Current Concepts and Techniques for Caries Excavation and Adhesion to Residual Dentin

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Abstract: The advent of “Adhesive Dentistry” has simplified the guidelines for cavity preparation enormously. The design and extent of the current preparations are basically defined by the extent and shape of the caries lesion, potentially slightly extended by bevelling the cavity margins in order to meet the modern concept of minimally invasive dentistry. New caries excavation techniques have been introduced, such as the use of plastic and ceramic burs, improved caries-disclosing dyes, enzymatic caries-dissolving agents, caries-selective sono/air abrasion and laser ablation. They all aim to remove or help remove caries-infected tissue as selectively as possible, while being minimally invasive through maximum preservation of caries-affected tissue. Each technique entails a specific caries-removal endpoint and produces residual dentin substrates of different natures and thus different receptiveness for adhesive procedures. This paper reviews the newest developments in caries excavation techniques and their effect on the remaining dentin tissue with regard to its bonding receptiveness.

Keywords: minimally invasive dentistry, dentin caries, caries excavation, bond strength of composite/dentin interfaces.

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he potential to bond restorative materials to tooth structure has altered the general principles of cavity preparation. While new steps were added to cavity preparation procedures, especially for bonding, others – such as cutting retentive cavity geometries – were omitted. In light of the minimally invasive dentistry concept,112 the macroretentive “G.V.Black” cavities15 have been replaced by cavities limited to removal of carious dentin that are at most extended with some additional rounding off of sharp margin edges and/or bevelling, the latter to the direct benefit of the subsequent bonding process.

However, the extent to which carious dentin should be removed in order to achieve a mechanically and biologically successful restoration is still a matter of debate. In particular, no definite diagnostic tool is today available to clinically define the caries-removal endpoint, enabling complete removal of infected tissue without overextending cavity preparation. In addition, the different techniques presently available for caries removal/cavity preparation produce residual dentin substrates of different natures and thus different receptiveness for adhesion. The extent of carious dentin excavation, the type of dentin substrate generated by each caries excavation technique, and the additional effect bonding agents exert on the residual dentin substrate are reviewed in this article, along with an in-depth discussion on aspects of dental caries histopathology. The latter is of direct importance for proper understanding of the rationale behind the different caries removal techniques.

WHY SHOULD CARIOUS DENTIN BE REMOVED BEFORE THE ACTUAL RESTORATION IS PLACED?

At the beginning of the past century, when the first operative dentistry guidelines were established, the term “caries excavation” was defined as a synonym for “cavity preparation”, which in turn consisted of “mechanical treatment of the injuries to the teeth produced by dental caries, as would best fit the remaining part of the tooth to receive a filling”.15 From this definition, it appears that caries excavation procedures were regarded as one of the many mandatory steps to prepare a tooth to receive the filling material. Furthermore, it has been described that the carious lesion should be excavated “until a hard pulpal floor...
was reached” and that “generally, when the cavity has been cut to form, no carious dentin will remain”. In short, carious dentin should be removed until a sufficiently solid layer of dentin was reached to support condensation of the restorative material (“stability form”) and to provide adequate retention for the filling material (“retention form”), promoting a successful and long-term survival of the restoration.

It is thus clear that when nonadhesive restorations were the only available option to directly restore decayed teeth, no distinct separation between caries removal and cavity preparation was made. In practical terms, it means that excavation of carious dentin was performed to remove necrotic, soft material in order to best accommodate the filling material. Perhaps it explains the general confusion still seen nowadays when dealing with the term “caries excavation” in view of the minimally invasive dentistry concept. As already mentioned, the ability to bond restorations has downgraded the rules for cavity preparation to simply and solely removing caries and, if needed, bevelling of the enamel cavity margins, while the main procedure of cavity preparation, or the excavation of caries, still lacks a more objective definition.

This leads to the initial question: Does carious dentin need to be removed prior to restoration placement? Clinical follow-ups of bonded restorations placed over soft carious dentin provided evidence that once the cavity margins are ready mentioned, the ability to bond restorations has downgraded the rules for cavity preparation to simply and solely removing caries and, if needed, bevelling of the enamel cavity margins, while the main procedure of cavity preparation, or the excavation of caries, still lacks a more objective definition.

It is generally advised to start carious dentin excavation when nonadhesive restorations were the only available option to directly restore decayed teeth, no distinct separation between caries removal and cavity preparation was made. In practical terms, it means that excavation of carious dentin was performed to remove necrotic, soft material in order to best accommodate the filling material. Perhaps it explains the general confusion still seen nowadays when dealing with the term “caries excavation” in view of the minimally invasive dentistry concept. As already mentioned, the ability to bond restorations has downgraded the rules for cavity preparation to simply and solely removing caries and, if needed, bevelling of the enamel cavity margins, while the main procedure of cavity preparation, or the excavation of caries, still lacks a more objective definition.

This leads to the initial question: Does carious dentin need to be removed prior to restoration placement? Clinical follow-ups of bonded restorations placed over soft carious dentin provided evidence that once the cavity margins are laid in relatively sound tissue, adequate marginal sealing is guaranteed and further progression of the carious lesion can be arrested. Apparently, therefore, well-sealed margins determine the long-term success of adhesive restorations, in particular with respect to arresting the caries progress. After all, since bonding to carious dentin is generally not as good as that to sound dentin, the somewhat unexpected answer to this question is that carious dentin is still removed in order to provide adequate retention for the filling material (achieving better bonding), thus producing long-term successful restorations.

As caries excavation is still an important step towards achieving good-quality bonded restorations, the next question arises: What is the current definition of the caries removal endpoint? Even now, there is still no better clinical criterion to define the caries excavation limit than the “normal” hardness feeling of sound dentin when probed by hand instruments. Although this so-called “cris dentinaire” is very subjective and dependent on the operator’s clinical background, it is still the gold-standard method to check residual caries. It was strongly corroborated after research showed that cariogenic bacteria were never found beyond the softening front of dentin. Further identification of a superficial infected dentin layer and a subjacent affected dentin layer has laid the foundation for a more rational approach for caries removal. Elimination of the heavily infected dentin and preservation of the residual affected dentin were thus defined as prerequisites for effectively arresting the carious process without harming the long-term survival of the pulp and the restoration. This has currently raised some discussion about moving toward more objective and hopefully more conservative approaches to selectively remove carious dentin.

HISTOPATHOLOGY OF DENTIN CARIES

Dentin is a mineralized tissue permeated by cellular extensions from odontoblasts, which are located at the peripheral zone of the pulp adjacent to the pre-dentin. For this reason, dentin, as a vital tissue, is perfectly able to respond to any stimuli, even when invoked at the enamel surface, such as an acid challenge produced by an organized, acid-producing biofilm.

The first detectable change in dentin in response to a cariogenic biofilm at the outer enamel surface is an area of sclerotic dentin subjacent to the demineralized enamel site (Figs 1A and 1B). The predominant feature of this reactive dentin is its increased translucency, which can be ascribed to intratubular mineral deposition. The translucent dentinal tubules will be those localized precisely beneath the demineralized enamel surface, and appear even before the enamel demineralization has reached the dentin-enamel junction (DEJ). Only when the caries lesion has progressed to a considerable length along the DEJ will the subjacent dentin be demineralized and become recognizable by a yellow to dark-brown discoloration (Figs 1C and 1D). At this point, bearing in mind that the dentin response to dental plaque is directly related to its metabolic activity and that different maturation stages can coexist in a fully-formed dental plaque depending on the self-cleaning ability of the surface, different phases of caries progression will coexist within one lesion (Figs 2A and 2B).

It is also well known that dentin caries will not spread laterally along the DEJ before dentin is cavitated and colonized by cariogenic bacteria. From this moment, the demineralized and thus unprotected organic dentin matrix (collagen) will be directly degraded through bacterial and host-mediating enzymes. Especially at peripheral parts of the cavity where the cariogenic biofilm is sheltered by the surrounding (undermined) enamel, the lesion may spread rapidly along the DEJ (“hidden” caries lesion) (Figs 2B and 2C).

CARIES-EXCAVATION PROCEDURES

Conventional Excavation with Burs
Carbon-steel or tungsten-carbide burs
Tungsten-carbide burs replaced carbon-steel burs once the process of hardening steel with tungsten carbide was introduced to the dental bur industry. Microscopic tungsten-carbide particles are held together in a matrix of cobalt or nickel at the head (working end) of the bur. The head has typical spiral-like cutting edges with or without additional cross cuts to improve cutting efficiency. Carbon-steel burs possess the same caries-removing properties as tungsten-carbide burs and are less expensive, but they are much more prone to corrosion and dulling. For caries removal, a round bur is recommended with diameters corresponding to the size of the carious lesion. Water irrigation is optional because generally low-speed (700 to 800 rpm) counter-angle handpieces are employed. It is generally advised to start carious dentin excavation from the periphery towards the center of the lesion in order to minimize the risk of infection in case of accidental...
pulp exposure. Larger burs are recommended for this reason as well.

Tungsten-carbide or carbon-steel burs in low-speed counter-angle handpieces are the most efficient method to excavate carious lesions in terms of time, and are therefore still the most widely used caries-excision method. However, in terms of minimal invasiveness, bur-prepared cavities, combined with the use of a dental explorer to check for the caries removal endpoint, tend to overexcavate. This was found, for instance, when auto-fluorescence induced by bacterial metabolites was used to detect carious tissue. When studied by scanning electron microscopy (SEM), this method leaves a homogeneous smear layer with more or less uniform roughness, and dentinal tubules visibly obstructed with smear plugs. With regard to bonding receptiveness, the smear-covered surface does not interfere with etch-and-rinse adhesives, but has been shown to potentially reduce the bonding effectiveness of self-etching adhesives.
Polymeric burs

In an attempt to develop a selective caries-removal rotating instrument, a “plastic” bur was made of a polyamide/imide (PAI) polymer, possessing slightly lower mechanical properties than sound dentin. However, soon it became clear that if the bur touches sound or caries-affected dentin, it quickly becomes dull and produces undesirable vibration, making further cutting impossible. The blade design was developed to remove dentin by locally depressing the carious tissue and pushing it forward along the surface until it ruptures and is carried out of the cavity. With a prototype, single-use instrument, complete removal of carious tissue could be accomplished from extracted teeth when a 1% acid-red-propylene glycol solution was used as caries detector.

The commercial version of these burs (SmartPrep, SS-White Burs; Lakewood, NJ, USA) consisted of a polymer (PEKK – polyether-ketone-ketone) with a particular hardness of 50 KHN, which was higher than the hardness attributed to carious dentin (0 to 30 KHN), but lower than that of sound dentin (70 to 90 KHN). As opposed to conventional carbide burs, their cutting edges were not spiralled but straight.

One disadvantage was that by keeping to the recommendation to excavate caries from the center to the periphery in order to avoid contact with sound tooth tissue, the bur would be prematurely and irreversibly damaged. Local anaesthesia was said not to be needed, based on the claim that these plastic burs would remove only the insensitive, soft, and necrotic carious dentin (caries-infected dentin), leaving the demineralized, noninfected sensitive layer (caries-affected dentin). Nevertheless, while the need for local anaesthesia during cavity preparation was in fact reduced, some patients still reported one or more episodes of pain sensation during treatment.

The efficacy of the SmartPrep burs for caries removal was questioned in a histological study when excavated tooth sections were stained with Mallory-Azan. More residual caries was found in cavities excavated with SmartPrep burs than in cavities prepared with conventional tungsten-carbide burs. In addition, not only the microtensile bond strength to carious dentin excavated with SmartPrep burs was lower for both etch-and-rinse and self-etching adhesives, transmission electron microscopy (TEM) of the bonded interfaces disclosed remnants of carious tissue at the excavated dentin/composite interface. It was then suggested that the efficiency of the polymer burs could be enhanced if the hardness of the polymeric material could be increased.

An improved version of the polymeric burs was more recently marketed (SmartBurs, SSWhite Burs; Lakewood, NJ, USA) and resulted, in primary teeth, in the highest coincidence between the caries removal endpoint obtained by autofluorescence of carious dentin and the actual degree of caries removal. A great amount of residual caries was nevertheless still found, especially in inactive caries-arrested lesions. This can probably be explained by the still rather low surface hardness of the SmartBurs (26.6 KHN) as compared to the hardness of arrested carious dentin (39.2 KHN).

Ceramic burs

A new line of slow-speed rotary cutting instruments made of ceramic materials is now commercially available for removal of carious dentin. The CeraBurs (Komet-Brasseler; Lemgo, Germany) are all-ceramic round burs made of alumina-yttria stabilized zirconia and are available in different diameter sizes (Fig 3). The manufacturer claims that besides its high cutting efficiency in infected, soft dentin, the use of this instrument for caries removal replaces both the explorer and the excavation spoon (commonly needed to evaluate the degree of decay removal) by simultaneously providing tactile sensation, self-evidently reducing prepara-
tion time.

However, an in vitro investigation of the caries-removal efficiency (time consumption for excavation) and efficacy (ability to remove all carious material from the cavity) did not show any significant difference between the ceramic and conventional tungsten-carbide burs. Nevertheless, one important aspect to be emphasized – and which applies to all kinds of bur instruments – is its nonspecificity. Especially if no tactile instrument is used to check the cavity for its hardness, areas of underprepared dentin are likely to be left, as can be observed in the 3D volumetric reconstruction of a carious tooth when caries was excavated using ceramic burs (Fig 4). Further in vivo studies testing the effectiveness of these new burs are unfortunately still lacking.

Caries-disclosing Dyes

Early TEM and biochemical characterization of carious dentin revealed that the most superficial carious layer is necrotic, highly decalcified, and contains irregularly scattered granular crystals and irreversibly denatured collagen fibrils. Underneath this “caries-infected” dentin, the deeper “caries-affected” dentin layer exhibits decreased collagen crosslinks, but comprises needle-like apatite crystals, regularly attached to collagen fibrils with no signs of bacterial invasion. Based on this knowledge, the ideal caries-disclosing dye should stain solely the caries-infected, but not the caries-affected dentin.
0.5% Basic fuchsin in a propylene glycol base

One of the first caries-disclosing dyes was based on a solution of 0.5% basic fuchsin in propylene glycol and was claimed to stain exclusively the top, irreversibly destroyed carious layer, enabling differentiation from what could be left in the cavity. The mechanism of this differential staining was initially ascribed to the irreversible collagen denaturation of caries-infected dentin, caused by breakdown of the intermolecular crosslinks through bacterial lactic acid. Later, the differential stainability was attributed rather to differences in the degree of mineralization in the carious lesion than being specific for denatured collagen fibrils. The exact mechanism for the differential staining is however still unknown.

The first combined clinical/laboratory study on the reliability of this caries-disclosing dye has pointed out that the extent of dentin excavated by the fuchsin-guided method was larger than the extent of demineralized dentin, as shown by conventional dental radiographs taken before histological sections were made. Later, others also showed that when caries was removed using conventional tactile probing to determine the caries removal endpoint, both in primary and permanent teeth, the cavity walls and floors were still fuchsin-stainable. Some concerns were also raised regarding possible carcinogenic effects of fuchsin for intra-oral use, and for this reason, alternative caries-disclosing dyes are sought.

1% Acid-red in propylene glycol base

Although a 1% acid-red solution (Caries Detector, Kuraray; Tokyo, Japan) was launched as an alternative to fuchsin for intra-oral use, clinical inconsistencies have been reported when assessing the presence of stained tissue at the DEJ by means of the usual tactile probing method. Two studies have shown that more than half of the teeth judged clinically as having no caries at the DEJ could be stained with acid red. Microbiological assessment of the caries-stained and stain-free dentin at the DEJ failed to disclose differences in level of infection. Moreover, it has been demonstrated that a 1% acid-red solution can lead to staining of dentin clinically judged as “sound”, with a 30% false positive diagnosis of residual caries. At the pulpal floor, also more than half of the teeth diagnosed as having “hard” and “sound” pulpal floors still took up some stain. In fact, it has been reported that sound circumpulpal dentin takes up stain more easily, because of its lower degree of mineralization (Fig 5). For all these reasons, the use of caries-staining agents is still much criticized.
Comparing acid red to basic fuchsin, both in propylene glycol bases, acid-red produces a less intense and less bound stain with a more intense staining of the outer than the inner layer of carious dentin. Further in vitro studies have shown that the light pink staining from acid red, typically seen at the inner layer of carious dentin, was related to a low degree or absence of bacterial infection as well as to a low level of peritubular dentin dissolution and increased hardness. For these reasons, the lightly stained tissue should not be removed.

Another concern is that the propylene glycol base of both staining agents can easily penetrate into normal dentin due to its low molecular weight (76 MW), which could also explain the overstaining frequently reported for commercial products, such as Caries Detector. This finding has recently led to the introduction of a 1% acid-red dye in a polypropylene glycol base (Caries Check, Nippon Shika Yahuhin; Japan). The higher molecular weight of polypropylene glycol (300 MW) makes it more caries specific than a propylene-glycol-based dye. The fluorescence readings of residual dentin using DIAGNOdent (Kavo Dental; Jena, Germany) after caries removal guided by acid red in polypropylene-glycol-based dye were higher than those when caries was removed using a propylene-glycol-based dye, indicating that less dentin was removed with the former caries-detecting agent.

Clinically, both formulations of Caries Check (1% acid red or a 1% brilliant blue FCF in a polypropylene glycol base) also produced significantly lower DIAGNOdent readings after caries removal than an 1% acid red in propylene glycol. The blue version of the dye was introduced to facilitate identification of caries in heavily stained cavities, where the red color is more difficult to differentiate.

**Chemo-mechanical Excavation**

**Sodium hypochlorite-based agents**

The first attempt to develop of a chemical solubilizer that would selectively act on carious dentin resulted in a sodium hypochlorite solution buffered with an amino-acid-containing mixture of amino butyric acid, sodium chloride and sodium hydroxide. Even though sodium hypochlorite is a nonspecific deproteinizing agent, the capability to selectively remove carious dentin was attributed to the buffering effect of the amino acid mixture, originally intended to reduce the aggressiveness of sodium hypochlorite on sound dentin and to enhance the disrupting effect on degenerated collagen within carious dentin. After chlorination and cleavage of the partially degraded collagen fibrils in the carious lesion, the resultant friable collagen fibrils could be more easily removed with a spoon excavator.

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Fig 5A Mesiodistal section of a tooth presenting occlusal dentin caries (black arrow) and an approximal lesion (white arrow). DD = demineralized dentin; HD = hypermineralized dentin.

Fig 5B Higher magnification of the dotted area in Fig 5A after staining with a 1% acid-red-in-propylene-glycol solution. Note staining of circumpulpal dentin (black arrow) and areas of hypermineralized dentin (white arrow).

Fig 6A Volume rendering based on x-ray micro-CT data (occlusal view) from a tooth presenting dentin caries (insert: stereomicroscopic view).

Fig 6B Volume rendering based on x-ray micro-CT data of the same tooth after excavation with the aid of a pepsin-based gel and a specially designed plastic instrument (SFC-VIII, 3M ESPE) (insert: stereomicroscopic view).

Fig 6C Volume rendering based on x-ray micro-CT data of one slice (corresponding to the dotted line in Fig 6A before excavation, showing the extent of the lesion into dentin (blue = carious lesion; green = sound dentin).

Fig 6D Volume rendering based on x-ray micro-CT data of one slice (corresponding to the dotted line in Fig 6B after excavation, showing the extent of the excavated dentin (blue = carious lesion; green = sound dentin).
However, this new caries-removing system, first commercialized as Caridex (National Patent Medical Products; New Brunswick, NJ, USA), was not fully successful in clinical practice. Not only its efficacy in caries removal was contested, but technical problems – such as the need of a specific apparatus to deliver the solution into the cavity, short shelf-life, longer treatment time, and higher treatment cost – were advanced as reasons why it was not adopted extensively by dental practitioners.

Renewed interest in chemomechanical caries removing agents was associated with the emerging concept of minimally invasive dentistry. A new caries removing system, also based on sodium hypochlorite, was introduced in the form of a gel (Carisolv, MediTeam Dental; Sävedalem, Sweden) which contained 0.5% w/v sodium hypochlorite, 0.1M of an amino acid mixture (glutamic acid, leucine and lysine), and water. The gel is applied in the cavity, after which the carious dentin is scraped off using specially designed noncutting hand instruments. The method has been shown to effectively remove caries and was readily accepted by patients. However, compared with conventional drilling, a substantially longer treatment time was reported. In fact, the operative steps in chemomechanical caries excavation include: (1) application of the solution, (2) scraping off the carious dentin with possible change of instrument size, (3) rinsing, and (4) repetition of the procedures until all caries is removed. However, if the use of local anaesthesia can be omitted, the total treatment time can be shortened.

Carisolv has proven its efficacy in establishing the endpoint of caries excavation by removing carious dentin to the same extent as the auto-fluorescence signature of carious tissue when measured using confocal microscopy. However, histological evaluation using toluidine blue as a staining agent still revealed a higher percentage of teeth presenting bacteria invading the dentinal tubules. A great amount of residual bacteria was also detected at the DEJ, where direct access of the gel and the hand instruments is difficult. The presence of bacteria at the bottom of the cavity was explained by the relative absence of smear layer formation when Carisolv was used, and presumably resulted from “pushing” bacteria into the dental tubules. On the other hand, the viability of such residual bacteria should be very low, because Carisolv has some bactericidal activity due to formation of chloramine compounds. In fact, Carisolv has proven to be somewhat superior in reducing the counts of viable bacteria in residual dentin, as compared to conventional bur excavation.

The chemical composition and microstructure of dentin after excavation with Carisolv does not seem to be significantly altered. The calcium and phosphorus content remain similar after excavation, while the hardness values of residual dentin left at the cavity bottom approximate those obtained for sound dentin. Actually, the chloride present in the gel does not seem able to interact with the collagen fibrils of sound dentin, since they are protected by mineral crystals.

Although the etch pattern of dentin in Carisolv-excavated lesions is deeper than that in dentin from which caries was removed with a conventional bur guided by a caries-staining dye, the bonding effectiveness of adhesives to Carisolv-treated dentin did not appear to be affected. Carisolv-excavated dentin has good bonding receptiveness, meaning that it is not covered by a smear layer, exhibits patent dentinal tubules and an irregular surface topography with improved wetting potential. Acceptable bond strengths have been reported after caries was excavated with Carisolv and a self-etching adhesive was employed. In other studies, bond strengths obtained with both etch-and-rinse and self-etching adhesives to dentin from which caries was excavated with Carisolv were even found to be similar to that of sound dentin.

Pepsin-based caries excavation

A new experimental gel consisting of pepsin in a phosphoric acid/sodium biphosphate buffer is being considered as an alternative chemomechanical caries excavation agent (SFC-VIII, 3M ESPE; Seefeld, Germany). The main advantage of this new enzyme-based solution is that it can be more specific by digesting only denatured collagen (after the triple-helix integrity is lost) than the sodium hypochlorite-based agents. According to the manufacturer, the phosphoric acid dissolves the inorganic component of carious dentin, while it at the same time gives pepsin access to the organic part of the carious biomass to selectively dissolve the denatured collagen. To avoid overexcavation, the SFC-VIII gel should be used in combination with a prototype plastic instrument having hardness between that of sound and infected dentin. Heavily pigmented, arrested dentin caries is known to be more resistant to pepsin digestion, but this does not seem to present a major drawback to the method.

An x-ray micro-CT evaluation of carious teeth excavated with SFC-V revealed that the new enzymatic caries-removing gel was able to remove equivalent volumes of carious dentin as Carisolv. Figure 6 shows volume-rendering slices based on micro-CT data of a carious tooth before and after caries excavation with SFC-VIII aided by the prototype plastic instrument, SFC-VIII selectively removed carious dentin, leaving residual dentin with an acceptably high mineral density (1.18 to 1.44g/cm³). Figure 7 shows the prototype plastic instrument (Star v 1.8, 3M ESPE) before and after caries excavation.

Others have found partially de-mineralized intertubular collagen fibrils and some tubule occlusion upon treatment of artificially-formed dentin caries with a pepsin-based caries-extraction agent. However, further laboratory studies and clinical trials are still lacking.

Excavation by sono-abrasion

Caries excavation by “sono-abrasion” is based on the use of cutting tips coupled to high-frequency, sonic, air-scaler handpieces under water cooling. The handpiece oscillates in the sonic region (< 6.5 kHz), while the tips perform an elliptical motion. A maximum 2-N torque force should be applied, otherwise the cutting efficiency is reduced due to damping of the oscillations.

Sono-abrasion excavation with diamond-coated tips appeared as efficient (time required for excavation) as conventional hand excavation using dental spoons, but still taking more time than the carbide-bur excavation method.
Regarding caries removal, the effectiveness of sono-abrasion based on its auto-fluorescence signature has shown a tendency to underprepare carious cavities. Some authors speculated that the oscillation of the diamond-coated tip is transferred to only a slight vibration at the dentin surface, impairing effective tissue cutting and resulting only in a compacting effect on the carious dentin substrate.8 No chemical or structural changes were observed in sono-abraded dentin, the surface characteristics of which resembled those of conventionally bur-cut dentin.113 The surface topography of dentin after sono-abrasion excavation with diamond-coated tips revealed relatively little9 or even no evidence of smear layer formation.116 According to another study, any smear layer produced tends to be thinner than the one yielded by diamond/carbide burs,95 which may be advantageous for the bonding effectiveness of so-called mild self-etching adhesives in particular.39

More recently, the Cariex system (Kavo Dental; Biberach, Germany) was launched, including two sets of cutting tips: two diamond-coated tips with different diameters for enamel preparation and two tungsten-carbide tips with different diameters for dentin excavation (Fig 8). The effectiveness and efficacy of these new tungsten carbide tips in removing carious dentin have, however, not yet been explored.

Air-abrasion Excavation

Air-abrasion systems for cavity preparation use the kinetic energy of abrasive particles to cut tooth structure in a less invasive way, while rounding off internal and cavosurface angles to the direct benefit of the subsequent adhesive restoration. Pure aluminium oxide particles (alumina) have been most frequently used as the abrading agent, thanks to their high cutting effectiveness, chemical stability, low cost, low affinity for water, and neutral color.16

Air-abrasion systems using 27-μm diameter alumina particles are currently available to remove tooth staining or to prepare shallow cavities. Aside from the type and size of the abrasive particles, other variables which also directly influence the cutting effectiveness of air-abrasion systems are the particle speed and the angle of surface approach, and naturally the properties of the substrate itself. The major drawback of air-abrasion excavation of carious dentin is that sound dentin is more efficiently removed than carious dentin.92 Although 27-μm alumina particles have proven to remove more carious dentin than particles with larger dimensions (50- and 125-μm diameter), cavities produced in sound dentin were still considerably deeper than in carious dentin.82 As carious dentin has a softer consistency, the energy of the particles is absorbed during the impact, reducing the cutting ability.

Other types of particles were tested in order to improve the effectiveness of caries removal with air-abrasion systems. Spherical glass beads with different diameters improved removal of artificially softened dentin, but although at lower rates, sound enamel and dentin were still removed. Polycarbonate resin-crushed powder removed artificially softened dentin more selectively without cutting sound dentin or enamel,45 but further clinical investigations with these particles are still lacking. A mixture of alumina and hydroxyapatite in a volume ratio of 3:1, with particle sizes ranging from 3 to 60 μm, was shown to be as efficient as conventional hand excavation with dental spoons, and was positively rated when related to the auto-fluorescence signature of the lesion.8 An air-abrasion system that makes use of a
bioactive glass powder (Bioglass, Novamin Technology; Alachua, USA) with a particle diameter between 25 and 32 μm was also explored. Although still removing sound dentin, the risk of unnecessary sound dentin removal was reduced because of the difference in cutting rate between sound and carious dentin. The authors suggested that other bioactive glasses with different hardness should be evaluated for their caries-removal selectivity.

The topography of residual dentin caries after removal with 50-μm alumina particles exhibits a porous, sponge-like appearance caused by the impact of the particles under compressed air. Remnants of alumina powder were also identified and tubules were fully occluded with surface debris. Although air abrasion produces a more irregular, imbricated surface pattern and a thinner smear layer when compared to bur-cut dentin, it does not seem to affect bonding performance of adhesives to dentin on the condition that it is still acid-etched if etch-and-rinse adhesives are employed.

Fluorescence-aided Caries Excavation ("FACE")

This technique was developed as a direct method to clinically differentiate between infected and affected carious dentin. Based on the fact that several oral microorganisms produce orange-red fluorophores as by-products of their metabolism (porphyrins), infected carious tissue will fluoresce especially in the red fraction of the visible spectrum due to the presence of proto- and meso-porphyrins. In this way, continuous visual detection of orange-red fluorescence during caries excavation was thought to be convenient for clinicians.

By feeding a slow-speed handpiece with a fiber-optic violet light source (370 to 420 nm) and allowing the operator to use a 530-nm yellow glass filter, areas exhibiting orange-red fluorescence can be selectively identified and removed with the bur. Compared to Caries Detector or the visual-tactile method for establishing the caries removal endpoint, the FACE method showed the highest sensitivity, specificity, percentage correct score, and predictive values for residual caries detection, as evaluated using confocal microscopy. Histological examination after staining with ethidium bromide revealed fewer samples presenting bacteria in dentin when the FACE method was used than was the case with conventional bur excavation. Others failed to find differences in the number of infected samples between FACE and conventional bur excavation, but observed a significant reduction in the number of samples presenting residual bacteria after excavation with FACE, when compared to Carisolv or bur excavation guided by Caries Detector.

The FACE method also proved to be very efficient, with less time needed to excavate caries and without a need to change instruments, apply chemical agents, or test the cavity with an explorer. Another important aspect is that the increased caries-removal efficacy of FACE was apparently not associated with an increased cavity size or overexcavation.

Excavation Aided by Laser-induced Fluorescence

Based on the above-mentioned fact that caries-induced changes lead to increased fluorescence of dentin at the 655-nm (red) wavelength, a laser-fluorescence device that irradiates at this particular wavelength has been developed to diagnose “hidden” occlusal carious lesions. A photodiode attached to the tip of the handpiece measures the feedback of fluorescence after initial irradiation, where the intensity of fluorescence at the occlusal surface is directly related to the degree of caries progression into dentin. Based on a diagnostic scale correlating the readings of fluorescence with the histological presence of caries, values above 30 should be considered a stage of caries progression demanding operative intervention.

Beyond using laser-induced fluorescence for occlusal caries diagnosis, these readings are currently being investigated as a possible end-point guide to caries excavation. Based on a comparison with histological examination in the confocal microscope after staining with ethidium bromide, a DIAGNOdent reading of 15 was seen to best predict the presence of residual caries at the bottom of the cavity. Lat- ter, this value was correlated to the absence of detectable bacteria, and thus set as the endpoint for complete caries removal. It is interesting to note that when Caries Detector was used as caries removal endpoint, a threshold of 11 was found, corroborating previous findings that the staining method invariably leads to overexcavation. When combined with caries removal using an erbium laser, a DIAGNOdent threshold between 11 and 20 was shown to best predict removal of infected carious dentin. Others who used a threshold value of 30 for dentin caries have found acceptable sensitivity values (ability to correctly diagnose caries) for DIAGNOdent when used to determine the caries removal endpoint. One should, however, realize that the DIAGNOdent readings increase with the proximity to the pulp as well as with stained, sclerotic dentin, which could lead to a false-positive threshold for caries removal.

Laser Excavation

The word “laser” is an acronym for “Light Amplification by Stimulated Emission of Radiation”, which means that laser devices produce beams of coherent and high-intensity light. The indications for the use of lasers in dentistry are nowadays broad, varying from caries diagnosis, disinfection of periodontal pockets or root canals, photodynamic therapy of oral tumors, soft-tissue surgery, caries removal, and cavity preparation. Especially in the field of operative dentistry, erbium lasers have been pointed out as most promising due to their specificity in ablating enamel and dentin without side effects to the pulp and surrounding tissues when the appropriate parameters are employed.

The erbium-loaded yttrium-aluminum-garnet (Er:YAG) and the erbium, chromium: yttrium-scandium-gallium-garnet (Er,Cr:YSGG) lasers are the two types of erbium-based devices currently available on the market. Both devices present very similar wavelengths (2.78 μm for Er:Cr:YSGG and 2.94 μm for Er:YAG), although the Er,Cr:YSGG laser is discretely more absorbed by hydroxyapatite than Er:YAG. Despite this difference, both wavelengths are very close to the absorption peak of water in the infrared spectrum, which makes their interaction with dental hard tissues very similar.
Fundamentally, the mechanism by which enamel and dentin are removed during Er:YAG irradiation consists of explosive subsurface expansion of water interstitially trapped in the dental hard tissues. During irradiation, the water molecules absorb the incident radiation, causing sudden heating and water evaporation. As a result, a high-stream pressure is formed, inducing a violent, yet controlled expansion and ejection of dental hard tissue components.\(^{50}\) In contrast, the Er:Cr:YSGG laser system, usually known as a "laser-powered hydrokinetic system", delivers photons straight into an air-water spray directed to the target tissue. This phenomenon induces micro-explosive forces into water droplets, which is said to contribute significantly to the mechanism of hard-tissue removal.\(^{44}\) Unfortunately, no systematic studies comparing these two types of erbium lasers have been performed so far, especially considering their particular effects on cavity morphology and on the characteristics of the residual dentin after caries removal.

Several advantages have been related to the use of laser irradiation in operative dentistry, such as a more conservative cavity design, an alleged antibacterial activity,\(^{111}\) and a significant decrease of enamel solubility, therefore also possibly playing a role in the prevention of recurrent caries.\(^{23}\) Moreover, laser ablation apparently provides more comfort to the patient due to the absence of vibration\(^{57}\) and a lower pain sensation. In fact, the need for local anaesthesia is reported to be lower when compared to the use of conventional rotary instruments.\(^{58}\) On the other hand, the major drawback related to their use in operative dentistry is the relatively long time needed for cavity preparation. The time required for a complete excavation is, in general, twice that with rotary instruments.\(^{4,12,58}\) Recently, one study succeeded in reducing the overall cavity preparation time by using considerably high energies (700 mJ).\(^{80}\) However, it should be noted that such high energies can also induce irreversible chemical and structural alteration to the dental hard tissues\(^{7}\) and even damage the pulp.\(^{114}\)

Irrespective of the parameters used during laser irradiation, the effectiveness of carious dentin removal with erbium lasers has been questioned. SEM has shown that the laser produces an undefined and random excavation pattern in dentin, with deep overprepared and wide underprepared zones present in the same cavity. For optimal irradiation, a noncontact beam emission mode is usually recommended, thus rendering caries excavation more difficult to control due to the lack of tactile sensation.\(^{12}\) Moreover, the irregular dentin surface left after laser ablation hampers an accurate tactile feedback when an ordinary probe is used for detecting the status of excavation.\(^{12,116}\) Despite this, some studies have relied upon visual/tactile methods\(^{44,57}\) or staining with 1% acid-red solution to evaluate the thoroughness of caries removal,\(^{4}\) obtaining residual dentin hardness values similar to sound dentin. Histological observations have also disclosed the same degree of bacterial removal by an Er:YAG laser and conventional bur excavation.\(^{4}\) Additionally, better DIAGNoDent scores of residual dentin were obtained after excavation with an Er,Cr:YSGG laser than with Carisolv.\(^{63}\)

Although Er:YAG laser ablation is not selective for carious dentin, it has been described that the popping sound emitted by these lasers when operating in dental hard tissues changes according to the presence or absence of caries. This change in sound could assist the user in determining when caries removal is complete.\(^{114}\) This approach is, however, not very objective or practical, and is susceptible to misinterpretation. An improvement in the caries-removal ability of erbium lasers is to combine it with laser-fluorescence technology for caries detection. In one unit (Key III, KaVo Dental), Er:YAG laser irradiation is controlled by the feedback response provided by the red-infrared diagnostic diode laser, resulting in a self-limiting laser ablation. Actually, the laser ablation is activated only if the fluorescence emitted from the dental tissue exceeds a pre-determined threshold.\(^{32}\) An initial threshold value of 7 for the laser fluorescence detection system removed all bacteria at the bottom of the cavity, as was detected histologically.\(^{32}\) This threshold value was corroborated by clinical studies in permanent\(^{31}\) and primary teeth,\(^{67}\) in which only clinically insignificant amounts of bacteria could be detected at the bottom of the excavated cavities. Beyond appropriate removal of infected dentin, this laser also precluded less sound dentin removal, resulting in smaller cavities compared to conventional bur excavation.\(^{33}\)

Absence of smear layer is very often mentioned as an advantage of laser irradiation of tooth surfaces, in particular for bonding procedures.\(^{5,56,63}\) However, while relatively high bond strengths have been reported with either an etch-and-rinse or a self-etching adhesive after caries removal with an Er:YAG laser,\(^{101}\) other authors found lower bond strengths to laser-irradiated dentin when compared to a conventionally bur-cut substrate.\(^{21,105,113}\) Such disappointing results have been related to the presence of subsurface microcracks produced in dentin during laser ablation, rendering it more prone to cohesive failures.\(^{21}\) Moreover, laser-irradiated dentin has also been reported to change the composition and conformation of the organic matrix of dentin,\(^{7}\) which may impair adhesive penetration and facilitate collagen degradation.

**ADHESION TO CARIOUS DENTIN**

Sound human dentin is most convenient to test the performance of dental adhesives by means of standard bond-strength protocols. This "model" dentin is, however, far from the clinically more relevant substrate remaining after caries removal, which exhibits “mixed” chemical and mechanical characteristics and includes caries-infected, caries-affected, sclerotic, eroded, and sound dentin.\(^{79}\)

In general, the presence of carious dentin results in thicker hybrid layers and lower bond strengths.\(^{83,84,123,124}\) The bond strength of adhesives to carious dentin has been reported to be inversely proportional to the degree of caries progression, with caries-infected dentin presenting the lowest bond strength.\(^{30}\) The thickness of the hybrid layer is indirectly correlated to the degree of caries progression, with caries-infected dentin presenting thicker hybrid layers, followed by caries-affected and sound dentin.\(^{52,123,124}\) Like in sound dentin, hybrid layers in caries-affected dentin are thicker using etch-and-rinse than self-etching adhesives.\(^{52}\) For caries-infected dentin, however, the thick-
ness of the hybrid layer tends to be similar, irrespective of the adhesive approach. Thicker hybrid layers in caries-affected dentin are explained by the increased porosity of intertubular dentin, which promotes diffusion of resin monomers. The lower bonding effectiveness to caries-infected dentin is related to its extremely low cohesive strength, due to its low degree of mineralization and the collagen-matrix disorganization. Although resulting in thicker hybrid layers, this type of dentin allows only superficial monomer penetration, keeping many dentin tubules completely free from tag formation. Considering the poor interaction with the substrate, bonding to caries-infected dentin is seldom indicated, except when aiming to prevent further caries progression in uncooperative patients while implementing behavior control.

The lower bonding effectiveness to caries-affected dentin than to sound dentin is related to the alterations that occur in this substrate as a consequence of caries progression. First, the reduction in mineral content and loss of crystallinity of the remaining mineral phase, coupled to the changes in the secondary structure of collagen, result in a dentin substrate with a lower hardness and modulus of elasticity than those of sound dentin, performing poorer in mechanical tests. Secondly, the deposition of mineral casts, namely of β-tricalcium phosphates (whitlockites), in the dentin tubules during caries progression also alters the etch pattern and thus the penetration capacity of resin monomers into the tubules. When bonding using the moist bonding technique with etch-and-rinse adhesives, some studies were able to achieve similar bond strengths to residual dentin after caries excavation (guided by Caries Detector) as to sound dentin. While one of these studies with sound dentin achieved a relatively “low” bond strength (20 to 30 MPa) compared to what is achieved nowadays with modern adhesives (40 to 50 MPa), the others may have achieved these favorable results by using a rather aggressive threshold to establish the endpoint of caries removal, that is, by having produced a substrate that is more receptive for bonding than that obtained in other studies. It was also demonstrated that acetone-based etch-and-rinse adhesives bonded better to caries-affected dentin than did ethanol-based adhesives, although both were able to produce acceptable bond strengths to non-stained (with Caries Detector) dentin left after excavation.

Although other studies were not able to produce similar results in bond strength to sound as to caries-affected dentin for many materials tested, it became clear that the chemical composition of the adhesive could strongly influence the bond strength to caries-affected dentin. Apparently, the immediate bond strength of etch-and-rinse adhesives to caries-affected dentin is higher than that of self-etching adhesives. However, no differences in bond strength of etch-and-rinse and self-etching adhesives to carious dentin was observed after the specimens were stored for 6 months in water.

In summary, although the bond strength at caries-affected dentin interfaces is lower than at sound dentin interfaces, they are both continually improving and have now reached relatively high values. Table 1 offers an overview of bond-strength values in relation to different caries removal endpoints employed, different methods used to produce the carious substrate, and different types of adhesives used. Figure 9 summarizes the bond strength values depicted in Table 1, when the caries removal endpoint was obtained with two different thresholds for staining (no staining vs light-pink staining) and after the carious dentin substrate was produced with a standardized surface-preparation method using 600-grit SiC paper. Figure 10 depicts the bond strength results for the studies presented in Table 1 that used a conventional bur and Carisolv to excavate cavities. In both cases, essentially no differences in bond strength between etch-and-rinse and self-etching approach were found. Altogether, irrespective of the caries excavation method chosen, it remains clinically recommended to finish the cavity margins in clean/sound tooth tissue in order to achieve the best performance of adhesives, while being at the same time least invasive with regard to caries excavation and most conservative with regard to sound-tissue preservation.

**REFERENCES**

Table 1. Bond strength related to the different caries removal endpoints, type of caries-affected substrate, and adhesive material used

<table>
<thead>
<tr>
<th>Method of caries excavation endpoint</th>
<th>Type of caries-affected substrate</th>
<th>Type of adhesive (brand name)</th>
<th>μTBS</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Staining with 0.5% fuchsin</td>
<td>220-grit SiC paper</td>
<td>2-step etch-and-rinse (Prime &amp; Bond NT, Dentsply)</td>
<td>41.3±10.7</td>
<td>Ceballos et al\textsuperscript{22}</td>
</tr>
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<td></td>
<td></td>
<td>2-step etch-and-rinse (Scotchbond 1, 3M ESPE)</td>
<td>36.3±12.2</td>
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<td></td>
<td></td>
<td>2-step self-etch (Clearfil SE Bond, Kuraray)</td>
<td>21.5±5.5</td>
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<td></td>
<td>1-step self-etch (Prompt L-Pop, 3M ESPE)</td>
<td>13.4±1.9</td>
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<td>Non-stained dentin remaining after using Caries Detector</td>
<td>600-grit SiC paper</td>
<td>3-step etch-and-rinse (Scotchbond MP, 3M ESPE)</td>
<td>48.2±3.9</td>
<td>Nakajima et al\textsuperscript{85}</td>
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<td></td>
<td>3-step etch-and-rinse (ART Bond, VITA)</td>
<td>30.2±13.4</td>
<td>Nakajima et al\textsuperscript{84}</td>
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<td></td>
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<td>2-step etch-and-rinse (One-Step, Bisco)</td>
<td>45±7.2</td>
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<td>2-step etch-and-rinse (Single Bond, 3M ESPE)</td>
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<td>2-step etch-and-rinse (Single Bond, 3M ESPE)</td>
<td>28.8±6.3</td>
<td>Yoshiyama et al\textsuperscript{123}</td>
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<td>2-step etch-and-rinse (Single Bond, 3M ESPE)</td>
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<td>Yoshiyama et al\textsuperscript{122}</td>
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<td></td>
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<td>2-step self-etch (Clearfil SE Bond, Kuraray)</td>
<td>30.3±11.9</td>
<td>Tachibana et al\textsuperscript{105}</td>
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<td>2-step self-etch (Clearfil Liner Bond 2, Kuraray)</td>
<td>30±10</td>
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<td>2-step self-etch (Clearfil Liner Bond 2, Kuraray)</td>
<td>29.7±10.3</td>
<td>Nakajima et al\textsuperscript{84}</td>
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<td>2-step self-etch (Clearfil Liner Bond 2, Kuraray)</td>
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<td>2-step self-etch (Clearfil Protect Bond, Kuraray)</td>
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<td>2-step self-etch (Tenure ABS System, Denmat)</td>
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<td>(FluoroBond, Shofu)</td>
<td>18.49±4.04</td>
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<td>(Scotchbond MP, 3M ESPE)</td>
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<td>(All Bond 2, Bisco)</td>
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<td>(Clearfil Liner Bond 2, Kuraray)</td>
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<td>2-step self-etch (Clearfil Liner Bond 2, Kuraray)</td>
<td>29±10.3</td>
<td>Tachibana et al\textsuperscript{105}</td>
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<td>320-grit SiC paper</td>
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<td>18.4±11</td>
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<td>2-step self-etch (Clearfil SE Bond, Kuraray)</td>
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<td>Conventional bur</td>
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<td>Er,Cr:YSGG Laser</td>
<td>2-step self-etch (Clearfil SE Bond, Kuraray)</td>
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<td>Carisolv</td>
<td>2-step self-etch (Clearfil SE Bond, Kuraray)</td>
<td>21.5±10</td>
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<td>Light-pink staining remaining after using Caries Detector</td>
<td>600-grit SiC paper</td>
<td>2-step etch-and-rinse (Scotchbond 1, 3M ESPE)</td>
<td>34.5±6.8</td>
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<td>2-step etch-and-rinse (Optibond Solo Plus, Kerr)</td>
<td>29.2±4.3</td>
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<td>2-step self-etch (Clearfil Protect Bond, Kuraray)</td>
<td>28.7±5</td>
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<td>2-step self-etch (AdheSE, Ivoclar Vivadent)</td>
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<td>21.5±5.3</td>
<td>Doi et al\textsuperscript{30}</td>
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<td>2-step self-etch (Mac-Bond II, Tokuyama)</td>
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<td>2-step self-etch (UniFil Bond, GC)</td>
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Table 1  Bond strength related to the different caries removal endpoints, type of caries-affected substrate, and adhesive material used (continued)

<table>
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<tr>
<th>Method of caries excavation endpoint</th>
<th>Type of caries-affected substrate</th>
<th>Type of adhesive (brand name)</th>
<th>μTBS</th>
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<td>Diagnodent value = 20</td>
<td>600-grit SiC paper</td>
<td>2-step etch-and-rinse (Optibond Solo Plus, Kerr)</td>
<td>25.7±5.9</td>
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<td>2-step self-etch (Clearfil Protect Bond, Kuraray)</td>
<td>35.4±9.7</td>
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<td>Hand excavation</td>
<td>2-step etch-and-rinse (Prime &amp; Bond NT, Dentsply)</td>
<td>25.06±10.16</td>
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<td>2-step self-etch (Tenure ABS System, Denmat)</td>
<td>22.33±6.9</td>
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<td>Er:YAG laser</td>
<td>Conventional bur</td>
<td>2-step etch-and-rinse (Single Bond, 3M ESPE)</td>
<td>24.8±15.9</td>
<td>Silva et al\textsuperscript{103}</td>
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<td>2-step self-etch (Clearfil SE Bond, Kuraray)</td>
<td>31.4±12.7</td>
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<td>Carisolv</td>
<td>2-step etch-and-rinse (Prime &amp; Bond NT, Dentsply)</td>
<td>26.99±11.69</td>
<td>Sonoda et al\textsuperscript{104}</td>
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<td>2-step self-etch (Clearfil SE Bond, Kuraray)</td>
<td>28.7±6.9</td>
<td>Burrow et al\textsuperscript{20}</td>
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<td>Smart Prep bur</td>
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<td>31.1±9.21</td>
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<td>2-step self-etch (Clearfil SE Bond, Kuraray)</td>
<td>13.9±7.1</td>
<td>Silva et al\textsuperscript{103}</td>
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</table>

Fig 10  Pooled data from Table 1 (Burrow et al;\textsuperscript{20} Sattabanasuk et al;\textsuperscript{101} Silva et al;\textsuperscript{103} Tachibana et al\textsuperscript{105}) comparing the bond strength results when caries was excavated with a conventional bur (left) or Carisolv (right). Similar mean bond strength values were recorded for etch-and-rinse and self-etching adhesives in both cases. Horizontal line represents the mean values and bars represent the upper and lower standard deviations.


Clinical relevance: The bonding performance to carious dentin is directly related to the caries-excision method and to the caries removal endpoint. Despite this, the bond strength achieved today to carious dentin using modern adhesives has shown major improvement.