The scientific management of deep carious lesions in vital teeth using contemporary materials—a narrative review

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Aim: The aim of this article is to review the scientific evidence for deep caries removal in permanent vital teeth and the choice of dentine replacement material and restoration of the teeth to maintain long-term tooth vitality and function.

Method: The two position statements, namely, the European Society of Endodontology and the American Association of Endodontists position statements on vital pulp therapy, will be scrutinized and compared with regard to the deep caries removal strategy and assessed for evidence of best practice. The properties of materials used to manage vital pulps and the best way to restore the teeth will be reviewed and guidance on the full management of vital teeth will be suggested.

Conclusions: Promoting new treatment modalities for reversible and irreversible pulpitis allowing for pulp preservation should be considered. Although debatable, cases with deep caries should be managed by complete non-selective caries removal which will allow for pulpal management if needed and a more predictable outcome can be expected when using the new materials and treatment modalities of vital pulp therapy.

KEYWORDS

vital pulp therapy, indirect pulp capping, materials choice, deep caries, caries-affected dentine (CAD), caries removal, tooth restoration, guidelines

Introduction

Dental caries, trauma, and tooth wear result in loss of coronal dental hard tissues. These are replaced effectively by dental restorative materials. Both the disease process and the tooth restoration compromise the vitality of the dental pulp. This review is concerned with deep caries management and its effects on dental pulp.

Changes to the dental pulp caused by disease and tooth restoration have been shown to start very early and are symptomless (1, 2). These changes disrupt the pulp tissue architecture but may not necessarily compromise the pulp enough to lead to loss of vitality. Changes to the pulp microstructure have been shown with application of fissure sealants specifically the use of acid etch where even if placed on enamel, the expression of inflammatory cytokines was upregulated while the mineralization-related genes were down regulated and cell viability was significantly reduced (3). While these

changes are reversible, a more invasive treatment such as restoration of deep cavities showed more prominent inflammatory changes that, depending on the remaining sound dentine thickness, may not be reversible and lead to permanent damage of the affected part of the pulp (4–7). The histological pulp status prior to any intervention is an important variable that may affect the pulp response postoperatively but is rarely studied in the literature (8). These changes in the pulp and the disease progression are not adequately reflected in the symptoms, and thus pulp testing procedures need to be refined to adequately correlate the microstructural changes within the pulp which can be reversible or irreversible. This will have an impact on the outcome of disease management. When diagnosing teeth with deep carious lesions, the clinician must make a choice based on knowledge of the caries process and its effect on the pulp and also on existing diagnostic methods (9, 10).

After caries removal, the remaining cavity sound dentine thickness mediates a powerful influence on underlying pulp tissue vitality and inflammatory activity, but it has little effect on reactionary dentine secretion (6, 11). Following restoration, a remaining dentine thickness of 0.5 mm or greater is necessary to avoid evidence of pulp injury. When the remaining dentine thickness is less than 0.5 mm, the choice of the pulp protection material used affects the success of the treatment (5). While it is difficult to determine the remaining dentine thickness in a clinical setting, this measurement gives the clinician the urge to consider the different pulp protection materials when a deep cavity is encountered.

It has been shown that the clinical management depends on the training received by the practitioner with the cardiologists opting for selective caries removal, the operative dentists will remove all caries and the endodontists will initiate root canal therapy (12).

The effective management of the dental pulp depends on various factors which will be discussed in the rest of the article. These include:

- Proper diagnosis
- Removal of caries if the disease process is carious
- Management of the dentine substrate
- Management of the pulp
- Dressing the dentine
- Tooth restoration

The best management of vital teeth with deep caries necessitating vital pulp therapy has been addressed by both the European Society of Endodontology and the American Association of Endodontists who have issued position statements to guide the clinicians on best practice (13, 14).

Effective management of the carious tooth

Proper diagnosis

Reaching a proper diagnosis and case selection is key to success in any intended treatment. Endodontic diagnosis depends on history, symptoms, and responses to a few clinical tests assessing the pulpal and periapical status of the tooth (15, 16). Significant limitations of pulp sensibility tests have been identified and summarized in a review paper (15, 16). Most importantly, these tests measure the nerve response rather than assess the blood flow of the pulp (15, 16). In the case of young and immature teeth, lack of accuracy of electric pulp testing has been shown and is attributed to the yet incomplete innervation of the pulp (15–20). The lack of correlation between the actual histopathological status of the pulp and the responses to the pulp testing adds another major limitation of such tests (21–23). As a result, it is speculated that pulp tests can only discern a necrotic pulp from a vital one but cannot determine the severity of pulpal disease (irreversible vs. reversible) (15, 16). A comparison of pulp testing methods used to assign cases their clinical diagnosis has shown that ethyl chloride is less effective than refrigerant sprays and dry ice in eliciting pulpal responses (18, 24). A recent histopathological study showed that there is a 96.6% correlation between the histopathologic status of pulps clinically diagnosed with reversible pulpitis or considered normal pulps while about 84.4% correlation in cases of symptomatic irreversible pulpitis cases was reported (25). In this study the normal pulps and the cases with symptoms of reversible pulpitis were placed in the same category as they were treated by vital pulp therapy. Although this may have possibly skewed the correlation percentage, the treatment is the same, so it justifies the classification in one group. The types of tests for pulp sensitivity are not indicated (25). Further communication with the corresponding author (26) (Ricucci D) clarified that a number of tests were used, and the cumulative results were used to identify the sensibility test per tooth treated. The cold test used was a refrigerant spray called Pulpofluorane (Septodont, Saint Maur des Fosses, France) which, along with more robust histological preparation procedures and bacterial staining, explains the good correlation between the sensibility tests and the pulpal status (25). More studies to evaluate this assumption are needed to possibly correlate the clinical signs and symptoms to the actual histopathological status of the pulp using more accurate pulp tests than used in older studies.

There is also some debate on the diagnostic terms regarding the reversibility of pulpitis (25, 27–29). These debates are mainly driven by the recent advances in deep caries and pulpal management. The term irreversible pulpitis can be

perceived as a pulp that cannot be saved, while it can be managed successfully using vital pulp therapy showing healing and maintained vitality of the remaining pulp (30–34). A suggestion of new terminology like "partial irreversible pulpitis" was made to be a closer representation of the histological status of the pulp. New classifications of pulpitis based on clinical symptoms were also introduced (27, 28) in an attempt to align the new treatment modalities more closely to pulpal condition as reflected by patients' symptoms and responses to pulp testing. While these classifications are probably very beneficial in expanding the operator's knowledge and understanding of the continuum of pulpal disease and awareness of the applications of the new procedures of vital pulp therapy, they may show some overlap from a clinical point of view and may allow for some confusion for the unexperienced, and the same limitations of our diagnostic tests and subjectivity of responses remain. One recent study (35) has evaluated the usefulness of using the new classification suggested by Wolters et al. (27). In this study, the new classification was compared to the currently used classification (36) in symptomatic cases of deep caries managed with partial pulpotomy. Cases where the pulp was not exposed were excluded from the study. The study reported a prognostic potential of the new classification as a significant difference in the outcome of mild pulpitis cases compared to severe pulpitis ones. Only 5 cases were diagnosed with severe pulpitis (new classification) out of all 23 cases diagnosed with irreversible pulpitis according to the current classification while one case of mild pulpitis category belonged to the irreversible pulpitis cases. Further studies are needed to evaluate this new classification and possibly fine-tune the categories suggested in relation to the outcome of treatments and the gold standard, the histopathological status of the pulp.

Since most studies (21–23) show no correlation of signs and symptoms to the histopathological status of the pulp so far, except for the study by Ricucci et al. (25), it may be more constructive to focus on promoting recent advances as new treatment modalities for each diagnostic category as was implemented by the recent guidelines of the American Association of Endodontists (14) with the understanding that the reversibility of pulpal disease will depend on the management and possibly removal of the affected part of the pulp, in addition to the expected status of the pulp. The publication resulting from the consensus conference committee which has been endorsed by the American Association of Endodontists (14) is currently the most relevant for nomenclature (36). This allows for standardization of case reporting in clinical studies, better comparisons in longitudinal studies, easier meta-analysis performance and easier understanding of evidence on behalf of the readers.

Removal of caries

Deep caries management poses a significant challenge to the practitioner especially if asymptomatic. The aim should be set to maintain pulpal vitality, inactivation of the caries activity, preservation of tooth structure, restoring the tooth back to function and avoiding the restorative cycle to prolong tooth survival for as long as possible (37). In an operative option of caries management where caries should be removed, the practitioner is faced with the dilemma of the extent of caries removal. Various levels of caries removal have been described in the literature, which can be classified into three groups according to a consensus report (37, 38).

- Non-selective caries removal (too hard dentine): All softened dentine is removed until only hard dentin remains in all parts of the cavity and the tooth is restored permanently.
- Selective caries removal (too firm or soft dentine): Caries is removed until hard dentin is reached in the periphery of the lesion and dentine which appears softened and still cuttable by excavators towards the pulp. After selective caries removal, a definitive restoration is placed immediately.
- Stepwise caries removal (in two visits): This treatment is performed in two sessions. In the first session, caries is removed in a selective approach and restored temporarily. After 6–12 months, the cavity is re-accessed, and residual caries is removed completely followed by definitive restoration. Therefore, this treatment approach should be considered a complete caries removal technique but in two visits (39).

In order to follow the approach of selective caries removal or stepwise caries removal; the consensus report (37, 40) recommends the use of magnification to be able to assess dentine colour, consistency and wetness, use of aids like dyes and caries detectors to help in caries excavation, use of isolation to manage any pulpal exposures should it happen having a proper pulpal diagnosis (should be asymptomatic or reversibly inflamed pulp), and use of sharp instruments for caries excavation having a good bonded restoration of the tooth to avoid leakage. In the European Society of Endodontists Guidelines, it is noted that cases amenable for selective or stepwise caries removal should present as deep caries (caries reaching the inner quarter of dentine) with a well-defined remaining rim of dentine between caries and pulp (13).

The aim of both the selective and stepwise caries removal is avoidance of pulpal exposure to avoid a perceived reduced overall survival and prognosis of the tooth (41–43). Case selection in both approaches includes cases that are asymptomatic or those with minimal symptoms of reversible pulpitis. No periapical changes or periodontal involvement are included in the cases treated. Participating patients are usually young patients with a mean age usually less than 18 years old.

The depth of caries in included cases is usually >1/2 of the dentine thickness, but it varies between studies. The remaining carious dentine was managed either by calcium hydroxide lining, glass ionomer lining/base, and resin-modified glass ionomer lining followed by a restoration. The clinical success obtained in these studies is not the same as that in clinical practice due to the standard setting and specific prognostic factors in the studies reporting the success rates (44).

The stepwise caries removal aims at reducing the microbial load and removing the necrotic demineralized dentine in the first visit while avoiding pulp exposures. After providing a proper temporary seal, the remaining microbial load was reduced and shifted towards an arrested caries microbiota (45–47) and demineralized dentine remineralizes or hardens (43, 47). Tertiary dentine formation driven by the reduced microbial load and proper seal was also demonstrated in some studies aiding in reducing the risk of pulp exposure on re-entry and removal of the remaining carious dentine (47). In clinical studies comparing stepwise caries removal to non-selective (complete one step) caries removal, a higher risk of pulp exposures was noted in one-step non-selective caries removal compared to stepwise caries removal (43, 48, 49). This risk was further reduced by 70% when stepwise caries removal was to soft dentine (50). While the Bjørndal et al. (43) study showed a higher risk of loss of pulp vitality at a one-year follow-up time in the case of non-selective caries removal compared to the stepwise caries removal, the study by Leksell et al. (49) showed no difference at around 43 months follow-up time. The difference in results could be attributed to the difference in caries depth included in the studies and the remaining dentine thickness as a result. In the study by Bjørndal et al. (43), they included caries extending 75% of dentine depth with a well-defined radio-dense zone of dentine between the caries lesion and the pulp. Leksell et al. (49) described included cases as deep caries with expected pulp exposure if completely excavated. The thickness of the remaining dentine after completion of caries excavation is a key factor in pulp response (5, 6, 11, 51). Pulp vitality assessment in both studies was either vague (43) or not mentioned (49) which could also affect the result of pulpal vitality at the follow-up appointment. In addition, Bjørndal et al. (43) included patients of an older age group compared to Leksell et al. (49). Younger pulps are expected to have better healing ability than older ones. In a further follow-up study at 5 years, Bjørndal and colleagues showed higher success in maintaining pulpal vitality in the stepwise caries removal group (60.2%) compared to non-selective caries removal (46.3%) (48).

Some disadvantages are expected from the stepwise caries removal. Loss of patient compliance with multiple appointments, added discomfort, added cost and loss or failure of temporary fillings and pulpal complications have been reported in clinical studies (52–54). Based on the results of

several microbiological studies showing reduced bacterial load in carious dentine following sealing the lesion (41, 46, 55–57), it was then suggested to apply partial caries removal (selective caries removal) without the need for re-entry and restoration of the tooth permanently (41, 42), thereby avoiding the disadvantages of stepwise caries removal technique.

Clinical studies comparing selective caries removal and stepwise caries removal showed less risk of pulpal exposure, less discomfort and reduced cost (53, 54, 58, 59). In a randomized clinical study comparing stepwise and selective caries removal where the operators and statistician were blinded to the approach applied, the success in maintaining pulpal vitality was higher in the case of selective caries removal compared to stepwise caries removal (53). This was attributed to the fact that a significant number of patients did not return for the second visit in case of stepwise caries removal increasing the risk of pulpal complications. When comparing only those who completed their stepwise caries removal procedure, success at a three-year follow-up was 88% compared to 91% of partial caries removal that was not statistically significant (53).

It should be noted, however, that in all studies of selective and stepwise caries removal, there is a lack of definition and standardization of the caries removal end point (and the remaining volume of residual caries) and in most studies, a clear description of techniques of determining dentine hardness was not mentioned (54), which can introduce some unaccounted bias. In fact, studies showed a moderate to high risk of bias and mostly are of low quality in several systemic reviews and meta-analysis on this topic (50, 58, 60). The limited number of cases included in these studies in relation to the very common disease (dental caries) makes the studies limited in their external validity. Bias in reporting failures and a few other design limitations undermine the study's quality. A recent Cochrane systematic review (38) evaluated the evidence regarding caries management in both permanent and primary dentition. Studies evaluating deep caries management techniques in permanent teeth showed a high risk of bias mainly due to the lack of blinding of participants and assessors. Low certainty of evidence in most studies was also reported, except in studies comparing stepwise caries removal to non-selective or complete caries removal. In these studies, the certainty of evidence was deemed moderate. Furthermore, the definition of deep caries in the included studies varied to some extent. Despite the above mentioned limitations, this Cochrane review still recommended selective caries and stepwise caries removal techniques in management of deep caries (38).

Both newly proposed approaches of deep caries removal were conducted mainly on deep caries with a remaining rim of dentine between the advancing front of caries and the pulp. Standardization of depth of caries assessment preoperatively was only mentioned in studies of Bjørndal's group (43, 48). The main goal of such approaches is to avoid pulpal

exposures that are often cited as a negative prognostic factor based on the results of often-cited studies (43, 61). In the retrospective study (61), non-selective caries removal was performed by supervised dental students under rubber dam and pulp exposures capped with setting calcium hydroxide followed by a base of zinc phosphate cement or glass ionomer cement. Only 30.7% of the cases could be followed up, and about 49 out of 123 cases were not actually examined but only notes from the patient's chart/dentist showed loss of the tooth or endodontic management with no attempts to determine the reason for postoperative management. Cases of questionable pulpal responses to vitality testing and/or clinical symptoms without any radiographic changes were rated questionable. In addition, some cases did not receive the permanent filling and were only temporized. The follow-up time was 5 years and 10 years postoperatively. The failure rate reported was 44.5% at 5 years and 79.9% at 10 years. Indeed, direct pulp capping shows a declining success rate with time and its success depends on the coronal seal provided (62–66), and the material used for pulp preservation with mineral trioxide aggregate and hydraulic calcium silicates showing better outcome in direct pulp capping procedures than calcium hydroxide (63, 66, 67).

It should also be acknowledged that pulpal inflammation increases in severity the deeper the caries lesion (21, 23, 68). Usually, inflammation would be localized to the area beneath the advancing front of the caries lesion and normal and healthy pulp is not uncommon in other distant areas (2, 68, 69). This means that the cariously exposed pulp is severely inflamed and possibly shows areas of necrosis and micro-abscess formation just in the vicinity of the caries lesion. Direct pulp capping without removal of the damaged part of the pulp (the irreversibly inflamed part) is not a predictable treatment in terms of pulpal survival. Partial or complete pulpotomy may be a better option to leave healthy pulp under the pulp-capping material capable of healing and surviving (68). Leaving soft dentine covering the pulp does not necessarily avoid progression of the pulpal inflammation or allow for healing. The remaining pulpal inflammation was confirmed in cases of selective caries removal along with the remaining contamination of the leathery/firm dentine (70). The authors concluded that the presence of potentially arrested caries does not necessarily mean that the bacterial infection is absent or under control (70). This can explain the declining pulp survival rate after selective or stepwise caries removal with time (41–43, 48, 53, 71–73). The studies reported by Bjørndal's group showed pulpal success rate of 74.1% out of 143 cases at 1 year for stepwise excavation compared to 60.2% out of 118 cases at 5 years follow-up with a drop-out rate of about 24%. Selective caries removal showed a 100% success rate of 22 out of 32 cases at 14–18 months review (71) while at 36–45 months, two cases showed restorative failures necessitating endodontic management, two

quit the study, and one could not be contacted, the remaining 24 reviewed cases showed normal responses to pulp cold tests (42).

Management of the dentine substrate

Depending on the caries removal strategy, the tooth will be left with either caries infected dentine, which is the type of substrate left after selective caries removal or the first stage of the stepwise caries removal or caries-affected dentine which results from the total removal of caries. If there is a breach in the dentine layer, pulp management will be necessary.

The caries removal strategy employed will determine the dentine to material interface. There is still a debate regarding caries removal approach, and excavation criteria should be validated against clinically relevant outcomes (74).

The microstructure of the dentine varies across a carious lesion as the mineral content significantly decreased across the zones with the most demineralized zone also containing considerable residual mineral (75). Another parameter that needs to be considered is the presence of bacteria in the lesion which leads to pulpal changes. There are very little opportunities for remineralization if the overlying enamel acts as a barrier (76). Most of the large carious lesions still have intact enamel which prevents mineral exchange with saliva and other sources of mineral that may help with the remineralization. Although there is a significant reduction in lactobacilli in the residual carious dentine after selective caries removal, the lesion still retains a significant volume of bacteria even after calcium hydroxide therapy (77). The metabolic activity of the biofilm in dental caries is the key to effective management (78). If the lesion is sealed, the availability of the nutrients will be reduced, and the chances of caries progression are low. Furthermore, it has been shown that the treatment received changes the microbiota. Thus, the choice of materials used to manage the carious lesion is important (77). However, the presence of bacteria is linked to pulpal pathosis.

In cases without pulpal exposures, the presence of bacteria and the specific dentine microstructure require dentine preparation prior to dressing with a suitable pulp preservation material. Both position statements (13, 14) suggest the use of sodium hypochlorite with the ESE statement (13) also suggesting the use of chlorhexidine; this was only suggested to be used over the exposed pulp rather than caries infected and affected dentine. The dentine substrate is infected thus suggesting that preparation with an antimicrobial agent prior to material placement will be beneficial.

The use of sodium hypochlorite on the caries-affected dentine improves the adhesion of hydraulic calcium silicate cements (79). The use of ethylene diamine tetra-acetic acid also enhances the interaction of the materials to the dentine

at the interface (80). Bonding to sound dentine yields better results compared to caries-affected dentine (81). Etch-and-rinse adhesives performed better than self-etch adhesives when applied to caries-affected dentine (81). Sodium hypochlorite has been used extensively in endodontics to reduce the microbial load. It is assumed that it will be effective in caries management. The use of sodium hypochlorite and EDTA over caries-affected dentine prior to material placement improves the tooth to material interface and bonding (79, 80).

Management of the pulp

When treating carious lesions, the primary goal is to preserve a healthy pulp (82) as this ensures the tooth's long-term survival (37, 83). The effect of the carious process on the dental pulp has been reviewed (84–86). Once the carious process has involved the dental pulp, this may necessitate the amputation of part of the pulp with a dressing of the wound and the use of a liner material (87). The thickness of the remaining dentine influences the pulpal response (5, 6, 11, 51).

The AAE position statement for management of the vital pulp (14) contrasts starkly with the ESE statement (13) as the AAE suggests the removal of all caries to the extent of investigating the pulpal status while the ESE guidelines recommend a selective caries removal or stepwise caries removal technique. Regardless of the size of the carious lesion, pulpal changes are present (2, 68, 70) with more severe pulpal inflammation with increasing depth of caries. A study attempted to link the radiographic depth of caries to the histological pulp status in cases of deep and extremely deep caries as seen radiographically (10). Out of 68 extracted molars of 12–18 years old patients, only 46 cases were assessed histologically. Partial necrosis (indicating irreversible pulpitis changes) was noted only in extremely deep caries. The inflammatory infiltrate in radicular pulp was noted also only in extremely deep caries. No clear information was given regarding the inflammatory status of deep caries cases. In addition, it is well known that carious lesions are usually larger or deeper clinically than shown on radiographs, which should be taken into consideration when applying the radiographic caries depth assessment.

From the molecular biology point of view, the presence of metalloproteinases-9 that are expressed only when tissue breakdown in the pulp occurs seems to be a good indicator and a promising tool to assess the severity of inflammation (88, 89). Therefore, the presence of MMP-9 may be a good indicator of the level of pulpal inflammation and help in proceeding with the relevant pulpal treatment. Further research is needed for a chair-side test to help in case selection for different modalities of vital pulp therapy. It should be noted that MMP-9 levels could be measured from the blood of an exposed pulp and indicate pulpal status more reliably than MMP-9 collected from dentinal tubules (88).

Once the pulp tissue is exposed, it requires management to reduce bleeding as well as the microbial load. The use of sodium hypochlorite (13, 14) and chlorhexidine (13) to manage the pulp will lead to remnants of the solutions on the dentine and in contact with the pulp preservation material. Sodium hypochlorite is effective in the reduction of haemorrhage (90–92) but is not compatible with the use of mineral trioxide aggregate if the MTA contains bismuth oxide. Tooth discolouration has been shown to be an unwanted sequela to successful vital pulp therapy using MTA (93, 94). Although not regarded as a failure, the discolouration will necessitate further intervention. The material and tooth discoloration induced by bismuth oxide in contact with dentine (95) and sodium hypochlorite (96, 97) is well documented with the discoloured bismuth complexes migrating from the material to the tooth structure within weeks of placement (98).

The use of chlorhexidine may have potential beneficial effects in reducing the microbial load in the pulpal tissues. Chlorhexidine has been added to MTA to enhance its antimicrobial activity (99, 100) but unfortunately exhibited adverse biological effects with cell apoptosis (101) and impacting negatively on the calcific bridge formation (102). When used as a final irrigating solution in root canal therapy (103–105), chlorhexidine also exhibited an enhanced antimicrobial action but was detrimental to the cell growth and differentiation (104) and also affected the physical properties of hydraulic calcium silicate-based materials (103, 106). Due to this, chlorhexidine cannot be recommended for the management of the dental pulp.

Dressing the dentine

The dentine requires dressing with the placement of a suitable material in deep carious lesions with and without carious exposure. In cases where no exposure to the dental pulp has occurred, production of reparative dentine and remineralization of demineralized dentine occurs with the use of a cavity liner (87). The sealing of the cavity limits the nutrition of the residual bacteria (107–110) with the tertiary dentine reducing the permeability of the dentine and limiting pulpal substrates for the residual bacteria to use as nutrients (108, 111).

When the remaining dentine thickness is less than 0.5 mm, the use of a liner material is necessary and calcium hydroxide lining has been recommended (112) as at the time of these studies, hydraulic cements were not available. A clinical randomized study is being undertaken to investigate the most appropriate liner in cases managed by selective caries removal (113). Calcium hydroxide is currently not indicated for use in any of the clinical guidance, except in the British Endodontic

Society Guide (114). The guidance given in the latter document is based on expert opinion using outdated scientific evidence. The clinical studies comparing MTA and calcium hydroxide (63, 115–120) indicated the better performance of MTA when compared to calcium hydroxide. Although the quality of evidence of the studies investigating the use of calcium hydroxide liner is moderate to low, it was shown that the calcium hydroxide did not influence the clinical success of treatment for deep caries lesions (110).

While glass ionomers have not been recommended for indirect pulp capping by the AAE (14), the ESE position statement (13) suggests that both glass ionomers and hydraulic calcium silicates are suitable for dressing the dentine. This is based on two clinical studies (28, 121) that have found no difference between the outcomes of indirect pulp capping using either glass ionomer (Fuji IX, GC Europe, Leuven, Belgium) or Biodentine (Septodont, Saint-Maur-des-Fosses, France). In these studies selective caries removal was employed and the outcomes of treatment were better with Biodentine when using cone beam computed tomography (121). Proper glass ionomer use necessities the use of cavity conditioning with a weak acid. Acid etching caused inflammatory changes that were more severe in deeper cavities (5, 6) and therefore cannot be undertaken in a deep cavity thus limiting the use of glass ionomers in deep carious lesions in close proximity to the dental pulp regardless of the ESE recommendations.

The AAE guidelines (14) suggest the use of hydraulic calcium silicate cements that are referred to by various names. Regardless of this and the numerous clinical studies showing the efficacy of using MTA (63, 115, 117–120), it should be noted that the use of MTA containing bismuth oxide is contraindicated for use due to the tooth discolouration as indicated earlier. Furthermore, the setting time of MTA is over 3 h, and this will compromise the adequacy of the tooth restoration as discussed later.

The research undertaken indicates that the use of fast-setting hydraulic calcium silicate cement which is bismuth oxide free such as Biodentine is the best treatment strategy. The research investigating the use of Biodentine as a pulp preservation material (93) indicates that Biodentine has a clinically acceptable setting time which is shorter than other hydraulic calcium silicate cements (122–124), high pH and calcium ion release which is initially high but drops over time (122, 123, 125, 126). Tooth discolouration has never been implicated with the use of Biodentine (127–131)- despite what is stated in the British Endodontic Society Guide (114).

If there is a breach and the dental pulp is exposed, the material used to dress the dentine in cases of indirect pulp capping needs to be effective in managing the dental pulp. Partial and full pulpotomy using calcium silicates showed very high success rates and predictable results (29–35, 64, 132). When tested in contact with human dental pulp stem cells, to assess cell proliferation, viability mineralization potential and morphology, Biodentine exhibited adequate biological characteristics (133, 134) even when employing advanced cell culture models (135). The cells adhered well to the material surface (136) and the material extracts exhibited cell proliferation and expression as well (137–139). A calcific bridge was shown in animal studies employing Biodentine as pulp preservation material (140–142).

The interface of Biodentine with the dentine has been described as having an alkaline etch with the formation of a mineral infiltration zone (143). This view has been debated in other studies where no mineral transfer has been observed at the tooth to material interface (80, 144). A recent study investigating the interaction of Biodentine and a glass ionomer cement on caries-affected dentine verifies the remineralization potential of both material types and suggests the efficacy of using Biodentine as part of a minimally invasive operative dentistry strategy in caries management (145). Although Biodentine has been tested quite extensively, a study investigating the interaction of a material with caries-affected dentine in extracted teeth without any microbiology testing and also over a short period of time can hardly be used for a clinical recommendation.

Tooth restoration

The adequate seal of the tooth is important for the success of vital pulp therapy (62, 63, 68, 132). The sealing of carious dentine results in lower levels of infection than traditional dentine caries removal thus it is important to provide an adequate restoration (146).

One of the key properties of hydraulic cements is their interaction with the clinical environment. This is more challenging when the material with a long setting time such as MTA is used when the tooth is sealed on the first visit. Such a procedure necessitates the layering with a fast-setting material such as glass ionomer cement (147). The use of glass ionomer and zinc oxide eugenol-based materials is contra-indicated over MTA due to material interaction which is detrimental to the MTA as the zinc in zinc oxide eugenol-based material interferes with the MTA setting and the acidity of the glass ionomer causes cracks at the material-to-material interface (148).

The use of fast-setting materials is thus indicated. Materials such as Biodentine are strong enough (122) to be used on their own over the pulp and serve also as a temporary filling material (149). Clinically, bonding of resin composite to Biodentine may be challenging. Biodentine has a hydrophilic surface while resin composites and their associated adhesive systems are hydrophobic, or mildly hydrophilic, respectively. Furthermore, the application of acid etch on the Biodentine surface has been shown to disrupt the material surface and result in the reduction of microhardness (150). The *in vitro* data showing

the bonding of resin composites to Biodentine has shown weak bond strengths. Therefore, bonding to Biodentine can be considered a compromise because the interface may include gaps resulting from the difference in moisture affinity of the two materials. There are conflicting data on the best method to bond a composite resin to Biodentine with some favouring total-etch (151) and others the use of self-etching primers (152). Most of the adhesives tested were adequate (153). Reduced acid-etching times avoided the detrimental effect on the material and did not result in deterioration of the bond between the materials (154). Delaying the restoration has not shown to be of added benefit (155–157). Methacrylate-based composites were better than silorane-based composites and glass ionomer cements (158). The type of adhesive system and restoration time affect the bond performance and ultra-morphological interface between composite adhesive restoration and hydraulic calcium silicates (159).

Double layering has also been considered. While glass ionomer is not indicated as it is acidic and will disrupt the interface and result in reduced bond strength (151, 160), resin-modified glass ionomer can be considered for use over the hydraulic cement and this can be etched fully when the composite restoration is placed (161).

Although self-etching adhesive systems may be useful and safe when applied on dentine, in contrast, persistent inflammatory reactions as well as delay in pulpal healing and failure of dentine bridging have been observed in human pulps capped with bonding agents (162). Vital pulp therapy using acidic agents and adhesive resins is contraindicated (162).

Restoration durability, sealing ability and survival are of paramount importance for pulpal survival and tooth function. Bonding systems deteriorate over time (163–165), and this results in a decline in pulpal survival (51). This, together with coronal microleakage and additional caries challenge were not addressed in the literature. Reduced bonding strength to caries infected or affected dentine was reported (166, 167). Therefore, in selective and stepwise caries removal, caries is removed completely at the periphery of the lesion and the dentine-enamel junction with caries selectively removed at the pulpal walls. This allows for proper bonding of the restoration and provision of a proper seal. At one year follow up (43) showed no difference in restoration survival between stepwise and non-selective caries removal.

Effect of stepwise and selective caries removal on pulpal health

While there are some clinical studies showing successful results of selective caries removal, there is a clear lack of histological studies to assess the pulpal response to both stepwise and selective caries removal and their biological success. In two histopathological studies, varying degrees of pulpal inflammation were noted in asymptomatic cases managed by selective caries removal to firm dentine and
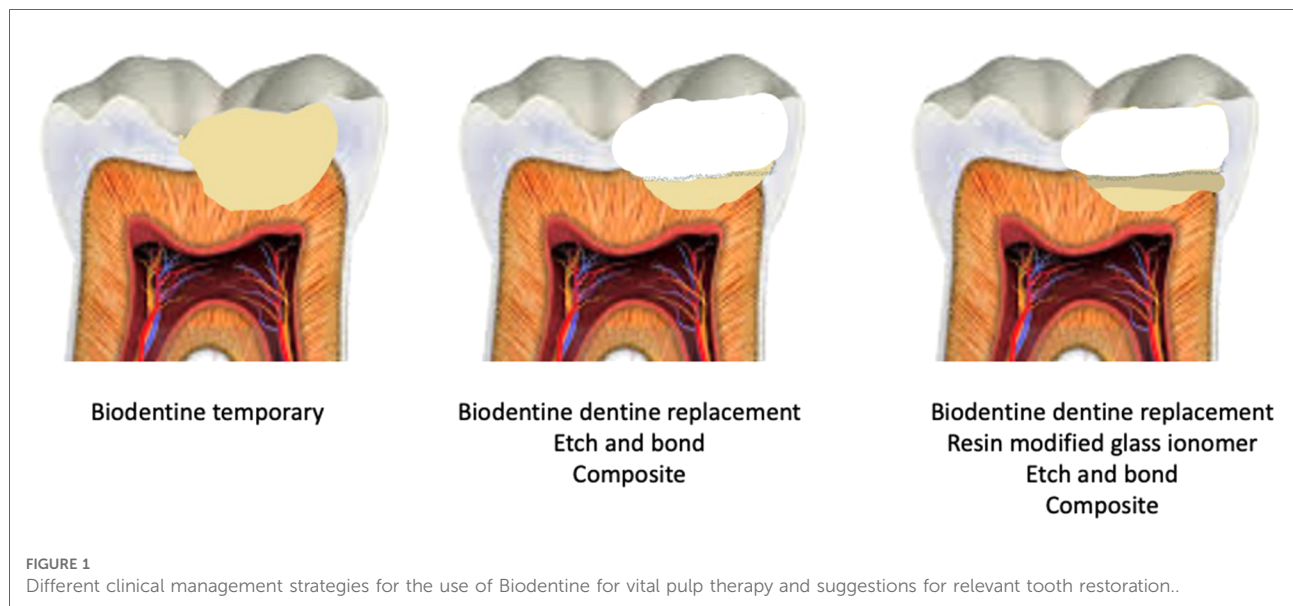
restored with adhesive restoration that responded normally to pulp testing after 15 months follow up (68) or 1–9 months follow up (70). Similar inflammatory status could be discerned in treated and untreated cases of similar caries depth (70). It is speculated that this inflammation is unlikely to subside if bacterial infection is not completely removed albeit the short follow-up time (one month) in some cases (70). In contrast, healed pulps with only a reduced number of odontoblasts, tertiary dentine and some segregated calcifications in cases restored heavily but with all soft caries removed and good coronal seal provided was shown (68). The pulpal wall management in both papers mentioned was either by application of calcium hydroxide liner, a form of calcium silicate material, or just an adhesive restoration placed immediately without a base or liner. Histopathological studies of pulpal status and healing after selective caries removal to soft dentine and after stepwise caries removal are lacking. It should be mentioned that a low-grade inflammation is crucial to induce healing (168, 169). However, the threshold between "beneficial" inflammation and destructive one has never been identified in histological studies; possibly because tissue healing and destruction are driven by molecular ques secreted by the same inflammatory cells that are not reported in histopathological studies (169, 170). However, the pulp inflammation can be sustained by remaining bacteria in the dentine by leaching endotoxins preventing regeneration or healing to take place (171). Further studies using molecular biology are needed to clarify this point with regard to selective caries removal technique.

Currently most studies showed lack of correlation of pulpal symptoms to the histological condition of the pulp (21–23) with exception of one recent study (25). In addition, a good possibility of lack of symptoms in pulpitis cases was reported (172) along with clinically high success rates of calcium silicate pulpotomy procedures, it makes clinical sense to remove caries completely and assess pulpal condition and manage it accordingly once exposed. It should be mentioned that there is a lack of properly designed and randomized studies comparing selective caries removal and partial or complete pulpotomy in cases of deep caries.

Clinical significance and suggested protocol

Based on the scientific literature assessed in this narrative review it can be concluded that the ideal clinical protocol for the management of vital mature carious teeth is the following

1. Complete caries removal is recommended when managing deep caries to allow for proper assessment of pulpal status.
2. Dentine cleansing with sodium hypochlorite and ethylene diamine tetra-acetic acid

FIGURE 1
Different clinical management strategies for the use of Biodentine for vital pulp therapy and suggestions for relevant tooth restoration..

3. Management of the dental pulp if necessary. The use of sodium hypochlorite reduces bacterial load.

4. Placement of a fast setting, bismuth oxide-free hydraulic calcium silicate cement. If strong enough it can be used as a temporary restorative material

5. Selective etching with a 5 s etch of the hydraulic calcium silicate pulp preservation material and a total etch of the dentine and enamel. The enamel etch can be undertaken prior to the placement of the hydraulic cement to avoid the washing out of the material.

6. Application of a dentine bonding agent or use of a resin-modified glass ionomer over hydraulic cement and placement of a composite resin restoration.

The clinical options are illustrated in Figure 1.

Conclusions of narrative review

Pulpal diagnosis remains elusive and necessitates further research and studies to improve its accuracy and to reproduce the correlation to the actual histopathological status. Consideration should be given to promote new treatment modalities for reversible and irreversible pulpitis allowing for healthy pulp preservation. Significant debate can be elicited about deep caries management. Even though selective caries removal may reduce the risk of pulpal exposure, cases with deep caries should be managed by complete non-selective caries removal which will allow for pulpal management if needed and a more predictable outcome can be expected when using the new materials and treatment modalities of vital pulp therapy. Hydraulic calcium silicate cements are the materials of choice for the management of the vital pulp.

Modified versions with enhanced physical properties and bismuth oxide-free are superior to other formulations.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Author contributions

Both authors have contributed equally to the development, writing and finalising the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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