Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 05 | Received 31.10.2026 | Accepted 5.11.2026 | Online 10.11.2026

MODERN BIOLOGICAL APPROACHES TO PRESERVING PULP VITALITY IN DEEP CARIES: EVIDENCE-BASED EFFECTIVENESS AND CLINICAL DECISION-MAKING

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Abstract

Background: The treatment of deep carious lesions has shifted from complete removal of infected dentine toward biologically oriented strategies that aim to avoid pulp exposure and preserve pulpal function. Objective: To critically compare contemporary vital pulp preservation strategies, including selective and stepwise caries removal, indirect and direct pulp capping, and partial or full pulpotomy, with emphasis on calcium silicate biomaterials. Methods: A structured narrative synthesis of professional guidelines, systematic reviews, and clinical studies was undertaken. Evidence was organized by initial pulp diagnosis, exposure status, material, follow-up and treatment outcome; no original patient cohort was available. Results: The latest S3 clinical guideline favors selective or stepwise removal over non-selective excavation in deep lesions, while hydraulic calcium silicate cements are preferred over calcium hydroxide for pulp exposure management. A published meta-analysis of 21 studies including 1,948 permanent teeth found a relative risk of clinical success of 1.21 (95% CI 1.02–1.42) for mineral trioxide aggregate versus calcium hydroxide in direct pulp capping. Comparative effectiveness varies according to clinical diagnosis, restoration quality and follow-up. Conclusion: Pulp vitality preservation in deep caries should be based on accurate diagnosis, conservative excavation, effective isolation, appropriate bioactive materials and a durable coronal seal. More standardized prospective trials are needed to determine material-specific and long-term outcomes.

Keywords: deep caries; vital pulp therapy; selective caries removal; stepwise excavation; direct pulp capping; partial pulpotomy; mineral trioxide aggregate; Biodentine; calcium silicate cement; pulp vitality.

Introduction

Deep dentinal caries creates a therapeutic dilemma: aggressively removing all softened dentine can expose a potentially recoverable pulp, whereas leaving infected tissue without an effective seal may permit continued microbial activity. The traditional assumption that complete excavation is universally necessary has consequently been challenged by evidence supporting selective removal in carefully evaluated permanent teeth. Current biologically oriented dentistry seeks to preserve the dental pulp as a living,

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immunologically responsive, sensory and reparative tissue rather than treating every deep lesion as an inevitable indication for root canal treatment [1–3].

Pulp vitality is not merely an anatomical endpoint. Viable pulp supports dentine deposition, nociception, host defense and preservation of tooth structure over time. Nevertheless, clinical success is influenced by baseline symptoms, degree of inflammatory involvement, bacterial control, pulpal bleeding management and restoration integrity. In this setting, the clinical question extends beyond choosing a single biomaterial: it concerns the entire therapeutic sequence from diagnostic classification and caries excavation to material placement and follow-up [1,2]. The objective of this article was to synthesize comparative evidence on biological methods of pulp preservation in deep caries and develop a practical, testable decision framework for permanent teeth.

Literature Review

The European Society of Endodontology position statement of 2019 established a biologically conservative approach to deep caries and exposed pulps, emphasizing assessment of symptoms, radiographic characteristics, aseptic conditions and maintenance of a sound coronal seal [2]. The American Association of Endodontists subsequently broadened its position on vital pulp therapy to include selected mature permanent teeth and situations previously managed exclusively by root canal treatment, while highlighting limitations of symptom-based diagnosis and the critical importance of case selection [3].

An interdisciplinary EFCD–ESE–ORCA S3-level guideline published in 2026 provides a recent evidence-based synthesis: selective or stepwise caries removal is favored over non-selective removal to reduce pulp exposure. Routine placement of a cavity liner after non-exposure treatment is not consistently supported. Where carious pulp exposure occurs, direct capping or pulpotomy may be appropriate depending on pulpal diagnosis; hydraulic calcium silicate materials are favored over calcium hydroxide for direct pulp capping and pulpotomy [1]. These recommendations emphasize that an exposure-free deep lesion and a lesion with established pulp exposure represent distinct clinical problems.

Material development has focused on mineral trioxide aggregate (MTA), tricalcium silicate formulations such as Biodentine, and other hydraulic calcium silicate cements. Their biological appeal includes sealing capability, alkalinity and support for hard-tissue formation, although setting behavior, discoloration potential, handling and product-specific composition affect selection. Conventional calcium hydroxide remains historically important but may have limitations related to long-term seal and interface integrity. In contrast, resin-modified calcium silicate products should not automatically be assumed equivalent to conventional hydraulic cements without product-specific clinical evidence [4–6].

Comparative reviews reveal both promise and uncertainty. A 2025 meta-analysis including 21 studies and 1,948 treated permanent teeth reported superior direct pulp capping success for MTA compared with calcium hydroxide (RR 1.21; 95% CI 1.02–1.42), whereas comparisons between MTA and Biodentine did not show a significant difference [4]. Another network synthesis including 16 randomized trials (1,093 teeth) evaluated materials

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for deep caries managed without pulp exposure, reporting evidence favoring selected materials over dentine bonding agents, but many comparisons were of low confidence [5]. A separate synthesis of eight trials (678 teeth) found no statistically significant one-year success difference between several liners following selective excavation, illustrating why material findings must not be generalized across treatment techniques [6].

Materials and Methods

This manuscript is a structured narrative review rather than a report of newly recruited patients. It integrates clinical guidance and peer-reviewed evidence related to management of deep and extremely deep caries in permanent teeth, with attention to direct pulp capping, indirect pulp treatment, partial pulpotomy and complete pulpotomy. Priority was given to the 2019 ESE and 2021 AAE position statements, the 2026 multidisciplinary S3 guideline, and published meta-analyses from 2025–2026 [1–7]. Evidence was summarized across clinical indications, operative intervention, material selection, outcome definitions and follow-up. This approach does not represent a registered systematic review; no PRISMA flowchart, exhaustive database search, patient-level meta-analysis or pooled effect estimate was generated independently.

For interpretative consistency, primary outcomes were defined as retention of a vital, functional pulp without clinical signs of persistent or progressive disease and without radiographic evidence requiring endodontic treatment. Secondary outcomes included patient-reported pain, need for further intervention, restoration survival and development of periapical pathology. Comparisons are described using statistics reported by source publications, and no unpublished outcomes or statistical significance levels have been inferred. The proposed research framework focuses on permanent teeth with a clinically assessable pulp; primary teeth require distinct evidence-based protocols.

Results

Across the selected evidence, preservation of pulp vitality was feasible under several biologically oriented approaches. For teeth with deep caries and no pulp exposure, selective or stepwise removal reduced the risk of accidental exposure compared with complete non-selective excavation, provided that peripheral margins were adequately prepared and a durable restoration was achieved [1,2]. Where the pulp was exposed, direct capping and partial or full pulpotomy offered clinically relevant alternatives in appropriately selected cases, but the evidence does not support a universal technique independent of diagnosis and operative conditions [1,3,4].

In the pooled 2025 analysis of permanent teeth, MTA direct pulp capping had a significantly higher probability of clinical success than calcium hydroxide (RR 1.21, 95% CI 1.02–1.42; P = 0.03) [4]. This relative effect is shown in Figure 1 and should not be interpreted as an absolute increase of 21 percentage points. Other reviews of liner materials after selective excavation reported no robust between-material difference at one year, demonstrating that the value of a biologically active covering material depends on exposure status and treatment category [5,6].

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Clinical scenario	Biologically oriented strategy	Evidence-based qualification
Deep caries, no pulp exposure	Selective or stepwise removal, definitive seal	Avoid unnecessary exposure; routine lining not always required [1]
Small pulp exposure, suitable diagnosis	Direct pulp capping with hydraulic calcium silicate	Adequate bleeding control, asepsis and seal are essential [1–3]
Exposed coronal pulp, potentially recoverable	Partial or full pulpotomy	Case selection based on clinical findings and bleeding assessment [1,3]
Persistent disease or signs of non-recoverable pulp	Root canal treatment or other indicated care	Biological treatment should not delay necessary definitive treatment [2,3]

Table 1. Comparative clinical pathways for preserving pulp vitality in deep caries. These are decision considerations, not a substitute for diagnosis.

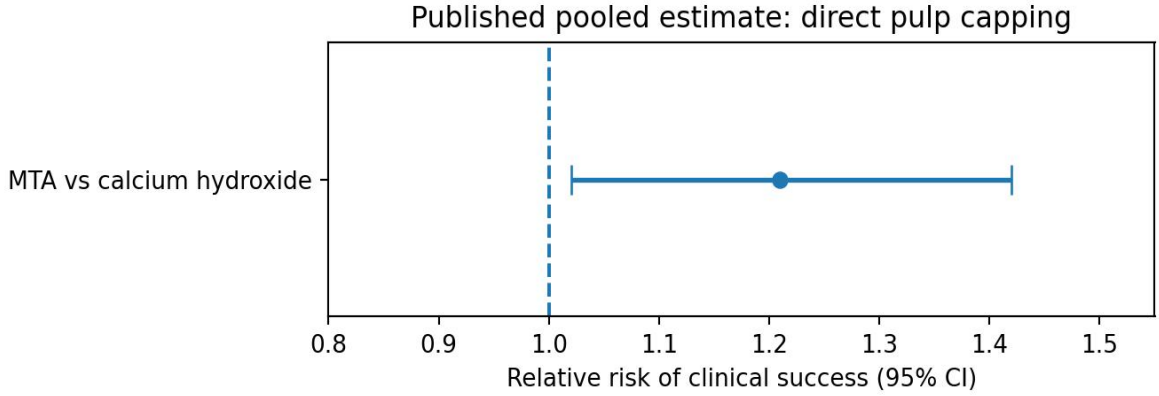


Figure 1. Published relative risk of success with MTA compared with calcium hydroxide for direct pulp capping: RR 1.21 (95% CI 1.02–1.42) [4].

Selected syntheses differ substantially in their clinical questions and inclusion criteria; the number of teeth represented in each review is shown only to describe the evidence base and cannot be summed because primary-study overlap is possible (Figure 2). The 2025 review of 21 studies included 1,948 permanent teeth, the 2025 network synthesis of non-exposure treatments included 1,093 teeth and the 2025 protective-liner review included 678 teeth [4–6].

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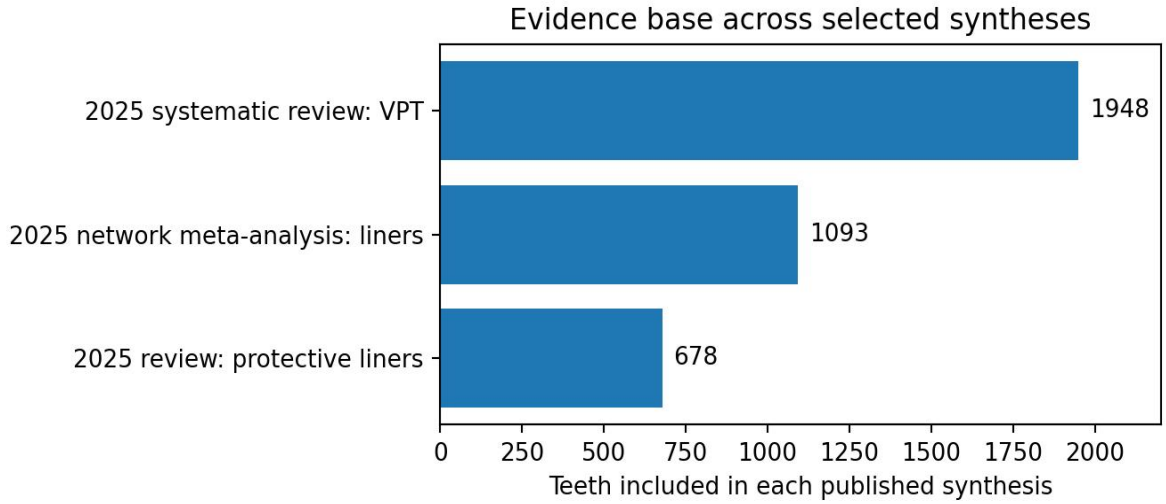


Figure 2. Size of published evidence syntheses (teeth; descriptive comparison only, not an effect-size comparison) [4–6].

Biomaterial	Potential strengths	Important limitations / role
Calcium hydroxide	Long clinical history; alkaline antimicrobial activity	Less favorable outcomes than MTA in some direct-capping comparisons [4]
MTA	Hydraulic bioactivity and established capping evidence	Handling, setting time and discoloration considerations vary by formulation
Biodentine / tricalcium silicate	Hydraulic biomaterial with favorable biological profile	Clinical performance depends on indication; no universal superiority to MTA [4,5]
Glass ionomer / resin-modified GIC	Sealing and restorative interface properties	Use and indications depend on whether the pulp is exposed [5,6]

Table 2. Main material-related considerations. Comparative statements must be interpreted within the procedural context and individual product instructions.

Discussion

The principal finding of this evidence synthesis is that preserving pulpal vitality is achievable through a sequence of biologically appropriate decisions rather than through an isolated choice of a "regenerative" material. Avoiding inadvertent exposure during excavation is an important protective intervention in its own right. The 2026 S3-level guideline therefore supports selective and stepwise excavation for deep lesions, while also distinguishing exposed-pulp management as a separate clinical decision in which hydraulic calcium silicate biomaterials have greater comparative support [1].

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The meta-analytic advantage of MTA over calcium hydroxide in direct pulp capping is clinically relevant but should be interpreted with care. Relative risk is not an absolute success probability, and outcomes across studies are affected by diagnostic criteria, tooth maturity, degree of carious exposure, haemostasis procedures, restoration type and the length of follow-up. Conversely, the absence of a statistically significant difference among liners after selective excavation does not mean that all pulp-capping materials are interchangeable when exposure occurs: the biological interface and clinical setting differ fundamentally [4–6].

Careful clinical assessment remains indispensable. Spontaneous pain, prolonged response to cold, percussion findings, radiographic changes and intraoperative pulpal bleeding may alter the interpretation of prognosis, yet no single symptom reliably describes the histological extent of inflammation. When vital pulp therapy is considered, isolation, contamination control, disinfection, appropriate management of exposed tissue and a high-quality coronal seal have substantial biological importance [2,3]. Long-term monitoring must address both subjective symptoms and objective evidence of function, including clinical tests and radiographs when indicated.

For an original prospective clinical study, a pragmatic comparison could examine selective excavation with definitive restoration, direct pulp capping and partial pulpotomy in distinct diagnostic strata, rather than treating these procedures as randomly interchangeable treatments for all deep lesions. Clinical diagnosis, age, tooth type, caries depth, baseline pain, presence of exposure, material batch, bleeding duration, restoration quality and follow-up should be prespecified. Outcome evaluation at 6, 12 and 24 months should include retention of pulp vitality, pain, need for root canal treatment, and radiographic evidence of apical disease. Ethical approval, informed consent, prospective registration where applicable, and CONSORT/STROBE-consistent reporting would be expected depending on study design.

This review has limitations. The selected publications were synthesized narratively without a reproducible systematic search or risk-of-bias reassessment. Aggregate evidence spans heterogeneous procedures and follow-up periods; no author-specific clinical cohort was available. The charts are faithful visualizations of published results and sample sizes, not newly collected observations. Future work should emphasize standardized pulp diagnostic categories, longer follow-up, patient-centered outcomes, and independent assessment of material-specific advantages. Claims of superiority must remain procedure-specific and supported by direct comparative evidence.

Conclusion

Contemporary biological management of deep caries increasingly emphasizes preserving the vital pulp by limiting unnecessary dentine removal, applying appropriate aseptic protocols and ensuring a durable coronal seal. Selective or stepwise caries removal is supported for deep lesions without exposure, while direct pulp capping and partial or full pulpotomy are viable options in selected exposed-pulp cases. Hydraulic calcium silicate cements, including MTA and Biodentine-type materials, offer evidence-supported

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biological alternatives to calcium hydroxide, particularly for direct pulp capping. The available comparative evidence does not justify a single universal biomaterial or technique for every clinical presentation. Prospective, diagnosis-stratified studies remain essential for determining durable outcomes and refining material selection.

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