

REVIEW ARTICLE

Theme 3 – Treatment Outcomes in Endodontics

Factors that influence the outcome of pulpotomy in permanent teeth

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Abstract

The promotion of minimally invasive treatments focussed on the maintenance of pulp vitality has become a priority area in Endodontics. These vital pulp treatments (VPT) include partial and full pulpotomy, during which diseased coronal pulp tissue is removed prior to placement of a capping biomaterial and restoration. Traditionally, pulpotomies were confined to the treatment of carious primary and traumatized permanent teeth. However, these treatments have now been proposed as definitive solutions for cariously exposed permanent teeth with mild symptoms or even symptoms indicative of irreversible disease. Until recently, it was recommended that carious exposure of mature permanent teeth be managed by root canal treatment. The promotion of pulpotomy as an alternative treatment has opened up a wave of laboratory and clinical research aimed at improving therapies or evaluating clinical outcomes. In modern evidence-based endodontics, it is imperative that the outcomes of both partial and full pulpotomy are considered and important prognostic factors identified, so that improvements can be made to aid clinical decision-making and to direct new research. In this narrative review, the outcomes of partial and full pulpotomy are discussed, before analysis of patient, intraoperative and postoperative factors that influence the outcome of the pulpotomy procedure. The review highlights that although partial and full pulpotomy for the treatment of even pulpal disease are highly successful procedures, this is based on low-quality evidence with a lack of prospective, comparative trials investigating potential prognostic factors. Based on current evidence, it appears that age, gender, tooth type, root development and intraoperative pulpal haemorrhage do not impact significantly on pulpotomy outcome, whilst others such as caries depth, inflammatory status of the pulp, capping material, level of inflammatory pulpal-biomarkers and the final restoration integrity do. Other factors, including the influence of exposure type, periodontal condition, pulpal lavage, magnification, operator experience, isolation of the operating field and type of pulpotomy, require further experimental investigation before definitive conclusions can be made relating to the success of the pulpotomy procedure. Finally, there is not only a need for future well-designed prospective research addressing these issues but also

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a widening of our understanding of outcome to include patient-reported as well as clinician-reported outcomes.

KEYWORDS

biomarkers, caries, pulp capping, pulpitis, pulpotomy, vital pulp treatment

INTRODUCTION

Vital pulp treatments (VPT) include a range of procedures focussed on maintaining the health of all or part of the dental pulp (ESE, 2019). VPT in permanent teeth encompasses one-visit techniques to manage deep caries avoiding pulp exposure, such as selective caries removal and indirect pulp capping, as well as two-visit stepwise excavation techniques (ESE, 2019). VPT also includes conservative management techniques if the pulp is exposed by trauma, mechanically or by caries, such as pulp capping and partial and full pulpotomy (ESE, 2006, 2019). According to the European Society of Endodontology (ESE, 2019), a full, coronal or complete pulpotomy involves the 'complete removal of the coronal pulp and the application of a biomaterial onto the pulp tissue at the level of the root canal orifice(s)', whilst a partial pulpotomy, also known as a 'Cvek pulpotomy' conducted after the pulp is traumatically exposed (Cvek, 1978; Donnelly et al., 2022; Mejare & Cvek, 1993), involves removal of a small portion of coronal pulp tissue after exposure followed by application of a biomaterial directly onto the remaining pulp tissue (ESE, 2019). After pulpotomy to remove diseased pulp tissue and biomaterial placement, the tooth should be permanently restored as quickly as possible to protect it from additional injury and infection and to promote healing and repair of remaining vital pulp tissue (ESE, 2006, 2019).

The fundamental purpose of the partial or full pulpotomy procedure is to remove pulp tissue that is irreversibly inflamed and to preserve the remaining normal or reversibly inflamed pulpal tissues (Cvek, 1978; Ricucci et al., 2014). As a result of a better understanding of pulp repair processes and the introduction of superior bioactive pulpal biomaterials (Nair et al., 2008), pulpotomy has re-emerged as a potential alternative to root canal treatment after carious pulp exposure (Simon et al., 2013), even in teeth with signs and symptoms indicative of irreversible pulpitis (Careddu & Duncan, 2021; Taha et al., 2017; Taha & Khazali, 2017).

If tissue removal during partial or full pulpotomy is extended to a level where the underlying tissue is not inflamed or is reversibly inflamed, the remaining pulp is capable of recovery following appropriate wound dressing and tooth restoration (Fuks, 2008). Even in cases with signs and symptoms of irreversible pulpitis, the inflammatory and

infective process is often confined only to the coronal pulp tissue, with the pulp tissue in the root canals relatively free of inflammatory change (Ricucci et al., 2014). It could be assumed that full pulpotomy will more predictably remove all the inflamed tissue than partial pulpotomy; however, partial pulpotomy has been reported to have several advantages compared with full pulpotomy, such as preservation of the cell-rich coronal pulp tissue, the physical apposition of dentine (Chailertvanitkul et al., 2014; Fong & Davis, 2002), as well as practical benefits such as the ability to effectively pulp test teeth, something that is not always effective after full pulpotomy (ESE, 2019). As full pulpotomy removes the entire coronal pulp, there is no possibility of continued physiologic apposition of secondary dentine in the pulp chamber, with a potential increase in the risk of cervical fracture of relatively fragile, immature teeth (Chailertvanitkul et al., 2014); however, this may not be so critical in mature permanent teeth.

Pulpotomies are considered technically simpler, less time-consuming, and more cost-effective compared with pulpectomy and root canal treatment (Bjørndal et al., 2019; Simon et al., 2013). Although current evidence suggests there may be little difference in the overall success rate between pulpotomy and root canal treatment in the management of cariously exposed mature molars (Asgary et al., 2017; Galani et al., 2017), the quality of available comparative evidence is poor, with several important variables including preoperative pulpal diagnosis and caries depth often not reported in the primary literature (Cushley et al., 2019). Additional information is critical to identify why VPT and pulpotomies fail (pain, tenderness, swelling, signs of infection, internal resorption, emerging apical radiolucency) (Careddu et al., 2021). Currently, failure may be considered as early or late (Bjørndal et al., 2019), with early failures related to a misdiagnosis of the severity of the pulpitis process and late more likely to be related to compromised asepsis during the technical procedure and the quality of the restoration, with the resulting microbial contamination compromising the reparative process (Bjørndal et al., 2019; Zanini et al., 2016).

In a systematic review, full pulpotomy in teeth exhibiting signs and symptoms of irreversible pulpitis (Cushley et al., 2019) was associated with a 97.4% clinical success rate (no spontaneous pain, no tenderness to percussion, and/or no swelling or sinus tract) and a 95.4% radiographic success rate (no abnormality suggestive of apical

periodontitis as well as decrease in the size or elimination of an existing radiographic periapical lesion) at 12 months, whereas partial pulpotomy has been reported to have a success rate of 75% at 12 months in teeth with signs associated with irreversible pulpitis and 98% success rate in teeth with reversible pulpitis (Elmsmari et al., 2019). A separate study reported an 85% success rate (clinical and radiographic) at 2 years following partial pulpotomy in teeth with a carious exposure and signs and symptoms indicative of irreversible pulpitis when MTA was applied as a pulp cap compared with 43% when a hard-setting calcium hydroxide cement was applied (Taha & Khazali, 2017).

When considering partial or full pulpotomy as definitive treatment options for the treatment of carious exposure in permanent teeth, the continued health of the retained pulp tissue and outcome of treatment has been reported to rely on a range of preoperative and intraoperative factors that form the basis of this review. The relationship between these factors and their subsequent influence on the outcome of the pulpotomy procedure is ambiguous and not always clearly defined. It is evident however that there is a lack of quality and consistency of reporting in the primary research on VPT, particularly in relation to management of the exposed pulp (Ballal et al., 2022; Bjørndal et al., 2019; Cushley et al., 2019; ESE, 2019). As a result, the aim of the current review is to identify the factors that influence the outcome of partial and full pulpotomy, which should assist clinicians' decision-making and management of pulpal disease in practice; and to highlight gaps and deficiencies in outcome reporting in this area, which could direct researchers to design and conduct high-quality clinical trials investigating this aspect of VPT in the future.

REVIEW

What is outcome in VPT?

Outcome in endodontics has traditionally been based on clinician-reported variables, such as radiographic assessment of tissue health, history and clinical examination and less on patient-reported variables such as pain, oral health-related quality of life (OHRQoL) or tooth retention (Duncan, Chong, et al., 2021). The systematic development of guidelines in Endodontics has focussed the minds of the profession on the need for not only clear measures to assess the outcome of procedures including VPT, non-surgical and surgical root canal treatment and regenerative endodontic techniques (Duncan, Nagendrababu, et al., 2021a), but also on the need to consider the patient's view as being critical to the selection of relevant outcome measures. To that end, the ESE S3-level guideline process

was selected and ranked by importance in a consensus process a group of outcome measures by which to evaluate the success of VPT (Table 1, Duncan, Nagendrababu, et al., 2021b). Tooth survival was ranked as the 'most critical', whilst other 'critical outcomes' were pain, tenderness, swelling, need for medication (analgesics), evidence of emerging apical radiolucency' and 'response to pulp sensibility test (not for full pulpotomy or pulpectomy)' and 'important outcomes' were tooth function (fracture, restoration longevity), need for further intervention, adverse effects (including exacerbation, restoration integrity, allergy), oral health-related quality of life (OHRQoL), presence of sinus tract and radiological evidence of continued root formation (Duncan, Nagendrababu, et al., 2021b). It should be noted that whilst this exercise was carried out using a Delphi process it does not constitute a formal process to establish a core outcome set (COS) in endodontics; however, that critical process is ongoing in a consensus project of which the protocol has already been published (El Karim et al., 2022) and the scoping review for VPT completed (Cushley et al., 2022). However, it is important in a review addressing factors that affect outcome, that these measures are considered as part of a broader analysis of outcome in VPT.

How is outcome currently assessed in pulpotomy?

Recent evidence from a scoping review to assess how, when and which outcomes are currently reported in VPT highlighted a high level of heterogeneity and lack of consensus amongst published clinical studies (Cushley et al., 2022). Generally, success after pulpotomy is by a combination of patient history and clinical examination supplemented by special tests (e.g. pulp sensibility, radiographs). It is recommended that pulpotomy procedures are assessed at 6 and 12 months postoperatively and at subsequent yearly intervals if required (ESE, 2019). The tooth should respond positively to pulp sensibility testing without an exaggerated response, which can be problematic to do after partial (Careddu & Duncan, 2021) and full pulpotomy (ESE, 2019). The patient should clearly not be in any pain and in the absence of evidence of pulp necrosis clinically and radiographically as well as radiological evidence of continued root formation in immature teeth and absence of signs of internal root resorption and apical periodontitis, the treatment can be deemed successful (ESE, 2006). One outcome measure not captured in the ESE-S3 guideline process (Duncan, Chong, et al., 2021) is pulp sclerosis after pulpotomy (Mc Donnell & Kinirons, 2007). Tertiary dentinogenesis and sclerosis reflect the natural defensive response

TABLE 1 Outcome measures ranked by importance, with recommended follow-up time and measurement tools used in ESE-S3 process

Outcomes	Ranked importance of outcome measure from Likert scale	Patient (PROM) or clinician-reported (CROM) outcome measure	ESE recommended minimum and maximum follow-up period	Tools necessary to measure the outcome
Tooth survival	Critical	PROM/CROM	Minimum: 1 year Maximum: long as possible	Clinical history examination
Pain, tenderness, swelling, need for medication (analgesics)	Critical	PROM	Minimum: 7 days Maximum: 3 months	Clinical examination and pain scale
Evidence of emerging apical radiolucency	Critical	CROM	Minimum: 1 year Maximum: long as possible	Intraoral periapical radiograph, limited FOV CBCT scan
Response to pulp sensibility test (not full pulpotomy or pulpectomy)	Critical	CROM	Minimum: 1 year Maximum: long as possible	Thermal and/or electric pulp test
Tooth function (fracture, restoration longevity)	Important	PROM	Minimum: 1 year Maximum: long as possible	Clinical history and examination
Need for further intervention	Important	PROM	Minimum: 1 year Maximum: long as possible	Clinical history and examination
Adverse effects (exacerbation, restoration integrity, allergy)	Important	PROM	Minimum: 1 year Maximum: long as possible	Clinical history and examination
OHRQoL	Important	PROM	Minimum: 6 months Maximum: long as possible	Validated OHRQoL questionnaire
Sinus tract	Important	CROM	Minimum: 1 year Maximum: long as possible	Examination
Radiological evidence of continued root formation	Important	CROM	Minimum: 1 year Maximum: long as possible	Intraoral periapical radiograph, limited FOV CBCT scan

Note: Modified with permission from Duncan, Nagendrababu, et al., 2021b.

Abbreviations: CROM, clinician-reported outcome measure; ESE, European Society of Endodontology; OHRQoL, Oral health-related quality of life; PROM, patient clinician-reported outcome measure FOV, Field of View.

of the irritated pulp tissue in the pulp chamber or root canal system and from a clinical perspective is likely to be more concern after full rather than partial pulpotomy as it will make re-entry more difficult in cases of failure (ESE, 2019). The prevalence of root canal sclerosis after pulpotomy is unknown and does not represent a negative outcome; however, establishing how common an occurrence it is after pulpotomy is a priority moving forward.

Factors that influence outcome

Although a range of prognostic factors has been reported to affect the outcome of VPT including; age, preoperative pulpal status (Al-Hiyasat et al., 2006), pulp capping material (Hilton et al., 2013), patient gender and pulpal lavage (Ballal et al., 2022), there remains a paucity of comparative evidence on which to base the true influence of these factors on outcome (Jakovljevic et al., 2022). Recent systemic reviews (Tables 2 and 3) including a range of study types (Donnelly et al., 2022; Elmsmari et al., 2019) and other reviews limited to comparative evidence (Jakovljevic et al., 2022) have highlighted only a handful of studies on which to base clinical decision-making in VPT. This review will analyse a range of prognostic factors and conclude with recommendations as to the strength of the evidence to support its effect. In the present review, we categorized the factors affecting the outcome of pulpotomy treatment in permanent teeth into three: patient, intraoperative and postoperative factors.

Patient factors

Age

Traditionally experimental, prospective studies investigating the reaction of the pulp tissue to different materials generally recruit young patients (Accorinte et al., 2008; Hörsted-Bindslev et al., 2003; Nair et al., 2008), as do prospective pulpotomy studies of carious teeth (Barrieshi-Nusair & Qudeimat, 2006; Mejare & Cvek, 1993; Qudeimat et al., 2007; Witherspoon et al., 2006). These younger patients, generally under 20 years of age, are chosen due to the greater blood supply and cellularity of their pulps, which is based on the assumption that this will result in more predictable pulp healing. By contrast, retrospective studies tend to include all age groups and have concluded that age had no influence on the clinical and radiographic success rates of pulpotomy (Kunert et al., 2015; Linsuwanont et al., 2017). Similarly, one randomized clinical trial concluded that age was not a prognostic factor related to the success rate of partial pulpotomy (Kang et al., 2017).

Several clinical studies have reported high success rates for partial/full pulpotomy in adult patients when their age ranged from 19 to 69 years (Asgary & Eghbal, 2013; Barnkggei et al., 2013; Taha & Abdelkader, 2018; Taha & Khazali, 2017). However, the influence of age was not the primary interest of these studies, which were focused on a comparison of success rate of pulpotomy relating to various pulpotomy materials (Asgary & Eghbal, 2013; Barnkggei et al., 2013). Binary logistic regression analysis could have been performed to study the relation between age and outcome, but was unfortunately not carried out.

A systematic review on pulpotomies (Aguilar & Linsuwanont, 2011) concluded that the data derived from the included studies were insufficient to allow an analysis of the impact of age. As a result, they were unable to report on the influence of patient age on the outcome of VPT in permanent teeth. However, a more recent systematic review that included studies with patients within the age range 6–52 years concluded that age did not affect the outcome of pulpotomy in permanent teeth (Elmsmari et al., 2019).

Conclusion: A number of randomized clinical trials have demonstrated that the removal of the cause of the disease, selecting an appropriate pulp capping material and following an appropriate clinical technique will allow residual pulp tissue to heal in adults following pulpotomy (Asgary & Eghbal, 2013; Chailertvanitkul et al., 2014; Kumar et al., 2016). As a result, from the available evidence (clinical trials and systematic review), albeit including studies with high level of bias, it can be concluded that the outcome of partial/full pulpotomy is not influenced by age and can be considered as a successful treatment in patients of all ages. However, further analysis in well-designed clinical trials is required to investigate the association between age and pulpotomy outcome.

Gender

In a similar way to age, gender is seldom chosen as a primary outcome variable of interest, although many studies do list the demographic details of the sample. One randomized clinical trial concluded that gender did not have a significant effect on the clinical and radiographic outcome of partial pulpotomy in mature permanent teeth with clinical signs and symptoms indicative of irreversible pulpitis (Taha & Khazali, 2017). This was supported by another randomized clinical trial, which reported that gender was not a prognostic factor affecting the success rate of partial pulpotomy (Kang et al., 2017). Conversely, Mass and Zilberman (2011) reported that there were significant differences between males and females in hard tissue bridge formation and pulp horn obliterations during radiographic examination after partial pulpotomy. However, this retrospective radiographic study had 49 patients of which only

TABLE 2 Published systematic reviews of cariously exposed teeth treated by pulpotomy

Author (year)	Journal	Search period	Language	Number of pulpotomy studies	Meta-analysis (studies)	Study design of included studies	Quality assessment tool	Coronal or partial pulpotomy	Pulp diagnosis, outcome and main conclusions
Aguilar & Linsuwanont, (2011)	Journal of Endodontics	1950–2010	Only English	Partial – 14 Complete – 18	No	Prospective or retrospective studies	Criteria from Torabinejad et al. (2007)	Direct pulp capping, partial pulpotomy, complete pulpotomy	Asymptomatic, reversible and irreversible pulpitis. Partial pulpotomy and full pulpotomy sustained a high success rate up to more than 3 years (partial pulpotomy: >6 months–1 year, 97.6%; >1–2 years, 97.5%; >2–3 years, 97.6%; and >3 years, 99.4%; full pulpotomy: >6 months–1 year, 94%; >1–2 years, 94.9%; >2–3 years, 96.9%; and >3 years, 99.3%)
Alqaderi et al. (2016)	Journal of Dentistry	1960–2015	Only English	6	Yes (5)	Prospective including RCT and retrospective	RCT – Cochrane Collaboration's tool Prospective or retrospective cohort studies – Newcastle–Ottawa scale	Complete pulpotomy	Asymptomatic, reversible and irreversible pulpitis. Full coronal pulpotomy had a favourable success rate in treating carious vital pulp exposure of permanent mature teeth with closed root apices. Weighted mean success rate 1 year 94%, 2 years 92%
Cushley et al. (2019)	Journal of Dentistry	Until 2018	No language restriction	8	No	Prospective including RCT and retrospective	Nonrandomized-modified Downs and Black quality assessment checklist. RCT Cochrane Handbook for Systematic Reviews of Intervention.	Complete pulpotomy in teeth with signs and symptoms indicative of irreversible pulpitis	Teeth with signs and symptoms of irreversible pulpitis. High success for pulpotomy treatment. 1 year—97.4% clinical and 95.4% radiographic 3 years—93.97% clinical and 88.39% radiographic
Elmsmari et al. (2019)	Journal of Endodontics	1950 to 2018	No language restriction	11	Yes (5)	Prospective including RCT and retrospective	Prospective cohort – Newcastle–Ottawa scale – RCT – Cochrane collaboration's tool	Partial pulpotomy	Asymptomatic, reversible and irreversible pulpitis. Success rate of 98%, 96%, and 92% after 6 months and only preoperative pulp status was identified as a significant factor. High success rates up to 2 years. Six months of monitoring can be considered an appropriate period when evaluating the success of a partial pulpotomy
Li et al. (2019)	Journal of Dentistry	Until 2019	No language restriction	17	Yes (5)	Prospective RCTs	Cochrane collaboration tool and GRADE	Partial and complete pulpotomy	Asymptomatic, reversible and irreversible pulpitis. Pulpotomy compared to other treatment modalities favoured pulpotomy. Meta-analyses favoured MTA over calcium hydroxide. Successful modality. Pulpotomy is highly successful, even in permanent teeth with irreversible pulpitis
Zafar et al. (2020)	Journal of Conservative Dentistry	2007–2018	Not stated	6	No	Prospective. Including RCT and retrospective as well as single-arm studies	Cochrane collaboration tool	Partial and complete pulpotomy	Teeth with signs and symptoms of irreversible pulpitis. Follow-up range 1–10 years. RCTs comparing pulpotomy with the root canal treatment and reported comparable and better success of the pulpotomy (78% success). Other studies showed better clinical and radiographic success of pulpotomy (68%–100%)

TABLE 2 (Continued)

Author (year)	Journal	Search period	Language	Number of pulpotomy studies	Meta-analysis (studies)	Study design of included studies	Quality assessment tool	Coronal or partial pulpotomy	Pulp diagnosis, outcome and main conclusions
Lin et al. (2021)	Quintessence	1980–2020	No restriction	11	Yes	Prospective, including RCT and retrospective	Cochrane RoB 2, ROBINS-I, and Newcastle-Ottawa scale	Partial and complete	Asymptomatic, reversible and irreversible pulps. The clinical and radiographic success rates of coronal pulpotomy ranged between 92.2% and 99.4%, whilst for partial pulpotomy, the success rates ranged between 78.2% and 80.6%. Different pulp capping medicaments and restorative materials showed no significant effect on the success rates. Coronal and partial pulpotomies demonstrated a high success rate

Abbreviations: RCT, randomized controlled trial; RoB, risk of bias.

13 were male and the authors conclusion ‘that calcium hydroxide placed directly on the vital pulp of a pulpotomized tooth in female patients had more odontoblastic activity compared to males’ (Mass & Zilberman, 2011), cannot be established using the selected study design.

Conclusion: Overall, the existing evidence suggests that gender has no influence on the outcome of pulpotomy. However, further analysis in adequately powered randomized clinical trials is required to investigate the association between gender and outcome of pulpotomy. Indeed, good practice suggests that a separate analysis on the success rate of pulpotomy between male and females is important in all randomized clinical trials.

General medical condition

Often patients with conditions conceived to be potentially significant are not included in clinical trials with several studies excluding patients with systemic disease (Asgary & Eghbal, 2013; Kang et al., 2017) or ‘contributory’ medical conditions (Taha & Abdelkader, 2018; Taha & Khazali, 2017; Taha et al., 2017) from their study. The term noncontributory medical condition is often used, but it is unclear without evidence what this exactly means (Taha et al., 2017). One study investigated the relationship between medical conditions and pulpotomy outcome and concluded that hypertension, cardiopathy and other systemic disease (hepatitis, diabetes, HIV) were not significant risk factors affecting the success of pulpotomy in young and adult patients (Kunert et al., 2015). Interestingly, very few pulpotomy studies have included supplemental information detailing the medical conditions of the included cohort of patients.

Conclusion: It is unclear if any general medical condition has an effect on the outcome of pulpotomy procedures. Trial authors should be encouraged at least as supplemental information to catalogue the medical condition of their sample so that analysis of any potentially confounding conditions is possible.

Tooth type

The vast majority of pulpotomy studies supply a breakdown of type of teeth included in their study population, but it should be noted that although partial pulpotomy is feasible, full pulpotomy is practically more difficult in single-rooted teeth as the pulp chamber is less well-defined (Careddu & Duncan, 2021). One study concluded that the use of premolar or molar teeth was not a prognostic factor related to the success rate of partial pulpotomy (Kang et al., 2017). Several other studies included only one tooth type, either molars (Asgary & Eghbal, 2013; Eghbal et al., 2009; Keswani et al., 2014; Mass & Zilberman, 2011; Nosrat et al., 2013) or premolars (Kiatwateeratana et al., 2009), whereas other studies included both molars

TABLE 3 Systematic reviews carried out analysing pulpotomy after traumatic exposure

Author (year)	Journal	Search period	Language	Number of pulpotomy studies	Meta-analysis (studies)	Study design of included studies	Quality assessment tool	Coronal or partial pulpotomy	Outcome and main conclusions
Donnelly et al. (2022)	International Endodontic Journal	Until 2021	Only English	7	No	Retrospective	Newcastle-Ottawa scale	Partial and complete pulpotomy	Studies reported high success rates for pulpotomy ranging from 75% to 96%. The findings of the review indicate high success rates for pulpotomy; however, there is a moderate risk of bias and small sample sizes
Matou-Elwerfelli et al. (2022)	International Endodontic Journal	Until 2021	Only English	14	No	Prospective, including RCTs retrospective	NIH quality assessment tool	Pulp capping, partial and complete pulpotomy	Partial pulpotomy was the main reported clinical procedure with an overall success rate between 82.9%–100%. Complete pulpotomy and direct pulp capping were associated with lower success rates of 79.4%–85.7% and 19.5%, respectively. High success but low-quality studies
Tzanetakis et al. (2022)	Journal of Endodontics	Until 2021	No language restriction	24	Yes (7)	Prospective, including RCTs retrospective	RCT – Cochrane Tool; Nonrandomized ROBINS-I	Pulp capping, partial and complete pulpotomy	For different pulp management, there was no evidence that pulpotomy performed better than pulp capping with either CaOH ₂ or mineral trioxide aggregate. Risk of bias was serious or critical for nonrandomized studies

Abbreviation: RCT, randomized controlled trial.

and premolars (Alqaderi et al., 2014; Simon et al., 2013) or included incisors, premolar and molars (Barnkgkei et al., 2013). However, all the listed studies investigating more than one type of tooth did not analyse the effect of tooth type on the outcome.

Conclusion: There has been limited analysis of the effect of tooth type on partial or full pulpotomy, and it would be valuable if this could be analysed in future studies. Existing evidence does not suggest that tooth type is a significant prognostic factor.

Stage of tooth development

For similar reasons to younger patients being selected for prospective VPT studies, partial and full pulpotomy in teeth with immature (open) apices would be expected to have a favourable response due to profuse blood supply and good regenerative potential (Mass & Zilberman, 2011; Nosrat et al., 2013). Few investigators have compared teeth with immature and mature apices directly in their studies, and for this reason, Cushley et al. (2019) noted the difficulty in performing systematic reviews of fully pulpotomized mature teeth as the level of root formation was often not recorded in the study. One study noted that there were no significant differences between the success rates of partial pulpotomy in teeth with varying degrees of maturity and root apex status (Kang et al., 2017). Others have selected only mature roots in their inclusion criteria and subsequently reported that partial pulpotomy with MTA had a high success rate (85%) over a 2-year follow-up in teeth diagnosed with symptoms indicative of irreversible pulpitis (Taha & Khazali, 2017) with a randomized clinical trial concluding there was no significant difference in the overall success rate between coronal pulpotomy (85%) and root canal treatment (87.5%) in mature cariously exposed permanent teeth (Galani et al., 2017). Two systematic reviews have concluded that pulpotomy had a favourable success rate in treating permanent mature teeth (Alqaderi et al., 2016; Cushley et al., 2019). A systematic review by Cushley et al. (2019) reported that average clinical and radiographic success rates for coronal pulpotomy were 97.4% and 95.4% respectively at 12-month follow-up in managing mature carious teeth with symptoms of irreversible pulpitis.

Conclusion: Pulpotomy can be performed in permanent teeth with open and closed apices, and at present, there is no evidence to suggest it to be more successful in patients with immature root formation.

Depth of carious lesion

The depth of the carious lesion is related to the preoperative condition of the pulp (Demant et al., 2021; Reeves & Stanley, 1966). Classic literature has demonstrated that pulpitis will accompany the carious process throughout

its progression through dentine; however, it is not until the infected demineralized carious dentine is close to the pulp and invades the tertiary dentine that the inflammatory response becomes severe and there is a risk of bacteria entering the pulp (Bjørndal et al., 1998; Reeves & Stanley, 1966). Recently, in order to make this distinction clinically relevant, caries depth determined radiographically has been categorized into deep and extremely deep (Bjørndal et al., 2019; ESE, 2019), where deep caries is defined as 'Radiographic evidence of caries reaching the inner quarter of dentine, but with a visible zone of dentine between the caries and the pulp, which carries a risk of pulp exposure during operative treatment' and extremely deep caries as 'Radiographic evidence of caries penetrating the entire thickness of the dentine with certain pulp exposure during operative treatment' (ESE, 2019). In extremely deep carious lesions, there are microorganisms penetrating into the tertiary dentine including the pulp and eliciting a severe inflammatory response (Bjørndal, 2018; Demant et al., 2021; Reeves & Stanley, 1966). In a recent histological study, 68 carious permanent teeth were radiographically divided into deep and extremely deep caries groups (Demant et al., 2021). The authors reported that teeth with deep lesions tended to have bacteria only in the primary dentine, whereas teeth with extremely deep carious lesions tended to have bacteria in contact with the pulpal tissue and the presence of an inflammatory infiltrate with partial pulp necrosis. However, as this was histological study the treatment outcome could not be assessed. Notably, hyperplastic pulps were seen only in teeth with extremely deep lesions (Demant et al., 2021). In a separate outcome study of teeth with deeply carious teeth treated by partial pulpotomy using Biodentine™ (Septodont), each tooth was categorized preoperatively not only by pulpal diagnosis but also radiographically by caries depth (deep, extremely deep) with teeth removed from the study if the pulp was not exposed during caries excavation. Of the 62 cases enrolled, most were 'extremely deep' ($n = 50$), not 'deep' ($n = 12$) caries with all failures occurring in the extremely deep group with the overall success rate of partial pulpotomy procedure being 90% (Careddu & Duncan, 2021).

Conclusion: Caries depth relates to preoperative status of the pulp, which is a factor likely to determine the outcome of treatment. Extremely deep caries is likely to have infection of the pulp and reduces the success of at least partial pulpotomy procedures.

Type of exposure

Although a retrospective study highlighted that the type of pulp exposure, mechanical or carious, had a significant effect on the success of a direct pulp capping procedure (92% compared with 33%) (Al-Hiyasat et al., 2006), currently

there are no available pulpotomy studies directly comparing outcome relating to the nature of the exposure, carious or traumatic. In a similar manner to pulp status, the type of exposure highlights the likely presence or absence of bacteria and inflammation in the pulp. Even with a lack of direct comparison, inference can however be drawn from studies and systematic reviews that analyse pulpotomy as a treatment for carious exposure (Alqaderi et al., 2016; Cushley et al., 2019; Li et al., 2019, Table 2) and traumatic exposure (Donnelly et al., 2022; Matoug-Elwerfelli et al., 2022; Tzanetakakis et al., 2022, Table 3). A recent systemic review focussing on complicated crown fracture included seven retrospective clinical studies and presented overall success rates ranging from 75% to 96% after at least 1-year follow-up; however, it was noted that none of the included studies were of high quality (Donnelly et al., 2022). Longer-term follow-up greater than 3 years highlighted that the success of the pulpotomy procedure did not reduce with time (Donnelly et al., 2022), a feature evident after carious exposure (Cushley et al., 2019). This finding was reported in other systematic reviews on the subject, which highlighted a highly successful procedure based on low-quality evidence (Matoug-Elwerfelli et al., 2022; Tzanetakakis et al., 2022, Table 3). Other systematic reviews analysing carious exposure and full pulpotomy in teeth with symptoms indicative of irreversible pulpitis revealed pooled success rates of 94% clinical and 88% radiographic at 3 years, albeit from studies with a high level of bias (Cushley et al., 2019). Systematic reviews in which the pulp diagnosis included asymptomatic and reversible pulpitis cases as well as irreversible pulpitis reported a pooled 94% at 2 years (Alqaderi et al., 2016, Table 2).

Conclusion: From the available evidence, it appears that the type of exposure does not affect the results of pulpotomy. This result may be surprising; however, it is limited by the fact that it is supported by weak evidence.

Pulpal diagnosis, severity of pulpal symptoms

The principal aetiological factors that induce pulpitis are of microbial, chemical or physical (mechanical and thermal) origin. In an attempt to make the histological-based classifications more clinically relevant, the American Association of Endodontists (AAE), (2013) classified pulpal diagnoses into normal pulp, reversible pulpitis, irreversible (symptomatic or asymptomatic) and pulp necrosis. Although the divisions between some conditions are somewhat arbitrary, it is considered that in reversible pulpitis, the pulp can predictably return to normal after removal of the stimulus, whereas in irreversible pulpitis, that portion of the pulp has no chance of recovery, and in such cases, total excision of the affected pulp tissue is required (Ricucci et al., 2014). Spontaneous or lingering pain and percussion sensitivity have been used as clinical predictors

of irreversible pulpitis (Bergenholtz & Spangberg, 2004); however, pain symptoms are subjective with many pulps being considered to die silently (Michaelson & Holland, 2002). Furthermore, the presence of spontaneous or severe preoperative pain does not always indicate that the pulp is incapable of repair (Glickman, 2009; Seltzer et al., 1963; Taha et al., 2017), whilst deep carious lesions are not unconditionally related to an irreversible pattern of pulpal injury (Bjørndal, 2008; Ricucci et al., 2014). Clinical symptoms have been widely accepted as indicators of the inflammatory status of the pulp. The presence of relatively mild symptoms is more often associated with reversible pulpitis, whereas more severe symptoms are associated with irreversible pulpitis (Levin et al., 2009). Pulpal inflammation has generally been considered the major factor in determining the fate of vital pulps undergoing VPT. The controlled inflammation of low-grade pulpitis promotes healing, whereas severe uncontrolled inflammation leads to severe damage to the pulp and cell death (Cooper et al., 2010; Simon et al., 2013).

A full pulpotomy procedure had a 100% clinical and 98.4% radiographic success rate in mature permanent teeth with clinical signs and symptoms indicative of irreversible pulpitis (Taha & Abdelkader, 2018). Several other clinical studies have shown that pulpotomy is a suitable alternative treatment for permanent teeth with signs and symptoms indicative of irreversible pulpitis (Asgary & Eghbal, 2013; Eghbal et al., 2009; Kumar et al., 2016; Qudeimat et al., 2017; Taha & Abdulkhader, 2018; Taha & Khazali, 2017; Uesrichai et al., 2019). A recent systematic review highlighted that pulpotomy in permanent teeth with a clinical diagnosis of irreversible pulpitis had 97.4% of clinical and 95.4% of radiographic success rate at 12-month follow-up (Cushley et al., 2019). A recent randomized trial investigating partial and full pulpotomy highlighted that partial pulpotomy was also successful in managing cases with signs and symptoms indicative of irreversible pulpitis, albeit a nonsignificantly higher success was observed after full pulpotomy (89.8%) in comparison to partial pulpotomy (80.8%) (Ramani et al., 2022).

Clinical signs and symptoms of irreversible pulpitis unfortunately do not reliably indicate that the pulpal tissue is histologically inflamed or damaged beyond repair: pain was present in 40% of the cases with pulps considered salvageable, and chronic pulpitis was present in 88% of painful cases (Dummer et al., 1980). Notably, other histological studies reported that the inflammation was confined to the area next to the carious exposure and not extending more than beyond 2 mm from the exposure site (Seltzer et al., 1963). Recently, in an attempt to link this to the AAE classification, Ricucci et al. (2014) reported that 15.4% of cases with clinical signs and symptoms of irreversible pulpitis had histological features of reversible pulpitis.

The word irreversible presents a problem when the above results indicate that at least part of the pulp can be saved in these cases. As a result, Wolters et al. (2017) proposed a system based on symptoms with four different categories of pulpitis, initial, mild, moderate and severe, with pulpal exposure and pulpotomy only indicated as modalities of treatment in selected categories. Importantly, the word 'irreversible' has been removed from all diagnoses in this proposed classification (Wolters et al., 2017). Recently, the AAE and Wolters classification were compared in a partial pulpotomy study (Careddu & Duncan, 2021), which concluded that partial pulpotomy was successful for treating symptomatic carious pulpal exposures and that cases with signs and symptoms indicative of irreversible (partial) pulpitis were not less successful than those with reversible pulpitis. Notably, Wolters classification highlighted that severe pulpitis cases were less successful than mild pulpitis, thereby providing a potential prognostic benefit in using this new classification system for VPT.

Conclusion: The preoperative status of the pulp is important as it will dictate the treatment selected with pulpotomy necessary in cases with more severe pulpitis. Based on the available evidence, permanent teeth diagnosed with irreversible pulpitis are not a contraindication for pulpotomy; in fact, success rates are similar to those of root canal treatment. Partial pulpotomy can also be successful but has a reduced success compared with full pulpotomy in permanent teeth with signs and symptoms indicative of irreversible pulpitis. Future clinical trials are necessary to confirm the influence of partial pulpotomy in teeth with irreversible pulpitis.

Periapical radiolucency

The American Association of Endodontists (AAE), (2013) classified periapical diagnoses into normal apical tissues, apical periodontitis (symptomatic/asymptomatic), apical abscess (acute /chronic) and condensing osteitis. Apical periodontitis (symptomatic /asymptomatic) indicates the presence of inflammation of the apical periodontium. Symptomatic apical periodontitis has a painful response to percussion or palpation and may or may not have radiographic changes, whereas asymptomatic apical periodontitis does not have pain on percussion or palpation and is associated with the presence of apical changes in the radiograph (AAE, 2013).

A retrospective study reported that teeth responding positively to pulp sensibility testing, but with an associated apical radiolucency could be treated successfully by MTA pulpotomy (combined clinical and radiographic examination) with rates of rates of 76% over a range of follow-up periods (Linsuwanont et al., 2017). Although the authors concluded that the presence of an apical radiolucency does not always represent pulp necrosis and is not a

contraindication to VPT, unfortunately, it is unclear from the study what constituted an apical radiolucency as a quantitative index such as the PAI was not used (Ørstavik et al., 1986). A prospective study reported the success (clinical and radiographic) of MTA pulpotomy in 19 teeth diagnosed with apical periodontitis of which 7 teeth had a periapical radiolucency (Qudeimat et al., 2017). They reported that all teeth with apical radiolucencies were associated with periapical healing, and three of the 7 teeth were also associated with hard tissue bridge formation (Qudeimat et al., 2017). These results were also supported in a separate prospective case series of full pulpotomies (Taha & Abdulkhader, 2018). In addition, several case reports have reported that complete resolution of periapical radiolucencies was observed following pulpotomy (Asgary et al., 2016; Foreman, 1980; Jiang et al., 2016; Moule & Oswald, 1983). It is logical that periapical rarefaction and apical radiolucency may represent more advanced pulpal inflammation; however, this has not been clearly shown as a prognostic factor for pulpotomy. The imaging modality itself will also determine the ability to visualize apical radiolucencies with Cone Beam Computed Tomography (CBCT) being shown to be more sensitive in the assessment of apical breakdown in teeth with pulpitis than planar radiography (Abella et al., 2012). Assessment of 307 paired roots of teeth with signs and symptoms indicative of irreversible pulpitis revealed the presence of apical lesions in 3.3% and absence in 96.7% when assessed with PA radiography; however, when the same 307 sets of roots were assessed with CBCT, this changed to a presence of AP in 13.7% and absence in 86.3% paired roots. Interestingly from an outcome perspective, the prevalence of AP lesions associated with irreversible pulpitis and detected with CBCT was significantly higher in patients with symptoms (Abella et al., 2012).

Conclusion: Although apical periodontitis occurs after pulp necrosis, varying portions of the radicular pulp can remain vital even when a large periapical radiolucency is observed on the radiograph (Lin et al., 1984; Ricucci & Siqueira, 2013). This suggests that pulpotomy can yield positive results and can be an alternative to root canal treatment in teeth with apical periodontitis when vital tissue is evident after pulp exposure. What is less clear, however, is how predictable this procedure is and what features are negative prognostic factors for pulpotomy in teeth with apical radiolucencies.

Intraoperative factors

Type of VPT

Pulp capping (Ballal et al., 2022), partial (Careddu & Duncan, 2021) and full pulpotomy (Taha et al., 2017) have recently been shown to be successful for managing the

cariously exposed pulps with success rates in the region of 90% after at least 1 year. In general, if the tooth has symptoms greater than reversible pulpitis, pulp capping is not recommended (ESE, 2019) and pulpotomy is preferred with several studies highlighting high success rates of full pulpotomy and signs and symptoms indicative of irreversible pulpitis (Cushley et al., 2019). Separately, case series have also highlighted the potential efficacy of partial pulpotomy in the same scenario (Taha & Khazali, 2017). As discussed in a previous section, 'Pulpal diagnosis, severity of pulpal symptoms' a recent randomized trial has been published comparing full pulpotomy with partial pulpotomy (Ramani et al., 2022). Until now, the bulk of the literature has constituted single-arm intervention studies or case series (Taha et al., 2017). This trial of 106 cariously exposed molars compared partial and full pulpotomy in teeth with signs and symptoms indicative of reversible pulpitis (Ramani et al., 2022). The study highlighted that partial and full pulpotomy were both successful although there was a nonsignificant trend towards full pulpotomy (89.8%) being more successful than partial pulpotomy (80.8%) (Ramani et al., 2022). The absence of a statistically significant difference between the two treatments was also highlighted in a recent randomized trial of patients with signs and symptoms indicative of irreversible pulpitis (Baranwal et al., 2022). Of the 66 patients treated, a success rate of 80% was noted for partial pulpotomy and 92% for full pulpotomy after 1 year, a result that highlighted a trend that was not significant (Baranwal et al., 2022).

Conclusion: Partial or full pulpotomy can achieve outcomes similar to those reported with root canal treatment. For the treatment of teeth with signs and symptoms indicative of irreversible pulpitis, currently it appears that partial pulpotomy is associated with similar success to full pulpotomy albeit based on studies with small sample sizes. Larger well-planned studies are clearly required to address this question in the future.

Isolation

The ESE position statement on the management of deep caries and the exposed pulp stresses the importance of aseptic, meticulous technique and use of rubber dam for tooth isolation (ESE, 2019). It should be noted that although the use of rubber dam is considered good practice and is generally employed at least in university-based efficacy studies investigating pulpitis (Careddu & Duncan, 2021; Taha et al., 2017), it has not been independently assessed as a variable linked to success of pulpotomy. In a recent large questionnaire-based study in the UK, rubber dam usage was low (37%) after pulp exposure in a range of general and community practices (Edwards et al., 2021).

Conclusion: Rubber dam and a strict aseptic protocol make logical sense during pulpotomy procedures as part

of good practice. However, the current literature is based on efficacy trials carried out in university or specialist clinics and not in the 'real world', where rubber dam isolation may not be employed. There is a need for effectiveness studies to be carried out in this area to assess the outcome of pulpotomy in a pragmatic environment.

Magnification and operator experience

It is not clear from the literature whether operator experience or use of magnification directly influences success of pulpotomy. The majority of the pulpotomy studies to date have been carried out in hospital or specialist settings where magnification is used routinely (Bogen et al., 2008; Marques et al., 2015), with only a few performed in general dental practices (Asgary & Eghbal, 2013) or without the routine use of magnification (Bjørndal et al., 2010). The outcome from these studies varies, and as a result, it is difficult to make conclusions unless this aspect is investigated in a prospective comparative manner. Operator skill and experience are likely to be important, but have not been tested independently to assess its potential to influence the success of pulpotomy (ESE, 2019).

Conclusion: The ESE (2019) recommended that magnification be used during management of the exposed pulp. This is not based on comparative trials, but rather on assimilation of evidence from studies using and not using magnification, as well as the logic that better vision will assist the management of the exposed pulp tissue.

Pulpal haemorrhage

Clinically, the exposed pulp tissue should appear red and vital, with an absence of grey areas indicating abscess or necrosis. That said, even the presence of a pulpal abscess does not indicate that the entire pulp is necrotic and pulpotomy is not possible (Okamoto et al., 2021). The pulp wound should bleed normally and the exposure site should be surrounded by noncarious dentine. Bleeding time has traditionally been used as indicator of extent of inflammation (Matsuo et al., 1996), and therefore, it has been suggested that if bleeding could not be controlled within 5–10 min, pulpectomy was indicated (Linsuwanont et al., 2017; Taha & Khazali, 2017). Notably, even in cases diagnosed with irreversible pulpitis, it has been reported that bleeding could be controlled within 6 min in 84% of cases during partial or full pulpotomy (Taha & Abdulhader, 2018; Taha et al., 2017). Pulpal haemorrhage was recently related to the outcome of partial pulpotomy after carious exposure (Careddu & Duncan, 2021). Using cotton wool pledgets soaked in sodium hypochlorite, haemorrhage could be arrested in all cases within 4 min, and although severe pulpitis took on average 1 min longer to stop bleeding, there was no significant relationship between bleeding time and outcome

(Careddu & Duncan, 2021). The time needed to achieve haemostasis did not influence the outcome after pulpotomy in another recent study (Tan et al., 2020).

Conclusion: A recent position statement on VPT by the American Association of Endodontists (AAE, 2021) concluded that direct visualization of the pulp and achieving haemostasis offers additional diagnostic information about the condition of the pulpal tissue. Certainly, achievement of haemostasis and the visualization of vital tissue are important for practical and decision-making; however, what has not been shown to date is any evidence that bleeding time affects the outcome of VPT.

Pulpal lavage

A range of solutions can be used to disinfect the pulp wound and control bleeding. These include saline, sodium hypochlorite and chlorhexidine (Ballal et al., 2020; Bjørndal et al., 2010); however, whether the choice of irrigant affects the outcome of the pulpotomy procedure is less clear. In teeth with cariously exposed pulps, the wound is likely to be contaminated and therefore use of sodium hypochlorite has been recommended (ESE, 2019). A recent systematic review on irrigant use after carious exposure in VPT highlighted that in the 27 studies included, 14 used sodium hypochlorite as an irrigating agent with 10 using saline or water (Munir et al., 2020). It was also noted that sodium hypochlorite tended to be used in more recent publications (Munir et al., 2020). A randomized trial comparing sodium hypochlorite to saline during a partial pulpotomy procedure on 80 permanent teeth with immature root formation reported no difference in outcome after 24 months between the two groups (Ozgur et al., 2017). Conversely, another randomized pulp capping trial of 96 patients with mild symptoms examined the clinical outcome after 1 year when 2.5% sodium hypochlorite was compared with saline (Ballal et al., 2021). After 1 year, exposed pulps washed with sodium hypochlorite were associated with significantly increased success (Ballal et al., 2021). Although they may appear contradictory, these results may highlight different approaches to the disinfection process, as in the Ozgur et al. (2017) study, the superficial 2–3 mm of pulp was removed with a high-speed bur, whilst in the Ballal et al. (2021) study there was no tissue removal only chemical disinfection. This may indicate that in one the superficial infectious challenge was removed physically and in the other chemically leading to similar results.

Conclusion: Sodium hypochlorite should be used to rinse the exposed pulp after carious exposure. Further randomized trial research is required to investigate whether the positive results highlighted after sodium hypochlorite wound irrigation before pulp capping can translate to improved pulpotomy outcome. Although not studied

at present, there seems no rationale for the use of saline over sodium hypochlorite even in the case of a traumatic or iatrogenic exposure treated by pulpotomy.

VPT wound dressing material

Traditionally, calcium hydroxide has been used as the treatment of choice, but has been superseded over the last 15 years by hydraulic calcium silicate cements, which have demonstrated improved histological (Aeinehchi et al., 2003; Nair et al., 2008) and clinical results in outcome studies (Cho et al., 2013; Hilton et al., 2013; Mente et al., 2014) and randomized clinical trials (Kundzina et al., 2017) compared with studies employing calcium hydroxide. Kundzina et al. (2017) used survival analysis at 36 months, to demonstrate a cumulative estimate of 85% for the MTA group and 52% for the calcium hydroxide group. One systematic review highlighted no difference in outcome with the pulp capping material used (Alqaderi et al., 2016), whilst another suggested that the evidence from the meta-analysis favoured the use of mineral trioxide aggregate (MTA) (Li et al., 2019). Interestingly, in spite of this growing evidence, calcium hydroxide was selected by 66% and hydraulic calcium silicate cements by only 20% for pulp capping procedures in a large questionnaire study of publicly funded or mixed practitioners in the UK (Edwards et al., 2021). These findings alter in a separate questionnaire that was limited to individuals who were members of Endodontic societies with 70% of members in Ireland and Italy indicating that hydraulic calcium silicate materials were the choice for managing the exposed pulp, although younger members of the Italian society preferred traditional calcium hydroxide materials (Careddu et al., 2021).

Conclusion: Hydraulic silicate materials are the evidence-based choice as pulpotomy wound dressing materials. It may be however that the role of the material in the success of pulpotomy has been overstated, as it is not completely clear how important the material is in overall success of the procedure. Suffice it to say it is one factor alongside a host of other prognostic factors including the inflammatory status of the pulp tissue (Murray et al., 2002).

Final restoration

The type of the final restoration has been shown to influence outcome with significant increase in late failure reported in studies in which pulpotomized teeth were restored with glass ionomer cements (Tan et al., 2020). The quality of the coronal restoration was also significantly associated with outcome in another pulpotomy study (Demarco et al., 2005). However, in a systematic review, Alqaderi et al. (2016) reported no difference in success when amalgam or composite was used as the final restoration.

Conclusion: The provision and maintenance of a suitable, well-placed permanent restoration should be considered an essential component of the pulpotomy procedure. The integrity of the material should be checked clinically and radiographically at appropriate intervals to ensure the success of the procedure in the long term. There is currently no strong evidence to guide clinicians on optimal coronal restoration to promote the success of pulpotomy procedures.

Level of pulpal biomarkers

Currently, clinicians rely upon an array of subjective ways to assess the inflammatory status of pulp tissue, which include history, examination, pulp sensibility tests, radiographs and direct inspection of pulp tissue. Unfortunately, there is a lack of objective diagnostic tools in VPT with the reference standard, histological assessment, of no value for patients as it necessitates tooth extraction (Duncan, 2022). The development of objective, robust inflammatory (Ballal et al., 2021) or other biomarkers (Al-Natour et al., 2021; Kearney et al., 2018; Rechenberg et al., 2016), which accurately reflect not only the level of inflammation in the pulp but also identifies the threshold between reversible and irreversible pulpitis, have long been considered a priority in endodontics (Zehnder & Belibasakis, 2022). In an ideal world, a small sample of pulpal blood, or another suitable analyte (dentinal fluid, gingival crevicular fluid), could be analysed in real time at chairside with a lateral flow antibody test and the results used to dictate tissue removal and subsequent treatment. Such a device has been developed to assess MMP8 in periodontal disease (Gupta et al., 2022) but is not available yet within endodontics.

After pulp exposure, researchers have investigated inflammatory cytokines and matrix metalloproteinases (MMPs) (Rechenberg et al., 2016) and have highlighted upregulation of various molecules in pulpitis. Clinical outcome studies have also emerged, which have to date largely focussed on the neutrophil marker MMP9 (Zehnder et al., 2011), with Mente et al. (2016) demonstrating that during partial pulpotomy there were significant differences in MMP9 levels between asymptomatic patients and patients with reversible and irreversible pulpitis. In a recent randomized clinical trial, 96 asymptomatic or mildly symptomatic patients received pulp capping and had MMP9 sampled at baseline before following up for 1 year (Ballal et al., 2021). MMP9 per total protein levels were shown to reflect in a highly significant manner the inflammatory state of the pulp and likelihood of subsequent failure with the authors concluding that MMP9/TP showed great promise as a predictive biomarker (Ballal et al., 2021).

Conclusion: The development of an objective chairside diagnostic assay that could determine the pupal

inflammatory state and assist the practitioner in treatment choice and likely prognosis would be a big step forward for the promotion of minimally invasive VPT. Although at present this remains experimental, there is clear evidence that certain pulp biomarkers can accurately determine the level of pulpitis and could potentially be developed into a 'point-of-care' assay in the future.

Postoperative factors

Hard tissue bridge formation

Hard tissue bridge formation is considered to represent a favourable outcome following pulpotomy on mature permanent molars (Asgary & Eghbal, 2013; Careddu & Duncan, 2021; Eghbal et al., 2009). Although this feature can often be observed radiographically on review, hard tissue bridge formation is not predictably visible and can merge particularly with capping materials of similar radiopacity (e.g. Biodentine™ [Septodont]). Recently, Taha et al. (2022) noted that a hard tissue bridge was detectable radiographically in only 8 cases out of 146 at 1 year. As a result, few studies report on the presence of hard tissue radiographically. In a retrospective analysis of 273 pulpotomies, Kunert et al. (2015) concluded that the radiographic detection of a 'dentine bridge' had a significant effect on success, suggesting this was due to a protective effect. Others have questioned the porosity of hard tissue bridge formed (Cox et al., 1996); however, its formation does indicate that at least vital cells were present at the time of the bridge formation.

Conclusion: Although not predictably visible radiographically, if a hard tissue bridge can be visualized this is generally considered a positive prognostic finding.

Postoperative interval before placing definitive restoration

In a similar way to the influence of the final restoration (discussed previous section), the time interval before placing the final restoration is important. Early failure was reported to occur within 6 weeks in a number of pulpotted teeth, suggesting that the provision of an interim restoration with good seal is required during this period (Tan et al., 2020). Indeed, the general advice is to place a sealing, definitive restoration immediately after placement of the pulpotomy material to avoid the potential of leakage (Cox et al., 1996; ESE, 2006, 2019; Hilton, 2009); however, hydraulic calcium silicate cements limit the ability to carry this out definitively in one-visit as many have a prolonged setting time. It has been suggested that for MTA the material should be placed with moist cotton wool and overlaid with a sealing provisional restoration before placing a definitive restoration at a second visit (Banava

et al., 2015; Parirokh & Torabinejad, 2010). They however reported no significant difference between one- or two-visit treatments with MTA as pulp-capping material in terms of clinical or histological outcomes, so definitive restoration may be possible even if the calcium silicate cement is not fully set. Newer hydraulic calcium silicate cements such as Biodentine™ (Septodont) are promoted as having a shorter setting time of 12 min; however, this has been questioned with a recent clinical pulpotomy study demonstrating that in only two cases did the material set within the manufacturer's stated time of 12 min, with one case taking 45 min. The average setting time for Biodentine™ was 22 min, which was significantly longer than stated by the manufacturer (Careddu & Duncan, 2021).

Conclusion: The provision of a definitive sealing restoration as quickly as practically possible after pulpotomy is important to avoid potential contamination of the newly restored wound. If a second visit is arranged due to the setting time of the wound dressing material, this should be arranged as quickly as possible.

Periodontal condition

The reason for extraction of endodontically treated teeth has been reported to be prosthetic (59%), followed by periodontal (32%) and finally endodontic (9%) (Vire, 1991). On that basis, it is interesting that the influence of periodontal disease on the outcome of pulpotomy is difficult to assess as prospective studies in this area often exclude patients with bone loss or periodontitis (Simon et al., 2013; Taha & Khazali, 2017; Tan et al., 2020). This is generally to avoid the influence of periodontal disease as a potential confounding factor on the treatment. Furthermore, retrospective studies do not comment on the influence of periodontal status either, perhaps as it has no obvious effect or because it was not the focus of the study (Kunert et al., 2015; Linsuwanont et al., 2017). Recent research has highlighted the presence of raised inflammatory cytokines in the pulp tissue of patients with advanced periodontal disease (Gomes et al., 2022), so it is ostensibly possible, but as yet untested that periodontal disease may influence the outcome of pulpotomy.

Conclusion: Periodontal disease is not a contraindication to pulpotomy; however, research is required to establish the relationship between pulpotomy and advanced periodontal disease.

Follow-up

An important aspect on the outcome of pulpotomy is the follow-up time required to determine outcome of the treatment. Failures in VPT can be considered as early, indicated by no response to treatment or pain (Ballal et al., 2020) or late failure indicated by emergence of new disease or pathology or restoration failure (Tan et al., 2020). Early

failure is generally considered immediately after treatment (up to 3 months [Ballal et al., 2020]), and late failure is usually considered to occur greater than 6 months after treatment. Cases should routinely be followed up for at least 6–12 months (ESE, 2019; Tan et al., 2020; Zanini et al., 2016). The ESE recently recommended follow-up periods for VPT suggesting clinical assessment at 6 and clinical/radiographic at 12 months postoperatively and at yearly intervals (if necessary) for 4 years thereafter (ESE, 2019). Ideally, the tooth should respond positively to pulp sensibility (thermal +/- electric) testing without a lingering or exaggerated response. It should be noted that certain teeth may not respond, for example, those which have undergone full pulpotomy or even partial pulpotomy (Careddu & Duncan, 2021). Furthermore, the patient should be free of pain and other symptoms, and there should be radiological evidence of continued root formation in immature teeth as well as absence of signs of internal root resorption and apical periodontitis (ESE, 2006). Notably, for the assessment of pulpitis and VPT within the ESE S3-level guidelines process, only comparative studies with a minimum of 1-year follow-up and ideally as long as possible were considered in the published protocol (Duncan, Nagendrababu, et al., 2021b).

Conclusion: Partial and full pulpotomy should be carefully monitored by history, clinical and radiographic examination at 6 months, 1 year and at yearly intervals, if healing is uncertain, sensitivity remains or the tooth does not respond to pulp sensibility testing thereafter.

CONCLUSION

In summary, many factors can potentially influence the outcome of pulpotomy including the inflammatory status of the pulp before treatment, the VPT procedure chosen, the capping material, restorative status and caries depth, whilst others have been shown to be less important such as patient age, gender, pulpal bleeding and tooth type. Overall, the evidence suggests that we should expect an overall high success rate ranging from 75% to 95% for pulpotomy to treat a traumatic exposure after 1 year. For pulpotomy (partial or full) to manage carious exposure with signs or symptoms of reversible or even irreversible pulpitis, similar results of 75%–95% after at least 1 year have been reported. These success rates, however, must be tempered by the fact that primary comparative evidence investigating pulpotomy for traumatic or carious exposure is limited and generally of low quality and new prospective, well-designed and adequately powered studies are more important than further systematic reviews of existing studies. Finally, from a dissemination of evidence perspective, it is clear that the positive results of

these pulpotomy studies are not reaching practitioners, as definitive pulpotomy for the management of teeth with signs and symptoms indicative of irreversible pulpitis was only chosen by 10% of UK dentists in a recent survey, who also highlighted a lack of training as the main reason for not carrying out the pulpotomy procedure (Edwards et al., 2021).

AUTHOR CONTRIBUTIONS

Planning of manuscript – HD, VN, JW, PD, IEK. First draft – HD. Writing sections – VN, IEK. Editing and final approval of the manuscript – HD, VN, JW, PD, IEK.

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CONFLICT OF INTEREST

The authors deny any conflicts of interest related to this study.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ETHICS STATEMENT

The study does not need ethical approval.

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