, SEM	Dental adhesive containing MDPB was able to inhibit caries progression when compared to the commercial products.
Yoshiyama et al., 2004 [88]	Dental adhesive	MDPB	Observed micro-tensile bonding strength and lesions of Protect Bond containing MDPB in different dentin qualities and regions.	Micro-tensile bond strength,Characteristics of lesions	Universal Testing Machine,TEM, SEM	Difference dentin qualities influenced the bonding strength (Sound dentin > affected dentin > infected dentin).

Table 4 (*Continued*)

Authors	Material	Bioactive agents	Study design	Parameter	Evaluation	Finding
Doi et al., 2004 [56]	Dental adhesive	–	Evaluated the micro-tensile strength of fluoride-releasing adhesive system in different dentin conditions (coronal, root, affected dentin, infected dentin).	Micro-tensile bond strength,Characteristics of lesions	Universal Testing MachineSEM, TEM	Difference in dentin quality and region influenced the bonding strength (Sound coronal dentin > sound root dentin > affected dentin > infected dentin). SEM and TEM images showed high porosity and irregular resin tag in affected/infected dentin infected dentin.
Itota et al., 2002 [54]	Dental adhesive and CR	PRG	Identified protective effect of fluoride-releasing dental adhesive and CR on dental caries after artificial caries formation.	Amount of fluoride releaseThickness and depth of acid resistant zone	Fluoride-specific electrode,soft X-ray unit	The restoration containing PRG resulted in increased fluoride concentration for up to 10 weeks. An acid-resistant zone was detected. Outer lesion depth was reduced when compared with the restorative material without PRG.
Imazato et al., 2002 [37]	Dental adhesive	MDPB	Evaluated penetration into artificial caries lesions and bactericidal activities (*S. mutans* or *L. casei*) of experimental dentin bonding agent containing MDPB compared to three commercial products.	Antibacterial activity,Resin penetration	CFU count,confocal laser scanning microscopy	No significant difference was observed on penetrating ability among all materials tested into artificial caries lesion. Dentin bonding agent containing MDPB showed a strong suppression on *S. mutans* or *L. casei.* Complete bactericidal effect was found in a dentin bonding agent containing 4% MDPB.
Yoshiyama et al., 1996 [57]	Dental adhesive	–	Micro-tensile bonding strength of two commercial dental bonding agents, All Bond 2 and Imperva Bond, were investigated in different areas of dentin (mid coronal area, cervical area, middle root area and apical root). Observed thickness of resin-infiltrated dentin using SEM.	Micro-tensile bond strength,Thickness of resin infiltrated dentin	Universal Testing Machine,SEM	Imperva Bond group presented no effect of dentin area on micro-tensile bonding strength. However, All Bond 2 showed significantly lower tensile bonding strength at the cervical and middle roots. The thickness of resin infiltrated dentin in the Imperva Bond group was less than 0.5 μm in all experimental areas. However, All Bond 2 presented a thicker resin infiltrated layer at the coronal area.

Abbreviations: AgNPs: Silver nanoparticles; CFU: Colony forming unit, CR: Composite resin; DMAHDM: Dimethylaminohexadecyl methacrylate; GIC: Glass ionomer cement; MDPB: 12-Methacryloyloxydodecyl pyridinium bromide; MPC: 2-Methacryloyloxyethyl phosphorylcholine; MTT: 3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyl-2*H*-tetrazolium bromide; NACP: Nanoparticles of amorphous calcium phosphate; PRG: Pre-reacted glass ionomer, SEM: scanning electron microscopy; TEM: Transmission electron microscopy.

3.3.2.1. Composite resin (CR) and adhesive systems containing antimicrobial agents. Multiple bacterial species play an important role in root caries formation and periodontal destruction. Therefore, new generations of CR restorations and adhesive systems have been developed based on the addition of bioactive functions. For example, silver nanoparticles (AgNPs), 12-methacryloyloxydodecyl pyridinium bromide (MDPB), 2-methacryloyloxyethyl phosphorylcholine (MPC), dimethylaminohexadecyl methacrylate (DMAHDM), and pre-reacted glass ionomer (PRG) have been developed. The experimental design of in vitro studies on root caries treatment, the chemical agents used, and their efficacies were collected and summarized in Table 4.

MDPB was introduced as a derivative agent of quaternary ammonium compounds in 1994 by Imazato et al. [32]. It has been confirmed to have strong antibacterial activity by destroying the bacterial membrane via a positive charge [33]. Since MDPB molecules can be copolymerized, they can be incorporated into dental materials. For root caries treatment, an in vitro study has suggested that the incorporation of MDPB into adhesive inhibits the progression of artificial root caries formation [34]. In addition, CR restorations containing MDPB showed a protective effect against secondary caries formation, similar to RMGI restorations [35]. Rolland et al. [36] compared the antibacterial effects of adhesive systems with and without MDPB in 36 patients using multispecies bacterial culturing. They found that Clearfil Protect Bond containing MDPB (Kuraray Noritake Dental, Tokyo, Japan) had a significantly higher inhibitory effect on streptococci than that of Clearfil SE Bond (Kuraray Noritake Dental, Tokyo, Japan). For another bacterial species, there was no significant difference between the materials [36]. Imazato et al. [37] proved that the incorporation of <5 wt% MDPB into dental primer had no negative effect on the penetrating ability of the dental adhesive. Moreover, MDPB showed a strong suppression on *Streptococcus mutans* and *Lactobacillus casei*; at a concentration of just 4 wt%, the MDPB addition completely prevented the recovery of these bacteria. Tezvergil-Mutluay et al. [38,39] reported that matrix metalloproteinase (MMP) and cathepsins, which can destroy collagen fibers in hybrid layers, were inhibited by MDPB. It is possible that this material may improve the longevity of the restoration trough and reduce hydrolysis in the hybrid layer. However, more studies are required to confirm this.

DMAHDM is another quaternary ammonium methacrylate. Quaternary ammonium methacrylates with various alkyl chain lengths have been synthesized to experimentally determine the best conditions for clinical applications. Li et al. [40] reported that a bonding agent incorporating DMAHDM with an alkyl chain length of 16 molecules presented a strong killing effect on *S. mutans* without compromising the micro-tensile bonding strength. The combination of DMAHDM and other agents has been adapted for use in dental root caries restorations [41–45]. Several studies have confirmed their strong antimicrobial activity against periodontal pathogens [41–43,45]. In addition, it has been confirmed that CR restorations containing DMAHDM can reduce biofilm formation by decreasing the production of polysaccharides and lactic acid by *S. mutans*, *Lactobacillus acidophilus*, *Candida albicans*, and multispecies models [46].

MPC is an inert biomedical membrane with the ability to inhibit non-specific protein adsorption related to cell adhesion and biofilm formation. Furthermore, this agent can bind with polymer matrixes, which are widely used in biomedical applications [47]. In dentistry, MPC has been incorporated in many kinds of dental materials, such as denture base resins [48] and CR restorations [42,43,49]. Combinations of CR, MPC, and other bioactive agents have been observed to reduce protein adsorption abilities nearly 10-fold when compared with control groups [41,42]. The restorations also retain good mechanical properties, including flexural strength, elastic modulus, and dentin shear bond strength [42]. In addition, Zhang et al. [43] reported that an adhesive (Scotchbond Multi-Purpose, 3M Co., St. Paul, MN) used as a control group showed approximately 18-fold higher protein adsorption than that of experimental groups containing MPC. However, the surface roughness increased when MPC was applied to the CR restoration [41]. Nevertheless, combinations of MPC and other bioactive agents present a strong antibacterial efficacy against periodontal biofilms [41,42].

AgNPs are antimicrobial agents that have been used for biomedical applications. The mechanism of action of AgNPs has been hypothesized to occur by one of three pathways [50]. The first pathway is that AgNPs interact with peptidoglycan, a component of the bacterial cell wall, resulting in cell wall disruption. The second pathway is by interaction with bacterial protein synthesis, which causes plasma membrane destruction. The third pathway is by inhibition of DNA replication via binding of the DNA base. Recently, nanocomposites containing several bioactive agents combined with AgNPs have been developed for preventing biofilm formation in root caries. An in vitro study confirmed that the newly developed nanocomposite demonstrated a strong antibacterial effect on several periodontal pathogens, including *Porphyromonas gingivalis*, *Aggregatibacter actinomycetemcomitans*, and *Fusobacterium nucleatum* [42].

3.3.2.2. Composite resin (CR) and adhesive systems containing remineralizing agents. In addition to antimicrobial agents, remineralization agents have also been incorporated into CR restorations to improve their therapeutic effect. For example, PRG, nanoparticles of amorphous calcium phosphate (NACP), and fluoroaluminosilicate glass have been used.

PRG has been introduced as a glass filler that can release several types of ions, such as aluminum, boron, fluoride, sodium, silicon, and strontium ions. In addition to its antimicrobial effects [51–53], PRG has also been confirmed to inhibit demineralization [54] and induce remineralization [54]. Itota et al. [54] investigated the anticaries behavior of adhesives and composite restorations containing PRG after artificial secondary caries formation for 14 days. They reported that a combination of adhesive and PRG-containing CR restoration reduced the outer caries lesion depth. In addition, no wall lesions were detected, and the thickness of the inhibition zone was increased. However, there is insufficient evidence regarding the efficacy of this material on root caries lesions.

NACP is a precursor of bioapatite. It has been developed for use as a remineralizing agent for tooth structures. Moreover, this agent also has anti-demineralization properties because it mainly contains calcium and phosphate [29]. It is present in many kinds of dental materials such as prophylaxis paste [55], adhesive systems [43], and CR [41,42,45]. Several studies have also demonstrated the good bioactivity of several bioactive agents, including NACP.

In addition to the materials development described above, retaining dentin quality is a key factor in successful root caries restoration. Several reports have mentioned that different dentin qualities affect the bond strength. Normal coronal dentin demonstrates the highest bond strength, followed by normal root dentin, affected root dentin, and finally infected root dentin [56,57]. From microstructural observations of the resin–dentin interphase of affected and infected dentin, a highly porous-thick hybrid layer and an irregular shape for the resin tag were found in the remaining carious dentin [56]. For this reason, caries removal techniques should be considered for improving the success of restorations.

3.3.3. Resin-modified glass-ionomer (RMGI)

The material concept of RMGI has been developed to combine the good mechanical properties of CR and biological properties of GIC into a single material. A number of studies have compared the biological efficacy and mechanical properties of RMGI with those of

Table 5

List of in vitro studies related to resin modified glass ionomer (RMGI) restoration for root caries treatment.

Authors	Study design	Parameter	Evaluation	Finding
Minakuchi et al., 2005 [58]	Flexural loadings applied to restorations (Fuji II LC, Prime & Bond NT combined with Dyract Flow, and Excite combined with Tetric flow). Marginal leakage at coronal and gingival margin were obtained using dry penetration method.	Microleakage	Stereomicroscopy	The marginal leakage in RMGI group was higher than that in the flowable composite group.
AL-Helal et al., 2003 [61]	Extracted teeth were prepared with Class V cavities on the buccal surface at the cemento-enamel junction. Different surface treatment methods were randomly performed on the prepared teeth, including no treatment, polyacrylic acid, phosphoric acid, and Scotchbond Multi-Purpose adhesive. Subsequently, RMGI (Photac-Fil) was used as a restorative material. Artificial caries formation was performed using the thermocycling method. Caries lesions and mineral density were evaluated using polarized light microscopy and computer software. Fluoride concentration in dental structure was detected using electron probe microanalysis.	Fluoride concentration,Lesion depth, Lesion area, mineral loss	Electron probe microanalysis, Polarized light microscopy, SEM	The phosphoric-acid-treated group presented significantly lower lesion depth, lesion area, and mineral loss when compared to the other groups. In addition, inhibition zone formation was found in 83% of this group. SEM revealed that the smear layer and smear plug were completely removed in the phosphoric-acid-treated group. Fluoride uptake to dentin was detected at 30–50 μm from the cavity. For RMGI restoration, removal of the smear layer by phosphoric acid treatment increased the cariostatic effect.
Torii et al., 2001 [59]	The caries-preventive effect of RMGI, compomer, and fluoride-releasing CR was evaluated. Fluoride released from the restorations was measured up to 10 weeks. Microradiographs of each material were obtained after acidic challenge for 14 days. Outer lesion depth and radio plaque zone were measured.	Fluoride concentration,Outer lesion depth,Thickness of radio plaque zone	Fluoride-specific electrode, Soft X-ray unit	The RMGI restoration released the highest level of fluoride. In addition, RMGI presented the highest effectiveness for root caries prevention (smaller outer lesion depth and thicker radio plaque zone) followed by compomer and fluoride-releasing composite resin. A strong relationship was found between the thickness of the radio plaque zone and amount of fluoride, whereas a weak relationship was found between amount of fluoride and outer lesion depth.
Creanor et al., 1998 [60]	The caries-preventive effect of RMGI (Vitremer) and amalgam fillings were observed after artificial caries simulation for four weeks using demineralizing solution or deionized water. Radiographic images were taken. Mineral loss and lesion body mineral content were measured using computer-based software.	Mineral loss, Lesion body mineral content	X-ray imaging with computer software	An RMGI-filled cavity showed higher subsurface remineralization than an amalgam filling. Increasing mineral content was observed with an RMGI restoration subjected to water cycling, but not for the amalgam restoration.

Abbreviations: CR: Composite resin; RMGI: Resin-modified glass-ionomer; SEM: Scanning electron microscopy.

other materials, as shown in Table 5. Minakuchi et al. [58] reported that, after flexural loading, RMGI (Fuji-II LC, GC) demonstrated a lower sealing ability than that of a flowable composite. Hara et al. [26] investigated the cariostatic effect of fluoride-releasing materials, including GIC, RMGI, compomer, fluoride-containing CR, and conventional CR through microhardness parameters. The results indicated that only GIC and RMGI presented a cariostatic effect. However, GIC presented a higher cariostatic efficacy than RMGI. Torii et al. [59] reported that RMGI showed higher fluoride ion release than compomer and CR. In addition, RMGI resulted in a lower lesion depth and thicker radio plaque zone surrounding the restoration after 14 days of acidic challenge. When compared to amalgam, the RMGI restoration exhibited a higher potential for remineralization [60]. This implies that RMGI causes a cariostatic effect by increasing the mineral density around the restoration site via fluoride ion release. McComb et al. [10] investigated the incidence of recurrent caries and failure of cervical restorations that were treated by a same-arch treatment using conventional GIC (Ketac-Fil, 3M Co.), RMGI (Vitremer, 3M Co.), and CR (Z100, 3M Co.) after 6, 12, 18, and 24 months in 45 Canadian patients (18 years or older) with a history of radiotherapy in the head and neck regions. This clinical study indicated that GIC restorations showed significantly higher failure rates than RMGI and CR restorations, with higher marginal leakage and anatomical deformity.

Al-Helal et al. [61] compared the effects of different pre-surface treatments on secondary caries protection by RMGI restorations after artificial caries formation by a thermocycling technique, including untreated surfaces, 35% phosphoric acid gel, 25% polyacrylic acid, and surfaces treated with Scotchbond Multi-Purpose adhesive (3M Co.). They found that the presurface treatment using 35% phosphoric acid gel before restoration by RMGI reduced demineralization, mineral loss, and lesion depth. Moreover, SEM images showed that the 35% phosphoric acid gel-treated group contained 83% acid-resistant zones, which was comparable to that found in the 25% polyacrylic acid-treated group. Koc Vural et al. [17] compared the clinical performance of RMGI and CR on the root caries surface. The results confirmed that there was no significant difference between RMGI and CR restorations with regard to marginal adaptation, anatomical form, caries formation, or tooth sensitivity after three years. However, 7.98 times more discoloration of the RMGI filling was found when compared to the CR restoration. Based on limited data, the anticariogenic effect of RMGI has been confirmed [10,26,59,61]. Although its performance is lower than that of conventional GIC restorations [26], its clinical performance and esthetics are strong advantages. RMGI may be an alternative restoration material for high caries risk patients.

4. Discussion

Dental caries is considered a multifactorial oral disease. Many risk indicators for root caries have been reported, such as root caries prevalence at baseline [2], number of remaining teeth [2,62], plaque index [2,62], exposure of the root surface [62], coronal decay [62], and xerostomia [62]. However, understanding of the root structure, caries progression, and characteristics of restorative materials is important for the selection of restorative materials.

At the dentin surface, dynamic mineral change can occur depending on the environmental conditions of the root surface. Demineralization, whereby the mineral composition of the tooth structure is removed, can occur due to acidity in the oral environment. When the pH reduces to 4.5–5.5, calcium and phosphate in the hydroxyapatite surface—the primary inorganic component of dentin—are released to neutralize the oral environment. On the other hand, supersaturated ions can also precipitate on the dentin surface [4]. Not only is the inorganic composition destroyed by acid-producing bacteria, but the organic composition also suffers from pathogens. The destruction of organic components has been hypothesized to occur according to three mechanisms [3]. The first hypothesis is that an acidic environment can reactivate MMP and cysteine cathepsins that are trapped in the dentin matrix during dentin formation, leading to self-proteolysis. The second hypothesis is that exposed proteins become denatured under acidic conditions. The last hypothesis is that bacteria produce proteolytic enzymes that affect the organic component in dentin.

The majority of in vitro studies have simulated artificial caries formation by one of two methods. The first method uses one or more species of cariogenic bacteria, such as pioneer acidogenic species (*S. mutans*, *Streptococcus sobrinus*, *Actinomyces naeslundii*) or aciduric species (*Lactobacillus rhamnosus*, *L. acidophilus*), for experimental caries formation [23,25,63,64]. The second method uses chemically induced caries-like lesions [22,27,65]. The anticariogenic effect of restorative materials has been measured and demonstrated through various parameters such as the character of the lesion, including outer lesion depth, wall lesion formation, inhibition zone formation, mineral content, mineral density, mineral loss, log[amide I: $HPO_4{}^{2-}$], microhardness loss, and microleakage. Recently, many bioactive agents have been synthesized for use as relining materials, and their effect on the suppression of the bacterial activity has been evaluated [41–44,46], as described above. It can be assumed that the development of restorative materials for root caries not only focuses on the preventive effect but also aims to enhance the antimicrobial performance of the materials.

Strengthening of the root dentin structure is another strategy for achieving root caries intervention. Fluoride offers numerous advantages, including acid neutralization, prevention of demineralization, enhanced remineralization, and fluoridated apatite formation; therefore, fluoride-releasing materials are commonly used in dentistry for caries prevention [66]. Regarding the results from many in vitro studies, GIC restorations have the greatest caries-preventing effects among direct restorative materials [23–26,28]. In contrast, one study reported that GIC had no preventive effect against secondary root caries [67]. The higher effectiveness of GIC can be explained by the effect of the material matrix on the ion-releasing behavior. Because of the higher hydrophilicity of the GIC matrix, the released fluoride ions can easily diffuse into the contacting structure, in comparison to resin-based matrixes, which act as a barrier and obstruct ion distribution [68]. To improve the effectiveness of resin-based materials containing fluoride-releasing glass fillers, the acidity of the resin matrix can be increased; however, this may lead to stronger dissolution of the fluoride-containing filler, resulting in excessive fluoride release. Furthermore, it may have an adverse effect on the mechanical properties, such as an increase of water absorption [68]. In addition, the remaining smear layer in the restorative–dentin interphase can have a negative effect on the caries-preventing behavior of fluoride-releasing restorative materials, as the released fluoride ions can be blocked from entering the dental substructure [61]. Total removal of the smear layer using phosphoric acid was found to enhance the precipitation of fluoride into the dentin subsurface in RMGI restorations. Recently, various types of remineralizing agents, such as CPP-ACP, NACP, and PRG, have been added to CR and GIC restorations. The results of in vitro studies indicate that this strategy is effective for caries prevention [30,44,46,54]. These remineralizing agents are good alternatives for root caries prevention. However, there are still limited data regarding the effects of these agents on the root dentin structure and root caries formation, and further studies are required.

Despite the multiple advantages of ART, including painlessness, ease of application, low cost, and release of fluoride from GIC [69], the long-term efficacy of these restorations has been questioned when compared with conventional techniques due to the limiting conditions during restorative procedures [70]. In addition, moisture control, lack of polishing, operator errors, and remaining affected dentin were identified as being responsible for ART failures [6]. Surprisingly, four clinical studies reported that the survival rate of both ART and conventional techniques were comparable at over two years follow up. Nevertheless, it is possible that ART could be an optional treatment under limiting conditions. Almost all the included clinical studies on ART used GIC as the main restorative material [12,13,15,19]. Only one study compared RMGI-based ART to conventional techniques [16]. Owing to this lack of data, the efficacy of different materials for ART is not presented in this review. Further research and evidence are required to understand the efficacy of ART with different materials. Interventions that combined chemical agents (e.g., chlorhexidine [71], SDF [72], fluoride varnish [73]) and restoration by ART have been introduced and studied in children, with some advanced benefits. However, there is still a lack of evidence for these combined root caries treatments.

The elderly population are considered particularly vulnerable to root caries. Multifactorial genetic and epigenetic factors further correlate with this risk factor [74]. One factor that is thought to worsen root caries formation is impaired salivary function [74]. Saliva plays a key role in the self-cleaning of the oral cavity by inducing mechanical flushing and immunoactivity. Some studies have indicated that the level of saliva production [75] and immunoglobulins [76] is not affected by age. However, some patients who take medication, receive head and neck radiation therapy, or suffer from systemic disease are found to have impaired salivary function or xerostomia (reduced saliva flow), which can be a cause of root caries [62]. Two clinical studies [10,14] compared the effectiveness of restorative materials in patients undergoing radiotherapy, who were either daily fluoride users or non-fluoride users. The results of both studies indicated that fluoride supplements could prevent caries formation with less influence of the restorative material. Interestingly, without fluoride supplements, the incidence of caries formation with GIC restorations was lower than that with RMGI or CR restorations [10,14]. Moreover, other factors such as diet, microbiome, oral hygiene, and systemic disease are crucial risk factors for pathogenicity and root caries progression [74]. The burden of tooth loss due to dental caries or periodontal disease also seems to be a common risk factor for the elderly population; those with 20 or more remaining teeth have been indicated to have better physical health than those with fewer than 20 [77]. Thus, it can be inferred that the number of remaining teeth may relate to quality of life in old age [77]. In Japan, the “80/20 Movement” was introduced in 2000 as a strategy to promote comprehensive health. One of the expectations of this campaign was that at least 20% of the population aged 80 or older should retain 20 or more teeth, and more than 50% of the population aged 60 years or older should retain 24 or more teeth [78]. The success of this policy proved that such campaigns can encourage good oral condition and health [79].

Mechanical failure has been indicated as an important factor for observing the effectiveness and durability of dental restorations. Marginal defects are a clinical sign of other complications such as staining, postoperative sensitivity, pulpal irritation, and the development of secondary caries. Material characteristics such as polymerization shrinkage, water resorption, solubility, elastic modulus, and shear bond strength may influence marginal gap formation [80]. In addition, difficulties in accessing the restoration site and moisture control are critical challenges for clinical situations, especially for the gingival margin. For resin-based materials, the relationship between water resorption and dimensional change has been studied. Hygroscopic expansion of the restoration produces stress against the lateral wall, which may cause debonding and marginal defects [81]. In addition, an increase of osmotic pressure from some components in the resin matrix, such as glass filler additions, has been identified as a cause of swelling [81]. However, when compared to hydrophilic materials such as GIC and RMGI, CR restorations present less water uptake within six months [82]. Polymerization shrinkage is another cause of CR restoration failure. However, incremental filling techniques have been designed to decrease the stress concentration in the cavity wall, and are recommended to reduce microleakage [83]. Besides the materials effects described above, occlusal loading may also lead to marginal gap formation. Restorations at the root area rarely suffer from direct forces from chewing; however, the distribution of the occlusal load can generate localized tension on the restoration [84].

A few papers have reported a correlation between microleakage in in vitro and in vivo testing [80], and the impact of material type on restorative failure. Stewardson et al. [85] identified factors associated with early failure in Class V restorations after two years follow up using multivariable analysis. Practitioner errors, elderly patients, glass ionomer and flowable composites, bur-preparation, and moisture contamination were identified as increasing the probability of failure [85]. Thus, it is assumed that the type of restoration is a relative cause of restorative failure.

Daily brushing with fluoride toothpaste is widely recommended for caries prevention. Inevitably, dentifrice particles in toothpaste may be harmful for the surface of restorations through abrasive wear. Rougher surface texture, loss of proper contour, and more color staining are all complications that can arise in restorations after long-term use. Two clinical studies reported that the mechanical failure rate of GIC restorations is significantly higher than that of CR restorations [10,14]. This can be explained by the wear-resistant nature of CR. Shabanian and Richards [86] investigated the effect of loading, material type, and pH on the rate of material wear in vitro. They found that CR restorations had a higher wear resistance than GIC restorations at high load and acidity. The filler content and acid tolerance of the resin matrix improve the wear resistance of CR restorations compared to that of GIC restorations.

Research and development of restorative materials and techniques is focused on improving caries prevention through two strategies: strengthening the root structure and hindering microorganisms. However, the basic properties of restorative materials affect their clinical performance. Fluoride-releasing materials have been widely studied and used as restorative materials for root caries. GIC and RMGI restorations present preventive effects against root caries formation, as shown in in vitro studies. Nevertheless, the limited data on the mechanical properties of the root dentin structure mean that the mechanical efficacy of these materials on root dentin are not well known. However, the incidence of mechanical failure in GIC restorations has been higher than that of CR restorations in several clinical studies [9,10,14]. Another limitation of our research is that the in vitro studies on GIC restorations could not be assessed for risk of bias owing to the differing nature of the study designs and the different purposes of the in vitro studies, which makes it difficult to determine appropriate criteria. In agreement with Tran et al.’s recent assessment [87], we posit that a comprehensive guide for solving this problem should be developed. Overall, while no universal material for root caries prevention has been identified, the impact of restorative materials on root caries formation is clear. Various bioactive agents can be incorporated into restorative materials to improve the bioactivity toward carious microorganisms, which may be a good alternative in the future. However, the long-term mechanical properties and biocompatibility of these materials should be investigated, along with clinical trials of new protypes.

5. Conclusions

Based on the evidence and limitations of this review, the following conclusions can be drawn.

From in vitro studies:

1 Among direct restorative materials, GIC and RMGIC present a high potential for secondary caries prevention.
2 A lack of cariostatic effect of CR was identified, while antimicrobial effects and tooth strengthening behavior improve the effectiveness of CR and adhesive systems on surface root caries treatment.

From clinical studies:

1 Owing to limited data, the most appropriate material for surface root caries treatment cannot be identified. Further studies are required to confirm the clinical efficacy.
2 ART is an optional treatment for root caries treatment under limiting conditions.

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Conflicts of interest

None.

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