Monika Marending
Thomas Attin
Matthias Zehnder

Clinic for Preventive Dentistry, Periodontology and Cariology, University of Zürich

CORRESPONDENCE
Prof. Dr. med. dent. Matthias Zehnder, PhD
Klinik PPK, Zentrum für Zahnmedizin
Universität Zürich
Plattenstrasse 11
CH-8032 Zürich
E-mail: matthias.zehnder@zzm.uzh.ch

SWISS DENTAL JOURNAL SSO 126: 1007–1017 (2016)
Accepted for publication: 5 February 2016

Treatment options for permanent teeth with deep caries

KEYWORDS
caries,
excavation,
pulp

SUMMARY

The goal of this narrative review was to summarize and compare treatment options for permanent teeth carious lesions that are radiographically close to the pulp chamber. Thanks to adhesive restorative materials, minimally invasive approaches are possible. In this context, the old question arises as to whether caries must be excavated completely, i.e., down to hard dentin, or whether it could be advantageous to leave some soft dentin, or even merely seal the whole lesion. To answer this question, the microbiological aspects of the lesion must be considered, along with the immunological response in the dental pulp, with the concurrent possible negative outcomes for the patient. Both aspects are considered in this review, and clinical studies comparing different treatment modalities are discussed. Situations in which calcium silicate cements could be advantageous over the gold standard calcium hydroxide preparations for covering the dentin/pulp wound are also discussed.

Introduction

Minimally invasive or lesion-oriented caries treatment has revolutionized restorative dentistry. Thanks to adhesive materials, a minimal destruction of healthy dental tissue following caries management is possible (Frankenberger & Blunck 2012). This has renewed interest in minimally invasive concepts also in teeth with deep caries, i.e. those with a lesion that reaches close to the pulp space on the radiograph. These procedures, aiming to preserve tooth vitality, shall be discussed in the current discourse.

The underlying ideas of minimally invasive caries excavation are not necessarily new. Different excavation methods to avoid pulp exposure were suggested a long time ago (Tomes 1859, Bonsack 1952). However, incomplete excavation concepts have neither become established in teaching institutions, nor in dental practices (Schwendicke et al. 2013b). Their achieved success rates vary considerably (Aguilar & Linsuwanont 2011, Schwendicke et al. 2013a). The classical "invasive" approach, on the other hand, is to excavate caries fully, i.e. to hard dentin. It is clear that when the pulp is not exposed during such complete caries excavation, there is a high probability of treatment success, i.e. continuing vitality of the pulp (Fitzgerald & Heys 1991). In case of pulp exposure, however, the question arises as to whether to cap the exposed pulp or perform a root canal treatment straight away. A correctly executed, complete root canal treatment (pulpectomy) shows stable results and non-infectious conditions in longitudinal studies (Ng et al. 2007). With the introduction of rotating nickel-titanium instruments, novel methods for filling the root canal, the surgical microscope, and accurate electronic length measurements, the quality of endodontic treatment has improved (Dahlström et al. 2011). Nevertheless, endodontology remains one of the most technique-sensitive fields in dentistry. It would appear that relatively few dentists seek endodontic training or adopt evidence-based

findings in their daily procedures (Dahlström et al. 2015). A root canal treatment is complex, time consuming, and therefore at least initially, more expensive than a simple filling. Cross-sectional studies from all over the world point to technically insufficient endodontic treatment of the general population (Pak et al. 2012). Yet, in a tooth with pulp exposure subsequent to caries excavation, the cost-benefit ratio between a capping procedure and root canal treatment could still be balanced or even favor primary pulpectomy, depending on the calculation model and the clinical circumstances (Schwendicke & Stolpe 2014). For the vitality-maintaining treatment of deep caries, follow-up treatments are necessary at shorter intervals than for endodontic treatment. Such calculations, however, are not valid for adolescents' teeth, in which the roots are not yet fully developed. Completed root formation is a prerequisite for pulpectomy after pulp exposure (Krakow et al. 1977). As an alternative to pulpectomy, the mere removal of the coronal pulp (pulpotomy) is being discussed as the definitive treatment (Simon et al. 2013). In terms of materials, newer studies suggest that direct pulp capping with calcium silicate cements (Portland cement or Mineral Trioxide Aggregate [MTA]) yields better results than the established technique using calcium hydroxide (Hilton et al. 2013, Mente et al. 2014). Contrary to calcium hydroxide, calcium silicate-based materials not only disinfect, but also form a bacteria-tight seal; they also induce calcium-phosphate precipitation in their vicinity (Torabinejad & Parirokh 2010, Zhang et al. 2009).

The purpose of this review was to critically evaluate treatment options for permanent teeth with caries appearing radiologically close to the pulp chamber (Fig. 1). The focus was on two issues: 1) the type of intervention and 2) the influence of the materials applied to the dentin and pulp exposure. The present review provides an overview of the common treatment methods, discusses studies, and deals with scientific, biological and clinical issues. Particular focus is placed on aspects which have not yet been sufficiently researched. Because the present problem is too complex to be dealt with by means of systematic review (Bergenholtz et al. 2013), this article approaches this topic from a narrative angle. To this end, modern treatment concepts are put in a historical context.

Materials and methods

For this literature review, the following Medical Subject Headings (MeSH) were used to conduct a search in the Medline database: "Dental Caries", "Dental Pulp", "Dental Pulp Capping", "Dental Pulp Exposure", "Dental Pulp Devitalization", "Dental Pulp Necrosis", "Dental Pulp Test", "Pulp Capping and Pulpectomy Agents", "Pulpotomy". These key words were connected with "and" or "or" according to context. In addition, the following terms were entered: "Stepwise excavation" and "Caries excavation". Articles in English, German and French with abstracts in English were taken into account. The literature lists of the articles found were examined manually and checked for further relevant studies. The same method was applied to textbooks and overview articles. The attempt was made to juxtapose the history and developments of each of the following topics.

Prerequisites for maintaining pulp vitality

Caries is the most common disease of the hard dental tissues and one of the most widely spread microbial diseases in general (Bowen 2015). With increasing lesion depth, the risk of pathological changes in the pulp increases accordingly (Reeves & Stanley 1966). The basis of all minimally invasive treatments in cariology and endodontology is the concept that the inflammatory conditions we prevent and/or treat are caused by bacteria in the wrong niche (Kakehashi et al. 1965). Vital pulp tissue is not essentially infected, whilst bacteria accumulate in already necrotic areas of the pulp (Langeland 1987). Thus, teeth that show histologically necrotic and bacterially colonized pulp tissue are classified as irreversibly damaged (Seltzer et al. 1963, Guthrie et al. 1965).

Various authors studied the connection between penetration depth of the bacteria and pulpal damage. First signs of inflammation were even documented for lesions only affecting the enamel (Brännström & Lind 1965), but as long as the caries does not penetrate at least half the depth of the dentin, there is no significant change in the pulp in most cases. If the remaining intact dentin is at least 0.5 mm thick, the underlying pulp can be considered non-infected (Reeves & Stanley 1966, Langeland 1987). A marked increase in pathological pulpal changes occurs as soon as microorganisms penetrate into the tertiary dentin (Reeves & Stanley 1966). Under deep carious lesions, a chronic inflammatory exudate with lymphocytes, macrophages, and plasma cells can be found in the pulp (Björndal & Mjör 2001). Such a pulpitis is not necessarily associated with pain (Seltzer et al. 1965). Alternatively, the pulp can show already infected tissue, necrotized by neutrophilic granulocytes (Guthrie et al. 1965, Langeland 1987). It is likely that the inflammatory reaction in the pulp is modulated by the composition of the microbiota (formerly "flora") of the carious lesion (Hahn et al. 1991, Hahn & Liewehr 2007). This essential detail is often overlooked. Currently, there are no diagnostic methods to identify the microbial composition of the infected dentin. Common methods of detection that illustrate the infection in the dentin are non-specific and do not differentiate between different kinds of bacteria (Lennon et al. 2006).

The discussion of merits and dangers of complete caries excavation have meant that even established authors can draw false conclusions. The assumption was that the biofilm covering the lesion or found in the outer layers of the lesions was mainly responsible for caries progression and should be removed, meaning that removing infected, demineralized dentin is not necessary (Kidd 2004). This assumption disregards the possibility that the pulp adjacent to the carious lesion could be locally irreversibly damaged and thus easily infected via the dentin tubules. This situation in turn inevitably leads to necrosis of the entire pulp and to apical periodontitis (Langeland 1987). The key to the survival of the pulp is not only the degree of infection of the dentin, but also the existing degree of pulpal damage at the time of the intervention is equally important (Tronstad & Mjör 1972). Microorganisms embed themselves in the necrotic parts of the pulp tissue and cause further progression of necrosis via the non-specific immune response. This occurs due to chemotaxis, i.e. molecular attraction of neutrophilic granulocytes which produce proteolytic enzymes, thus causing micro-abscesses (Wahlgren et al. 2002).

Diagnostics for advanced dentin lesions

The clinical diagnosis "reversible pulpitis" is given under the assumption that the pulp can recover from noxious stimuli after their removal (Warfvinge & Bergenholtz 1986, Glickman 2009). If the chances of recovery of the damaged pulp tissue after removal of these stimulus are low, the pulp is considered to be

"irreversibly" damaged. A partial or total excision of the affected pulp is then necessary in most cases. It should be made clear that studies which compare histological images of the pulp with their chances of survival after vital pulp therapy are methodologically impossible. Thus, all studies in which pulpitis is divided into reversible and irreversible by means of histological images are questionable to a certain extent. It is even more dubious whether or not pulpitis can be categorized as reversible or irreversible according to its clinical presentation, due to the lack of pertinent diagnostic tools (Marending Soltermann 2014). Older studies have already shown that a correlation between clinical and histological pulp diagnosis is rather limited (Baume 1970, Seltzer et al. 1963, Johnson et al. 1970, Garfunkel et al. 1973, Dummer et al. 1980). This is especially applicable to teeth without spontaneous pain. Consequently, the terms "reversible" and "irreversible" are not well-founded. However, concerning the diagnosis of "irreversible pulpitis", Ricucci et al. (2014) recently published an article showing that, when using defined criteria, there can be a correlation between the clinical and the histological diagnosis nevertheless. Spontaneous pain was the main symptom; when a tooth with deep caries was spontaneously and chronically painful, in 27 of 32 cases investigated the pulp was infected to a degree that maintaining vitality of the tooth without removing at least part of the coronal pulp (pulpotomy, Fig. 1) was unlikely or impossible. This study clearly suggests that teeth with deep caries and with spontaneous pain need endodontic treatment, but leaves open the question of what to do with teeth that are not painful. The control group in this study was not well selected; only healthy teeth and teeth with minor caries were considered. Retrospective studies on teeth with apical periodontitis show that almost half the affected teeth were never painful, meaning that the irreversible pulpitis existed without coming to the patient's attention (Michaelson & Holland 2002).

Excavation concepts

The literature describes various minimally invasive techniques. The primary goals are stopping caries progression and to (partially) maintain pulpal vitality. The terms used are not standardized and there are considerable differences among the studies concerning the degree of caries removal. Nevertheless, three different concepts can be distinguished (Fig. 1).

1) Caries-sealing method: Caries is only removed from the enamel, leaving caries in the dentin (Jeronimus et al. 1975, Handelman et al. 1976).

2) Partial caries removal: A portion of caries close to the pulp is left. Two different methods are specified:
- stepwise caries excavation: the remaining caries is chemically treated and after a period of temporization for a few months, excavated completely (Bodecker 1938, Sowden 1956);
- indirect capping with an immediately subsequent definitive restoration: the defect is filled with a permanent restorative material (Gruythuysen et al. 2010, Maltz et al. 2012).

From excavating until reaching sound dentin to intentionally leaving some carious dentin, there are other excavation concepts that remove dentin less aggressively than the standard method with the rose bur; namely, the use of non-metal burs for excavation (Boston 2003) or the chemical treatment of caries followed by excavation with manual instruments (Schutzbank et al. 1978, Ericson et al. 1999). These methods may differ slightly or not at all from intentionally leaving caries near the pulp, owing to the similar number of cultivable bacteria left by such approaches (Schwendicke et al. 2015). Thus, the present review does not explicitly focus on these methods. The Hall and ART (Atraumatic Restorative Treatment) techniques are also not further discussed. The Hall technique – which was introduced around the turn of the millennium for primary teeth and later also for permanent teeth – leaves the caries on enamel and dentin untouched and covers it with a stainless steel crown (Innes et al. 2006). The ART technique – which was developed in Tanzania in the 1980s for rural areas in third-world countries for Community Oral Health Workers (COHWs) – cleans a carious lesion with manual instruments only and restores it with a temporary filling material, e.g., glass ionomer cement (Bresciani 2006). In the studies on caries sealing and the Hall technique, only carious lesions reaching no deeper than half of the dentin layer were considered.

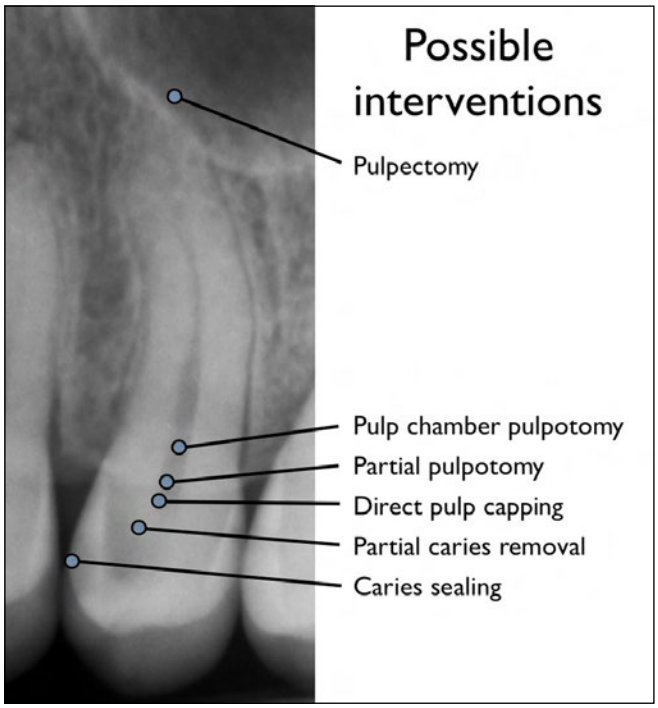

Fig. 1 Intervention options presented for a maxillary premolar with caries showing radiological pulpal proximity.

3) Complete caries removal: In this traditional method, the softened dentin is completely removed. In case of pulp exposure, there are three methods to maintain full or partial pulp vitality:
- direct capping (Glass & Zander 1949, Castagnola & Orlay 1950);
- partial pulpotomy (Cvek 1978);
- complete pulpotomy, also known as pulp chamber pulpotomy (Zander 1939).

For all procedures, the cavity is ultimately treated with a permanent restoration, which ensures good peripheral sealing and prevents further access of microorganisms to substrates in the oral cavity.

Numerous aspects must be considered in terms of the different excavation concepts. It is difficult to estimate whether or not complete caries removal, done in one or several steps, will

lead to pulp exposure both preoperatively and during caries excavation. It is neither known how much tertiary dentin has built up, nor how thick the dentin will be that remains after complete excavation. Finally, it is also not clear in partial caries excavation how much infected dentin will remain (Bergenholtz & Spångberg 2004). These issues are considered in more depth in the following chapters.

1) Caries sealing

In the 1970s, the necessity of caries excavation was called fully into question. In prospective studies, various authors showed that caries activity was stopped under sealed lesions due to the lack of nutrients for the microoganisms in the sealed lesions (Jeronimus et al. 1975, Handelman et al. 1976, Mertz-Fairhurst et al. 1979, Jensen & Handelman 1980, Handelman et al. 1981). Firstly, the clinically and radiologically measured depths of the lesions decreased in the observation period of two to five weeks. Secondly, the existing microorganisms were greatly reduced in number or even eliminated if the seal stayed tight. In a prospective long-term study over a period of ten years with a four-cell study design, Mertz-Fairhurst et al. showed that composite-sealed occlusal caries showed better results (less secondary caries and marginal imperfections) than unsealed conventional amalgam restorations with complete excavation (Mertz-Fairhurst et al. 1998). However, the group with sealed amalgam restorations after complete caries excavation performed significantly better than the two other groups over the ten-years observation period. In this study enamel caries was removed, leaving completely untouched dentin caries. In the aforementioned studies, enamel caries was not removed, rather only etched. Due to the methodological differences, a direct comparison of these studies is not possible. In all studies concerning sealing caries, lesions that affected only half the dentin layer at most were considered. It is thus questionable whether these concepts are appropriate for lesions that are radiologically close to the pulp. Microbiologically, the many asaccharolytic bacteria existing in the deep layers of the dentin lesion represent a disadvantage of this procedure (Hahn et al. 1991); such bacteria survive without the supply of exogenous nutrients, for example, by metabolizing peptides from the dentinal fluid. In a retrospective study, Weerheijm et al. found cariogenic microorganisms in less than 50% of sealed lesions (Weerheijm et al. 1992). Microorganisms seem to persist in deep caries, while they decrease in shallower lesions, often to under the detectable amount (Jeronimus et al. 1975).

Another problem of partial caries removal is that when changing dentists, the existing restoration may be categorized as insufficient and replaced by a new one (Bakhshandeh et al. 2012). In an in vitro study published in 2014, Schwendicke et al. tested various substances for marking carious dentin. The idea was to enable a differentiation between inactive and progressing lesions during radiological check-up examinations. However, further clinical studies are necessary to test the validity of such an approach (Schwendicke et al. 2014). In the studies on sealing, only class I lesions were included. From studies on partial caries removal, it is evident that multiple-surface lesions show worse long-term results than class I lesions do (see below). In adults, interproximal lesions are much more common than occlusal defects (Varrela 1991, Menghini et al. 2010). Lesions in the lateral areas of the tooth that are radiologically found to extend into middle dentin were cavitated in 100% of cases (Pitts & Rimmer 1992). For cavitated interproximal lesions, sealing is no longer indicated. Thus, recent methods of interproximal caries infiltration (Phark et al. 2009) are not included in the current review.

2) Partial caries removal

As early as 1859, the textbook by John Tomes stated that it was preferable to leave discolored dentin above the pulp than risk losing the tooth (Tomes 1859). An article by Bonsack concerning "le coiffage naturel ou indirect" published in the Swiss Monthly Journal of Dentistry in 1952 (Bonsack 1952) shows that even then there were heated disagreements between the supporters and opponents of purposely leaving some of the caries. The author recommended leaving a thin layer of caries close to the pulp for teeth with an advanced lesion to avoid endangering the vitality of the pulp. However, in the periphery of the cavity, he recommended complete caries excavation to ensure a tight seal. In this way, progression of caries would be stopped even without removing all of the bacteria. The concept of stepwise excavation was, like almost all minimally invasive excavation methods, initially described only for primary teeth (Bodecker 1938). Sowden later reported applying the method not only to primary but also to permanent teeth with deep dentin caries (Sowden 1956). During a seven-year period, he treated approximately 4,000 asymptomatic teeth (primary and permanent teeth, patients 2 to 79 years old). During the first session, lesions were partially excavated and later covered with a 1 mm thick layer of calcium hydroxide and temporarily sealed with a non-compacted amalgam filling. Two to three weeks later, complete excavation was performed and the tooth was definitively restored with conventional amalgam. During the radiological and clinical follow-up examination, remineralization of the remaining caries was noted, starting at the pulp (Sowden 1956). Law & Lewis applied the same method to primary teeth and young permanent teeth (Law & Lewis 1961). Complete excavation was performed after six months. Radiological follow-up examinations were carried out at various intervals and compared to the immediate postoperative images. After seven days, in almost all cases, a radiopaque contrast was visible on the pulpal side of the remaining caries. After an observation period of two years, a success rate of 76% was achieved (no pulp exposure after complete excavation and normal clinical and radiological conditions). An initially undiagnosed, irreversible pulpitis and the loss of temporary non-compacted amalgam fillings were identified as reasons for the unsuccessful results for 14 teeth (Law & Lewis 1961). In the 1960s, other in vivo studies reported possibilities of remineralization of caries-infected dentin (Ehrenreich 1968, Kerkhove et al. 1967) and confirmed that complete caries removal is not an absolute prerequisite for stopping infection of the hard tissue. Leaving part of the deep caries was, nevertheless, heavily criticized by several prominent authors, because neither the depth of the lesion nor the degree of the infection can be estimated reliably preoperatively (Langeland 1981, Bergenholtz & Spångberg 2004).

Stepwise excavation or direct final treatment?

The question is whether or not a two-session procedure with a temporary interim phase is necessary following partial caries excavation. If arresting remaining caries close to the pulp is actually possible without complications, it does not seem necessary to excavate a second time (Kidd 2004, Ricketts et al. 2006, Björndal 2013). Neither researchers nor clinicians agree among

themselves whether a re-intervention during the stepwise excavation technique is necessary. It is difficult to say which of the two treatment procedures is better, because there is a paucity of high-quality randomized clinical studies (Ricketts et al. 2013, Schwendicke et al. 2013a). Stepwise complete excavation in two or more sessions has the following advantages: re-intervention provides the opportunity for visual and tactile reassessment of the demineralized dentin. Furthermore, complete excavation is safer, because dry dentin is easier to remove and the thickness of the remaining dentin has increased during the interim phase by apposition of tertiary dentin. Additionally, changes in the pulpal stimulus conduction can be noted and the reaction of the tooth to sensitivity tests can be checked. The supporters of partial excavation with immediate final treatment criticize that many patients do not attend the second session and the restoration is not successful due to a loss/partial loss of the temporary filling (Maltz et al. 2012).

More recent studies show that teeth can remain symptom-free and without any radiological signs of periapical rarefaction for years after **partial caries excavation, indirect pulp capping and immediately subsequent final treatment** (Maltz et al. 2012). This treatment method, when successful, is simpler, patient-friendlier and less expensive than a root canal treatment, which may be necessary after complete excavation. The shorter treatment time is particularly advantageous when treating uncooperative, young patients (Gruythuysen et al. 2010). It remains unclear, however, if leaving caries leads to positive or negative development of the general situation. Less pulp exposure and postoperative symptoms are weighed against technical failures and possible inevitable long-term caries progression. In a randomized two-center study, partial caries removal with immediate definitive treatment was compared to stepwise excavation and re-examined both clinically and radiologically after three years (Maltz et al. 2012). The success rate (positive cold test, no spontaneous pain, no percussion sensitivity and no periapical radiolucency) was 91% (5 failures) for the partial excavation and 69% (21 failures) for stepwise excavation. Of the 147 teeth in the stepwise excavation group, 46 were not available for the second session. These teeth had a significantly worse success rate than the teeth in which treatment could be completed (13% versus 88%). This means that stepwise excavation can have similar success rates as partial caries excavation with direct definitive restoration after three years, but only if the patients attend the second appointment for complete excavation and final restoration. The main cause for failure was leakage of the temporary filling, indicating that this point deserves critical consideration. One-surface restorations lead to much better results compared to multiple-surface restorations, which confirmed earlier studies on stepwise excavation of deep dentin caries (Maltz et al. 2011).

The influence of materials used

A systematic review led to the conclusion that the material used under the filling has no influence on stopping caries progression (Miyashita et al. 2007). Contrasting results were found in a study about treatment of dentin caries with calcium hydroxide (Eidelman et al. 1965). In this study, only half of the caries was initially removed from the pulpal wall of teeth with deep caries (split-tooth-design). The excavated half as well as the remaining caries were both covered with calcium hydroxide and the tooth was treated with amalgam. Teeth were re-opened after two, four, six, eight or twelve weeks, and the other half was completely excavated. Carious dentin shavings of the first and second session were collected and tested for phosphorus as an indicator of remineralization. The concentration of phosphorus increased significantly during the treatment with calcium hydroxide. No relationship was found between treatment intervals and the increase in the phosphorus concentration. Almost all teeth showed a radiopaque zone close to the pulp. The teeth in the control group, in which the dentin was covered with wax instead of calcium hydroxide, showed neither increasing concentration of phosphorus nor sclerosis in the radiological follow-up. This study suggests that calcium hydroxide (which does not contain any phosphorus) can indirectly favor remineralization via the disinfection of the carious dentin. This was confirmed by a similarly designed study with 40 permanent teeth (Leung et al. 1980). Before and after indirect capping with Dycal (Dentsply Tulsa Dental Specialties), partially excavated dentin was examined for existing cultivable bacteria. The control also underwent indirect capping with wax. Under calcium hydroxide layer, bacteria were reduced by 1.5 $\log_{10}$ steps after four weeks (i.e., over 90%); whereas under wax, there was no reduction. It was later proven that antimicrobial substances, such as glutaraldehyde, can improve disinfection under composite restorations (Felton et al. 1989). Glutaraldehyde is a component of certain older dentin-bonding systems, which are, at least in in vitro studies, superior to newer systems without glutaraldehyde with respect to dentin disinfection (Schmidlin et al. 2004). Although the toxicity of glutaraldehyde is reduced by its binding ability to collagen through cross linking, it remains a potentially pulp-toxic substance (Zielinski 2010). Whether incorporating disinfectants in bonding systems is necessary, or if it is better to clean the cavity with a conventional aqueous disinfectant, still remains to be investigated. In a recently published randomized clinical trial (Hashem et al. 2015), teeth with severe caries (penetrating at least ¾ of the dentin) were indirectly capped with either a calcium silicate cement (Biodentine; Septodont) or glass-ionomer cement (Fuji IX; GC). Some caries was left close to the pulp. Although reversible pulpitis was clinically diagnosed in all teeth, the intensity of the symptoms varied from mild to strong. Using single-tooth radiographs and cone-beam computed tomography (CBCT), the periapical status was evaluated before indirect capping and twelve months later. The clinical success rates of the two materials were similar (both 83%). Teeth that were capped with Biodentine showed higher success rates, however, when examined using CBCT. In the glass-ionomer group, new periapical lesions developed more frequently than in the calcium silicate cement group. However, teeth with mild and severe symptoms were not equally distributed across the two groups. In total, 18% of the teeth developed pulpal necrosis (Hashem et al. 2015).

Adhesion to carious dentin

Adhesive bond strength decreases with increasing caries severity. The hybrid layer developed in infected dentin (30–60 µm) was notably thicker than that of demineralized dentin (6–8 µm) and normal dentin (<1 µm) (Yoshiyama et al. 2003). In a study by Maltz et al. (2011), five of twelve teeth with partial caries excavation and multiple-surface restorations exhibited tooth or restoration fracture. In an in vitro study, teeth with single-surface occlusal restorations also showed significantly lower fracture resistance after partial caries excavation (Hevinga et al. 2010). These findings suggest that during partial excavation

and subsequent adhesive restoration, only an absolute minimum of caries-infected dentin should be left close to the pulp, as the stability of the restored tooth will otherwise be compromised.

3) Complete caries removal

The probability of pulpal exposure is significantly higher for one-session complete caries removal than for the stepwise procedure with ultimate, final complete caries excavation (Leksell et al. 1996, Björndal et al. 2010). In a randomized multi-center study by Björndal et al. on fully developed permanent teeth whose radiographs showed caries reaching to the inner fourth of the dentin, the pulp chamber was opened in 28.9% of cases where caries was completely excavated in one session and in 17.5% of cases where stepwise excavation was performed. The authors speculated that shifting and introducing caries-infected material into the pulp during complete excavation with pulp exposure has a negative influence on its chances of survival (Björndal et al. 2010). This is the main argument of the supporters of partial caries excavation. In the Björndal study, if the pulp had to be directly capped, it did not survive the first year in more than 65% of the cases. In this study, contrary to a much older study on this topic (Leksell et al. 1996) which showed higher success rates, the patients were adults and thus root growth was completed. Additionally, teeth with mild and moderate preoperative pain were included in the Björndal study (exclusion criteria: teeth with persistent, unbearable pain, pain disrupting sleep), which could have led to the high failure rate. These teeth then had a significantly lower success rate than pain-free teeth. For teeth with mild and moderate postoperative pain, the risk of pulp exposure was higher, even with stepwise excavation (Björndal et al. 2010). Preoperative pain is thus a strong diagnostic and prognostic criterion, which is confirmed by the previously mentioned histological observations (Ricucci et al. 2014). Regarding diagnostics, complete caries excavation is advantageous compared to leaving remnants of deep caries. If the pulp is not exposed during complete excavation, it is very probable that it will remain vital for at least the following year (Fitzgerald & Heys 1991, Björndal et al. 2010). If the pulp is exposed, further important information can be gathered. Clinically, instead of blood, a drop of pus often exudes from the pulp chamber under the carious dentin. This is a clear sign that the tooth needs endodontic treatment. The extent of the bleeding itself enables estimating the degree of infection of the pulp. In a Japanese study on direct pulp capping with calcium hydroxide after complete caries excavation, the amount of blood exuded from the pulp chamber was examined (Matsuo et al. 1996). If there was a slight bleeding, 31 of 37 treatments were successful (follow-up examinations between 3 and 36 months). If bleeding was heavy, however, such that blood filled the cavity, only five of nine treatments were successful.

Direct capping

If, after complete caries excavation, the pulp chamber is opened, the minimally invasive treatment is direct pulp capping. The published results concerning the chances of success vary greatly. This is basically due to the heterogeneity of the studies concerning the inclusion criteria of the teeth to be capped. The success also depends on the clinical procedures and the technical skills of the dentist. Even so, various factors can be identified that seem to play a central role. In order to preserve the remarkable healing and repair abilities of the pulp-dentin complex, the absence of bacteria is the most important factor (Kakehashi et al. 1965, Bergenholtz et al. 1982, Cox et al. 1982). Direct pulp capping of teeth with caries reaching the pulp chamber is less likely to be successful than in teeth where the pulp was iatrogenically exposed from hard dentin (Al-Hiyasat et al. 2006). Moreover, the degree of infection of the pulp at the time of capping also plays a pivotal role in the matter. As mentioned above, the degree of bacterial penetration is directly correlated with the pulpal inflammation (Reeves & Stanley 1966). In the 1950s, Nyborg already drew the conclusion from his cases that although symptom-free directly capped teeth have a relatively high clinical success rate (86%), this was adjusted to 62% based on the histological examination. Teeth with preoperative symptoms also had lower chances of clinical success (46%) (Nyborg 1958). Success rates of 80–90% were achieved after four years, if the method was applied to symptom-free teeth with iatrogenic pulpal exposures and not to teeth with penetrating caries (Haskell et al. 1978, Baume & Holz 1981, Hörsted et al. 1985, Al-Hiyasat et al. 2006). The results of a study from a student course that examined direct capping with calcium hydroxide over a pulp opening of less than 1 mm² after caries excavation were more sobering. The authors studied initially symptom-free teeth over a period of ten years: the annual failure rate did not decrease over time. After five years, 37% of the directly capped pulps were still vital, falling to 13% after ten years (Barthel et al. 2000). Adolescent teeth without a fully closed apex showed better chances of success with direct capping using calcium hydroxide after seven years than mature teeth did (Auschill et al. 2003). The superior vascularization of these teeth ameliorates the immune response as well as the repair mechanisms of the pulp.

All of the above-mentioned studies used a calcium hydroxide compound for direct pulp capping. The question remains if newer materials might result in higher success rates.

The influence of materials used

Calcium hydroxide was introduced into dentistry by Hermann in 1920 to disinfect and fill root canals (Hermann 1920). The effect was that various suspensions containing calcium hydroxide were developed and marketed, firstly only in Germany and then also in other countries such as Switzerland, France, and the USA, as German products were not accessible elsewhere during the second World War (Castagnola & Orlay 1950). In their classic study of healthy premolars that were extracted for orthodontic reasons, Glass & Zander showed that upon direct capping with calcium hydroxide, a dentin bridge is formed, whereas after the same intervention with zinc oxide eugenol, the pulp did not heal (Glass & Zander 1949). The consequence of this observation was that the concept of direct pulp capping with calcium hydroxide was applied even for small exposures of the pulp during caries excavation (Castagnola & Orlay 1950). The goal of direct capping would be complete dentin bridge formation with or without a minor inflammatory reaction of the surrounding pulp tissue. Reparatory dentin formation via calcium hydroxide after accidental, traumatic, and caries-related pulp exposure was studied by numerous authors. The application of calcium hydroxide leads to local tissue necrosis and not always to complete dentin bridge formation (Stanley & Lundy 1972, Klaiber 1984, Beetke et al. 1990). The capacity of calcium hydroxide to induce dentin bridge formation is better the shorter the pulp has been exposed to bacteria (Cox et al. 1982). An existing infection of the pulp reduces its ability to

form hard tissue (Pajarola 1940, Nyborg 1958, Harris & Bull 1966, Sela & Ulmansky 1970). However, dentin bridge formation has been observed even in teeth with irreversible pulp infection (Tronstad & Mjör 1972). A dentin bridge is thus not necessarily a criterion for healing of the pulp (Tronstad & Mjör 1972). Animal studies with monkeys have also shown that when the pulp is infected, calcium hydroxide as a capping material tends to worsen rather than improve the state of the pulp, because aside from its antimicrobial effect, it also induces pulpal inflammation (Tronstad & Mjör 1972).

Aside from the conventional procedure of direct capping with calcium hydroxide, different materials (zinc oxide eugenol, Biorex, Ledermix, zinc phosphate, composite resin) were tested regarding their efficacy in maintaining pulp vitality. The reaction of both healthy teeth and infected pulps to these materials was histologically studied in rats, dogs, monkeys and humans. Complete dentin bridge formation was seldom found and the reaction of the pulp varied from a few inflammatory cells around the area of exposure to total pulp necrosis, regardless of the capping material (Glass & Zander 1949, Sela & Ulmansky 1970, Shovelton 1972, Tronstad & Mjör 1972, Langeland 1981, Cox et al. 1987).

Bioactive cements on a calcium silicate basis, such as MTA (ProRoot MTA; Dentsply), are however the materials of choice for direct capping today. Retrospective clinical studies have consistently shown similar or better results compared to capping with a calcium hydroxide compound (Cho et al. 2013, Mente et al. 2014). A randomized clinical trial in 35 dental practices showed clearly better results when the pulp capping was performed with MTA instead of calcium hydroxide (Hilton et al. 2013). The clinical failure rate after 24 months was a little over 30% for direct capping with calcium hydroxide and just under 20% for teeth capped with MTA (Hilton et al. 2013). In histological studies where healthy teeth were capped (Accorinte et al. 2008, Nair et al. 2008), formation of hard tissue occurred sooner after capping with MTA than with calcium hydroxide. After 60 days, however, the results regarding hard tissue formation and inflammatory reaction in the pulp were similar (Accorinte et al. 2008).

The first generation of calcium silicate cements (ProRoot MTA; Dentsply) has the disadvantage that they may discolor dental hard tissue and thus should not be applied in esthetic areas, e.g. the crowns of front teeth (Krastl et al. 2013). Calcium silicate cements of the first generation contain bismuth oxide to yield better radiographic images (Camilleri et al. 2013). Newer materials, for example Biodentine (Septodont) and EndoSequence (Brasseler, USA) that contain zirconia as the radiopaque substance, seem to have the same effect (Beatty & Svec 2015), albeit not as pronounced (Kohli et al. 2015). The bismuth oxide in calcium silicate cements is held as chiefly responsible for staining the tooth (Xuereb et al. 2015). A Swiss manufacturer offers calcium silicate cement (MedCem GmbH) which does not contain any radiopaque substance. Studies about its tendency to discolor teeth do not exist.

In conclusion, it can be stated that calcium silicate cements have a biological advantage over calcium hydroxide compounds for direct pulp capping. Even so, it is no miracle cure and indication for direct capping is limited to painless posterior teeth with accidental or minimal pulp exposure. For esthetic reasons, alternatives for such incisors are bismuth-free calcium silicate cements or a calcium hydroxide compound (Krastl et al. 2013).

Pulpotomy

Root canal infections progress from the crown apically. It is impossible to clinically locate the front of the infection (Rechenberg & Zehnder 2014). However, the probability of finding healthy pulp tissue naturally increases as the intervention is performed further apically (Langeland 1987). Cvek used this knowledge to introduce the partial pulpotomy. For this, the first roughly 2 mm of exposed tissue are removed with a sterile rose bur until reaching presumably healthy tissue to then apply the capping material (Cvek 1978). The concept was initially based on histological observations of traumatically exposed pulps with complicated coronal fractures. It was only applied in these cases. Later, partial pulpotomy with calcium hydroxide appeared to be successful also for permanent teeth of children and adolescents with deep caries (Mejare & Cvek 1993). However, interpretation is difficult, as this study lacks a control group, as all merely observational studies and case reports do. In their randomized study on caries excavation, Björndal et al. also randomized cases with pulp exposure in a so-called "nested trial", i.e., a randomized trial within the main study. The first group of exposed pulps was conventionally capped directly, the second group after a partial pulpotomy (Björndal et al. 2010). The results were equally poor for both groups: a 68% failure rate for direct capping and 66% after partial pulpotomy. The partial pulpotomy does not seem to be more advantageous than direct capping in adult teeth.

As early as the 1930s, Zander reported on the reaction of the pulp to placement of calcium hydroxide during a **full pulpotomy** (Zander 1939). He presented a case report of a 9-year-old boy whose root growth in the affected tooth was completed by conducting a so-called vital pulp amputation. This differed from then-common pulpotomies, which necrotized and fixated the remaining soft tissue in the tooth. Since then, pulpotomy has become the most common treatment for vital teeth with incomplete root growth whose pulp is exposed traumatically or due to caries (Goldsmith et al. 2002, Krakow et al. 1977). Leaving the vital pulp in the roots enables the pulp-dentin complex to continue root growth. The potential for healing is high as long as the pulp in the root is not instrumented and no microorganisms infiltrate the pulp. A pulpal response is productive rather than degenerative (Massler 1972). The authors of the classic studies on this topic (Patterson 1967, Goldman 1974) merely considered pulp chamber pulpotomy as a first step of endodontic therapy. As soon as root growth was completed, conventional root canal treatment was recommended to avoid calcifying degeneration, obliteration of the root canal, or internal resorption. The degree and the speed of dentin formation after a pulpotomy are in fact highly variable. Traumatized teeth did not form any new dentin in some cases and in other cases the root canal system was completely obliterated (Hallet & Porteous 1963). Unfortunately, there are not many long-term studies about pulpotomies and none concerning this treatment option after caries excavation and excavation-related exposure of the pulp.

Estimating vitality after a pulp chamber pulpotomy is difficult. In a prospective study, most teeth did not react to cold testing or yielded questionable results after a pulp chamber pulpotomy and capping with MTA (Simon et al. 2013). Most of the teeth did react to electric testing of the pulp, but to different levels of the stimulus (Simon et al. 2013). Consequently, the survival rate of the pulp after this intervention can only be estimated clinically. It can be assumed that it is overestimated,

because many pulps necrotize without attendant symptoms (Michaelson & Holland 2002). In the study by Simon et al., 14 of 17 carious, pulpotomized teeth caused postoperative pain (Simon et al. 2013). The pain subsided only in five teeth within the first five days; and three teeth (18%) needed a pulpectomy afterwards. The estimated success rate in terms of survival of the apparent pulp tissue in the roots was thus 82% (Simon et al. 2013). Studies comparing full (pulp chamber) pulpotomy and direct capping do not exist.

The influence of materials used

The first randomized study on partial pulpotomy does not make it clear whether calcium silicate cements have an advantage over calcium hydroxide (Chailertvanitkul et al. 2014). There are no studies comparing full pulpotomies with calcium hydroxide versus calcium silicate cements. The generally accepted opinion is that calcium hydroxide compounds are advantageous when working in esthetic areas, or if a second session is desirable, for example when root growth is completed and a conventional root canal treatment is to be undertaken. Under these circumstances, calcium silicate cements have the disadvantage that they bond with the dentin and set hard (Caronna et al. 2014). Thus, the second intervention for a tooth with a full pulpotomy and calcium silicate cement capping can be difficult, so that a dental microscope needs to be used to remove the material and locate the root canals. The estimated success rate after a pulpotomy with calcium silicate cement as a final treatment is very high (90%) for young patients after two to three years (Alqaderi et al. 2014), and is thus comparable to success rates of endodontic treatment in teeth without initial apical osteolysis. In an Iranian randomized multi-center study comparing pulpotomy and one-session root canal treatment for teeth with irreversible symptomatic pulpitis, calcium silicate cements were used to cap vital root pulps in the pulpotomy group. After two years, the success rate of the vital pulp therapy was 80%, comparable to that after the pulpectomy (Asgary & Eghbal 2013, Asgary et al. 2013). The authors were of the opinion that maintaining pulp vitality via pulpotomy is not only a time- and cost-effective alternative to pulpectomy, but also yields better results. It must be cautioned, however, that in this study, instead of using sodium hypochlorite, sterile water was used to irrigate the root canals during endodontic treatment.

General uncertainties for vitality-maintaining measures

Several authors of classic studies have expressed their concern that continuous stimulation of dentin formation could occur after direct or indirect capping, rendering it hard or impossible to perform a full pulpectomy if necessary (Seltzer & Bender 1958, Massler 1972). In a study in monkeys, the highest dentin formation rate after capping was observed within the first 50 days, thereafter decreasing until reaching normal levels after 100 days (McWalter et al. 1977), suggesting that calcium hydroxide as a capping material does not lead to a persistent stimulation of dentin formation. However, in animal studies, the pulp is usually healthy, which fundamentally cannot be compared with the clinical situation, in which the pulp is usually damaged.

There is hardly any mention made of pulp obliteration being a frequent complication in studies concerning treatment of deep caries lesions. The endodontist's daily clinical routine tells a different story (Fig. 2). While some authors consider reparative dentin formation as a consequence of previous pathological changes (Reeves & Stanley 1966), others believe that this effect is potentially useful for pulp regeneration (Goldberg et al. 2008), and that a conservative therapy procedure can have a positive prognosis despite significant inflammation of the pulp (Gruythuysen et al. 2010). Long-term studies on this question with human subjects are elusive. The topic cannot be conclusively discussed until such data is produced.

Fig. 2 a) 8-year-old patient with an advanced dentin lesion on tooth 36 (bitewing radiograph left, baseline). b) Situation after excavation, capping with a calcium hydroxide liner (Kerr Life; Kerr) and a glass-ionomer filling. Root growth is incomplete at this point (single-tooth radiograph one month after baseline). Due to intense postoperative pain, a pulp chamber pulpotomy was conducted a few days later. The wound in the dentin was capped with a calcium hydroxide/iodoform compound (Vitapex; Neo Dental International Inc.) and the tooth temporarily sealed again. c) Symptom-free conditions for about 17 months, then (at the time of this image) pain occurred with hot/cold and percussion stimuli. The respective single-tooth radiograph shows that root growth is now complete. However, the root canals are also markedly narrower and sclerosis is visible in the canal entrances, which renders the now-indicated pulpectomy difficult. On top of this, this patient had restricted mouth opening.

Another aspect which remains minimally if at all addressed in the literature is the disinfection of the dentin and pulp wound after mechanical therapy. Despite the fact that in many of the above-mentioned studies disinfection procedures were performed before the tooth was prosthetically treated, how and with which material the wounds were disinfected has neither been standardized nor systematically evaluated. As mentioned above, there are indeed indications that disinfecting solutions or capping materials are advantageous (Eidelman et al. 1965, Leung et al. 1980). Moreover, the tight sealing of the cavity against the inherently bacteria-filled environment of the oral cavity certainly plays an important role (Bergenholtz et al. 1982). This should be done as quickly as possible after the vitality-maintaining treatment (Mente et al. 2014).

Conclusion and final remarks

Based on the current knowledge, it is not clear which type of intervention is best under which conditions. Particularly for permanent teeth with completed root growth and caries reaching

dentin close to the pulp, nothing contradicts excavating down to hard dentin and, if the caries reaches the pulp, conducting a root canal treatment. All other procedures are of high academic interest but not yet supported by sufficient reliable data. It is different for teeth that have not completed root growth. Even though this topic also lacks credible, comparative studies, it makes sense to maintain a vital pulp in the root canals, so that the root can complete its development. How much of the infected substance should be excavated depends on the compliance of the patient and also on the degree of pulpal infection. If the patient already experiences pain, a full pulp chamber pulpotomy should be considered to increase the probability of capping in healthy tissue. Then the technical question arises as to whether capping the pulp stumps in the root canals should be done with calcium silicate cement or a standard calcium hydroxide compound. Using the latter renders it easier to find the root canals in case a complete root canal treatment (pulpectomy) becomes necessary later on.

In conclusion, the following statements can be made:

- Merely sealing lesions on permanent teeth with deep caries is not indicated.
- Vitality-maintaining methods are not recommended for spontaneously painful teeth that have completed root growth and show deep caries lesions.
- Non-invasive excavation methods, i.e., leaving residual caries, bear the inherent disadvantage of not being able to judge the degree of infection of the dentin close to the pulp itself. Thus, the long-term success of the therapy is uncertain. Intentionally leaving some caries is currently only recommended for uncooperative children with symptom-free teeth and incomplete root growth.
- Direct capping should be done with calcium silicate cement such as MTA, rather than with a calcium hydroxide compound, at least in non-esthetic areas. In esthetic areas, a bismuth-free calcium silicate cement or a calcium hydroxide compound should be used.
- Pulp chamber pulpotomy could prove to be a valid alternative to conventional root canal treatment (pulpectomy) for teeth with caries reaching into the pulp. Reliably controlled studies and long-term observations on obliteration of the root canals are not yet available and should be performed.

Résumé

Le but de cet article est de montrer les différentes possibilités thérapeutiques des caries avancées, proches de la pulpe des dents permanentes, en considérant les avantages et les inconvénients de plusieurs techniques. Aujourd'hui, grâce aux matériaux adhésifs, on peut traiter les atteintes dues à la carie. Dans ce cadre, il faut remettre cette ancienne question sur le tapis: faut-il excaver complètement la dentine cariée, malgré le risque d'une exposition de la pulpe, ou bien est-ce qu'il est peut-être plus judicieux de laisser consciemment une couche carieuse ou même ne faire que sceller la lésion carieuse? Du côté des réflexions cliniques, d'une part on a l'infection de la dentine et de l'autre, la réponse immunologique de la pulpe avec toutes les conséquences pour le patient. Dans ce travail, ces deux aspects seront évalués. Les réflexions sur la biologie ainsi que des études cliniques comparatives sur les différentes modalités d'interventions seront discutées. On analysera également dans quelle situation un coiffage avec des ciments modernes à base de calciumsilicate sera plus favorable que le «goldstandard» hydroxide de calcium.

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