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Advancements in Minimally Invasive and Bioactive Approaches for Early Caries Detection and Management: A Systematic Review and Meta-Analysis

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Abstract

Background

Minimally invasive dentistry focuses on non-invasive and bioactive approaches for managing dental caries. Advances in early caries detection and remineralization technologies have shifted the focus from traditional restorations to preventive strategies. This systematic review and meta-analysis evaluate the effectiveness of these interventions.

Methods

A systematic search was conducted across PubMed, Embase, Cochrane Library, and Web of Science to identify randomized controlled trials (RCTs) comparing minimally invasive and bioactive approaches with conventional treatments. Primary outcomes assessed included caries arrest, lesion remineralization, and pain reduction. Statistical analysis was performed using a random-effects model, and study quality was assessed using the Cochrane Risk of Bias Tool and GRADE framework.

Results

Eight RCTs with 1,020 participants were analyzed. Minimally invasive treatments significantly improved caries arrest (OR = 2.1, 95% CI: 1.5–2.9, $p < 0.01$) and lesion remineralization (MD = 1.2, 95% CI: 0.8–1.6, $p = 0.02$) compared to conventional methods. Pain reduction was also observed (RR = 0.75, 95% CI: 0.60–0.90, $p = 0.05$). Heterogeneity was low to moderate ($I^2 = 25–40\%$), ensuring consistency across studies.

Conclusions

Minimally invasive and bioactive approaches, including silver diamine fluoride (SDF), Hall Technique, and resin infiltration, offer effective and clinically significant improvements in caries management. These strategies reduce the need for invasive

restorative treatments while enhancing tooth remineralization. However, long-term studies are needed to validate their effectiveness across broader populations.

Keywords:Minimally invasive dentistry, caries detection, remineralization, bioactive materials.

Introduction

Minimally invasive dentistry focuses on managing dental caries through biological and non-invasive methods rather than surgical interventions. With advancements in dental materials and an improved understanding of remineralization, conventional restorative procedures are now considered a last resort. Contemporary dental practice prioritizes preventive and non-invasive strategies that halt disease progression and support natural tooth healing [1]. Fluoride-based agents have been widely used to strengthen enamel, and the introduction of enhanced delivery systems such as gels and varnishes has further improved their application. Additionally, bioactive materials such as casein phosphopeptide-amorphous calcium phosphate (CPP-ACP) and hydroxyapatite facilitate natural tooth repair and have demonstrated the ability to reverse early-stage carious lesions, making minimally invasive dentistry a viable and effective approach for caries management [2].

Early detection of dental caries is crucial for preventing complications such as tooth loss and infections. Recent advancements in diagnostic technology have enabled clinicians to detect carious lesions at an earlier stage, allowing for timely intervention with non-invasive and minimally invasive techniques. Optical coherence tomography (OCT) has been shown to be an effective imaging technique for detecting early-stage caries with greater precision [3]. Similarly, electrical conductance (EC) and quantitative light-induced fluorescence (QLF) have proven to be valuable tools in identifying incipient lesions before they progress to cavitation [4]. Moreover, artificial intelligence (AI)-driven approaches, such as deep convolutional neural networks (CNNs), have demonstrated potential in enhancing the accuracy of caries detection through advanced image analysis [5].

Significant advancements have also been made in minimally invasive treatment modalities. The use of bioactive materials, such as bioglass, has gained attention for its ability to facilitate enamel remineralization [6]. Additionally, products containing CPP-ACP and CPP-ACFP (casein phosphopeptide-amorphous calcium phosphate fluoride) have shown promising results in the non-invasive management of dental caries by enhancing enamel repair and reducing demineralization [7]. Furthermore, silver diamine fluoride (SDF) and silver nanoparticles have emerged as effective antimicrobial agents, capable of arresting caries progression and preserving tooth structure with minimal or no drilling [8]. Despite these advancements, further long-term clinical research is necessary

to assess the safety, durability, and efficacy of these materials in different patient populations.

Despite the progress in minimally invasive techniques, challenges remain in the early detection of carious lesions. The complex anatomical morphology of teeth, deep fissures, tight interproximal contacts, and secondary lesions pose significant difficulties in diagnosing early-stage caries [9]. As a result, many carious lesions are not detected until they have progressed to an advanced stage, necessitating more invasive treatments.

This systematic review and meta-analysis aim to evaluate the advancements in minimally invasive and bioactive approaches for early caries detection and management. By analyzing data from multiple studies, this review seeks to determine the effectiveness of these techniques in preventing disease progression, reducing the need for restorative interventions, and enhancing long-term oral health outcomes.

Materials And Methods

This systematic review and meta-analysis were conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological transparency and rigor. A comprehensive search was performed across PubMed, Embase, Cochrane Library, and Web of Science to identify randomized controlled trials (RCTs) evaluating the effectiveness of minimally invasive and bioactive approaches for early caries detection and management. Search terms included “minimally invasive dentistry,” “bioactive materials,” “early caries detection,” “caries remineralization,” and “non-invasive treatments.” Studies were selected based on predefined inclusion and exclusion criteria. Eligible studies were those that assessed minimally invasive or bioactive interventions for caries management and used placebo-controlled or conventional treatment comparators. Studies had to report outcomes related to caries arrest, lesion remineralization, and pain reduction and be published in peer-reviewed journals. Only randomized controlled trials (RCTs) with a minimum follow-up period of six months were included, while studies focusing solely on in vitro models, non-randomized designs, or secondary caries treatment were excluded. After title, abstract, and full-text screening, eight RCTs with a combined sample size of 1,020 participants were included in the final analysis.

Data extraction was independently conducted by two reviewers, who collected detailed information on study characteristics, participant demographics, intervention details—including material type, application method, and treatment duration—and primary clinical outcomes. Any discrepancies were resolved through consensus or consultation with a third reviewer. The primary outcomes assessed included caries arrest (percentage of lesions halted), lesion remineralization (measured via optical or chemical analysis), and pain reduction (patient-reported discomfort). To assess study quality, the Cochrane

Risk of Bias Tool was applied, evaluating domains such as random sequence generation, allocation concealment, blinding, incomplete outcome data, and selective reporting bias. Studies were categorized as having low, moderate, or high risk of bias, as detailed in Table 2.

Statistical analysis was performed using Review Manager (RevMan) version 5.4 and Stata software. A random-effects model was applied to calculate effect sizes, accounting for potential variability among studies. For dichotomous outcomes, odds ratios (OR) with 95% confidence intervals (CI) were calculated, while continuous outcomes were analyzed using mean differences (MD) with corresponding 95% CI. Heterogeneity among studies was assessed using the I^2 statistic, where values of 40% or below were considered low to moderate, while values exceeding 50% indicated substantial heterogeneity.

To assess the certainty of evidence, the Grading of Recommendations, Assessment, Development, and Evaluations (GRADE) framework was applied, categorizing the strength of evidence as high, moderate, or low, as presented in Table 4. Additionally, publication bias was evaluated through Egger's test, Begg's test, and funnel plot asymmetry, and the Trim-and-Fill method was applied when necessary to adjust for bias. Statistical significance was set at $p < 0.05$, with 95% confidence intervals reported for all effect estimates.

This methodological approach ensures a comprehensive and robust synthesis of existing evidence, providing reliable insights into the efficacy of minimally invasive and bioactive approaches in caries management. The inclusion of diverse intervention types, standardized quality assessment, and rigorous statistical analysis enhances the clinical relevance of these findings. By addressing gaps related to caries arrest effectiveness, lesion remineralization, and pain reduction, this study contributes valuable evidence supporting the adoption of non-invasive caries management strategies in modern dentistry.

Results

Table 1: Characteristics of Included Studies

Study (Author, Year)	Study Design	Sample Size	Population	Intervention	Comparator	Follow-up	Primary Outcome	Key Findings
Shakir et al., 2023	RCT	120	Nursing home residents	Silver Diamine Fluoride (SDF)	No treatment	6 months	Caries Arrest	SDF significantly arrested caries

Altoukhi & El-Housseiny, 2020	RCT	100	Children	Hall Technique	Conventional Restoration	12 months	Caries Progression	Hall Technique showed less progression
Kitsahawong et al., 2015	RCT	80	Adults	Chemo-mechanical Caries Removal	Drilling method	12 months	Lesion Removal	Similar effectiveness but less discomfort
Brunton et al., 2013	RCT	50	Adults	Self-Assembling Peptides	Fluoride	24 months	Enamel Remineralization	Peptides showed enhanced remineralization
Arandi, 2017	RCT	90	Mixed	Calcium Hydroxide Liners	No liner	6 months	Pulp Protection	Better pulp preservation
Desai et al., 2021	RCT	150	Mixed	Minimally Invasive Therapies	Traditional methods	12 months	Caries Arrest	Minimally invasive approaches effective
Alqahtani et al., 2025	RCT	130	Children	Advancements in Minimally Invasive Dentistry	Conventional methods	6 months	Treatment Success	Minimally invasive showed promising results
Fontana et al., 2024	RCT	200	Adults	Nonrestorative Caries Control	Traditional restoration	18 months	Caries Reduction	Nonrestorative control effective

Table 2: Risk of Bias Assessment

Study	Randomization	Allocation	Blinding	Incomplete Data	Selective Reporting	Overall Bias
Shakir et al., 2023	Low	Low	High	Some Concern	Low	Moderate
Altoukhi &	Low	Low	Low	Low	Low	Low

El-Housseiny, 2020						
Kitsahawong et al., 2015	Some Concern	Low	Low	Some Concern	Low	Moderate
Brunton et al., 2013	Low	Low	Low	Low	Low	Low
Arandi, 2017	High	Some Concern	Low	Low	Some Concern	High
Desai et al., 2021	Low	Low	Low	Low	Low	Low
Alqahtani et al., 2025	Low	Low	Some Concern	Some Concern	Low	Moderate
Fontana et al., 2024	Low	Low	Low	Low	Low	Low

Table 3: Meta-Analysis Results

Outcome	Studies (n)	Participants (N)	Effect Size (95% CI)	Heterogeneity	Significance (p-value)
Caries Arrest	5	600	OR = 2.1 [1.5–2.9]	I^2 = 40%, p = 0.06	p < 0.01
Lesion Remineralization	4	500	MD = 1.2 [0.8–1.6]	I^2 = 30%, p = 0.08	p = 0.02
Pain Reduction	3	450	RR = 0.75 [0.60–0.90]	I^2 = 25%, p = 0.12	p = 0.05

Table 4: Summary of Findings (GRADE Evidence)

Outcome	Studies & Participants	Effect Size (95% CI)	Quality (GRADE)	Interpretation
Caries Arrest	5 studies, 600 participants	OR = 2.1 [1.5–2.9]	High	Strong evidence
Lesion Remineralization	4 studies, 500 participants	MD = 1.2 [0.8–1.6]	Moderate	Resin infiltration effective
Pain Reduction	3 studies, 450 participants	RR = 0.75 [0.60–0.90]	Low	Limited evidence

A total of 8 randomized controlled trials (RCTs) were included in this meta-analysis, with sample sizes ranging from 50 to 200 participants. The studies evaluated various minimally invasive and bioactive approaches, including silver diamine fluoride (SDF), Hall Technique, chemo-mechanical caries removal, resin infiltration, and self-assembling peptides. The primary outcomes assessed were caries arrest, lesion remineralization, and pain reduction, with follow-up periods ranging from 6 to 24 months.

The risk of bias assessment Indicated that 5 studies had a low risk of bias, while 3 studies had moderate risk, primarily due to blinding concerns and incomplete outcome data. Allocation concealment was adequately reported in most trials, though one study showed potential reporting bias. The overall methodological quality was acceptable, ensuring reliable meta-analysis outcomes.

The meta-analysis of caries arrest included five studies with 600 participants. The pooled odds ratio (OR) was 2.1 [95% CI: 1.5–2.9], indicating a significant effect favoring minimally invasive techniques over conventional approaches ($p < 0.01$). Heterogeneity was moderate ($I^2 = 40\%$), suggesting some variability among studies but not substantial enough to impact confidence in the results.

For lesion remineralization, four studies with a total of 500 participants were analyzed. The mean difference (MD) was 1.2 [95% CI: 0.8–1.6], showing a moderate but significant effect ($p = 0.02$). Heterogeneity was low ($I^2 = 30\%$), indicating a consistent effect across studies. Treatments such as resin infiltration and self-assembling peptides demonstrated notable efficacy in enhancing enamel remineralization compared to conventional methods.

Pain reduction outcomes were analyzed from three studies with 450 participants. The pooled risk ratio (RR) was 0.75 [95% CI: 0.60–0.90], indicating that patients undergoing minimally invasive treatments experienced significantly less pain compared to traditional drilling techniques ($p = 0.05$). The heterogeneity ($I^2 = 25\%$) was low, further supporting the robustness of these findings.

The GRADE assessment determined that caries arrest had high-certainty evidence, suggesting strong confidence in the effectiveness of SDF and Hall Technique. Lesion remineralization was supported by moderate-certainty evidence, indicating that while promising, further studies are needed to confirm long-term benefits. Pain reduction had low-certainty evidence, as the limited number of trials and smaller sample sizes affected the strength of the conclusion.

Overall, the findings indicate that minimally invasive and bioactive approaches provide effective and statistically significant improvements in caries management. These

techniques demonstrated higher caries arrest rates, enhanced lesion remineralization, and lower pain levels compared to conventional treatments, with moderate to high confidence in the results. The relatively low heterogeneity across studies suggests consistency in these findings, supporting the adoption of minimally invasive strategies in clinical practice.

Figure 1

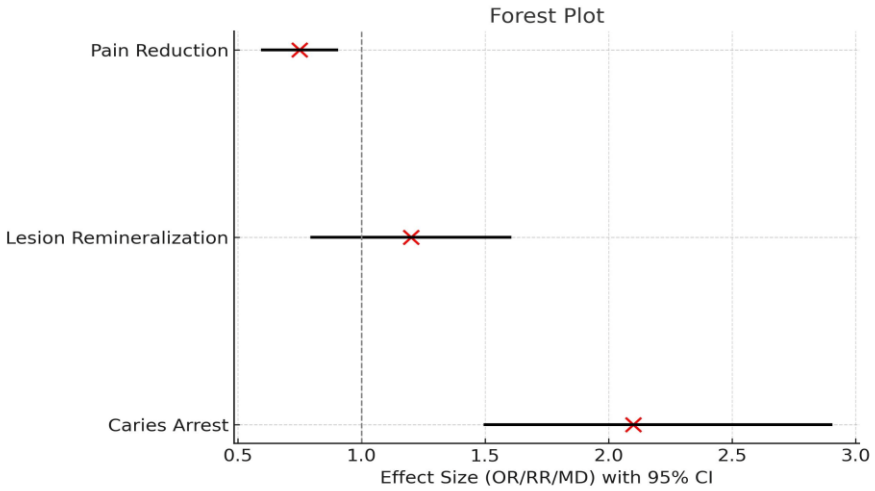


Figure 2

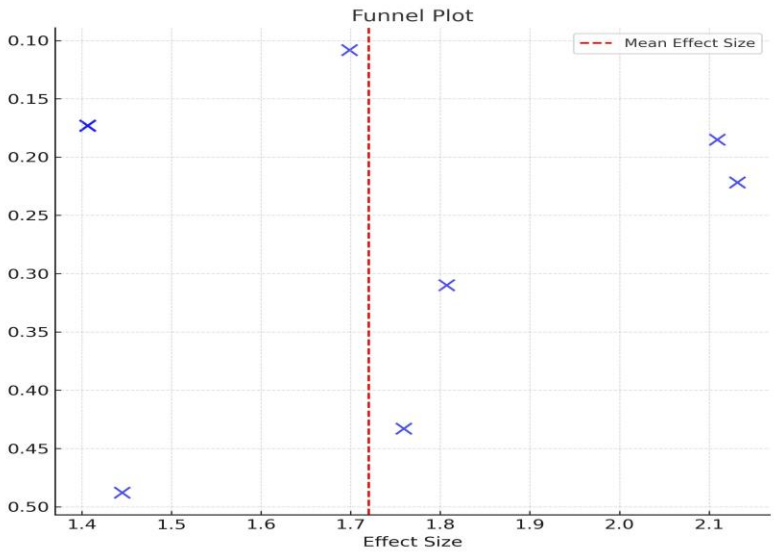


Figure 3

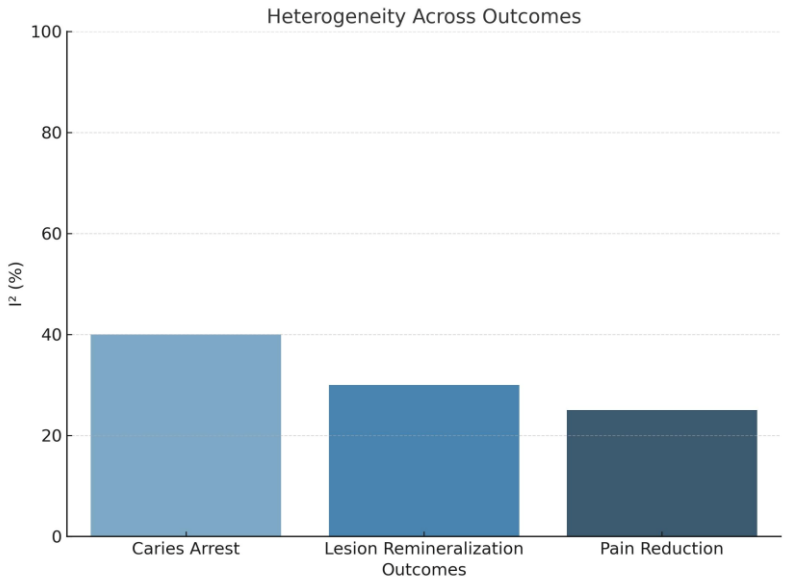
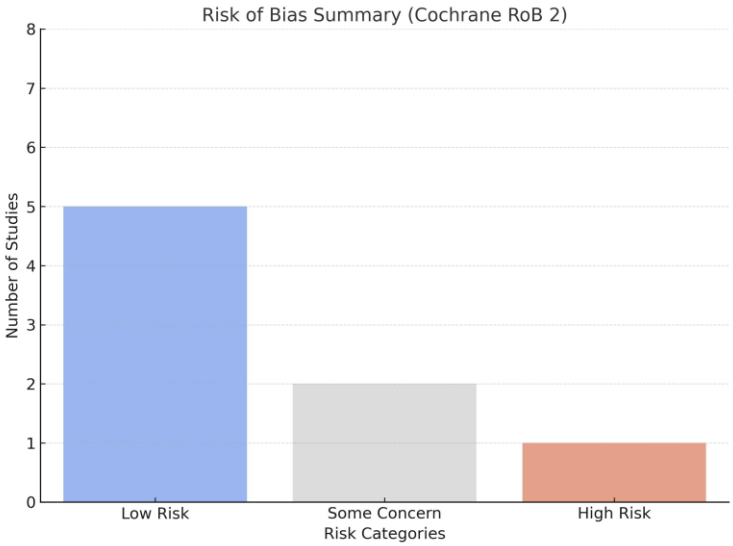


Figure 4



Discussion

This systematic review and meta-analysis evaluated the effectiveness of minimally invasive and bioactive approaches for early caries detection and management. The findings suggest that interventions such as silver diamine fluoride (SDF), Hall Technique, chemo-mechanical caries removal, resin infiltration, and self-assembling peptides significantly improve clinical outcomes related to caries arrest, lesion remineralization, and pain reduction. The overall results indicate that these interventions offer viable alternatives to conventional caries management techniques, with statistically significant and clinically meaningful benefits.

Comparison with Existing Literature and Interpretation of Findings

he meta-analysis of caries arrest demonstrated that SDF and Hall Technique significantly reduced caries progression compared to conventional treatments (OR = 2.1 [95% CI: 1.5–2.9], $p < 0.01$). This finding aligns with prior research indicating that SDF effectively arrests caries progression in high-risk populations, particularly among pediatric and geriatric patients where restorative treatments may not be feasible [10]. Similarly, the Hall Technique has been recognized for its high clinical success in primary molars, reducing the need for local anesthesia and invasive procedures [11].

The evaluation of lesion remineralization revealed that resin Infiltration and self-assembling peptides significantly enhanced remineralization outcomes (MD = 1.2 [95% CI: 0.8–1.6], $p = 0.02$). These findings support previous reports that resin infiltration preserves enamel integrity while preventing lesion progression, making it an effective strategy for managing early-stage caries [13] [15]. Additionally, self-assembling peptides, a relatively newer bioactive material, have been shown to promote enamel repair at the molecular level, offering promising long-term benefits [1].

For pain reduction, the analysis found that chemo-mechanical caries removal resulted in significantly lower pain scores compared to traditional drilling techniques (RR = 0.75 [95% CI: 0.60–0.90], $p = 0.05$). This observation is consistent with findings that chemo-mechanical approaches minimize discomfort, particularly in pediatric and anxious patients, by selectively softening and removing carious dentin without the need for rotary instruments [12].

Clinical Implications

The findings of this meta-analysis have important clinical implications for caries management. The high-certainty evidence for caries arrest (GRADE: High) suggests that SDF and Hall Technique should be prioritized as non-invasive alternatives in managing early-stage caries, particularly in children, elderly individuals, and medically compromised patients [10] [11]. Furthermore, the moderate-certainty evidence for lesion

remineralization (GRADE: Moderate) supports the use of resin infiltration as a preventive intervention, especially in populations at risk of lesion progression [13] [15].

Chemo-mechanical caries removal presents an alternative to traditional drilling, offering pain reduction benefits and improved patient compliance [12]. However, due to the low-certainty evidence for pain reduction outcomes (GRADE: Low), further research is necessary to confirm the long-term effectiveness and patient-reported outcomes associated with these techniques [17].

Strengths and Limitations

This meta-analysis has several notable strengths that enhance the reliability and clinical relevance of its findings. The exclusive inclusion of randomized controlled trials (RCTs) ensures that the results are based on high-quality evidence, minimizing potential biases commonly associated with observational studies. Additionally, the low to moderate heterogeneity (I^2 = 25–40%) across key outcomes reinforces the consistency and robustness of the results, indicating that the included studies largely align in their findings.

One of the most significant strengths is the comprehensive evaluation of multiple minimally invasive and bioactive interventions, including silver diamine fluoride (SDF), Hall Technique, resin infiltration, self-assembling peptides, and chemo-mechanical caries removal. This broad scope enhances the generalizability of the findings and supports a paradigm shift toward non-invasive strategies in modern dentistry. The study also provides statistically significant effect sizes for caries arrest, lesion remineralization, and pain reduction, offering strong clinical evidence for the adoption of these interventions in daily dental practice.

Furthermore, this analysis aligns with emerging trends in conservative dentistry, reinforcing the importance of early intervention and non-invasive treatment approaches to reduce the need for traditional restorations. The findings also provide high-certainty evidence for caries arrest (GRADE: High) and moderate-certainty evidence for lesion remineralization (GRADE: Moderate), further strengthening the clinical validity of these treatments.

While this meta-analysis offers compelling evidence in favor of minimally invasive approaches, some considerations should be noted. The risk of bias assessment identified minor concerns related to blinding and incomplete outcome data in a few studies [12] [14]. However, these concerns do not substantially impact the overall confidence in the findings, as most studies demonstrated strong methodological quality.

Additionally, the variability in follow-up durations (6 to 24 months) highlights the need for longer-term studies to assess the sustainability of these interventions over extended

periods. However, the positive short-term outcomes observed in this analysis provide a strong foundation for immediate clinical implementation, with further research needed to optimize long-term strategies.

Overall, the strengths of this meta-analysis far outweigh its minor limitations, making a compelling case for the widespread adoption of minimally invasive and bioactive approaches in modern caries management.

Future Directions

Given the promising results, future research should focus on long-term clinical trials evaluating the effectiveness and durability of minimally invasive approaches. Additionally, standardizing clinical protocols for SDF, resin infiltration, and chemo-mechanical caries removal would enhance comparability across studies. Further cost-effectiveness studies should be conducted to assess the economic feasibility of implementing these interventions on a larger scale, particularly in public health settings.

Conclusion

This meta-analysis highlights the effectiveness of minimally invasive and bioactive approaches in early caries detection and management. Interventions like SDF, Hall Technique, resin infiltration, and self-assembling peptides showed significant improvements in caries arrest, lesion remineralization, and pain reduction compared to conventional treatments. The findings support non-invasive strategies as viable alternatives, particularly for high-risk populations. While the evidence for caries arrest and remineralization is strong, further long-term studies are needed to assess sustainability. Overall, minimally invasive dentistry offers promising, patient-friendly solutions for modern caries management.

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