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DENTAL RESTORATIVE MATERIALS (M ÖZCAN, SECTION EDITOR)

Current Concepts in Carious Tissue Removal

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Abstract

Purpose of Review To summarize current concepts in carious tissue removal.

Recent Findings Traditionally, caries has been seen as an infectious disease and was treated by attempted complete removal of all cariogenic bacteria. The logical traditional aim of carious tissue removal—removing all bacteria from carious lesions—no longer applies. The contemporary aim of carious tissue removal is to maximize restoration longevity, without unnecessarily removing sound or remineralizable dentin. This is based on recent perspectives that dental caries is a biofilm-based and lifestyle-mediated disorder. In shallow lesions, as much carious tissue as possible should be removed, with removal until hard dentin is felt around the periphery of a cavity (to maximize restoration survival and seal the cavity) while centrally firm dentin is left (to retain remineralizable dentin). For deep lesions in teeth with vital pulps (without irreversible pulpitis or pulp necrosis), maintaining pulp vitality is the priority. Dentists should aim to avoid pulp exposure and accept leaving soft or leathery dentin in areas close to the dental pulp, while at the periphery, carious tissue should be removed until hard tissue is felt, ensuring that any remaining bacteria are sealed and inactivated and that the restoration has sufficient mechanical support against masticatory forces. An alternative for deep lesions is stepwise removal. Carious tissue strategies where no carious tissue removal at all is performed include sealing using plastic materials or stainless steel crowns, or non-restorative cavity control.

Summary A range of carious tissue removal strategies are available and should be applied according to lesion characteristics, pulp vitality, and other patient related factors. Always striving to remove carious tooth tissue until hard dentin remains is not in line with current evidence and not recommended.

Keywords Dental caries · Deep caries · Ecological plaque hypothesis · Selective removal · Stepwise removal

Introduction

Our understanding of the disease caries and its causes has dramatically changed over the last three decades. Historically, caries was understood to be an infection associated with one or few specific bacteria like streptococci (especially *Streptococcus mutans*) or lactobacilli. If these were present, it was assumed that the patient was at risk for caries and would develop the symptoms of the disease, carious lesions, at some point. This has been termed "specific plaque hypothesis" [1]. It was assumed, therefore, that to "heal" or prevent caries, there had to be eradication of all causative bacteria from the mouth (using antibacterial rinses or, again based on the infection idea, vaccinations). Furthermore, to avoid transmission of *S. mutans* and prevent the "spread" of the infection, mothers were told not to share spoons with their children and sometimes even to avoid kissing their babies. If dental hard tissues were found to be "infected", i.e., carious (clinically detected by them showing a different texture, color, or hardness, as will be discussed), they needed to be fully removed as only then would the infecting bacteria be removed, too. The treatment of carious lesions was essentially by removing them and replacing them with a restorative material (at this time, mainly non-adhesive amalgam, cements, or indirect metal restorations) [2].

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The Aims of Carious Tissue Removal

If we think about the aim for these procedures, historically, it was simply to remove carious tissue and therefore all bacteria from the dental tissues. However, as stated earlier, the understanding of caries has changed: the disease is now seen as the result of an ecological imbalance within the biofilm composition and its activity. The main driver behind this is the abundant intake of fermentable carbohydrates. The "normal" flora of the mouth contains only a relatively few cariogenic, i.e., acid-producing (acidogenic) and acid-tolerant (aciduric), bacteria (evolution has achieved a balanced homoeostasis between the physiological biofilm and us as its host!). With the advent of fermentable carbohydrates being the main nutritional source, this balance has been disturbed: carbohydrates are fermented by the few cariogenic species, with subsequent acid release leading to a pH decrease. As most physiologic bacteria do not tolerate such acidic conditions, cariogenic species become more competitive and this leads to them dominating the biofilm. Eventually, undisturbed mature biofilms grown under regular carbohydrate (mainly sugar) supply are capable of rapidly reducing the pH to levels at which enamel and, even more so, dentin are demineralized. This creates a cariogenic niche and the process, if uninterrupted, will continue. The result is a dysbiosis, as opposed to the healthy symbiotic relationship between host and bacteria, and a net mineral loss in the dental hard tissues [3].

This means that it is not necessary to remove all, or specific species, of bacteria from the mouth to control caries and arrest carious lesions; this historical aim of carious tissue removal no longer applies. Dentists should not attempt to "heal" carious teeth by removing bacteria and should not manage carious lesions by invasively removing all presumably infected (a better word is contaminated) dental hard tissues. Instead, the aim is to control the composition and activity of the dental biofilm within the cavity. The activity at the tooth surface can be controlled through regular biofilm removal (toothbrushing) supported by dietary sugar regulation. The importance of managing the cause of the disease at a patient level through these means, alongside managing the carious lesion at the tooth level, cannot be overemphasized and must be part of the overall treatment plan.

One very useful management option for carious lesions is sealing them: sealing bacteria deprives them from the dietary carbohydrates by placing a barrier on top of the lesion. The majority of bacteria are unable to withstand this starvation long-term and are inactivated when sealed in [4].

Based on this, it could be argued that there is no longer any need to remove carious tissue at all; to control a carious lesion, sealing the bacteria should suffice. Speaking strictly from a biological viewpoint, this is probably true, although there is still uncertainty as to the impact of great amounts of starvation on the biofilm and the effect that dying bacteria and their by-products will have on the dental pulp. Clinical studies on primary teeth where cavitated lesions were sealed using stainless steel crowns, however, have not found this to be a problem.

However, there are also structural considerations; carious dentin is softer than sound dentin. A plastic sealant placed on top of large amounts of carious dentin may not be sufficiently strong to resist masticatory forces. In addition, bond strengths of modern adhesives and also glass ionomers are significantly lower when placed on carious than sound dentin. As a result, sealants placed over larger amounts of carious dentin might be prone to retention loss or leakage (which would compromise the hermetic seal and the lesion arrest) [5–8, 9••, 10]. As a consequence, from a restorative point of view, some carious tissue removal is necessary prior to placing a restoration. The main aim of contemporary carious tissue removal is to create conditions which maximize the longevity of the restoration that is subsequently placed.

If sealing can arrest carious lesions, but some carious tissue removal is necessary to allow secure placement of a long-lasting restoration, we should now be asking where exactly should we remove more, and where less, carious dentin and enamel? The answer to this question is found by following the contemporary principles of carious tissue removal.

The Principles of Carious Tissue Removal

For carious tissue removal, a number of principles have been agreed on by the International Caries Consensus Conference (ICCC) [11, 12••]:

(1) "avoid discomfort/pain and dental anxiety (…)
(2) preserve non-demineralized as well as remineralizable tissue (…)
(3) achieve an adequate seal by placing the peripheral restoration onto sound dentin and/or enamel, thus controlling the lesion and inactivating remaining bacteria (…)
(4) maintain pulpal health by preserving residual dentin (avoiding unnecessary pulpal irritation/insult) and preventing pulp exposure (…)
(5) maximize longevity of the restoration by removing enough soft dentin to place a durable restoration of sufficient bulk and resilience" [12••].

We can elaborate on how these principles are justified by explaining the relevance of each of them to modern dental care, where the focus is on patients as a whole, rather than just their teeth.

(1) Avoiding discomfort and pain is one of the most relevant factors for patients; providing comfortable and pain-free dental care will also help to avoid dental anxiety and

could thus increase adherence for future dental therapies [13–16].

(2) Preserving sound or demineralized but remineralizable tissue helps to avoid unnecessary loss of dental hard tissue. With every invasive/restorative therapy, hard tissues are sacrificed to some degree; this has been termed repeat restoration cycle or the death spiral of teeth or restorations [17–20]. Slowing down this spiral by being minimally invasive enhances tooth longevity by reducing tooth substance loss and structural weakening. Both biologically assisted remineralization (via pulpal fluids or saliva) and restoration material-assisted remineralization (through fluoride release or, in the future, biomimetically mineralizing adhesives or restorative materials) promote retention of demineralized tissue within a cavity before placing a final restoration, at least in the central aspects of the cavity.

(3) When a tight seal is established the bacterial environment becomes unfavorable for sustaining or further developing a cariogenic biofilm. This is best achieved using adhesive materials. It is only when the seal is secure that bacteria can be left beneath the restoration [21]. It is not necessary, however, to establish the seal everywhere in the cavity; it seems sufficient to achieve a tight seal peripherally. In the central parts of the cavity, close to the pulp, it is acceptable to leave bacterially contaminated dentin, as long as peripherally the transport of dietary sugars to the sealed bacteria is inhibited. Removing carious tissue at the periphery of a cavity also aligns with aim (5), i.e., maximizing restoration longevity.

(4) In deep lesions, extending close to the pulp, maintaining pulpal health essentially means avoiding pulp exposure. This is relevant, as exposed pulps are treated either via direct pulp capping (or other alternatives aiming at maintaining pulp vitality) or via root canal treatment. Under certain, optimal conditions, direct capping (or, for example, partial pulpotomy) can be performed successfully in maintaining pulp vitality [22–28]. This success has not been replicated in general dental practice setting or when performed by non-specialized operators. Here, directly capping the exposed pulp often puts the tooth on a pathway towards root canal treatment [29–31] (Fig. 1). While, again, root canal treatment can be highly successful under specific optimal conditions or when performed by specialized operators, it has been shown that these results are not necessarily achieved in general practice or by non-specialized operators, where success rates are far lower and a significant proportion of root canal treated teeth is eventually re-treated or, more often, extracted [32, 35] (Fig. 1). Avoiding pulp exposure and consequently avoiding endodontic therapy thus helps to retain teeth!

(5) Maximizing restoration longevity helps to slow down the repeated replacement cycle of restorations. It requires removing as much carious, i.e., soft and bond strength-reducing dentin as necessary from a cavity.

The last two principles need to be balanced against each other depending on the lesion depth: in shallow or moderately deep lesions (i.e., those not extending into the inner third or quarter of dentin radiographically and not clinically extending close to the pulp), maintaining pulpal health by avoiding pulp exposure is usually not a significant problem (pulpal health is not at risk here). Dental treatment choice should be aimed at maximizing restoration longevity by removing as much carious dentin as possible. However, in deep lesions with vital pulps, avoiding pulp exposure becomes a priority when making treatment decisions, and carious dentin should be left in proximity to the pulp, while peripherally (where pulp exposure is unlikely), carious dentin should be removed to allow an effective peripheral seal to be achieved. For teeth with deep lesions but irreversibly inflamed pulps (where there is spontaneous, constant, or long-lasting pain) or necrotic ones (no positive response to sensibility testing, or signs/symptoms of peri-apical or peri-radicular inflammation), maintaining pulp vitality and

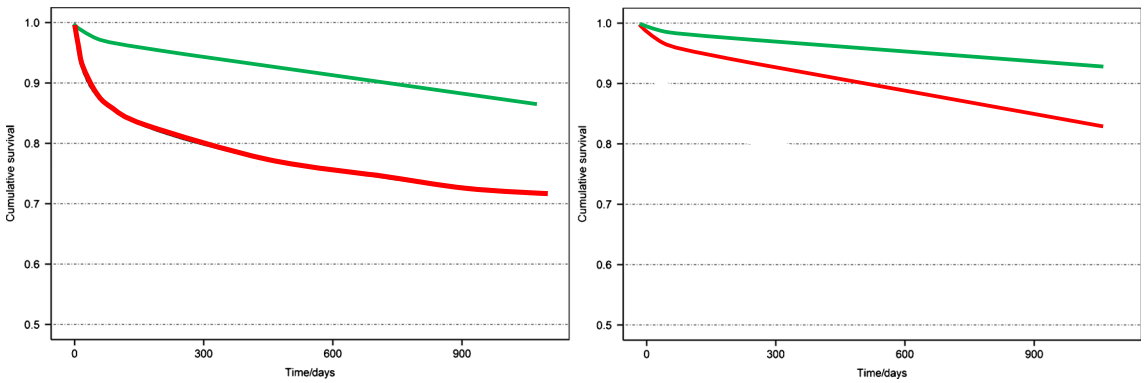

Fig. 1 Survival (measured via clinical and/or radiographic outcomes) of direct capping (left) and root canal treatment (right) in specialized settings (green), being highly successful, or routine general dental practice settings (red), with significantly lower long-term survival. Survival curves were constructed based on assumptions from [31–34] and serve to exemplify the stark differences in survival in different settings (note that extrapolations were needed)

avoiding pulp exposure is no longer meaningful. Root canal treatment should be performed after removing all carious tissue.

In summary, a tailored carious tissue removal is recommended, depending on the status of the pulp and the expected depth of the carious lesion.

Assessing Carious Tissue Removal

Clinically, assessing how much carious tissue is being removed is challenging: the clinical appearance of carious dentin does not correlate well with the "zones" that are described histologically. These zones are artificially circumscribed and cannot be replicated clinically, as carious dentin is not zone-specific, but characterized by a gradient of hardness, color, bacterial contamination, and collagen degradation (Fig. 2). Clinically, it is not possible to tell with precision, during carious tissue removal, where exactly along the histological "zones" the clinician is working.

However, the histology and the idea that at some defined dentin quality, no bacteria would be present have driven carious tissue removal for decades. This was desirable based on caries being understood as an infection (see above): carious tissue removal was thought to be either "complete" (aiming for bacteria eradication) or "incomplete" (leaving bacteria behind). However, understanding that clinically it is not possible to distinguish contaminated from non-contaminated dentin, and also that this contamination follows a gradient, it is very unlikely that carious tissue removal has ever been "complete" [37]. Moreover, removing bacteria from a cavity is no longer an aim of carious tissue (as explained above).

Consequently, it is currently agreed that carious tissue removal should not be described (or termed) according to how "complete or incomplete" the aim of carious dentin removal is, but is better described using the characteristics of the remaining dentin when removal is carried out [11]. This can best be done using the hardness of the removed or retained dentin as criterion [38]. Hardness can be assessed using probes or an excavator or a bur. Hardness can be described using a number of terms; the standard and most accepted ones are briefly defined here [11]:

- Hard dentin: "A pushing force needs to be used with a hard instrument to engage the dentin and only a sharp cutting edge or a bur will lift it. A scratchy sound or 'cri dentinaire' can be heard when a straight probe is taken across the dentin."
- Firm dentin: "Firm dentin is physically resistant to hand excavation and some pressure needs to be exerted through an instrument to lift it."
- Leathery dentin: "Although the dentin does not deform when an instrument is pressed onto it, leathery dentin can still be easily lifted without much force being required."
- Soft dentin: "Soft dentin will deform when a hard instrument is pressed onto it and can be easily scooped up (e.g., with a sharp hand excavator) with little force being required."

Hardness is easy to assess and relatively reliable. Nevertheless, during training, repeated re-calibration may be needed, and standardization of remaining dentin hardness is not easy to achieve [39]. Other criteria like moisture, color, and dye stainability do not correlate with the extent of caries or have not, or not fully, been validated clinically; dye stainability even seems harmful, as the risk of pulp exposure increases by several times [40–43, 44•]. Hence, carious tissue removal is easiest and best described using hardness as criterion.

Carious Tissue Removal Strategies

Based on the understanding of the disease as outlined and on the aims of carious tissue removal and using hardness as the criterion for what is removed or left during carious tissue removal, a number of removal strategies can be described.

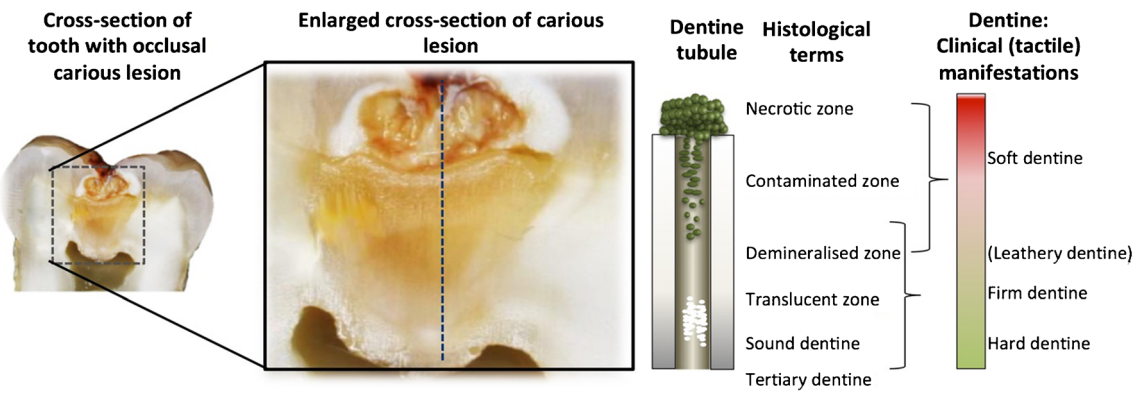

Fig. 2 The histology [36] and the clinical manifestation of deep carious lesions. The artificial "zones" derived from histologic assessment cannot be replicated clinically. Figure from [11]. Copyright © 2018 (Copyright Holder). Reprinted by permission of SAGE Publications

Non-selective Removal to Hard Dentin (no longer recommended)

In non-selective removal to hard dentin (formerly also known as "complete removal"), all softened dentin is removed from everywhere in the cavity (non-selectively), i.e., carious tissue removal is stopped when only hard dentin remains [11]. This approach is not recommended any longer, especially not for deep carious lesions [12••, 38, 45] because of the adverse effects associated with it (pulp exposure, loss of tooth tissue, etc.) for no additional benefit over the other procedures (Fig. 3).

Selective Removal to Firm Dentin

In selective removal, different carious tissue removal criteria are used at the periphery and in the pulpal aspects of the cavity. As described, and based on the principles of achieving a tight, effective seal and maximizing restoration longevity, at the periphery of a cavity, carious tissue is removed until only sound enamel and hard dentin are left. In the pulpal aspects of the cavity, firm or (as described in the next paragraph) soft dentin can be left [11]. Selective removal to firm dentin is recommended for lesions which are not deep, i.e., do not extend into the inner third or quarter of the dentin or close to the pulp radiographically or clinically, respectively. Selective removal to firm dentin is, therefore, recommended for shallow or medium deep lesions. For deep lesions, it is not recommended.

Selective Removal to Soft Dentin

In deep lesions, where pulp vitality should be maintained, selective removal to soft dentin should be performed (Fig. 3). Peripherally, only hard dentin and sound enamel are left (achieving a good seal and maximizing restoration longevity). In the pulpal areas, the aim is to avoid pulp exposure. Hence, carious (soft, leathery) dentin is left here. This reduces the risk of pulpal exposure compared with non-selective removal to hard or selective removal to firm dentin [38, 45, 47]. The cavity seal is relied upon to reduce the activity of the biofilm by depriving the bacteria of nutrients, stopping the carious lesion progression.

Stepwise Removal

Stepwise removal is carious tissue removal in two steps (visits) [48–50]. In a first step, selective removal to soft dentin is performed. A temporary restoration is placed, and over the next 6–12 months, reactionary dentin continues to develop, remineralization takes place, and bacteria are inactivated. After this period, the restoration is removed and removal to firm dentin is carried out in the central part of the cavity (Fig. 3). The idea behind stepwise removal is that in the first step, pulp exposure is avoided while in the second step, less carious dentin needs to be removed (given the alterations that are taking place between the two steps) than would have to be removed when immediately excavating to firm dentin. The temporary restoration should be made of a material that provides a seal and is durable for at least 12 months, such as glass ionomer cement. Premature failure of the temporary restoration is one main complication of stepwise removal, jeopardizing the vitality of the pulp [51]. Stepwise removal might have higher risks of pulp exposure than selective removal to soft dentin, but has been shown to have lower risks than non-selective removal. Stepwise removal is recommended for very deep lesions (those involving the inner quarter of the dentin) [38, 51, 52].

No Removal at All and Sealing-In Lesions

Sealing-in lesions builds on the logic described earlier: lesions can be sealed and, therefore, arrested, as carbohydrates are no longer available to sealed bacteria. Moreover, sealing protects the sealed enamel or dentin by installing a diffusion barrier against acids [53, 54]. Fissure sealing over non-cavitated occlusal lesions and sealing and infiltration of proximal lesions can be successful although it is critical that the sealants are maintained. As discussed, such a sealant strategy involving plastic sealants is not suitable for cavitated, load-bearing carious lesions. Here, sealing using more durable materials, like preformed stainless steel crowns, the Hall Technique, has been

Fig. 3 Removal strategies. **a** For deep carious lesions in teeth with sensible pulps, a number of strategies are available. **b** Non-selective removal to hard dentin. Everywhere in the cavity, hard dentin remains. This is over-treatment; in deep lesions, this additionally results in high risk of pulp exposure. **c** In stepwise removal, soft dentin is left in the first step in proximity to the pulp and sealed temporarily. A second step after 6–12 months (dashed line) involves removal until only firm dentin remains in the pulpo-proximal areas. **d** Selective removal to soft dentin involves carious tissue removal to hard dentin peripherally, while soft dentin is left centrally. This avoids pulp exposure in deep lesions. **e** No removal can, as shown, involve sealing using crowns (note that the Hall Technique is not available for permanent teeth; this is only shown for demonstration purposes within the figure). Image from [46]

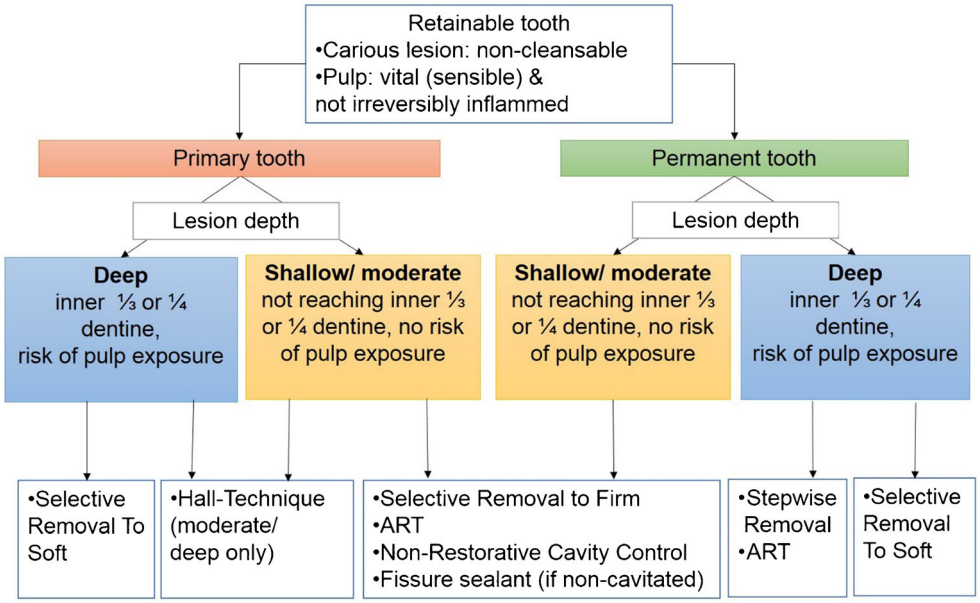

Fig. 4 Decision tree. Atraumatic restorative treatment (ART) has not been discussed in this review. Figure from [12••]. Copyright © 2018 (Copyright Holder). Reprinted by permission of SAGE Publications

suggested (Fig. 3). This technique is indicated for primary molars only. It involves placing a crown without any carious tissue removal and also without any tooth preparation. The advantages of this therapy is that it is very well tolerated by children [55, 56], biologically controls the lesion activity, and provides a long-lastingly restorative option for the cavity (most other direct restorations have a very limited performance in primary teeth) [57]. The Hall Technique has been found highly efficacious compared with conventional restorative treatment (involving carious tissue removal and placement of amalgam or glass ionomer restorations, for example) and also non-restorative cavity control [58, 59•].

No Removal at All and Managing the Biofilm Non-Restoratively

Non-restorative cavity control builds on the idea that the main reason why restorations are needed is to reinstall a cleansable surface (which is then amenable to oral hygiene from the patient again). Using this technique, cleansability is achieved by chiseling or drilling away the overhanging enamel or dentin, opening up the cavity [60]. Then, an oral hygiene program (including fluoride varnish application in the clinic) is instigated, working with the patient, and maintained. So far, this technique has been restricted to primary teeth and root surface lesions. Although clearly potentially successful in theory, in practice, the limited practice-based data available for primary teeth are not very supportive: the ability to change patients and, in the case of children, their parents' behavior to keep the cavity clean is limited [61]. Under certain circumstances that include assurance of optimal supervision, evidence of diet/brushing habit change, careful selection of tooth cavities, and frequent, regular, and well-recorded monitoring of lesion status over time, a non-restorative cavity control approach may serve children who are unable to accept any other treatment [61–64].

Conclusions

Historically, the aim of carious tissue removal prior to placing a restoration was to "eradicate" all bacteria from the enamel and dentin to "heal" the presumed infection. Caries is not seen as an infection any longer. Carious enamel, but also dentin lesions, even those containing large amounts of bacteria, can be sealed, depriving the bacteria from the dietary carbohydrate nutrition and inactivating them, thus arresting the lesion. Sealing over non-cavitated lesions can be effective, however, for most cavitated lesions, a sealant placed on top of them will be unable to withstand masticatory forces, meaning sealant fracture and/or retention loss, and lesion reactivation. Consequently, the contemporary aim of carious tissue removal prior to placing a restoration is to maximize restoration longevity. However, this aim should not be pursued at all costs: Especially in deep lesions with vital pulps, carious tissue removal should be performed in a way that avoids pulp exposure. Thus, in pulpo-proximal areas, soft or leathery dentin should be left if necessary to avoid exposure. Peripherally, removal should aim to have hard tissue around the cavity, allowing a tight, effective seal of any bacteria and promoting sufficient mechanical support for the restoration. In shallow or moderately deep lesions, peripherally, the tissue should again be hard after carious tissue removal, while centrally, firm (remineralizable) dentin should remain. Other carious tissue removal strategies include stepwise removal and sealing-in or non-restorative strategies.

In summary, the decision around which strategy to choose is guided by the pulpal status and the lesion depth, but also differs depending on the dentition (Fig. 4). Other patient related factors should be considered too. Always striving to remove until hard dentin remains is not in line with evidence and not recommended any longer.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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