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Vital Pulp Therapy: Evidence-Based Techniques and Outcomes

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Vital pulp therapy (VPT) comprises a range of conservative treatment modalities aimed at preserving the vitality of the compromised dental pulp in primary and permanent teeth. This PubMed-based review comprehensively evaluates seven distinct VPT techniques; including their historical development, broad definitions, clinical protocols and treatment outcomes as evidenced by systematic reviews and meta-analyses. The VPT modalities covered in this review include stepwise excavation, indirect pulp capping, direct pulp capping, miniature pulpotomy, partial pulpotomy, full pulpotomy and partial pulpectomy. Stepwise excavation, as a minimally-invasive option, has demonstrated effectiveness in reducing the risk of pulp exposure, particularly in permanent teeth. Clinical outcomes of indirect and direct pulp capping are promising; specifically with the application of advanced calcium silicate cements. Miniature and partial pulpotomies emphasize the importance of precise definitions and standardised protocols due to their subtle differences. Full pulpotomy has emerged as a viable alternative to root canal treatment, achieving comparable success rates in managing irreversible pulpitis. While partial pulpectomy remains the most invasive approach, it has shown potential in managing complex cases, such as root resorption, through selective tissue preservation. Despite advancements in biomaterials and technique standardisation, challenges remain, including variability in clinical protocols, limited high-quality evidence, and the need for long-term studies to better evaluate anticipated outcomes. Nevertheless, emerging biotechnologies hold promise for enhancing the precision and predictability of VPT procedures in the future.

Keywords: Biodentine; Calcium Derivative; Calcium-enriched Mixture; Calcium Silicate Cement; Dental Pulp Capping; Endodontics; Irreversible Pulpitis; Mineral Trioxide Aggregate; Miniature Pulpotomy; Partial Pulpectomy; Pulpotomy; Root Canal Treatment; Stepwise Excavation

Introduction

Vital pulp therapy (VPT) has become a cornerstone in modern endodontics; aiming to preserve the vitality and functionality of the compromised dental pulp tissue in cases of carious or traumatic pulp exposure [1]. As an umbrella term, VPT contains techniques designed to maintain pulp health to avoid invasive procedures; i.e. full pulpectomy and root canal therapy (RCT) [2]. The aforementioned methods, ranging from non-invasive approaches, e.g. stepwise excavation and indirect pulp capping (IPC), to more invasive techniques, *e.g.* direct pulp capping (DPC), miniature pulpotomy (MP), partial pulpotomy (PP), full pulpotomy (FP) and partial pulpectomy, have been studied, developed and applied in primary and immature/mature permanent teeth across different age groups [3].

In addition, VPT modalities can be categorised based on the materials used as the pulp protecting/capping agent. Traditional pulp-protecting material, i.e., calcium hydroxide (CH), has been widely used due to its accessibility, antibacterial properties, and reparative dentine promotion; however, its limitations, *e.g.*, poor mechanical strength and high solubility, have led to the development of other more advanced biomaterials. Bioactive materials, e.g., mineral trioxide aggregate (MTA), calcium-enriched mixture (CEM) cement, and Biodentine™, have shown superior clinical outcomes [4]. The research has shown that the above-mentioned endodontic bioactive materials can promote

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pulp healing, enhance dentinogenesis and provide long-term seal integrity; making them suitable for VPT in primary and permanent teeth. In primary teeth, conventional reliance on fixative agents, *e.g.* sodium hypochlorite (NaOCl), formocresol (FC) and ferric sulfate (FS), has shifted in favour of bioactive materials; reflecting advancements in modern pediatric dentistry [5].

Additionally, techniques for pulp removal and haemostasis remain essential for VPT success. While traditional hand instrumentation offers tactile feedback, high-speed rotary systems using coolant provide better efficiency. Moreover, innovative methods, e.g. laser-assisted and electrosurgical approaches, enable minimally invasive and precise tissue removal with further sterilisation and haemostatic benefits [6]. Achieving haemostasis through natural coagulation methods, *e.g.,* saline irrigation and wet cotton application, is common; nevertheless, chemical agents, *e.g.*, NaOCl and FS, are used when bleeding persists. Furthermore, the tampon approach using biomaterials, e.g. CEM cement, ensures bleeding control, could improve healing and prognosis [7].

Objectives

The present manuscript provides a PubMed-based review of the current techniques and outcomes of all 7 VPT modalities as well as their respective success rates. By synthesizing data from best current evidence, specifically systematic reviews and meta-analyses (SR/MAs), it was aimed to present a clear understanding of the clinical effectiveness of these techniques, address existing challenges, and suggest future research directions. Ultimately, the goal was to provide evidence-based insights that would inform clinical decision-making, improve treatment outcomes and guide future advancements in vital pulp preservation.

Methods and Materials

As this review involved analyzing previously published data, no direct involvement with human participants was necessary, and thus, ethical approval for the review itself was not required. A systematic literature search was performed using PubMed from its inception to October 1, 2024. Primary search terms included keywords; *e.g.*, "vital pulp therapy," "stepwise excavation," "indirect pulp capping," "direct pulp capping," "miniature pulpotomy," "partial pulpotomy," "full pulpotomy," and "partial pulpectomy." The objective was to identify the earliest references to terminology associated with VPT techniques.

Then the PubMed search was restricted to clinical studies to evaluate the outcomes of VPT techniques, with a priority on SR/MAs as they represent the highest level of evidence. When SR/MAs were unavailable, randomized controlled/clinical trials were considered, followed by other types of clinical studies if necessary. Non-clinical research, animal studies, editorials, expert opinions, and studies lacking specific treatment outcomes were excluded. The initial search focused on SR/MAs published within the past five years; however, when relevant studies were limited, the timeframe was expanded to include articles published within the last ten years or earlier, as needed. Only studies evaluating VPT techniques in primary and permanent teeth with clearly defined clinical and/or radiographic outcomes were included.

Results

The concept of '*vital pulp therapy*' was first introduced in 1956 by McDonald, who proposed its use for primary teeth [8]. In 1967, Massler expanded its scope to endodontics, framing VPT as a preventive approach to preserving pulp vitality and function [9]. By the early 2000s, Tziafas *et al.* [10] emphasized the significance of leveraging molecular and cellular mechanisms of tooth development and repair to design innovative VPT strategies. In 2011, Aguilar and Linsuwanont conducted the first SR on VPT in permanent teeth, demonstrating that vital teeth with cariously exposed pulp could be successfully managed with VPT techniques [1]. However, they noted the lack of robust evidence on factors influencing treatment success, highlighting the need for high-quality observational studies. In 2017, Coll et al. published a SR/MA on primary teeth and concluded that IPC and pulpotomy with MTA and FC, respectively, yielded the highest success rates for managing deep caries [11]. Additionally, in a scientometric study, Kodonas et al. demonstrated that the USA is the leading country in VPT research, while Iranian researchers are recognized as leaders in advancing this field [12].

As VPT covers a spectrum of techniques, we now explore specific modalities, progressing from minimally invasive to more invasive approaches. Each technique aims to preserve pulp vitality while addressing varying extents of pulp involvement.

1. Stepwise Excavation

Introduction and History: First introduced by Magnusson and Sundell in 1977, '*stepwise excavation*' revolutionised caries management by prioritizing pulp preservation over the complete removal of carious tissue [13], marking a significant departure from conventional practices.

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Definition: Stepwise excavation is a caries management technique for deep carious lesions where the bulk of the carious tissue is initially removed, and the cavity is sealed with a provisional material such as CH and zinc oxide eugenol. This interim sealing allows for the recovery and remineralization of the remaining dentine. After a period of 8 to 24 weeks, the residual carious dentine is removed after re-entry, and the cavity is permanently restored with materials, such as CH, and a permanent restorative material. This staged approach aims to minimize the risk of dental pulp exposure compared to complete caries excavation, which involves the immediate removal of all carious dentin [14].

Outcomes: Stepwise excavation is a cornerstone of minimal intervention dentistry (MID), focusing on pulp preservation through staged caries removal.

A Cochrane review by Ricketts *et al.* [15] reported that stepwise excavation results in a 56% reduction in pulp exposure incidence compared to complete caries removal in permanent teeth (15.4% vs. 34.7%). This evidence supports stepwise excavation as a viable, MID alternative that safeguards pulp vitality without increasing the risk of pulpal disease. However, long-term data on restoration success and durability remain inconclusive, highlighting the need for further research.

In primary teeth, a SR by BaniHani *et al.* [16] highlighted the efficacy of this technique in reducing the risk of pulp exposure by 69% compared to complete caries removal. This reduction underscores its role in managing deep lesions without compromising pulpal health. Moreover, the technique demonstrated lower rates of pulp treatments or extractions, emphasizing its value in pediatric dentistry where cooperation can be a limiting factor.

A recent Cochrane MA concluded that compared to complete caries removal, Stepwise excavation reduces the risk of pulpal exposure, particularly in permanent teeth, and demonstrates lower failure rates, as indicated by moderate-certainty of evidence [17]. However, the evidence in primary teeth remains at low certainty, indicating the need for further studies to optimize its application and outcomes.

Current Challenges and Future Directions: The necessity of multiple visits for stepwise excavation poses challenges for patient compliance, particularly in pediatric settings. Emerging research on bioactive materials capable of promoting dentine regeneration in a single-step approach offers a promising avenue for simplifying the procedure. Further studies focusing on long-term outcomes, restoration durability, and patient-reported measures are essential to solidify stepwise excavation's role in modern caries management.

2. Indirect Pulp Capping

Introduction and History: '*Indirect pulp capping*' was first introduced by Hess in 1951 [18], as a technique aimed at preserving pulp vitality while managing carious dentine without causing pulp exposure.

Definition: IPC involves placing a protective material over a thin layer of softened dentine near the pulp. The incomplete removal of carious dentine, followed by proper tooth sealing, has been shown to arrest carious lesions, suggesting that complete caries removal is not essential for effective caries control [19]. This approach promotes pulp healing and facilitates the formation of reparative dentine.

Outcomes: Recent SR/MAs provide robust evidence supporting the high clinical and radiographic success rates of IPC as an effective management strategy, solidifying its role as a cornerstone in the performance of VPT in primary teeth.

A SR comparing CH with other IPC materials in primary molars confirmed CH's efficacy as a conventional agent [20]. However, the review highlighted the need for higher-quality studies to evaluate its performance against newer biomaterials. IPC demonstrated a 94% success rate at 24 months in primary teeth, surpassing DPC (88.8%) and pulpotomy (82.6%) [21]. While success rates were comparable among IPC medicaments, the lack of robust evidence precluded definitive conclusions on the superior biomaterial or technique. Similarly, another study revealed that IPC was identified as the most clinically successful treatment for deep caries in primary teeth, outperforming DPC and pulpotomy [22]. Materials such as MTA, FS, and FC showed similar success rates, all exceeding CH. However, radiographic success rates remained inconsistent, warranting further investigation [22].

A recent review explored silver diamine fluoride (SDF) as an emerging IPC material [23]. While initial studies reported favourable clinical and radiographic outcomes for SDF compared to CH, a MA revealed no significant differences. Despite promising results, the low-quality evidence emphasised the need for rigorous trials to establish SDF's role in pediatric dentistry.

For permanent teeth, no SR/MAs are available thus far. However, a recent randomised controlled trial [24] compared three IPC protocols (TheraCal, Dycal, and no liner) in permanent teeth with deep carious lesions restored with resin composite. Success rates exceeded 96% across all protocols, with no significant differences in tooth sensitivity or clinical outcomes. These findings align with other studies, suggesting that the choice of capping material does not significantly influence IPC success in permanent teeth [25].

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Overall, IPC's success is attributed to its ability to preserve pulp vitality, minimize pulp exposure risk, and promote reparative dentine formation. While CH remains a reliable option for primary teeth, newer materials such as SDF and MTA show promising potential.

Current Challenges and Future Directions: Despite its high success rates, IPC faces challenges due to variability in study designs, follow-up durations, and the lack of direct comparisons between traditional and emerging (bio)materials. Long-term evidence, particularly for permanent teeth, remains scarce which makes it difficult to establish standardized protocols. Future research should prioritize exploring advanced biomaterials to enhance clinical outcomes, conducting rigorous studies comparing conventional and novel agents, and incorporating patient-centered metrics to better evaluate treatment effectiveness. These steps are essential to solidify IPC's role as the gold standard for managing deep caries in primary and permanent teeth.

3. Direct Pulp Capping

Introduction and History: The concept of '*pulp capping*' was first introduced in the literature by Barrett in 1877, marking the initial steps towards preserving pulp vitality in cases of dental trauma or carious exposure [26]. However, the specific term '*direct pulp capping*', was coined by Hess in 1951; emphasizing the application of protective materials directly over exposed pulp tissue to promote healing and to maintain pulp function [18].

Definition: Historically, DPC was defined as a procedure used to treat pulp exposures resulting from accidental trauma, with no other signs of infection. In these cases, CH was directly applied to the exposed pulp. This approach was typically recommended for vital pulps without pre-existing inflammation, as success rates diminish when the pulp is already diseased prior to capping. Clinical studies had shown success rates of 80% for DPC when performed by students, and up to 90% when carried out by experienced clinicians, provided that a hermetic seal is achieved [27]. Currently, DPC is considered a MID procedure that involves placing a biocompatible material directly over an exposed pulp, commonly resulting from carious lesions as well as trauma [28]. Carious exposures in deep lesions are frequent in clinical practice. The exposures may still be unavoidable, even when a selective caries removal approach is used. The primary goal of DPC is to protect the inflamed pulp, preserve its vitality, and stimulate reparative dentine formation, thereby maintaining the tooth's natural structure and function.

Outcomes: DPC has been extensively studied, with SR/MAs offering valuable insights into its clinical and radiographic success rates. Matsuura et al. evaluated long-term DPC outcomes using calcium silicate-based cements (CSCs) and CH, concluding that MTA is a more effective and predictable biomaterial compared to CH [29]. Similarly, an SR/MA by Alsubait & Aljarbou reported no significant differences in success rates between MTA and Biodentine [30]. Pinto *et al.*'s [31] SR/MA aligned with these findings, demonstrating significantly higher success rates for DPC with MTA compared to CH, while MTA and Biodentine exhibited comparable success rates ranging from 80% to 100%. These findings underscore the superior efficacy and reliability of CSCs; however, the high risk of bias in the included studies calls for cautious interpretation.

Cushley *et al.* analyzed DPC success rates in teeth with carious pulp exposures diagnosed as reversible pulpitis [28]. While CH exhibited declining success over time (74% at 6 months to 56% at 4-5 years), MTA and Biodentine™ consistently achieved long-term success rates exceeding 80%. The superiority of MTA over CH was significant at 1, 2, and 3 years. However, the included studies were of low methodological quality, limiting the strength of evidence.

Ruiz-González *et al.* [32] reviewed DPC outcomes in teeth diagnosed with irreversible pulpitis. A meta-analysis of three studies involving 62 teeth reported a pooled success rate of 95.3%, with all (bio)materials achieving success rates exceeding 80%. Despite supporting DPC as a viable option for irreversible pulpitis, methodological weaknesses and small sample sizes highlight the need for further high-quality research.

In an SR/MA, Fasoulas e*t* al. [33] compared materials used in DPC and pulpotomy. MTA consistently outperformed CH in mature teeth. However, significant heterogeneity in study designs precluded a network meta-analysis. Evidence strength was moderate for DPC in mature teeth but lower for other subgroups, emphasizing the need for rigorous trials.

Priya *et al.* [34] explored the efficacy of laser-assisted DPC in permanent teeth. The meta-analysis of seven studies demonstrated that lasers significantly reduced clinical and radiographic failure rates compared to non-laser approaches, likely due to enhanced decontamination and bio-stimulation. However, variability in study methodologies limits the generalizability of these findings.

Current Challenges and Future Directions: Despite advancements in materials and techniques, DPC faces significant challenges limiting its predictability and broader clinical adoption. The cost and accessibility of CSCs and bioceramic materials present barriers in resource-limited settings. Additionally, the procedure's success is heavily reliant on operator skill, particularly in accurate pulp vitality diagnosis,

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case selection, and precise material handling. Inaccurate diagnoses can lead to inappropriate treatment decisions, undermining outcomes. Compounding these issues, many studies suffer from small sample sizes, methodological weaknesses, and limited follow-up periods, leaving gaps in long-term evidence essential for guiding clinical practice.

To overcome these challenges, future research should prioritize developing cost-effective, widely accessible materials with superior biocompatibility and bioactivity. Standardized diagnostic criteria and treatment protocols are crucial to enhance consistency and reliability in practice. Adjunctive therapies such as laser-assisted DPC need further investigation for their potential to improve outcomes by providing enhanced decontamination and bio-stimulation. Finally, high-quality randomized controlled trials with large sample sizes and extended follow-up durations are necessary to establish a robust evidence base for optimizing DPC techniques and broadening their clinical applicability.

4. Miniature Pulpotomy

Introduction and History: '*Miniature pulpotomy*' is a VPT procedure first introduced by Asgary in 2012 [35]. Asgary proposed MP as an optimized version of DPC, addressing several key factors that can influence healing and treatment success. These include cleaning the pulp wound, removing infected dentine and damaged pulp tissue, and enhancing the interaction between the pulp capping agents and the undifferentiated stem cells within the dental pulp.

Definition: MP refers to a minimally invasive procedure in which a thin layer (~1 mm) of superficial, inflamed pulp tissue is removed from the exposed site, without significantly enlarging the pulp exposure. This technique aims to preserve the coronal pulp, aids with bleeding control, and improves the adaptation of caping material with underlying healthier pulp tissue that contains undifferentiated mesenchymal stem cells that have the potential to differentiate into odontoblast-like cells and are essential for pulp regeneration [35]. MP was initially employed for managing traumatic pulp exposure with vital non-inflamed pulp [36], but has since demonstrated effectiveness in cases of irreversible pulpitis [3].

Outcomes: Currently, no SR/MA specifically evaluates the outcomes of MP in permanent teeth. Available data are limited to a recent randomized clinical trial comparing four VPT techniques in mature molars [25]. This study demonstrated favorable and comparable clinical and radiographic outcomes for MP alongside IPC, DPC, and FP. MP showed high success rates in managing deep caries in mature permanent molars, including cases with clinical signs of irreversible pulpitis and apical periodontitis. Pain relief was consistently observed across all treatment groups after adjusting for baseline pain levels, with no significant differences. Specifically, MP achieved success rates of 98.4% at three months and 91.4% at twelve months, comparable to other groups, highlighting its potential as a viable option for VPT in mature molars. These findings suggest that MP is an effective approach, offering success rates on par with other established VPT methods.

Current Challenges and Future Directions: While MP shows promising outcomes as a VPT method for mature molars, challenges remain in standardizing the procedure and establishing its long-term effectiveness. The lack of comprehensive SR/MA on MP's outcomes in permanent teeth necessitates further large-scale studies to establish its outcomes across diverse populations. Additionally, optimizing procedural parameters such as the depth of tissue removal and the ideal pulp capping material, use of magnification, as well as understanding the long-term effects on pulp regeneration, are critical areas for future research. Investigating the biological mechanisms behind MP's success, particularly its impact on mesenchymal stem cells and odontoblast differentiation, will provide valuable insights. Overcoming these challenges through continued research could solidify MP's role as an effective, MID alternative to more aggressive VPT methods.

5. Partial/Cvek/Shallow Pulpotomy

Introduction and History: The term '*partial pulpotomy*' was first introduced by Cvek in 1978 as a treatment for trauma-induced pulp exposures in permanent incisors, using CH as a pulp-capping material**[**37**]** . Since then, many researchers have used the term '*Cvek pulpotomy*' interchangeably with PP in various studies. In 1989, Bakland and Boyne introduced the term '*shallow pulpotomy*' as a parallel name for partial pulpotomy, further establishing its use in dental literature [38].

Definition: Cvek defined PP as the removal of 1–2 mm of inflamed pulp tissue beneath an exposed area in cases of traumatic pulp exposure, particularly in young, immature permanent teeth, with the goal of preserving the remaining healthy pulp and maintaining its vitality. In 2002, Fong and Davis expanded the concept of PP to include the management of carious pulp exposures in vital, immature permanent teeth, further broadening its clinical application [39].

Outcomes: PP has been widely studied to evaluate its success in maintaining pulp vitality. The following are key findings from SR/MAs:

Lin *et al.* [40] evaluated the clinical and radiographic outcomes of PP and FP in mature permanent molars with cariously exposed vital pulp. FP had a success rate ranging from

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92.2% to 99.4%, while PP success rates ranged from 78.2% to 80.6%. The review found no significant effect of different pulp capping agents on FP success but noted a significant impact on PP outcomes. Both techniques demonstrated high success rates, but the review recommended further studies with longer follow-up periods to validate these results.

Madhumita *et al.* [41] assessed the efficacy of PP as a conservative treatment option for traumatized permanent anterior teeth with pulpal involvement. The analysis showed that PP had an overall success rate of 89%, with no publication bias detected. The review concluded that PP is a reliable treatment option for asymptomatic traumatized permanent anterior teeth, offering better outcomes than FP.

Matoug-Elwerfelli *et al.* [42] evaluated the success of VPT in managing traumatized human vital permanent teeth with complicated crown fractures. The review included 14 studies and reported a high success rate for PP (82.9%–100%), whereas FP and DPC had lower success rates. MTA, Biodentine, IRoot BP, and CH were found to be effective pulp capping agents, with success rates ranging from 79.4% to 100%. The review highlighted the need for higher-quality clinical studies to confirm these findings.

Donnelly *et al.* [43] assessed the success rate of pulpotomy for treating complicated crown fractures in permanent anterior teeth. The review found high success rates for PP and FP (75%–96%) but noted that the evidence was limited due to small sample sizes and moderate risk of bias in the included studies. The study suggested that PP should be considered over pulp-capping techniques in these cases, though the findings should be interpreted with caution due to the lack of homogeneity in the studies.

Albaiti *et al.* [44] focused on evaluating PP for cariously exposed vital posterior permanent teeth. The study reported high success rates of 94%, 93%, and 90% at 6, 12, and 24 months, respectively. It concluded that PP is a reliable treatment option for cariously exposed posterior teeth, with preoperative pulp diagnosis identified as the most significant predictor of success. Notably, the treatment outcome was unaffected by factors such as the type of restoration, pulp capping agent, or patient age.

Camoni *et al.* [45] evaluated the success of PP in young permanent teeth with deep caries or post-eruptive defects. The cumulative success rate was 91.8%–92.3%, with no significant differences in clinical and radiographic success between different materials. The study concluded that PP is a reliable procedure for managing vital pulp in young permanent teeth, offering biological benefits while postponing more invasive treatments.

Li *et al.* [46] evaluated pulpotomy (PP and FP) as a treatment for irreversible pulpitis in mature permanent teeth. The study found comparable efficacy between pulpotomy and RCT, with pulpotomy showing a clinical success rate of 92.9% and radiographic success of 78.5% after 24 months. The review highlighted PP and FP as viable alternatives to RCT, though the need for standardized methodologies and further research was emphasized.

Kumar *et al.* [47] compared PP and FP in treating teeth with irreversible pulpitis. The review found no significant difference in clinical or radiographic outcomes between the two techniques, with FP showing slightly better results in one study. It concluded that both treatments have similar success rates, and further research is needed to establish clearer guidelines.

Louzada *et al.* [48] compared PP and FP for managing deep caries in permanent teeth with non-traumatic pulpitis. It found no significant difference in clinical or radiographic success between the two techniques after one year. The study suggested that PP is as effective as FP for managing irreversible pulpitis and that further high-quality studies are needed to validate these findings.

An umbrella review by Lin *et al.* [49] evaluated the outcome of pulpotomy in treating permanent teeth with pulp exposure and signs of pulpitis. The study analysed SRs published between January 1970 and May 2021. The analysis included nine SR that focused on PP and FP procedures. While the overall success rates for both procedures ranged from 88.5% to 90.6%, the evidence regarding the impact of different pulpal medicaments and restorative materials on success rates remained inconclusive. The authors concluded that pulpotomy is a promising treatment modality for both mature and immature permanent teeth with carious or traumatic pulp exposure, emphasizing the need for further high-quality clinical trials with longer follow-up periods to address gaps in the evidence.

Current Challenges and Future Directions: Despite promising outcomes, several challenges persist in PP. A primary issue is the lack of a precise, scientifically accepted definition for PP. It is commonly defined as the removal of ~2 mm of pulp tissue beyond the exposure site; however, this definition remains somewhat vague. Logically, the pulp tissue between this 2-mm removal and the complete removal of the coronal pulp (i.e., FP), if removed in a VPT procedure, should also be considered part of the PP procedure. This lack of clarity contributes to inconsistencies in the literature. While high success rates have been reported for both PP and FP, the effects of various pulpal medicaments and restorative materials remain inconclusive, necessitating further studies. Additionally, the current body of

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evidence is limited by variations in study quality. Future research should focus on well-controlled, high-quality clinical trials with long-term follow-ups, greater standardization in defining procedures, and better control of confounding factors. These steps will help to clarify the benefits and limitations of PP, potentially establishing it as a more reliable and widely accepted treatment modality in endodontics.

6. Full/Coronal/Total/Cervical Pulpotomy

Introduction and History: The concept of '*pulpotomy*', which involves the removal of diseased pulp tissue while preserving the vitality of the remaining radicular pulp tissue, dates back to 1946 when Tobin first described its use [50]. This procedure has evolved significantly over the years. Britton introduced the term '*coronal pulpotomy*' in 1976 [51], followed by '*cervical pulpotomy*' by Vinckier et al. in 1984 [52], and '*total pulpotomy*' by Amini & Parirokh in 2008 [53]. The term '*full pulpotomy*' was later coined in 2011 by Aguilar and Linsuwanont [1]. FP was initially employed for managing the exposure of non-inflamed pulp but has since demonstrated effectiveness in cases of irreversible pulpitis in primary and permanent dentition [54-56]. This evolution underscores continuous advancements to refine pulpotomy techniques to improve clinical outcomes in both primary and permanent teeth.

Definition: FP is defined as the complete removal of the coronal portion of dental pulp tissue, leaving the radicular pulp intact and viable. The procedure is followed by placing a suitable pulp-protecting (bio)material over the amputated pulp within the pulp chamber to fill and seal the pulp chamber cavity.

Outcomes: FP has been widely studied to evaluate its success for VPT in permanent and primary teeth.

Permanent teeth

Logically, FP is a less invasive alternative to RCT for managing carious pulp exposure in permanent teeth. FP using CSCs is as successful/feasible/acceptable as RCT, yet it offers several advantages, including improved accessibility, affordability, availability, and safety [57]. From a socioeconomic perspective, FP can be more effective/efficient than RCT, particularly in mature permanent molars with irreversible pulpitis, positively impacting oral health status and quality of life [57]. Studies have demonstrated that FP provides comparable clinical success rates to RCT while offering the additional benefit of reduced postoperative pain, enhancing patient comfort and overall quality of life [58, 59]. Furthermore, FP is more cost-effective and technically simpler than RCT, requiring fewer visits and less complexity, making it a more practical option for clinicians managing carious pulp exposure [57, 60]. FP also minimizes the need for postoperative analgesics and improves patient outcomes [55].

Taylor *et al.* [61] reviewed 11 studies (from a total of 4,172 records) focusing on endodontic therapies for compromised first permanent molars in children under 16; They reported that both FP and PP techniques demonstrated high short-term and long-term success rates, consistent with the findings of other SR/MAs [40, 47].

Tong et al. evaluated 12 studies on VPT techniques for deep caries in immature permanent posterior teeth [62]. Twelve studies were included, focusing on DPC, IPC, and FP, with follow-up periods of at least 12 months. Success rates were 98% for DPC, 93.5% for IPC, and 93.6% for FP, with no significant differences. Root development exceeded 83% across all modalities, with no significant differences in apical closure outcomes among techniques. Further research was recommended to address evidence gaps.

Ather *et al.* [63] included 11 studies from 1,116 records to evaluate FP success in irreversible pulpitis, yielding a pooled success rate of 86%. Success was higher in open-apex teeth (96%) than in closed-apex teeth (83%). Biodentine™ achieved significantly better outcomes compared to other biomaterials, including MTA and CEM cement.

Afrashtehfar *et al.* [64] analyzed FP and RCT in mature and immature permanent teeth with pulpitis and spontaneous pain. Five studies showed comparable clinical success rates at 1 year (98%), declining over 5 years (78.1% for FP, 75.3% for RCT). Similar findings were reported by Tomson et al. [65], supporting FP as effective and less invasive than RCT.

Silva *et al.* [66] reviewed 16 randomized controlled trials on FP success with ProRoot MTA, CH, and other bioceramics. FP achieved a mean 92% success rate at 1 year. ProRoot MTA outperformed CH but showed similar results to Biodentine and CEM cement. Despite promising findings, low quality of evidence highlighted the need for better-designed trials.

Li *et al.* [46] included 23 studies adhering to PRISMA 2020 guidelines, reporting pooled clinical and radiographic success rates of 92.9% and 78.5%, respectively, in managing irreversible pulpitis in mature permanent teeth over 24 months. FP showed comparable outcomes to RCT. MTA and CEM cement demonstrated high efficacy as pulp protecting biomaterials. These findings highlighted pulpotomy as a viable, less invasive alternative to RCT for managing irreversible pulpitis in mature permanent teeth; however, the study also noted limitations, emphasizing the need for standardized protocols and high-quality research to validate these promising outcomes and enhance patient care.

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Wang *et al.* [67] found no significant differences between FP using CSCs and RCT in mature permanent teeth with carious pulp exposure. Both techniques achieved over 90% success at 1- and 2-year follow-ups. FP also demonstrated lower postoperative pain in the first week, reinforcing it as a less invasive alternative to RCT with better patient-centered outcome due to less post-operative pain.

Li *et al.* [68] included 25 randomized controlled trials with an average follow-up duration of ≥12 months to evaluate the success rate of FP in permanent teeth with carious pulp exposure. The overall success rate of FP was found to be 86.7%. However, teeth with irreversible pulpitis showed a lower success rate compared to those with normal or reversible pulpitis. They highlighted MTA and Biodentine™ as superior to CH, with MTA showing slightly better outcomes. Despite these findings, no significant difference between MTA and other biomaterials was observed.

Primary teeth

Guo *et al.* conducted a network meta-analysis of 43 randomized trials to compare pulpotomy medicaments [69]. MTA and Biodentine™ showed superior outcomes over FC, FS, and NaOCl. CH was the least effective. The study concluded that MTA offers the most significant improvement in both clinical and radiographic success, making it the optimal choice for pulpotomy.

Coll *et al.* [70] analyzed 299 studies, reporting 97% success rate for IPC and 94% for MTA pulpotomy in primary teeth affected by caries or trauma. DPC had lower success rates at 86%. The study found that FC pulpotomy had a significantly lower success rate than MTA pulpotomy, and FS pulpotomy had a significantly lower success rate than MTA at 24 months. The Hall technique has shown no significant difference in pulp vitality preservation compared to complete or selective caries removal methods (The Hall technique, introduced by Hall and investigated in 2006 [71], involves placing a preformed metal crown over a tooth without removing caries or performing any form of local anesthesia. This MID technique aims to arrest the progression of caries by sealing the affected tooth with a crown, thereby preventing further bacterial activity and reducing the need for traditional drilling. The procedure is particularly beneficial for managing caries in primary molars in children, as it requires no tooth preparation, minimizes patient discomfort, and preserves the tooth structure).

Pandiyan *et al.* [72] compared laser FP to conventional FP in 18 trials. Diode laser and low-level laser therapy (LLLT) showed no significant differences compared to FC/FS/MTA but warrant further validation through high-quality studies.

Current Challenges and Future Directions: Significant challenges in FP include considerable inconsistencies in clinical protocols, such as case selection, pulp removal techniques, irrigation methods, hemorrhage control, and sealing procedures, emphasizing the need for standardized guidelines to optimize treatment outcomes. While biomaterials like MTA, CEM cement, and Biodentine™ have shown efficacy, their long-term performance and comparative advantages are still under investigation. Emerging technologies like lasers require robust trials to establish their validity. Furthermore, decision-making between FP and other VPT techniques may be influenced by specific factors, underscoring the need for additional research to clarify indications and contraindications for each treatment modality.

7. Partial Pulpectomy

Introduction and History: '*Partial pulpectomy*' was first introduced by Driak in 1947 [73].

Definition: Partial pulpectomy was initially defined in 1950 as the excision of pulp tissue from the pulp chamber while leaving the root canal contents intact [74]. Today, it is recognized as an intermediate procedure between FP and complete pulpectomy, involving the selective removal of root canal pulp tissue while preserving the remaining pulp stump [75, 76].

Outcomes: Although SR/MAs or randomized clinical trials on this topic are unavailable, two PubMed articles highlight its potential.

Asgary *et al.* [77, 78] reported the successful application of partial pulpectomy in managing external cervical resorption, including a case series of six teeth and a case. The case series included six teeth treated with various VPT techniques, including DPC, PP, FP, and partial pulpectomy, based on the accessibility of resorptive lacunae. Over an average follow-up period of 19.6 months, all teeth remained functional and asymptomatic, with no progression or recurrence of resorption. In the case report [78], the authors documented the successful application of partial pulpectomy in a mature mandibular molar presenting with hyperplastic pulpitis, internal root resorption, and periradicular periodontitis. At a six-month follow-up, the tooth demonstrated clinical functionality accompanied by radiographic evidence of periradicular healing.

Current Challenges and Future Directions: Several aspects of this technique, including pulp removal, bleeding control and capping material, need to be studies due to lack of research. Future research must focus on standardizing guidelines, conducting multicenter clinical trials, and leveraging advanced imaging technologies to enhance treatment precision and predictability.

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Conclusions

VPT offers a range of conservative treatments to preserve dental pulp vitality in both primary and permanent mature/immature teeth. The techniques reviewed (stepwise excavation, indirect/direct pulp capping, miniature/partial/full pulpotomy, and partial pulpectomy) demonstrate favorable efficacy levels, depending on clinical indications and pulp conditions. Advancements in bioceramics, such as MTA, CEM cement, and Biodentine™, have significantly improved outcomes, particularly in terms of success rates and long-term efficacy. However, inconsistencies in clinical protocols and the need for high-quality, long-term trials remain to be addressed. Despite these gaps, VPT continues to be a promising alternative to more invasive treatments such complete pulpectomy, RCT or tooth extraction. Further research is essential to standardize protocols and refine techniques for better clinical outcomes.

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Conflict of interest
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Authors' contributions
Conceptualization: SA, Methodology: SA and AN, Formal analysis and investigation: SA and AN, Writing-original draft preparation: SA, Writing-review and editing: AN, Supervision: SA. All authors read and approved the final manuscript.

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