REVIEW ARTICLE

CONTENTS

Modern biomaterials for direct pulp capping: A literature review

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ABSTRACT

The development of biomaterials for direct pulp capping has significantly transformed modern vital pulp therapy. For decades, calcium hydroxide was considered the gold standard, but its limitations – such as lack of sealing ability and tendency for resorption– have prompted the search for improved solutions. The introduction of calcium silicate cements and new-generation bioceramics has led to better biological and clinical outcomes. This review aims to discuss the latest advances in biomaterials used for direct pulp capping and to compare their properties, efficacy, and limitations. Literature published between 2018 and 2024, including systematic reviews, meta-analyses, and clinical studies, was analyzed. The results show that bioceramics and contemporary calcium silicate cements exhibit high bioactivity, enable the formation of a dentin bridge, and present a favorable safety profile. Appropriate material selection, meticulous clinical technique, and effective control of infection and moisture are essential for clinical success. The review also highlights certain limitations, such as the higher cost of new materials, technical requirements, and the lack of long-term clinical data. In conclusion, bioceramics currently represent the best choice for direct pulp capping, and further research should focus on optimizing clinical protocols and evaluating long-term outcomes to ensure predictable, minimally invasive dental care.

KEY WORDS: bioceramics, calcium silicate cements, dental pulp therapy, dental biomaterials, pulp regeneration

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INTRODUCTION

Recent years have seen significant advances in vital pulp therapy, especially direct pulp capping (DPC) and partial pulpotomy, which are now considered the gold standard for managing exposed or nearly exposed pulps in both permanent and primary teeth. The introduction of novel bioactive materials – including hydraulic calcium silicate cements (e.g., Biodentine XP, NeoPUTTY, WellRoot PT, and TheraCal LC) – has improved the prognosis of these procedures and shifted the focus from traditional calcium hydroxide to materials with superior sealing ability, bioactivity, and clinical longevity [1, 2].

Contemporary protocols emphasize the preservation of pulp vitality, which not only maintains the tooth's natural function and proprioception but also allows clinicians to avoid or delay the need for conventional endodontic treatment in appropriately selected cases [1, 3].

Systematic reviews and meta-analyses from 2018–2024 confirm that, with modern protocols and case selection, vital pulp therapy achieves high rates of pulp vitality preservation and radiographic success – even in cases of carious or mechanical pulp exposure [1,3].

For many years, calcium hydroxide was the standard capping material, later replaced by mineral trioxide aggregate (MTA), which became the gold standard for vital pulp therapy. However, contemporary bioactive materials such as hydraulic calcium silicate cements have demonstrated improved clinical and biological performance, prompting a shift in clinical protocols and material selection in recent years [2, 3].

AIM

The aim of this literature review is to summarize the latest evidence (2018–2024) regarding clinical protocols, indications, material selection, treatment outcomes, and future directions in direct pulp capping and partial pulpotomy, with special attention to the effectiveness of new-generation bioceramic and light-cured materials.

MATERIALS AND METHODS

For this literature review, publications from 2018 to 2024 (including systematic reviews, meta-analyses, and clinical studies) were analyzed to gather relevant evidence on direct pulp capping and partial pulpotomy. The analysis focused on high-quality clinical studies and reviews to ensure comprehensive coverage of current advances in biomaterials and vital pulp therapy technique

REVIEW

PATHOPHYSIOLOGY AND BIOLOGICAL PRINCIPLES

The clinical success of direct pulp capping and partial pulpotomy relies on understanding the biological response of the dental pulp to injury and biomaterial application. When the pulp is exposed by caries or trauma, the inflammatory response and healing capacity depend on the extent of bacterial contamination, the duration of exposure, and the biological compatibility of the capping material [1, 2].

Modern research confirms that the pulp retains the ability to regenerate if bacterial contamination is limited and a biologically compatible material is placed [2, 3]. Bioactive calcium silicate materials (e.g., Biodentine XP, NeoPUTTY) initiate a sequence of events at the pulp-dentin interface:

- Calcium ion release: The high calcium ion release and alkaline pH stimulate the differentiation of pulp stem cells into odontoblast-like cells [2, 4].
- Reparative dentin formation: These cells lay down a matrix of reparative (tertiary) dentin, leading to the formation of a mineralized dentin bridge at the exposure site [4,5].
- Natural seal: The dentin bridge acts as a natural barrier, protecting the pulp from further injury and sealing it from bacterial ingress [4, 7].

Calcium silicate cements also exhibit antimicrobial properties and excellent sealing, which minimize pulpal inflammation and support a favorable healing environment [4, 7]. Histological studies and recent clinical trials demonstrate that new-generation cements induce the formation of a continuous, mineralized dentin bridge of good quality, superior to that formed by older materials such as calcium hydroxide [4, 5, 7]. Light-cured resin-modified materials (e.g., TheraCal LC) are easy to apply and set rapidly, but ongoing clinical trials are still assessing their long-term ability to induce complete, homogeneous dentin bridge formation and to support true pulp healing [6]. An evidence-based choice of capping material is thus critical for achieving predictable biological repair and long-term tooth survival [1, 8] .

MATERIAL SELECTION AND COMPARATIVE EFFECTIVENESS

Recent advances in biomaterials have transformed the landscape of direct pulp capping and partial pulpotomy. Historically, calcium hydroxide was the material of choice for decades due to its ease of use and initial biocompatibility. However, its limitations – including poor sealing, high solubility, and formation of porous, incomplete dentin bridges – led to a search for better alternatives. For many years, mineral trioxide aggregate (MTA) emerged as the gold standard for vital pulp therapy, thanks to its excellent biocompatibility, sealing ability, and consistent formation of continuous dentin bridges. However, MTA's handling properties (e.g., long setting time, potential discoloration) motivated the development of new-generation hydraulic calcium silicate cements [1, 2].

Current options include:

- **Biodentine XP, NeoPUTTY, Well-Root PT**: These materials offer improved handling, faster setting, and enhanced bioactivity compared to traditional MTA. Multiple systematic reviews and meta-analyses published between 2021 and 2024 confirm that modern calcium silicate cements result in similar or higher clinical and radiographic success rates compared to MTA, while minimizing drawbacks such as discoloration and handling difficulty [2,3,4] .
- **Light-cured resin-modified materials (e.g., TheraCal LC):** These materials offer easy application and rapid setting but show variable long-term performance in terms of dentin bridge quality and pulpal healing. Ongoing trials are further evaluating their clinical effectiveness in comparison to bioceramic cements [5, 6].

A 2023 systematic review and network meta-analysis found that new-generation hydraulic calcium silicate cements (Biodentine, NeoPUTTY, Well-Root PT) were associated with equal or superior outcomes for pulp vitality, dentin bridge formation, and periapical health compared to both MTA and resin-modified materials [2,3,4] . Material selection should therefore prioritize modern calcium silicate cements in most cases, with resin-modified or light-cured materials reserved for select indications or as adjuncts [1-4]. The comparative characteristics of these materials are summarized in Table 1**.**

CLINICAL PROTOCOL

Successful vital pulp therapy depends on strict adherence to contemporary protocols, established for both direct pulp capping (DPC) and partial pulpotomy in permanent and primary teeth. Recent systematic reviews and meta-analyses (2018–2024) support the following evidence-based steps for optimal clinical outcome [1-3]:

Table 1. Comparative characteristics of pulp capping materials (2018–2024)

Material	Advantages	Limitations / Drawbacks	Key References
Biodentine XP	Fast setting, high biocompatibility, strong sealing, bioactivity, promotes homogeneous dentin bridge	Handling sensitive to moisture, higher cost	[2,3,4]
NeoPUTTY	Putty consistency (easy to apply), rapid setting, bioactive, stable color	Limited long-term data, higher price	[2,3,4]
Well-Root PT	Excellent sealing, biocompatible, good handling, minimal discoloration	Newer product – less long-term evidence	[2,3,4]
MTA	Gold standard for years, excellent pulp healing, robust dentin bridge	Prolonged setting time, handling difficulties, possible discoloration	[1,2]
TheraCal LC	Light-cured (rapid set), easy to handle, useful for small exposures	Resin content may cause cytotoxicity, less mineralization, lower long-term pulp vitality	[5,6]
Calcium Hydroxide	Historic standard, widely available, low cost	Poor sealing, dissolution over time, incomplete dentin bridge, low long-term success	[1,2,3]

Direct Pulp Capping (DPC) protocol

1. **Diagnosis and Case Selection:** Confirm that pulp exposure is small, recent, and without signs of irreversible pulpitis; best results are achieved in exposures due to trauma or shallow caries, especially in young or asymptomatic teeth [1, 4].
2. **Isolation:** Achieve strict rubber dam isolation to prevent contamination [2, 4] .
3. **Hemostasis:** Control bleeding with a sterile saline or 2.5–3% sodium hypochlorite–soaked cotton pellet for up to 5 minutes; persistent bleeding indicates a poor prognosis and may require pulpotomy or endodontic treatment [2, 5].
4. **Disinfection (optional):** A brief rinse with sodium hypochlorite may be recommended for antimicrobial effect, followed by a saline rinse [2,5].
5. **Application of Capping Material:** Place a 1–2 mm layer of hydraulic calcium silicate cement (e.g., Biodentine XP, NeoPUTTY, Well-Root PT) directly over the exposure site; ensure material adaptation and absence of voids [7]. If a light-cured material (e.g., TheraCal LC) is used, follow the manufacturer's guidelines for incremental layering and curing [6].
6. **Permanent Restoration:** After the capping material has set, place a protective base or liner if indicated, and restore the tooth with a well-sealed adhesive restoration. Achieving an immediate and adequate coronal seal is critical to prevent microleakage [2,3,4].
7. **Follow-Up:** Perform clinical and radiographic evaluations at approximately 6, 12, and 24 months to confirm continued pulp vitality and normal periapical status. Long-term monitoring is important to ensure success [1, 3, 9].

Partial pulpotomy protocol

- **Indication:** Partial pulpotomy is indicated if hemostasis cannot be achieved with direct capping (e.g., persistent bleeding at the exposure site) or in deeper carious exposures where a larger volume of inflamed pulp needs removal [10].
- **Pulp removal:** Using a sterile, water-cooled diamond bur, remove about 2–3 mm of the exposed superficial pulp tissue to excise inflamed pulp until healthy, bleeding pulp remains [10].
- **Capping and restoration:** Achieve hemostasis as described above, then apply a bioceramic capping cement over the remaining pulp stump, and restore the tooth immediately with a well-sealed restoration [5, 7, 9].
- **Outcomes:** Partial pulpotomy is especially effective in young permanent teeth. Recent studies report >90% success rates at 1–3 years of follow-up for partial pulpotomies in appropriate cases, demonstrating excellent potential for long-term pulp vitality preservation [7].

Key points

- **Material choice matters:** Modern calcium silicate cements provide the highest long-term success rates and are preferred for most direct pulp capping cases [2-4].
- **Technique sensitivity:** These procedures are technique-sensitive, requiring careful case selection, strict moisture control (rubber dam use), and precise adherence to the protocol for each material [2, 4, 7].
- **Age and pulp status:** The best outcomes occur in teeth with young, vital, and minimally inflamed pulps; older teeth or those with significant pulp inflammation have lower success rates for vital pulp therapy [1, 9, 10].

Indications and contraindications

Recent evidence (2018–2024) supports the use of vital pulp therapy (direct capping or partial pulpotomy) in the following clinical situations:

Indications:

• Mechanical or shallow carious pulp exposures in asymptomatic, vital permanent teeth without clinical or radiographic signs of irreversible pulpitis [1,3,4].

• Recently erupted or young permanent teeth (children/adolescents) with open apices, due to their high regenerative potential; vital pulp therapy can also be considered in mature teeth with careful case selection [2,5].

• Cases where bleeding at the exposure site is easily controlled within approximately 5 minutes, indicating a healthy or only reversibly inflamed pulp status [2,7].

• Teeth where preserving pulp vitality is desirable to maintain normal root development (in immature teeth), proprioception, and to avoid or delay more invasive endodontic treatment [1,2,3].

Contraindications:

Vital pulp therapy is not recommended when any of the following are present:

• Signs or symptoms of irreversible pulpitis, such as spontaneous pain (especially nighttime pain) or prolonged sensitivity to hot/cold, or presence of swelling indicating pulpal degeneration [3, 5].

• Radiographic evidence of periapical pathology (e.g., periapical radiolucency, root resorption, or furcation involvement in multi-rooted teeth) suggesting loss of pulp vitality or chronic infection [3, 7].

• Uncontrolled bleeding at the exposure site (hemorrhage cannot be stopped within ~5 minutes), which is indicative of advanced pulpal inflammation or partial necrosis [2, 7].

• Extensive tooth structure loss from caries or trauma that would prevent achieving an adequate seal or proper restoration (high risk of microleakage or restoration failure) [3,7].

• Teeth with a poor overall prognosis due to periodontal disease or non-restorable crown/fracture, where maintaining the pulp is futile [4,7].

Clinical pearls:

• **Case selection is critical:** Accurate assessment of pulp status (to confirm that the pulp is vital and only reversibly inflamed) and the ability to achieve complete hemostasis are essential for success in vital pulp therapy [2,8].

• **Partial pulpotomy preference:** In situations where hemostasis cannot be quickly achieved with direct capping, or when the pulp exposure is large with suspicion of deeper pulp inflammation, a partial pulpotomy is often the preferred approach over a simple direct cap [7,9].

Limitations and complications

Despite the high success rates of modern vital pulp therapy, several important limitations and possible complications should be considered.

• **Technique and case-sensitive outcomes:** The success of direct pulp capping or pulpotomy is highly dependent on proper case selection, accurate diagnosis of the pulp's condition, and strict adherence to the clinical protocol (including excellent isolation and asepsis). Errors or deviations in any of these steps can significantly increase the risk of failure [1, 2].

• **Material-related limitations:** Hydraulic calcium silicate cements (bioceramics) are technique-sensitive and can be relatively costly or difficult to handle in some clinical scenarios [3, 4]. Light-cured resin-modified materials have limited long-term clinical data, and their resin components may reduce bioactivity and increase cytotoxic effects on pulp tissue [2]. Additionally, MTA, while effective, can cause tooth discoloration and has a prolonged setting time which may be impractical in certain cases [4].

• **Inappropriate case factors:** Vital pulp therapy is unlikely to succeed in teeth that actually have irreversible pulpitis, in cases where pulpal bleeding cannot be controlled, or when a durable coronal seal cannot be achieved (for example, due to extensive decay or insufficient tooth structure) [2, 3, 7]. Such cases are better managed with more advanced endodontic treatment.

• **Restorative failures:** Even after initial successful pulp capping, failure of the coronal restoration (e.g., microleakage, secondary caries, or restoration fracture) can lead to bacterial re-contamination and late-onset pulp necrosis [7].

Complications

• **Pulp necrosis or chronic inflammation:** In some instances, the capped pulp may undergo necrosis or remain chronically inflamed, especially if bacteria were not fully eliminated or if the pulp's initial inflammatory status was underestimated [3,7]. This outcome would necessitate root canal therapy despite the initial vital pulp therapy attempt.

• **Tooth discoloration:** Some pulp capping materials, particularly certain MTA formulations, can cause discoloration of the crown dentin over time. While newer bioceramics aim to minimize this issue, discoloration remains a potential cosmetic complication, notably for anterior teeth [4].

Future directions

Most studies to date report outcomes only up to 1–3 years of follow-up, highlighting the need for longer-term data (≥5 years) to fully assess the durability of new biomaterials and techniques [2, 4, 5, 8]. Addi-

tionally, further research is needed to optimize clinical protocols, evaluate emerging biomaterials, and determine the effectiveness of vital pulp therapy in more challenging scenarios (e.g. older patients or teeth with significant comorbid conditions) [3, 4, 11].

• **Development of novel biomaterials:** Continued innovation is focused on next-generation pulp-capping materials, including advanced bioceramics, nanomaterials, bioactive additives, and injectable scaffolds. These are being investigated to improve the quality of dentin bridge formation, enhance pulpal healing, and provide superior antimicrobial properties [1, 2, 4, 11].

• **Combination therapies:** Researchers are exploring the combined use of hydraulic calcium silicate cements with other therapeutic modalities (such as remineralizing agents, growth factors, or even stem cell therapy) to further enhance pulp regeneration and improve long-term vitality of the tooth [12].

• **Digital diagnostics and artificial intelligence:** Modern imaging techniques and AI-driven diagnostic tools are under development to improve the accuracy of pulp status assessment and to aid in standardized case selection. Such technologies could help predict which cases are ideal for vital pulp therapy and improve clinical decision-making [13].

• **Long-term randomized controlled trials:** There is a clear need for extended follow-up studies (>5 years) and multicenter randomized controlled trials to definitively determine the long-term success, durability, and optimal treatment protocols for new pulp capping materials and techniques as they continue to evolve [2, 4, 5].

CONCLUSIONS

Modern vital pulp therapy, based on current high-quality evidence, enables the preservation of pulp vitality and natural tooth structure in appropriately selected cases. The evolution from calcium hydroxide to bioceramic cements, and ongoing innovation in material science, has significantly improved the success and predictability of direct pulp capping and partial pulpotomy. Strict adherence to clinical protocol, careful case selection, and use of contemporary materials are essential for optimal outcomes. As new technologies and materials are validated, the role of vital pulp therapy in minimally invasive and regenerative dentistry is expected to expand further.

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

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