OPERATIVE DENTISTRY

SUPPLEMENT 3
1984

Smear Layer on Dentin

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OPERATIVE DENTISTRY

Aim and Scope

Operative Dentistry publishes articles that advance the practice of operative dentistry. The scope of the journal includes conservation and restoration of teeth; the scientific foundation of operative dental therapy; dental materials; dental education; and the social, political, and economic aspects of dental practice. Review papers and letters also are published.

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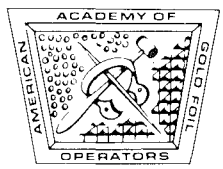

volume 9
1984

AMERICAN ACADEMY OF GOLD FOIL OPERATORS
ACADEMY OF OPERATIVE DENTISTRY

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INDEX

Index to Volume 9 for 1984

Entries for editorials, press digests, book reviews, letters are indicated by the symbols (E), (PD), (BR), (L).

OPERATIVE DENTISTRY SUPPLEMENT 3 1984

Smear Layer on Dentin

A symposium sponsored by the Pulp Biology Group of the International Association for Dental Research and supported in part by the L D Caulk Company

INTERNATIONAL ASSOCIATION FOR DENTAL RESEARCH
American Association for Dental Research
Annual Meeting, 18 March 1984
Dallas, Texas, USA

Smear Layer on Dentin

WILLIAM R COTTON, Symposium Moderator

Introduction

WILLIAM R COTTON

The term 'smear layer' is used most often to describe the grinding debris left on dentin by cavity preparation. However, the term applies to any debris produced iatrogenically by the cutting, not only of dentin, but also of enamel, cementum, and even the dentin of the root canal.

It is difficult to say when, or by whom, the concept of the smear layer was first introduced. Early attempts to define the cut surface of tooth structure were limited principally to light microscopy (Lammie & Draycott, 1952; Street, 1953; Peyton & Mortell, 1956; Charbeneau & Peyton, 1957; Charbeneau, Peyton & Anthony, 1957; Lammie, 1957). During two workshops sponsored by the National Institute of Dental Research in 1961 and 1965 on adhesive restorative materials, the nature of the cut surface of tooth structure, as observed by electron microscopy, was described (Scott & O'Neil, 1961; Provenza & Sardana, 1966), but in neither instance was a label applied to the debris of cavity preparation. It was not until the advent of scanning electron microscopy that the grinding debris was first referred to as the smear layer by Boyde, Switsur and Stewart (1963) and further defined by Eick and others (1970), who referred to it as the smeared layer.

Light microscopy has consistently failed to identify the smear layer, principally due to the fact that light microscopy depends upon histologic sections or shadowing techniques. Although specific techniques have not been developed to preserve the intact smear layer for light microscopy, techniques have been developed, as demonstrated in this symposium, for observing the layer by transmission electron microscopy. This is exciting new information from Ray Bowen and coworkers.

The full significance of the smear layer has been slow to be perceived. Its increasing importance has paralleled the interest in adhesive bonding to tooth structure. Undoubtedly, little attention would have been paid to the smear layer without interest in adhesive techniques. The significance of the smear layer acquires

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WILLIAM R COTTON, DDS, MA, MS, EdS, professor and chairman

added dimension when we consider that viable microorganisms may be present within the layer. This single realization has provided some fascinating new concepts, which are presented by Martin Brännström. The total understanding of the significance of the smear layer is far from complete. Its effect as a so-called natural cavity liner is just beginning to be appreciated. As suggested by David Pashley, in this symposium, the smear layer as a cavity liner may unquestionably have both beneficial and detrimental effects. How does the restorative dentist modify his treatment to take advantage of the beneficial effects and avoid, at will, the detrimental effects? Is all of this new? Yes. Is it important? Yes, for it may indeed alter the traditional procedures of restorative treatment.

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Smear Layer: Morphological Considerations

A JOHN GWINNETT

The Smear Phenomenon

Significant amounts of energy are expended at the interface of a substrate and a tool during cutting and abrading. The generation of frictional heat and plastic and elastic deformation can all contribute potentially to alteration and deterioration of the substrate. These consequences are well understood in lapidary and machining contexts in which grinding debris from the substrate or the tool itself may be deposited or smeared upon the work surface unless steps are taken to control the cutting process. Such smeared contaminants lower the surface energy and therefore have a profound effect upon the reactivity of the substrate surface. The foregoing remarks are applicable when dental tissues are cut and abraded. In a dental context Eirich (1976) stated that smearing occurs when "hydroxyapatite within (the tissue) is either plucked out or broken, or swept along and resets in the smeared-out matrix." Hard dental tissues are heterogeneous, comprising submicroscopic crystallites of apatite enveloped in an organic matrix. Significant variations in the proportions of these components exist between enamel, dentin, and cementum, thus contributing to a wide range of topographical anomalies, which can be related to the type of instrumentation and the manner and conditions under which it is used.

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Literature Review

The earliest studies on the effects of various instruments on dental tissues were those reported by Lammie and Draycott (1952) and Street (1953). After the use of different burs and abrasive stones, these authors, using powdered graphite, disclosed ridges and troughs on the cut surfaces. Viewed with a light microscope and epi-illumination, the pat-

tern and magnitude of the grooves varied, with diamond abrasives producing the most striking anomalies. This technique for disclosing the topographical detail has a significant limitation, namely, that the powdered graphite might tend to obscure more surface detail than it would highlight. Peyton and Mortell (1956) understood this problem and substituted a thin metal coating for the graphite. Employing a technique of metal vaporization described by Scott and Wyckoff (1946), they deposited copper on cut surfaces of teeth and examined them with reflected light microscopy. Significant differences were noted between burs and stones, though different speeds, with and without coolant, produced no notable differences. Diamonds produced relatively deep and uniform grooves whereas burs showed less evidence of grooves and a tendency toward nonuniform, uneven cutting.

Charbeneau and Peyton (1957) and Charbeneau, Peyton and Anthony (1957) drew similar conclusions from using aluminum-shadowed collodion replicas taken from the cut surfaces of teeth. They were among the first to quantify and rank the differences between burs and abrasives by using a profilometer to record the surface topography of cut and abraded dental tissues.

There are significant limitations to the amount of morphological detail that can be disclosed by light microscopy. The use of reflected light microscopy in particular is hampered by a narrow depth of field and limited resolution of detail. While others, for example, Cantwell, Alpin and Mahler (1960), continued to use metal coating techniques and light optical methods, it was not until Scott and O'Neil (1961) reported a transmission electron microscope study that a major advance was made in the description of the morphological detail of cut surfaces of teeth. They observed the microscopic anomalies left from the action of the tool and found no marked differences in surface texture with different instruments. Repeated replication of the surfaces with collodion continued to extract cutting debris, identified as apatite by electron diffraction. While the prismatic structure of enamel was recorded in replicas, cut surfaces of dentin were usually irregular and without any evidence for the tubular nature of this tissue. This study was conducted during the advent of research into adhesive restorative materials. In this context, and importantly, Massler (1961) and Skinner (1961) emphasized Scott and O'Neil's conclusion that a knowledge of the structural qualities of cut surfaces of teeth is a key to formulating adhesive restorative systems.

The introduction of the scanning electron microscope and energy dispersive x-ray analysis marked a significant technological advance in instrumentation. The improvement in resolution of microscopic detail compared to that revealed by the light microscope, coupled with a large depth of field, makes this instrument ideally suited to detailing surface morphology and identifying surface composition. Boyde, Switsur and Stewart (1963) appear to have been among the first to describe in greater detail, using scanning electron microscopy, the nature of the surface deposits *in situ,* which Scott and O'Neil (1961) removed with their replication procedures. Boyde and his coworkers also appear to have been the first to describe and demonstrate the presence of what they called a "smear layer" on surfaces of cut enamel. Such a layer was readily removed with sodium hypochlorite, leading them to conclude that an organic layer containing apatite particles was deposited or smeared on the enamel through frictional heat generated during cutting. They believed the heterogeneous nature of enamel was the source of the smeared components.

Using replication techniques, Provenza and Sardana (1966) also evaluated means of removing debris from enamel and dentin after the use of steel burs, diamond stones, and hand instruments. They reported variations in the degree to which debris was removed. Detergents were relatively ineffective, the organic solvent ethylene diamine left behind a film, and 0.1N hydrochloric acid was considered too destructive in its action; hydrogen peroxide appeared to be the most effective agent. While speculation was made that the dentinal tubules were probably packed with cutting debris, it was significant that no reference was made to the existence of a smear layer. Clearly, the indirect collodion technique failed to disclose this feature, thus emphasizing the importance of scanning electron microscopy in studying such a phenomenon. In a discussion of the Provenza and Sardana

paper, Nelsen (1966) and Zisman (1966) described the dynamics of cutting dental tissues and appeared to imply the existence of an altered surface layer due to elastic and plastic deformation of the tissue.

Eick and others (1970) used an electron microprobe with a scanning electron microscope attachment to quantify and identify cutting debris on tooth surfaces. They confirmed previous reports that surfaces abraded with diamonds were rougher than those cut with tungsten carbide burs. Surfaces cut dry were rougher and more smeared than those in which water was used as a coolant. Boyde and his coworkers (1963) attributed smearing of enamel to melting of the tissue by frictional heat. Indeed, studies have shown that temperature will rise up to 600 °C in dentin when it is cut without a coolant (Eirich, 1976; Lloyd, Rich & Brown, 1978). This value is significantly lower than the melting point of apatite (1500-1800 °C) and has led most to conclude that smearing is a physicochemical phenomenon rather than a thermal transformation of apatite (Pearlman, 1976) involving mechanical shearing and thermal degradation of the protein (Tateosian, 1976). Plastic flow of hydroxyapatite is believed to occur at lower temperatures than its melting point (Eirich, 1976; Westwood, 1976) and may also be a contributing factor to smearing.

Eick and his coworkers (1970) found the smear layer to be composed of an organic film less than 0.5 μm thick. Included within it were particles of apatite ranging from 0.5 to 15 μm. Such layers were present on all surfaces though they were not necessarily continuous. The quantity of debris did not seem to differ significantly whether diamond or carbide burs were used or whether a coolant was utilized. Several studies, for example, Boyde (1973) and Tronstad and Leidal (1974), continued to confirm the presence of smear layers on operatively prepared dental tissues.

Jones, Lozdan and Boyde (1972) also showed that smear layers were common on enamel and dentin following the use of periodontal instruments. Others have shown smear layers after the use of endodontic instrumentation (Goldman & others, 1982).

A timely symposium titled *The Cutting Edge* presented a detailed overview of the interfacial dynamics of cutting and grinding, in which the physical, morphological, and chemical alteration of teeth were discussed at length. In key papers, Eirich (1976) and Koblitz and his coworkers (1976) detailed the role of friction and abrasion in the drilling of teeth. They accounted for the formation of smear layers, especially in dentin, by a brittle and ductile transition and alternating rupture and transfer of apatite and collagen matrix onto the surface. Dentin, comprising approximately 35% collagen matrix and water, is a more abundant source of protein than enamel, which contains approximately 2% protein matrix and water. Dentin matrix may contribute to smears found on enamel.

The Smear Dilemma

While there is little equivocation concerning the necessity to remove the smear layer so as to optimize the bonding of restorative materials to enamel and dentin, an important dilemma exists concerning what is viewed as the protective role of such layers. Gilboe and others (1980) addressed the phenomenon of dentinal smearing and detailed a method by which controlled smearing and occlusion of dentinal tubules could be achieved with specially designed burs. Compromise may be possible in which the biologic integrity of the pulp and dentin may be preserved by developing unique chemical formulations compatible with adhesive biomaterials.

Morphology of the Smear Layer

Our current research is directed toward furthering the understanding of the morphological qualities of operatively prepared dental tissues, to measure their reactivity, and to formulate and develop biocompatible methods and agents necessary to promote and sustain a bond between restorative materials and dental tissues. In the context of my assigned topic, our morphological studies confirm the findings and support the conclusions outlined earlier. We make extensive use of scanning electron microscopy because it is well suited to identifying and characterizing the changes produced during cutting and abrading dental tissues.

The differences in topographical detail after cutting dentin and enamel with steel and tungsten carbide burs and abrading it with diamond stones are clearly evident (Figs 1 & 2).

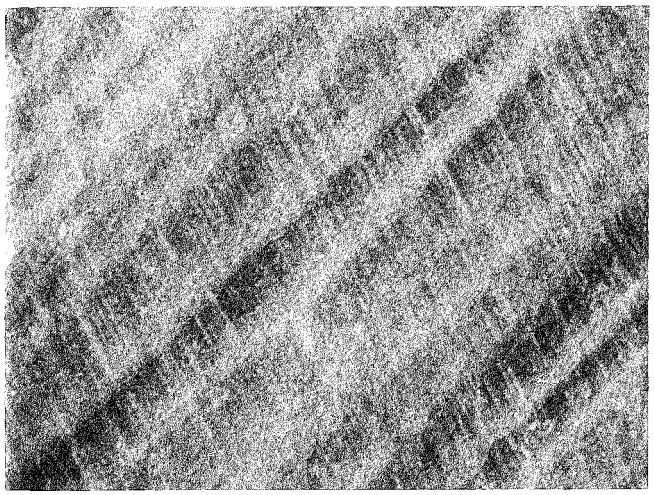


FIG 1. *Scanning electron micrograph showing the galling pattern on a dentin surface cut with a water-cooled, tungsten carbide bur. X150.*

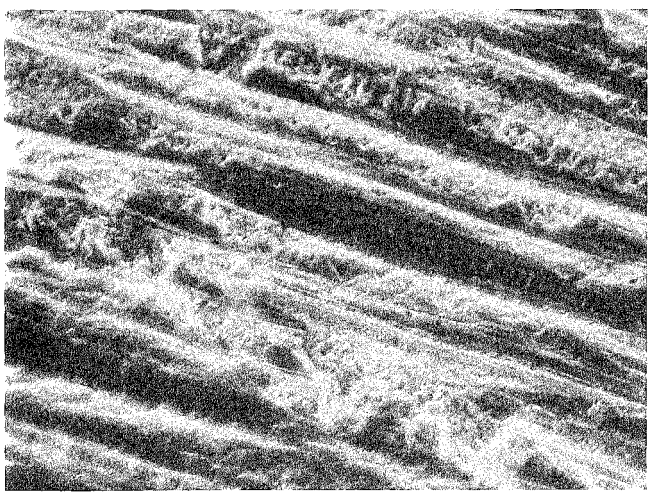
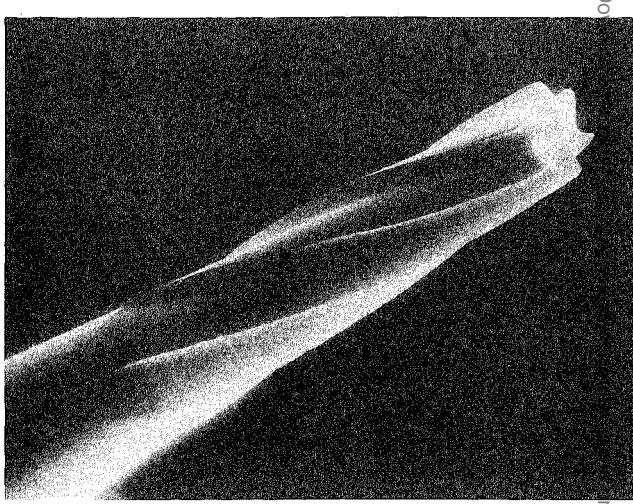
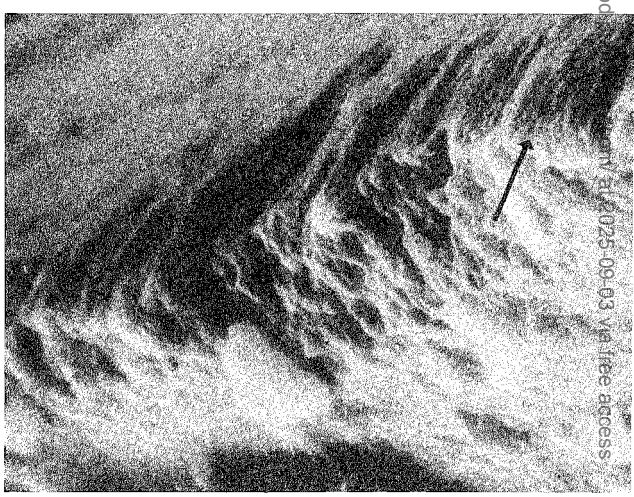


FIG 2. *Scanning electron micrograph showing grooves traversing a dentin surface abraded with diamond. X300.*

Steel and tungsten carbide burs produce an undulating pattern, the troughs of which run perpendicular with the direction of movement of the handpiece. Fine grooves can be seen running perpendicular to the undulations and parallel with the direction of rotation of the bur.

Such a phenomenon is referred to as galling and the frictional humps represent a "rebound effect" of the bur against the tissue. The galling phenomenon appears more marked with tungsten carbide burs run at high speed. The fine grooves can be related to small facets found on the cutting flutes of the bur. These scabrous facets arise because of wear of the flutes (Figs 3 & 4) and act as abrading points,





FIGS 3 & 4 *Scanning electron micrographs of the flutes of tungsten carbide bur. At higher magnification evidence o brittle fracture (arrow) of the cutting edge is seen togethe with the formation of facets. X9, X1520.*

scratching the plastically and elastically deformed surface as the bur rotates. An examination of both steel and tungsten carbide burs showed a rapid deterioration of the cut-

ting edges through what appeared to be brittle fracture. This supports the conclusion of Eames and Nale (1973) and that of Reisbick and Bunshah (1973). Brittle fracture significantly diminishes the cutting efficiency of the bur, probably increases frictional heat, and causes smearing.

At higher magnification, steel and tungsten carbide burs can be seen to have obliterated the normal structural detail of the tissue (Fig 5). Debris, irregular in shape and nonuniform in size and distribution, remains on the surface even after thorough lavage with water. The first signs of smearing are evident. These relatively flat, sometimes finely grooved, homogeneous islands often appear to be oriented in a direction parallel with the movement of the handpiece. Discontinuities exist in the smear layer as pits and gouges are formed in the tissue by tearing and brittle fracture. While some portions of the smear layer appear firmly attached to the tissue surfaces, others have lifted free by delamination. This, as well as cracks, may be exaggerated by the severe desiccation of the tissue during preparation for the high vacuum necessary for the normal operation of the scanning electron microscope. The topological difference between the use of friction grip, tungsten carbide burs run at high speed with and without a coolant of water spray appears to be subtle. No attempt has yet been made to quantify the differences. Further research is being conducted.

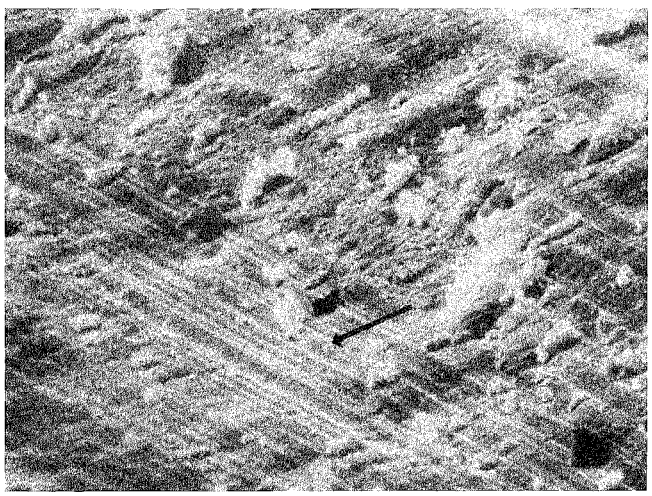


FIG 5. *Scanning micrograph of the cutting anomalies on dentin following the use of a cross-cut steel bur. Note the debris and evidence of smearing (arrow). X760.*

The mechanism by which burs remove dental tissue is significantly different from the abrading action of a diamond. As burs rotate, the flute undermines the tissue, the amount being determined by such factors as the angle of attack of the flute. This angle forms part of the design of the bur. On the other hand, abrasive particles, passing across the tissue, plough troughs (Fig 6) in which substrate is ejected ahead of the abrading particle and elevated into ridges parallel with the direction of travel of the particle. Several factors govern the size of the grooves, including particle size, pressure, and hardness of the abrasive relative to the substrate. In this context hardness is defined as scratch resistance usually measured on the Mohs scale or its Woodell modification. On a scale of 1–10, diamond is the hardest at 10 and dental tissues are approximately 5–6. The latter value is merely an approximation because the scales apply strictly to homogeneous mineral systems. Clearly diamond abrades enamel and dentin with relative ease and produces the most striking anomalies of abrasion.

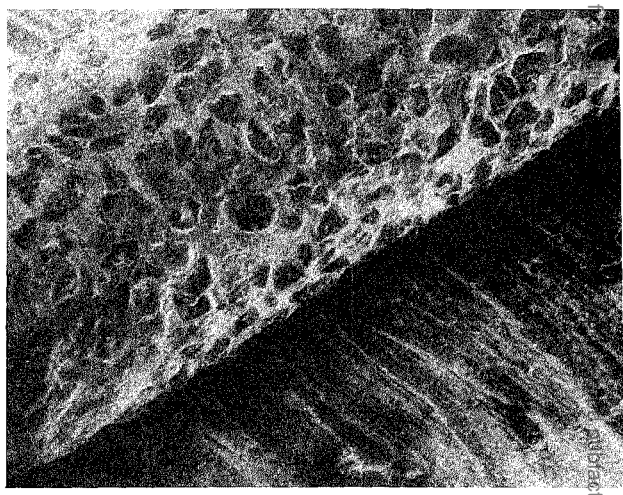


FIG 6. *Scanning electron micrograph of a diamond stone in situ. Note the abrasive particles and the grooves left by them in the tissue. X15.*

Diamond burs range widely in the grit size of the particles and the means by which the par-

ticles are bonded to the shank. Following the action of the burs on dental tissues, the magnitude of the grooves left by the particles is governed, for a given pressure, largely by the size of the abrasive particle. At low magnification (Fig 7) the surface is traversed by relatively parallel deep grooves, the size of which varies modestly for any given diamond stone, though marked differences exist in the size of the grooves depending upon the coarseness of the abrasive. The grooves run parallel with the direction of motion of the handpiece. At higher magnification (Fig 8) fine grooves run within the deep grooves, which are often discontinuous and punctuated by roughness due to localized brittle fracture of the tissue. There is no evidence of the tubular structure of dentin or the prismatic content of enamel when relatively coarse diamonds are used. Other abrasives such as green stones and white stones appear similar to diamonds in their topographical effects. Following the use of fine abrasives, such as diamond and silicon carbide, the structure of both enamel and dentin was partly disclosed though the tubules of the dentin (Fig 9) were frequently occluded.

IGS 7 & 8. *Scanning electron micrographs of the grooves left y a diamond stone on dentin. Fine grooves run within the eeper grooves and pitting is also evident. X150, X600.*

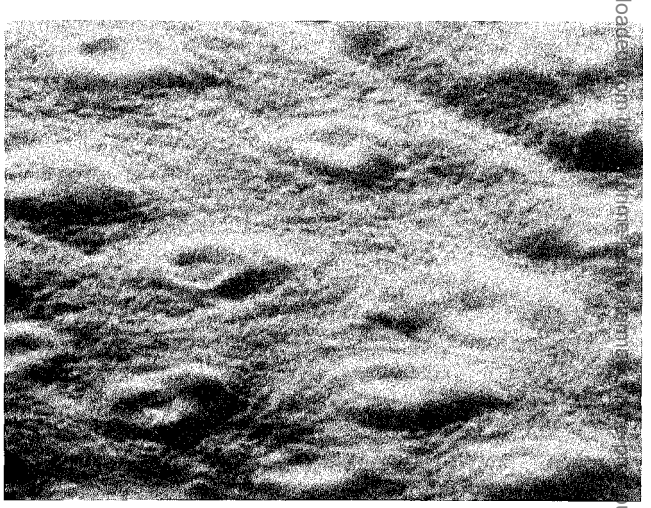


FIG 9. *Scanning electron micrograph of dentin abraded with 600-grit silicon carbide abrasive paper. Note the occluded tubules and the prominent peritubular dentin mounds. Surface cleaned with 3% hydrogen peroxide. X3800.*

A significant difference exists between diamond burs used with and without a coolant of water spray. In the absence of coolant, smeared debris can be found commonly on the surface. The smeared debris does not form a continuous layer but exists rather as localized islands with discontinuities exposing the underlying dentin. If the diamond is allowed to clog with cutting debris, the smear layer appears to cover a wider area (Fig 10). Coolant of water spray does not prevent smearing but appears to significantly reduce the amount and distribution of it. If the tissue is cleaved at right angles to the cut surface, a qualitative estimate of the thickness of morphological change can be made. The extent of tissue alteration is usually quite superficial involving approximately 5 μm of the surface (Fig 11). The tubules are often occluded with cutting debris.

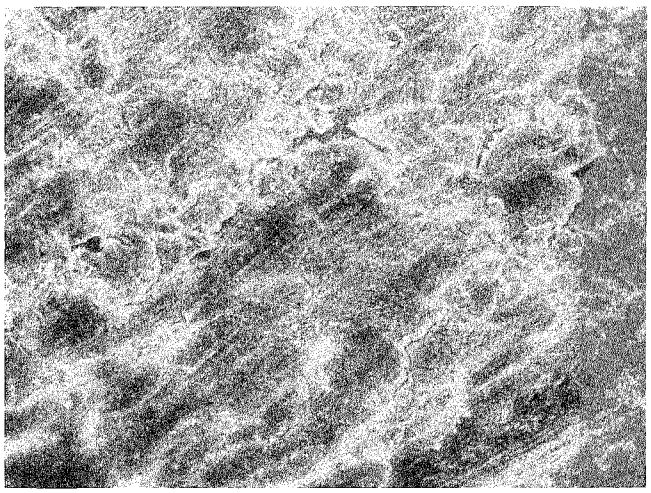


FIG 10. *Scanning electron micrograph showing considerable smearing of dentin after the use of a clogged diamond using water as a coolant. X114.*

FIG 11. *Scanning electron micrograph of dentin cleaned to show that deformation after abrading and cutting is confined to a few superficial micrometers of the tissue. X1140.*

Bonding and the Smear Layer

In general, diamonds, through the introduction of grooved anomalies, produce a greater surface area than burs. This has implications in bonding where differences in the bond strength of resin attached to enamel have already been reported to be higher for diamonds compared to burs (Aker, Aker & Sorensen, 1979). The increased surface area probably offered a larger number of reaction or retentive sites. These sites in enamel are primarily micromechanical and the retention mechanism for this tissue lies in the multitude of superficial micropores enhanced following acid conditioning of the tissue. Acids are among several agents that can remove the smear layer. For enamel, phosphoric acid in gel or solution in a concentration ranging from 30 to 65% is the most popular agent. The application of this agent to dentin removes the smear layer and, by dissolution of the peritubular dentin, the lumen of the dentinal tubules is significantly enlarged. Brännström and Nordenvall (1977) and Gwinnett (1977) demonstrated that conditioning of dentin with phosphoric acid facilitates penetration of resin into the dentinal tubules (Fig 12). Such penetration

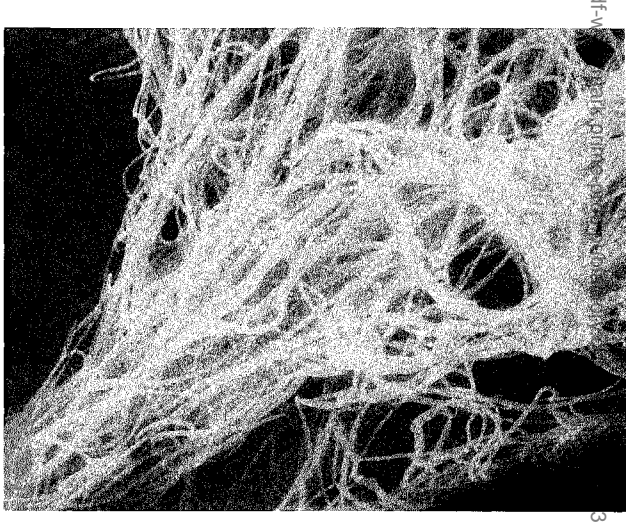
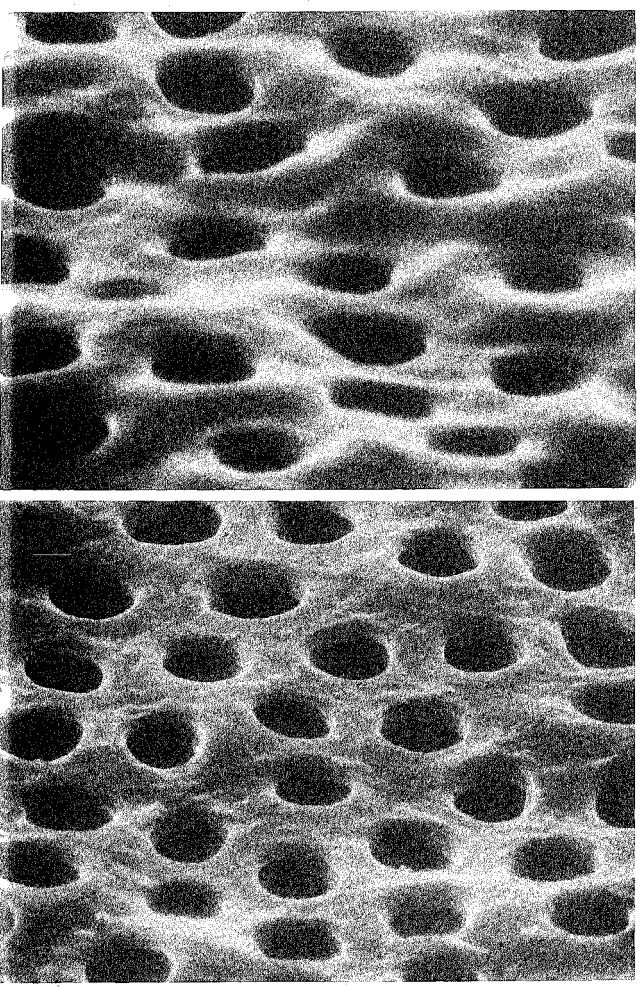


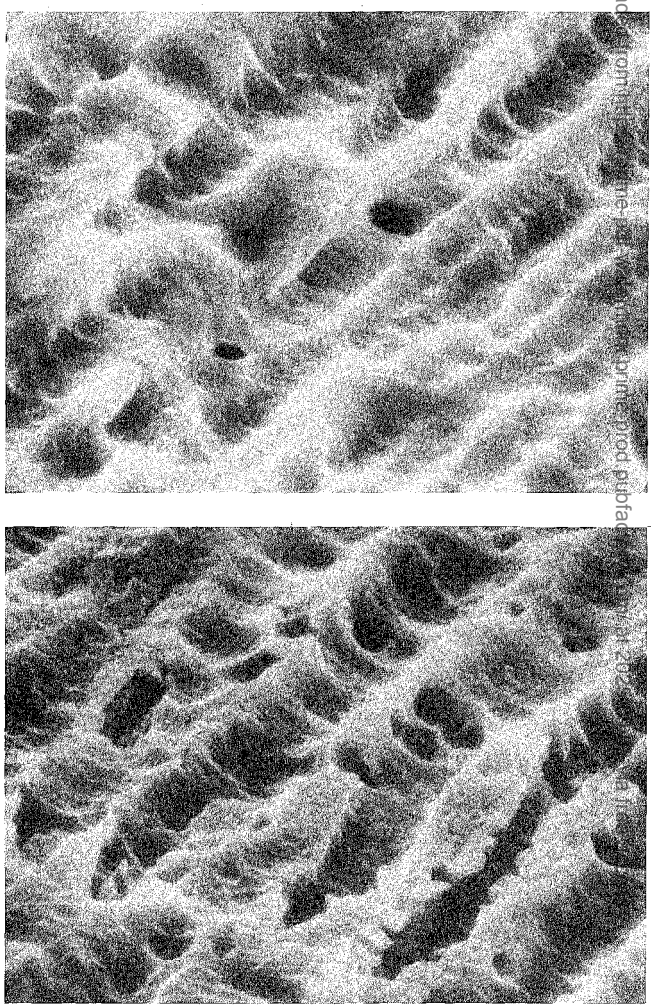
FIG 12. *Scanning electron micrograph of "strings" of resin which had penetrated deep into the dentinal tubules after conditioning with phosphoric acid and sodium hypochlorite. Resin was disclosed by tissue dissolution. X150.*

probably contributes to the increased bond strength of resins employing acid conditioning of dentin (Fusayama & others, 1979). There is equivocation as to whether the values decline or are stable with time in the presence of water. It was clear from our recent studies that while phosphoric acid removes the smear layer and enlarges the dentinal tubules, it also appears to degrade the collagen matrix. Some of the degradation products may be

removed with water but the surface of the acid-conditioned dentin appears relatively smooth with a gelatinous quality even after a thorough lavage. Subsequent treatment of the same surface with a solution of sodium hypochlorite brings about a significant morphological change (Figs 13 & 14). The sodium hypochlorite dissolves the organic material to produce a rougher texture to the surface, which is dependent upon the time of application of this agent. When tubules are exposed in longitudinal section, lateral canals increase in number with time of application of sodium hypochlorite (Figs 15 & 16). The biocompatibility of this method is contentious but lessons may be learned from it. The preparation of dentin surfaces for bonding must take into account the viability of this tissue and its morphological and physiological association with the pulp. In addition, the composition of dentin and its surface following instrumentation also dictates the choice of treatment. We are presently pursuing different chemical



FIGS 13 & 14. *Scanning electron micrographs show dentin etched for 10 seconds with 50% phosphoric acid. A significant morphological difference exists following additional treatment for 60 seconds with 5-25% sodium hypochlorite (Fig 14). X1520.*



FIGS 15 & 16. *Scanning electron micrographs showing tubules exposed in longitudinal section. After 60 seconds of 50% phosphoric acid and 60 seconds of 5-25% sodium hypochlorite treatment, the surface appears smooth (Fig 15). Increasing the time of application of sodium hypochlorite brings about a roughening of the surface and the exposure of numerous lateral canals. X1520.*

treatments and, like others, we are encouraged by methods that raise the surface energy of the dentin by removing the smear layer while leaving the tubules plugged with cutting debris. Combinations of conditioning agents show promise in the laboratory.

Conclusion

Smear layers, comprising organic and inorganic components, form during cutting and abrading of dental tissues. Such layers exist irrespective of the type of instrumentation or the manner in which it is used. The quality and quantity of such layering is influenced by the operating conditions in which coarse diamond abrasives, used dry, produce the thickest deposits. Most rotary instruments create surface anomalies such as grooves which, together with cutting debris, obliterate the normal structural features of the dental tissues. The smear layer is not always firmly attached to or continuous over the substrate. The surface is not conducive to the development and retention of optimum bond strengths with restorative materials and of necessity must be modified with biocompatible agents.

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Smear Layer: Physiological Considerations

DAVID H PASHLEY

DEFINITION, DESCRIPTION, AND PRODUCTION

Whenever dentin is cut with either a hand instrument or a rotary instrument, the mineralized matrix shatters rather than being uniformly sheared or cleaved, producing considerable quantities of cutting debris. Much of the debris, made up of very small particles of mineralized collagen matrix, is spread over the surface of the dentin to form what has been called a 'smear layer' (Eick & others, 1970). It is analogous to wood being covered by wet sawdust. Although a similar phenomenon occurs in enamel, only the smear layer of dentin will be discussed here.

The smear layer is absent from specimens of demineralized teeth examined by light microscopy because the smear layer is dissolved during demineralization. When examined in undemineralized specimens by scanning electron microscopy the smear layer looks like an amorphous, relatively smooth, featureless surface (Fig 1A). Its constituents are below the resolution of the scanning electron microscope (SEM). Transmission electron microscopy may provide important new information about the size of the particles constituting the smear layer as well as

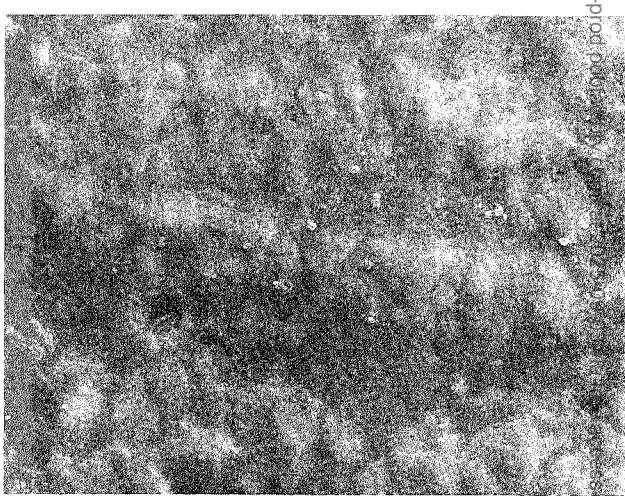

FIG 1A. *Disc of human dentin cut with a fine-grit diamond blade on a metallurgical saw. Half of the specimen was etched with acid, leaving the smear layer intact on the other half. Note the uniformity and amorphous nature of the smear layer. Scanning electron micrograph X1560. See Fig 1B.*

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their packing density and the dimensions of the diffusion channels between the particles.

The depth of the smear layer varies widely depending upon whether the dentin is cut dry or wet, the amount and composition of the irrigating solution used, the size and shape of the cavity (or root canal), and the type of instrument employed (Gilboe & others, 1980). Generally speaking, cutting without water spray generates a thicker layer of debris (smear layer) than cutting with a copious spray of air and water. Further, coarse diamond burs tend to produce thicker smear layers than carbide fissure burs (Brännström, Glantz & Nordenvall, 1979a; Shortall, 1981). Perhaps the thickest smear layers that have been produced (~10–15 μm thick) were produced in vitro with a coarse diamond blade mounted on a metallurgical saw. This device tends to pack and burnish the debris into a smooth, highly glossy finish (Pashley, Michelich & Kehl, 1981).

As will be discussed later, in some detail, the smear layer increases the resistance to movement of fluid across dentin discs, both in vivo and in vitro. As the rates of filtration of fluid provide a convenient, quantitative method of assessing the presence of a smear layer, they were used to compare a variety of different methods of producing a smear layer on dentin etched with acid in vitro (Fig 1B). The results are shown in Figure 2. The ease with which fluid could flow through etched dentin (dentin free of a smear layer), termed 'hydraulic conductance', was determined for each specimen. This quantity was then assigned a value of 100% and the effects of subsequent manipulations of the dentin surface were redetermined and expressed as a percent of the control value. Thus, each disc served as its own control. Brushing etched dentin with phosphate-buffered saline produced little debris. Brushing etched dentin with common, marketed dentifrices (120 circular strokes per minute for one minute) decreased hydraulic conductance by 50% (see Fig 2). It is difficult to determine if the reduction is due to abrasive particles falling down into the tubules or to the smearing of dentin matrix over the orifices of the tubules. Burnishing etched dentin with an orangewood stick decreased hydraulic conductance 66%. The use of a rotary rubber cup containing prophylaxis paste was even more effective at reducing hydraulic conductance. These pastes are much more abrasive than dentifrices and hence are far more effective at creating a smear layer. Burs operated at either low or high speed were equally effective at producing a smear layer. A No 37 inverted cone bur occluded dentin as effectively as a coarse-grit diamond point (Fig 2).

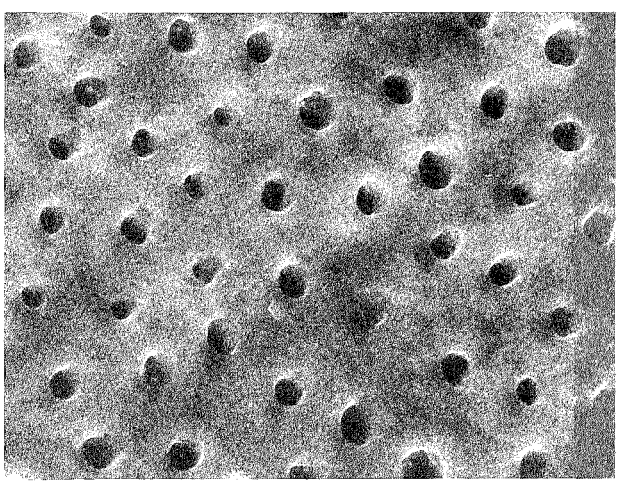

FIG 1B. *Appearance of the other half of the specimen shown in Fig 1A after etching with 6% citric acid and for two minutes. The orifices of the patent dentinal tubules are flared due to removal of peritubular dentin. Scanning electron micrograph X1560.*

METHODS OF REMOVAL

The depth of most clinically produced smear layers is about 1–5 μm (Brännström, 1982). Unless authors indicate that the dentin surface was etched with acid or treated with ethylenediaminetetracetic acid (EDTA) or similar chelating solutions, one can conclude that there is a smear layer present on the dentin whenever teeth are prepared. The smear layer is far more tenacious than one would expect. Brännström's group has published several articles describing the use of water, hydrogen peroxide, benzalkonium chloride, EDTA, and other agents to remove the smear layer (Brännström & others, 1979a; Brännström, Nordenvall & Glantz, 1980). Brännström has formulated several commercially available products (Tubulicid Blue Label, Tubulicid Red Label, Dental Therapeutics AB, Nacka, Sweden) that are designed to remove most of the smear layer without removing the smear debris that has fallen into the

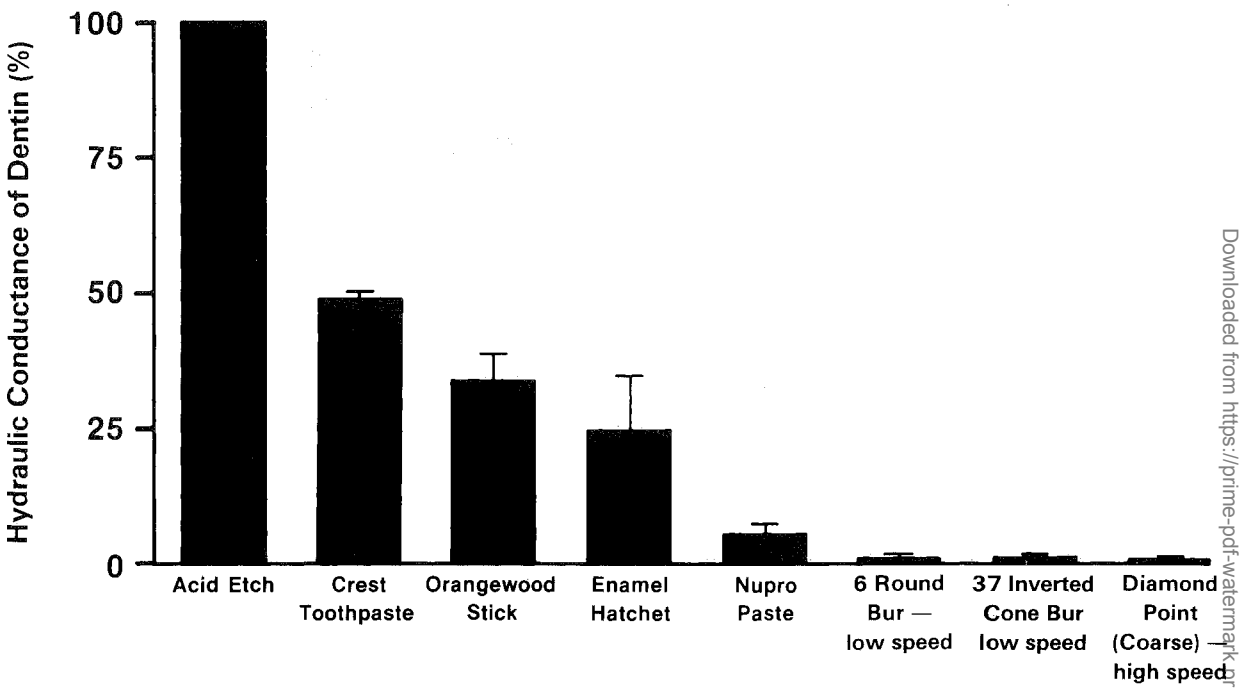

FIG 2. *Effects of various manipulations of the surface of dentin on the permeability of dentin expressed as hydraulic conductance (Lp) of dentin. All specimens were etched with acid, a control Lp taken, the surface manipulated, and the Lp redetermined and expressed as percent. Brackets indicate standard error of the mean.*

orifices of the tubules to form plugs on the cut surface of dentin. Brännström (1982) believes that the smear layer is a liability to the extent that it can harbor bacteria. Although numerous authors agree that the presence of the smear layer prevents bacterial invasion of dentinal tubules (Olgart, Brännström & Johnson, 1974; Vojinovic, Nyborg & Brännström, 1973; Michelich, Schuster & Pashley, 1980), it is still permeable to bacterial products, which can diffuse through the smear layer and permeate the tubules to the underlying pulp where they can elicit an inflammatory reaction (Brännström & Nyborg, 1973; Bergenholtz, 1977; Bergenholtz & Reit, 1980). Brännström's (1982) concept of removing most of the smear layer over the tubules without removing the smear plugs in the tubules is an ideal that is difficult to achieve clinically because of the complex geometry of many cavities and the difficulty of obtaining adequate access.

FUNCTIONAL IMPLICATIONS

Dental Materials

Dental materials scientists have been concerned about the smear layer insofar as it masks the underlying dentin matrix and may interfere with the bonding of adhesive dental cements such as the polycarboxylates and glass ionomers being developed, which may react chemically with the dentin matrix. Dahl (1978) demonstrated that simply pumicing the dentin surface produced a threefold increase in the tensile strength of the bond between dentin and polycarboxylate cement (Durelon, Premier Dental Products Co, Norristown, PA 19401, USA) over that seen with zinc phosphate cement (Mizzy, Inc, Clifton Forge, VA 24422, USA), which relies strictly upon mechanical roughness for retention. Presumably, allowing

cements to react chemically with the smear layer, rather than with the matrix of sound intertubular dentin, produces a weaker bond due to the fact that the smear layer can be torn away from the underlying matrix. When cements are applied to dentin covered with a smear layer and then tested for tensile strength, the failure can be either adhesive (between cement and smear layer) or cohesive (between constituents of the smear layer). The distinction between these two possibilities has seldom been made in the past. If one wants to increase the tensile strength of a cement-dentin interface there are several approaches to the problem.

1) Remove the smear layer by etching with acid (Lee & others, 1971, 1973; Bowen, 1978; Brännström & others, 1979b, 1980; Pashley & others, 1981). This seemingly extreme procedure does not injure the pulp (Brännström, 1982), especially if dilute acids (Bowen, 1978) are used for short periods of time. Etching dentin with 6% citric acid for 60 seconds removes all of the smear layer (and smear plugs) as does 15 seconds of etching with 37% phosphoric acid (Pashley & others, 1981). The advantages are that the smear layer is entirely removed, the tubules are open and available for increased retention, and the surface collagen is exposed for possible covalent linkages with new experimental primers for cavities (Fusayama & others, 1979; Bowen, Cobb & Rapson, 1982; Bowen & Cobb, 1983). Further, with the smear layer gone, one doesn't have to worry about it slowly dissolving under a leaking restoration or being removed by acid produced by bacteria, leaving a void between the cavity wall and the restoration, which might permit bacterial colonization. The disadvantage of removing the smear layer is that, in its absence, there is no physical barrier to bacterial penetration of dentinal tubules. Further, with nothing occluding the orifices of the tubules, the permeability of dentin increases four- to ninefold depending upon the size of the molecule (Pashley & others, 1978b; Boyer & Svare, 1981). It is clear why Brännström (1982) and others would prefer to remove the smear layer over and between the tubules without removing the smear plugs. Unfortunately that is very difficult to accomplish clinically.

2) Another entirely different approach would be to use a resin that would infiltrate through the entire thickness of the smear layer and either bond to the underlying matrix or penetrate into the tubules. The impressive tensile strengths recently obtained for Scotchbond (3M Dental Products Division, St Paul, MN 55144, USA) may be due to such a process. Results indicate stronger bonds between the resin and pumiced dentin than between the resin and etched dentin (Hill, Jensen & Zidan, 1983). Etching with acid, in addition to removing the smear layer and exposing surface collagen, also removes the peritubular dentin from the top 5–10 μm of the tubules, yielding a tubule with a funnel-shaped orifice. If the resin penetrates only into the funneled portion of the tubule rather than into the region where the tubules are normal, that is, of uniform diameter, then retention would be less, due to diverging tubular walls rather than the normal parallel walls of unetched tubules. Additionally, etching with acid demineralizes the surface, which would lower the adhesive bond between cements and mineralized dentin. Nakamichi, Iwaku and Fusayama (1983) recently reported that Clearfil resin (Kuraray Co, Ltd, Medical Products, Osaka, Japan) gave adhesive strengths to dentin with a smear layer present that were as high as those for any of the polycarboxylate or glass-ionomer cements. Etching dentin doubled the adhesion of Clearfil resin to values twice that of Adaptic (Johnson & Johnson Dental Products Company, East Windsor, NJ 08520, USA) to etched superficial dentin. Their work also provides interesting hints as to the mechanism of this retention. Against the notion that penetration of resin into dentinal tubules increases adhesion of resin is their observation of adhesion of a variety of cements and resins to 'superficial' and 'deep' bovine dentin. 'Superficial dentin' was defined as dentin prepared near the enamel. This dentin has fewer tubules per area of surface than dentin near the pulp, which they termed 'deep dentin'. The adhesive strength of all cements was always about 50% greater in superficial than in deep dentin even in the presence of a smear layer. This may mean that either the quality or the quantity of the smear layer produced by grinding superficial dentin is different from that produced on deep dentin. Smear layers on deep dentin may have more organic material in them than those on superficial dentin. This may be due to the

greater number of odontoblastic processes or to the greater amount of proteoglycans lining the tubules (Thomas & Paine, 1983). This suggestion must be regarded as speculation but could be tested. Etching with acid, that is, removal of the smear layer, increased the adhesive strength of composite resins (Adaptic, Clearfil) to superficial dentin by 800–1000% over that to deep dentin even though far more tubules were available for penetration of resin in deep dentin than in superficial dentin. This indicates that composite resins probably do not derive their adhesiveness from penetration of resin into the tubules, but rather by interacting with mineralized intertubular dentin. Further support for this concept is seen when one examines the data of these authors on adhesion of Clearfil to superficial and deep dentin before and after etching with acid. Adhesion of Clearfil to deep dentin etched with acid fell below almost all other cements indicating that Clearfil requires a mineralized surface for bonding.

Another variable interfering with the adhesion of substances to dentin is the presence of dentinal fluid, a fluid much like other interstitial fluids (Pashley, 1979), both within dentinal tubules and within the smear layer. Brännström and others (1979a) indicated that, in dentin etched with acid, dentinal fluid could be removed by blasts of air and replaced by tags of resin extending deep into the tubules. Bowen's approach is to treat the dentin with solutions of resins in acetone which is miscible with dentinal fluid yet compatible with hydrophobic polymers (Bowen & others, 1982). This approach seems worthy of more investigation. Fusayama's bonding agent (Clearfil) is in alcohol, which is also soluble in water. Just prior to inserting the bulk of the composite, Fusayama recommends that the alcohol be evaporated with a stream of air.

3) Another approach is to try to fix the smear layer with glutaraldehyde (Hoppenbrouwers, Driessens & Stadhouders, 1974) or tanning agents such as tannic acid or ferric chloride (Powis & others, 1982). The idea is to increase the crosslinking of exposed collagen fibers within the smear layer and between it and the matrix of the underlying dentin to improve its cohesion.

4) A fourth and most convenient approach to the problem is to remove the smear layer by etching with acid and replace it with an artificial smear layer composed of a crystalline precipitate (Causton & Johnson, 1982). Bowen has used this approach by treating dentin with 5% ferric oxalate (an acidic solution), which replaces the original smear layer with a new complex permitting extremely high bond strengths to be produced between resin and dentin (Bowen & others, 1982; Bowen & Cobb, 1983). Greenhill and Pashley (1981) have produced similar artificial smear layers with a variety of chemicals as a method of desensitizing hypersensitive radicular dentin. These may prove useful in the future as materials for lining cavities.

Endodontics

The presence or absence of the smear layer is of interest not only to restorative dentists, but to endodontists as well. Whenever dentin is filed, a smear is produced on its surface (Fig 3). If a smear layer containing bacteria or bacterial products were allowed to remain within the pulp chamber or root canals, it might provide a reservoir of potential irritants. The removal of

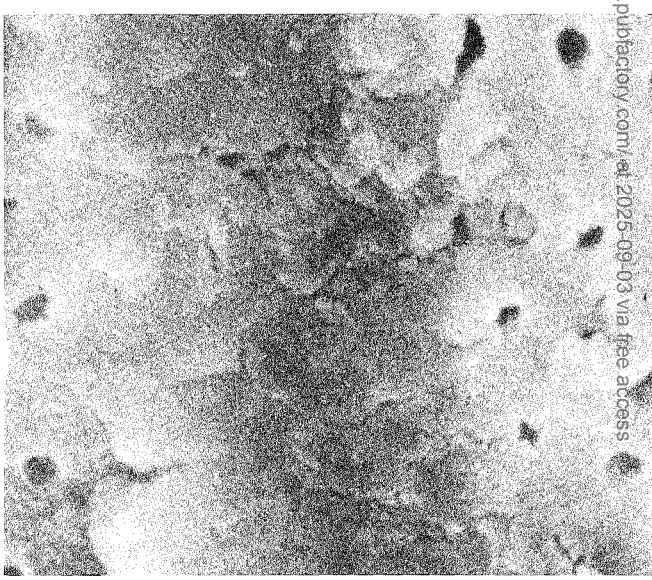

FIG 3. *Dentin of a root canal treated with 5% NaOCl and 17% EDTA to remove pulpal tissue and the smear layer. A No 8 file was drawn over the clean surface in the middle of the scanning electron micrograph, creating a smear layer. Scanning electron micrograph X2000; from Goldman and others (1981), p 200 courtesy of Melvin Goldman and C V Mosby Company.*

the smear layer from the dentin lining the pulp chamber and root canals has been the subject of numerous investigations (see Goldman & others, 1982, for review). Figure 4 is a fortuitous scanning electron micrograph of the smear layer lining a root canal that pulled away from the underlying dentin during processing. This shows clearly that the smear layer is a separate structure from underlying dentin. Goldman and others (1982) recommend alternate use of sodium hypochlorite (NaOCl) and EDTA to remove smeared dentin. The sodium hypochlorite removes organic material, including the collagenous matrix of dentin, and EDTA removes the mineralized dentin, thereby exposing more collagen. Such preparative treatment of root canals presumably permits a better adaptation of obturating materials and sealers to the dentin. Goldman's group has recently demonstrated that removing the smear layer from the root canal permits increased tensile strength of plastic posts (Goldman & others, 1984a,b). The increased retention was associated with penetration of the resin into the open dentinal tubules (Fig 5).

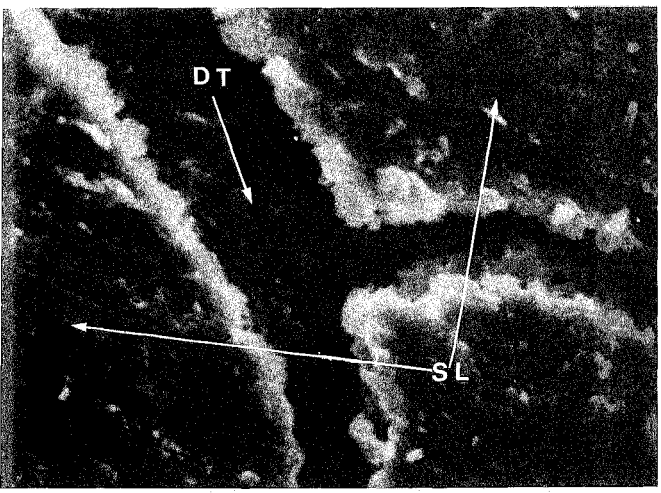

FIG 4. *Scanning electron micrographs of a region in the root canal where the smear layer (SL) cracked open and pulled away from the underlying dentinal tubules (DT) X1700; from Goldman and others (1981); courtesy of M Goldman and C V Mosby Company.*

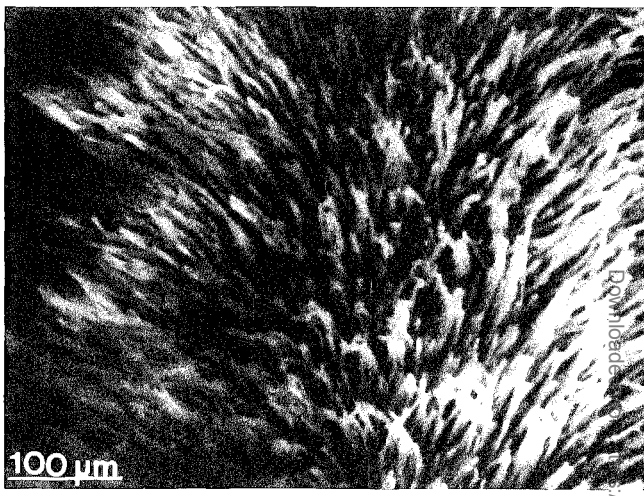

FIG 5. *Unfilled resin was applied to cleaned dentin inside a root canal just prior to insertion of a plastic post covered with more unfilled resin. After polymerization, the tooth substance was demineralized and the organic matrix digested away to leave a plastic cast of the thousands of resin tags extending into open dentinal tubules. Root canals covered with a smear layer did not permit resin to penetrate the tubules. Scanning electron micrograph X89; from Goldman and others (1984); courtesy of M Goldman and the* Journal of Dental Research.

Periodontics

Periodontists produce a smear layer on root dentin during deep scaling or root planing. Register (1973) found, empirically, that etching radicular dentin with saturated citric acid facilitated reattachment following periodontal flap surgery. Register (1973), Register and Burdick (1975, 1976), Ririe, Crigger and Selvig (1980), and Nalbandian and Cote (1982) have shown that this procedure (etching with citric acid) stimulates cementogenesis and the subsequent intertwining of collagenous fibers of the periodontal ligament with fibers of the matrix of dentin or cementum. They also demonstrated that cementum did not form as readily on dentin covered with a smear layer (Figs 6, 7 & 8). In those cases where repair did take place in the presence of a smear layer, the cementum or periodontal fibers, or both, pulled away from the underlying dentin during histologic processing, indicating a very weak bond or attachment (Fig 8). Apparently, cementoblasts do not find the smear layer a very hospitable environment. Further, epithelial cells rapidly migrate across planed (smeared) radicular dentin but not dentin etched with acid.

In the past, many authorities thought that the lack of attachment was due to contamination of the dentin or cementum by microbial products

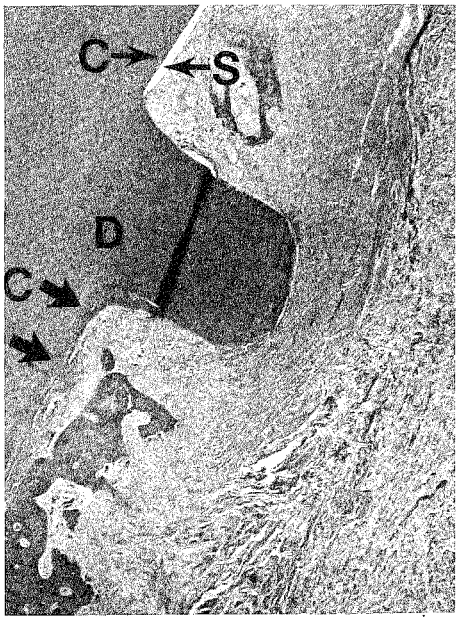

FIG 6. *Surfaces of healthy roots of teeth of beagle dogs were surgically exposed and two adjacent cavities prepared 72 days prior to sacrifice. The upper cavity (control) shows separation (S) of the soft tissue from the dentin surface (D) and minimal formation of cementum (C). The lower cavity into which citric acid (pH 1) was placed for four minutes shows a thick layer of cementum (C). H&E X31; courtesy of J Nalbandian.*

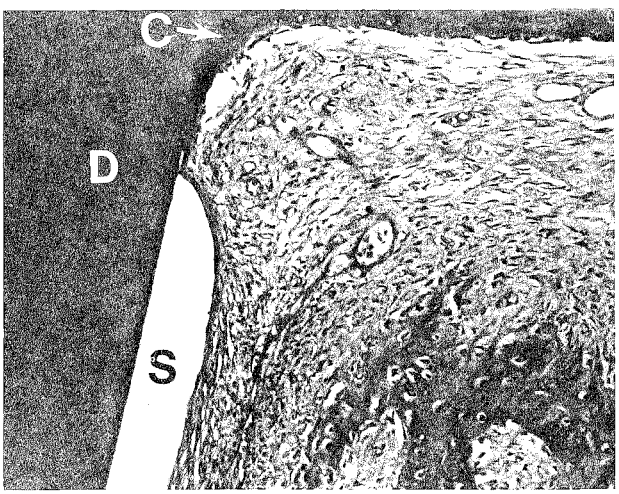

FIG 7. *High magnification of an internal angle of a control (unetched) cavity showing thin cementum (C) and separation (S) of tissue from the dentin. H&E X110; courtesy of J Nalbandian and the* Journal of Periodontal Research, *vol 17, p 556.*

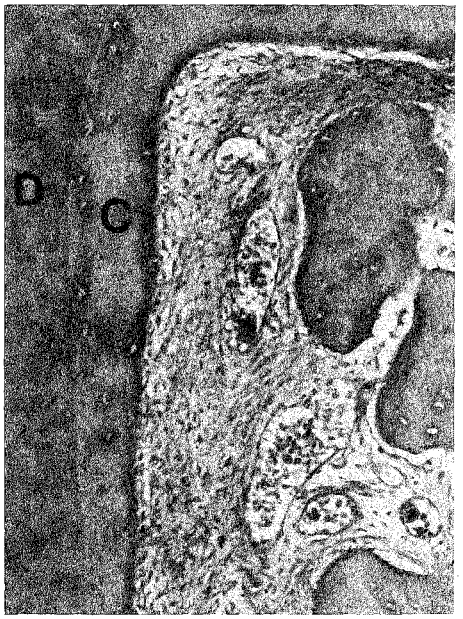

FIG 8. *High magnification of an internal angle of an experimental cavity treated with citric acid, showing thick cementum (C) lining the dentin (D). H&E X110; courtesy of J Nalbandian and the* Journal of Periodontal Research, *vol 17, p 558.*

such as endotoxin (Aleo & others, 1974, 1975; Daly, Seymour & Kieser, 1980). Nalbandian and Cote's (1982) recent experiments eliminate that possibility, as they were done on healthy dentin of roots, the only variables being the presence or absence of the smear layer.

Careful examination of published transmission electron micrographs taken of mineralized sections of roots that were planed but not etched with acid reveals the presence of a finely granular organic layer interposed between root dentin and developing cementum. This has been demonstrated in monkeys (Listgarten, 1972), cats (Nalbandian & Frank, 1980), and humans (Frank, Fiore-Donno & Cimasoni, 1983). These authors have called it 'zone 3' or 'granular junctional cementum'. It probably represents simply a fine, thin, smear layer created on the surface of radicular dentin during root planing (Jones, Lozdan & Boyde, 1972; Polson & others, 1984). Its presence clearly modifies local reactions of tissue in that it apparently inhibits attachment of firm new

connective tissue while permitting migration of the epithelium over its surface. Etching effectively removes the smear layer in addition to exposing collagen fibers in the matrix of radicular dentin. Even after removal of the mineral phase of the smear layer by saturated citric acid, there still remains an organic smear layer, which may interfere with subsequent interdigitation of collagen fibers of periodontal ligament and dentin matrix (Don Adams, unpublished). The organic smear layer is easily rubbed off with a cotton pellet and this indicates how important it may be to standardize techniques of etching, namely, specifying concentration of acid, time of exposure, time of rinsing, dabbing, or rubbing, and so forth.

Restorative Dentistry

Whenever castings are cemented into place, patients are asked to bite down on a cotton roll or seating aid that places all of the masticatory force on that one tooth. The maximum biting force that is comfortable for a patient is about 9–12 kg in the incisor region and 200 kg in the molar region (Hannam, 1976; Van Steenberghe & DeVries, 1978; Mansour & Reynik, 1975). If, for the sake of simplicity, we assume that only 10% of that maximum force is concentrated on 1 cm^2 of a molar crown, then the force per unit area, that is, pressure, generated on and inside the casting would be 20 kg cm^{-2} (284 lbf in^{-2}). Since the cement is an incompressible liquid, it will transfer this pressure to fluid on and in dentin. There is even danger that the cement may enter the dentinal tubules before it sets, displacing an equal volume of dentinal fluid into the pulp. This may be responsible for the pain that some unanesthetized patients feel during cementation of crowns, and can be explained by the hydrodynamic theory of dentin sensitivity (Brännström, Lindén & Åström, 1967). Thus, it may be movement of fluid per se, rather than the acidity of the cement, that produces pain and pulpal irritation.

The pressures generated during the seating of castings can be even higher if the surface area of the cavity is smaller (Pashley, 1983). For instance, seating an onlay into a premolar may place the same masticatory force on a smaller area of surface thereby producing higher pressures. Table 1 lists the pressures that would be produced when biting forces of 1 kg are applied

Table 1. Potential Hydrostatic Pressures Generated by Masticating Forces

Surface Area of Casting	Force Applied	Pressures Generated		
cm^2	kg	mmHg	lbf in^{-2}	kg cm^{-2}
0.01	1	73556	1422	100
0.05	1	14711	284	20
0.10	1	7355	142	10
0.15	1	4904	95	7
0.20	1	3678	71	5
0.50	1	1471	28	2*
1.00	1	736	14	1

Note: The force of 1kg used in the above sample is very conservative. Forces of 10 kg would generate 10 times higher pressures.

*Brännström reported that patients experience dental pain at a threshold of 1 – 3 kg cm^{-2}.

to smaller and smaller areas of surface. Thus, it is of more than academic interest to ask, how much pressure is required to move fluid across dentin?

If one accepts Brännström's hydrodynamic theory as being correct, that is, that pain is due to movement of fluid, then his observation that pain is produced in unanesthetized patients when pressures of 1–3 kg cm^{-2} are applied to dentin answers the previous question. In other words, if dentinal pain is due to movement of fluid across dentin and pressures of 1–3 kg cm^{-2} cause pain, then they must produce movement of fluid. It is interesting to note that Brännström's experiments were done in the presence of a smear layer. Much less pressure is required to force fluid across etched dentin. Apparently, few clinicians have given much thought to the pressures they create with castings during cementation or on the floor of a cavity during condensation of amalgam. Fewer still have compared the pressures Brännström demonstrated as being required to produce pain with the pressures generated in dental practice. Obviously, much remains to be done in this area.

The ease with which fluid can forced across dentin is formalized by a term called the hydraulic conductance (Lp). This term describes the volume of fluid transported across a known area of surface per unit time under a gradient of unit pressure (Reeder & others, 1978).

$$Lp = \frac{Jv}{A, t, \triangle P}$$

where

Jv = volume of fluid (μl)
A = surface area (cm^2)
t = time (min)
$\triangle P$ = pressure gradient (cm H_2O)
Lp = $\mu l\ cm^{-2}\ min^{-1}\ cm\ H_2O^{-1}$

This is of obvious interest to restorative dentists. For instance, it is apparent that one should not purposely etch dentin prior to cementing castings. Zinc phosphate cement is quite acid before it sets. Some preliminary work from our laboratory indicates that zinc phosphate cement may etch away the superficial smear layer during the cementation of a casting. We have also recently measured the effects of zinc phosphate cement on hydraulic conductance of dentin. We found hydraulic conductance fell significantly regardless of whether or not the dentin was covered with a smear layer, even if we removed the cement wafer from the dentin discs (unpublished observations). This suggests that even though zinc phosphate cement may remove some of the smear layer, the cement flows into the smear layer or, even deeper, into the dentinal tubules, to effectively occlude them. How long they would remain occluded if exposed to microleakage or oral fluids remains unanswered.

The question of microleakage of restorative materials is beyond the scope of this review. It is worth mentioning, however, that there are at least two or three routes by which substances can leak into the pulp. First, even if there were no gap between dentin and a restorative material, bacterial products could theoretically diffuse **around** the material via small channels and interstices within the smear layer (Fig 9). Unfortunately, one cannot perfectly adapt amalgam or any other restorative material to the walls of a prepared cavity. Thus, there are voids and spaces between amalgam and dentin that allow considerable microleakage (Going, 1972). Most clinicians use a cavity varnish or liner to "seal" dentin. These organic films are placed on moist dentin, which, microscopically, has pools of liquid on it, which produce an uneven layer of film of variable thickness and permeability. One wonders how well these films adapt to dentin and how well the restorative material adapts to them. Each layer provides potential routes for microleakage. Viewed in this theoretical perspective, if one could produce a truly adhesive filling material that had no shrinkage upon polymerization and a coefficient of thermal expansion close to that of tooth structure, then one would want to remove the smear layer and omit the use of any cavity liner or varnish that did not react chemically with both the dentin and the resin.

Influence on Sensitivity of Dentin

Etching the dentin of roots, whether done therapeutically or by the action of microorganisms of plaque, can remove the thin layer of covering cementum or smear layer, or both, thereby exposing patent dentinal tubules to the oral cavity. This can lead to sensitivity of dentin

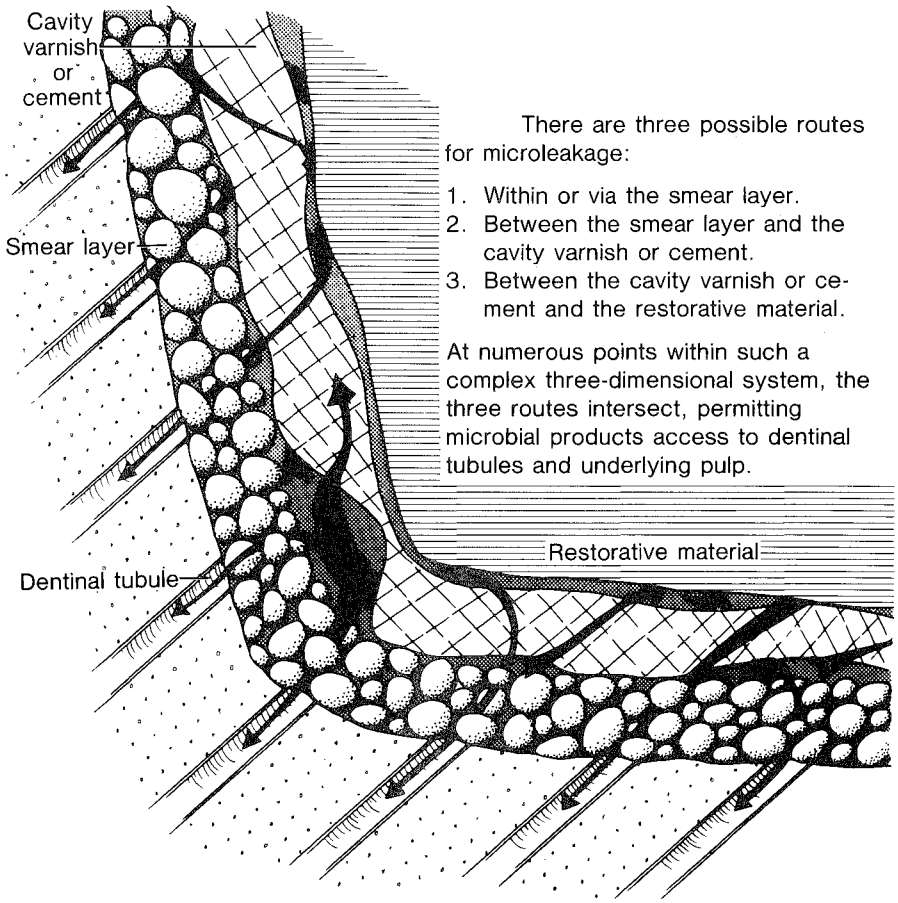

FIG 9. *Schematic representation of the interface of dentin and restorative material in a typical cavity. The granular constituents of the smear layer have been exaggerated out of their normal proportion for emphasis. Three theoretical routes for microleakage are indicated by arrows.*

to the point where it interferes with the patient's oral hygiene. As movement of fluid is central to the hypothesis, several careful studies have been made of the most important variables influencing movement of fluid through dentin (Reeder & others, 1978; Pashley, Livingston & Greenhill, 1978a; Boyer & Svare, 1981; Pashley, Thompson & Stewart, 1983b). These studies indicate that most of the resistance to the flow of fluid across dentin is due to the presence of the smear layer. Etching dentin greatly increases the ease with which fluid can move across dentin. This is accompanied clinically by increased sensitivity of dentin to osmotic, thermal, and tactile stimuli (Johnson & Brännström, 1974).

Several laboratories interested in the sensitivity of dentin use the canine tooth of the cat as an in vivo model. Three small cavities are prepared well into the dentin and recording electrodes placed in two of these cavities. The third cavity, often called the test cavity, is exposed to hypertonic solutions to osmotically induce flow of fluid, which is detected as an increase in the rate of firing of pulpal nerves recorded by the electrodes in the other two cavities. Using this model, Panopoulos, Gazelius and Olgart (1983) found that few of their test cavities responded

to osmotic stimuli prior to etching, that is, in the presence of an intact smear layer. After a two-minute exposure to 1M lactic acid, cavities responded to the same stimuli that previously had been ineffective.

Similar results were reported by Närhi, Hirvonen and Hakumäki (1982) using a similar model but recording from single nerve fibers. These observations corroborate clinical impressions that etching with acid increases sensitivity of dentin (Johnson & Brännström, 1974).

If dentin is sensitive, then according to the hydrodynamic theory of dentin sensitivity, the dentinal tubules must be patent and must allow movement of fluid across dentin. If fluid can move, it seems reasonable to assume that bacterial products from plaque covering those surfaces of sensitive dentin may also permeate dentin into the pulp. The presence of a smear layer will prevent bacterial penetration of the tubules but will permit bacterial products to diffuse slowly into the pulp. This may produce a mild, low-grade inflammatory response that lowers the pain threshold in the affected teeth, making them more sensitive than they would be in the absence of plaque.

Influence on Permeability of Dentin

The presence of a smear layer has a large influence on permeability of dentin. Substances diffuse across dentin at a rate that is proportional to their concentration gradient and the surface area available for diffusion. The area available for diffusion in dentin is determined by the density of dentinal tubules, that is, the number of tubules per square millimeter, and by the diameter of these tubules. Both of these values vary as a function of distance from the pulp chamber (Forssell-Ahlberg, Brännström & Edwall, 1975; Garberoglio & Brännström, 1976). Table 2 lists the density and diameters of tubules obtained at various distances from the pulp. The actual area of diffusional surface is the product of tubule density and the area of each tubule. Thus, we see that the theoretical area of diffusional surface varies from about

Table 2. Area of Surface of Dentin Available for Diffusion at Various Distances from the Pulp

Distance from Pulp	Number of Tubules million cm^{-2}		Tubular Radius cm x 10^{-4}		Area of Surface (Ap) %	
mm	mean	range	mean	range	mean	range
Pulp	4.5	3.0-5.2	1.25	2.0-3.2	22.1	9-42
0.1-0.5	4.3	2.2-5.9	0.95	1.0-2.3	12.2	2-25
0.6-1.0	3.8	1.6-4.7	0.80	1.0-1.6	7.6	1-9.0
1.1-1.5	3.5	2.1-4.7	0.60	0.9-1.5	4.0	1-8.0
1.6-2.0	3.0	1.2-4.7	0.55	0.8-1.6	2.9	1-9.0
2.1-2.5	2.3	1.1-3.6	0.45	0.6-1.3	1.5	0.3-6
2.6-3.0	2.0	0.7-4.0	0.40	0.5-1.4	1.1	0.1-6
3.1-3.5	1.9	1.0-2.5	0.40	0.5-1.2	1.0	0.2-3

Modified from Garberoglio and Brännström (1976).
$Ap = N\pi r^2$ where N is the number of tubules/cm^2; Ap represents the percent of the total area of the physical surface available for diffusion.

1% at the dentinoenamel junction to 22% at the pulp (these values have very large ranges). These areas of diffusional surface were calculated for surfaces of fractured dentin that were free of debris. Such conditions are seldom seen clinically except in dentin etched with acid.

If one looks at the surface of a smear layer in a scanning electron micrograph (Fig 1A), one would predict that it might be impermeable. However, experiments both in vitro and in vivo have demonstrated that isotopically labeled solutes of various molecular sizes easily penetrate the smear layer (Pashley & Livingston, 1978; Pashley & others, 1978b; Pashley, & others, 1981). By measuring the fluxes of radioactive water and albumin across known areas of surface, and by knowing the rates of diffusion of these substances in free solution, one can calculate the effective area of diffusional surface available for the diffusion of these tracers, even through a smear layer. In dentin discs prepared by sawing from midcoronal dentin, which, if they had been prepared by fracturing, should have had an area of diffusional surface of approximately 7–8%, were determined by the use of tritiated water as a tracer to have an effective, or functional, area of diffusional surface of the smear layer of 1.7% (Table 3). Removal of the smear layer by etching with acid increased the area of diffusional surface of the tubules to 7.9% (Pashley & others, 1978b). If one uses the value for etched dentin of 7.9% of the total surface area as representing the theoretical maximum area of effective diffusional surface, then the value of 1.7% obtained in the presence of the smear layer suggests that (1.7/7. 9x100) 21.5% of the total area occupied by the smear debris was available for diffusion of radioactive water and that the orifices of 78.5% of the tubules were occluded with debris. In that same paper, the authors demonstrate that treating etched dentin with a solution of 3% (w/v) monopotassium-monohydrogen oxalate produced an artificial smear layer that reduced the area of diffusional surface to near that of the control, namely, the authentic smear layer.

It is important to distinguish between transport of materials by diffusion and by convection. Diffusion varies with the square of the radius, since cross-sectional area is equal to πr^2. Diffusion occurs from areas of higher concentration to areas of lower concentration. During diffusion, the concentration of substances is dissipated over distance. For instance, the concentration of microbial products entering the pulp chamber through very thick dentin (that is, long tubules) is only a fraction of the concentration of these agents on the dentin surface. The transport of materials across dentin by convection is due to the presence of a pressure gradient. In convection, there is no change in the concentration of substances dissolved in the fluid because the fluid and all that is dissolved in it is made to flow from one point to another. The driving force is the pressure, which is dissipated over distance. Transport across dentin by convection, or fluid filtration, varies with the fourth power of the radius (πr^4). Thus, movement of fluid across dentin by convection is much more sensitive to the degree of occlusion of tubules, that is, the presence or absence of a smear layer, than is movement of substances by diffusion (Merchant, Livingston & Pashley, 1977). If the hydrodynamic theory of dentin sensitivity is correct (Brännström & others, 1967), then one needs to evaluate the struc-

Table 3. Comparison between Areas of Surface of Dentin Available for Diffusion before and after Etching

Distance from Pulp mm	Area of Surface (Ap) %	Area of Surface Available for Diffusion of Water: Before Etching %	Area of Surface Available for Diffusion of Water: After Etching %
Pulp	22.1		
0.1 - 0.5	12.2		
0.6 - 1.0	7.6	1.72	7.89
1.1 - 1.5	4.0		
1.6 - 2.0	2.9		
2.1 - 2.5	1.5		
2.6 - 3.0	1.1		
3.1 - 3.5	1.0		

Modified from Pashley, Livingston, Reeder & Horner (1978).

tures and mechanisms influencing movement of fluid across dentin.

Flow of fluid across dentin obeys the Poiseuille-Hagen Law:

$$\dot{Q} = \frac{\pi \triangle P r^4}{8 \eta l}$$

where

- $\dot{Q}$ = rate of fluid flow
- r = tubule radius
- $\triangle P$ = hydrostatic pressure gradient
- l = length of tubule or thickness of remaining dentin
- η = viscosity of dentinal fluid

The important variables in this equation are the radius raised to the fourth power (which obviously is the most important variable), the pressure gradient, the thickness of dentin, and the viscosity of dentinal fluid. If we assume that viscosity remains relatively constant at a constant temperature, then the major variables are tubular radius, tubular length, and pressure gradient. The presence of the smear layer has a profound effect on the resistance to movement of fluid across dentin by modifying the tubular radius. This was shown in vitro in experiments on isolated segments of crowns of freshly extracted teeth. The teeth were extracted, the root sectioned at the cementoenamel junction, and the enamel removed to leave a crown segment that possessed a smear layer on the enamel side of the dentin and odontoblasts on the pulpal side of the dentin. The total resistance to flow of fluid was measured, followed by etching the smear layer with acid and repetition of the measurement of resistance to flow of fluid. Following this, the pulpal tissue was removed and rates of flow of fluid remeasured. Using this approach, the authors concluded that the smear layer accounted for 86% of the total resistance to flow of fluid (Pashley & others, 1978a). Thus, after etching with acid, the rate of flow of fluid increased 15-fold in that study, 32-fold in another study (Reeder & others, 1978) and 42-fold in a more recent in vitro study (Pashley & others, 1983b). Boyer and Svare (1981) reported only a sevenfold increase in flow of fluid across etched dentin compared to pre-etched dentin in a single disc. Their values indicate that they had a rather thin smear layer on the dentin disc that they studied.

It should be clear that removing the smear layer increases dentin permeation by diffusion about 5–6 times in vitro but increases dentin permeation by convection (that is, filtration) about $(5–6)^2$ or 25–36 times. These data were obtained in vitro on dentin that had been prepared with a diamond blade on a metallurgical circular saw. Such procedures tend to increase the density and thickness of the smear layer relative to those produced clinically with high-speed burs. This was demonstrated recently by measuring filtration rates of fluid across dentin in cavities prepared in dog teeth in vivo. In this preparation, etching with acid produced only a fivefold increase in dentin permeability. The major difference in vivo was in the values obtained in the presence of the smear layer before etching. They were about five times higher than those measured in vitro, whereas the values obtained after etching dog dentin in vivo were very similar to the values observed in vitro in human dentin etched with acid (Pashley & others, 1983a). These authors reported an inverse relationship between the initial permeability of dentin and the subsequent per cent change in permeability after etching with acid in vivo. They interpreted the relationship as follows: If the smear layer is thick, the initial permeability of dentin will be low but should increase more after etching. Teeth that have little or no smear layer will have high initial permeabilities, which will not change much following etching since there is little debris occluding the tubules. Thus, the magnitude of the change in the rate of flow of fluid across dentin before and after etching indicates the thickness or density of the smear layer.

CONCLUSION

The smear layer occupies a strategic position in restorative dentistry. It exists at the interface of most restorative materials and the dentin matrix. Because it is a very thin layer and is soluble in acid, it is not apparent on examination with the light microscope of routinely processed specimens. This is probably why the smear layer has received so little attention by restorative dentists.

There are two extreme points of view regard-

ing the smear layer. One is that it is a beneficial, iatrogenically produced cavity liner that reduces dentin permeability far more effectively than any of the marketed cavity varnishes. At the other extreme is the view that it interferes with the apposition or adhesion of dental materials to dentin and that it may serve as a depot of microorganisms or their products, both of which are injurious to the pulp. Both points of view are correct. The former perspective is the most appropriate for clinicians using the commonly available restorative materials, which exhibit microleakage and a lack of adhesion to tooth structure. The latter perspective may be more appropriate in the future when truly adhesive restorative materials are in routine use.

Our knowledge of the smear layer, its structure and function, is rapidly growing and will influence all areas of clinical dentistry in the near future. Much more work needs to be done, but the promise of greater understanding of the smear layer should provide increased benefits through improved dental therapy.

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Smear Layer: Removal and Bonding Considerations

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This paper constitutes Part XXIX of a series of reports on adhesive bonding of various materials to hard tooth tissues.

INTRODUCTION

Disturbed surface layers of dentin and enamel that are formed by cutting or abrading instruments must be removed or altered to obtain strong adhesive bonding between restorative materials and dentin and enamel. These layers can be removed by acids, including formic and ascorbic acids, or chelating compounds, both of which form soluble or insoluble reaction products (Bowen, 1978). Treating prepared cavities for 60 seconds with isotonic solutions of formic acid did not change responses to zinc oxide and eugenol cements (Mjör, Hensten-Pettersen & Bowen, 1982).

Solutions of ferric oxalate also dissolve the smeared surface layer yet form insoluble reaction products that apparently occlude the openings of dentinal tubules (Bowen, Cobb & Rapson, 1982). These solutions also remove the smeared layer on cut enamel, revealing typical patterns of enamel prisms. When the ferric oxalate is followed by treatment with solutions of a specific surface-active compound and then a polymerizable coupling agent, strong adhesive bonds with composites are possible on dentin and enamel in vitro (Bowen & others,

1982). Removal of the smeared layer, however, may be inappropriate if there is to be no bonding or improved adaptation.

Surface layers of hard tissues of teeth that are disturbed by cutting or abrading instruments have been studied extensively with scanning electron microscopy (SEM) (Boyde, 1973; Barnes, 1977; Iwaku & others, 1981; Pashley, Michelich & Kehl, 1981; Smith, 1982) but a search of literature revealed no studies of smeared surfaces with the higher magnifications possible with transmission electron microscopy (TEM). This report contains original observations by TEM and SEM of smeared surfaces of dentin.

MATERIALS AND METHODS

A human mandibular third molar was extracted and stored in distilled water under refrigeration. The tooth was sectioned approximately parallel to the occlusal surface with a diamond saw under running water and was then abraded dry against a 320 grit abrasive cloth strip with hand pressure (once forward and backward on fresh abrasive) to simulate the surface conditions used in current testing of adhesion (Bowen, 1965; Bowen, Cobb & Misra, 1984). The specimen was then fixed by immersion in 10% buffered formalin acetate at room temperature (about 22 °C) for three days, washed for one hour with distilled water, and blown dry with filtered compressed air.

It was then further sectioned, with a diamond wheel cooled with distilled water, into blocks small enough to be processed for TEM and SEM.

Transmission Electron Microscopy

Blocks for TEM were postfixed in 1% osmium tetroxide (buffered with 0.10M sodium cacodylate) for three hours at room temperature. Prior to postfixation, several blocks were demineralized for two weeks at 4 °C in a solution of ethylenediaminetetracetic acid (EDTA) (Warshawsky & Moore, 1967). All blocks for TEM were dehydrated in a graded series of ethanol and embedded flat in low viscosity epoxy resin (Spurr, 1969) so that sections perpendicular to the original abraded surface could be made. Thin sections showing interference colors of silver to pale gold were cut with a diamond knife and mounted on uncoated copper grids. These were examined and photographed at 80 kV on a Phillips 400 electron microscope with or without prior staining with uranyl acetate and lead citrate (Reynolds, 1963).

Scanning Electron Microscopy

Blocks for SEM were mounted conventionally, then coated with 20 nm of gold-palladium. These were examined and photographed at 20 kV on a Jeol JSM 35C scanning electron microscope.

RESULTS

Scanning Electron Micrography

Scanning electron micrographs showed a smeared and somewhat flaky appearance with tubules evident only where the smeared layer over the tubular lumina was cracked as an artifact of desiccation (Fig 1).

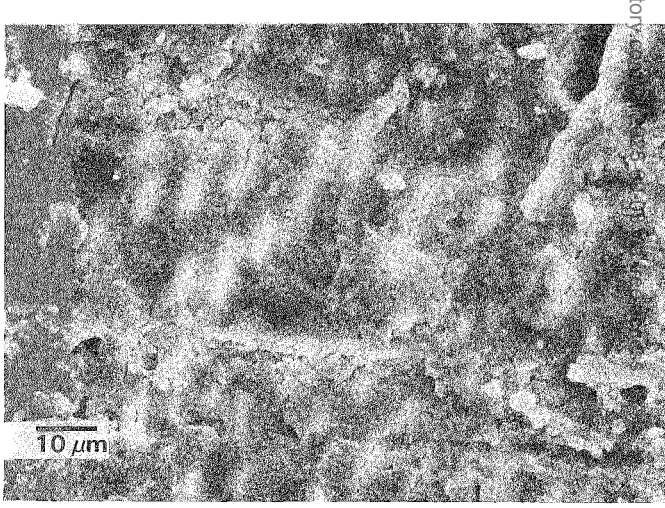

FIG 1. *Scanning electron micrograph of the surface of dentin sectioned with a diamond saw under running water, then abraded dry against coarse (320 grit) abrasive strip. Flaky, smeared surface material nearly occludes lumina of dentinal tubules except for cracks as a result of desiccation. X730; width of field about 114 μm.*

Transmission Electron Micrography

Transmission electron micrographs of undemineralized, unstained dentin sectioned approximately perpendicular to the abraded surface revealed the presence of some loose material appearing disconnected from the surface in the plane of the section. There were also microcracks extending two to three micrometers (μm) from the outermost surface. In some areas the apatitic material appeared somewhat scrambled compared with the subjacent dentin.

Observations of undemineralized sections that had been subjected (on the TEM grid) to the acidic stain, uranyl acetate, showed an electron-dense region in the outermost surface that averaged a few tenths of a micrometer in depth. At a magnification of 100 000 this dense region appeared to be apatitic. These outer crystallites may have been encapsulated by the impregnating resin used for embedding, thus preventing their demineralization by the acidic stain. Deeper layers may have been denser and impregnated less by the epoxy resin, therefore more susceptible to the acidic stain. Deep to the smear layer, the acidic stain apparently removed much of the apatitic material and either denatured the collagen or failed to stain it, as the micrographs showed very little evidence of either apatite crystals or the characteristic striations of collagenous fibrils.

The most revealing transmission electron micrographs were of specimens demineralized and stained. In Figure 2 can be seen sectioned dentinal tubules that contain stainable matter near the surface of smeared dentin. The lumina appear empty at distances farther from the surface. The remnants of the peritubular dentin appear more intact in the tubules that are filled compared to those that appear empty. There is a region at the surface, typically 1 μm or less in thickness, where the staining is less dense than it is in deeper areas. Figure 3 shows also a region of dentin about 1 μm or less in depth wherein the demineralized and stained material appears amorphous. There is a clearcut distinction between this layer and the patterned staining of collagenous fibrils located farther from the surface. In Figure 4 as in Figure 3, mottled white (unstained) regions are scattered throughout the intertubular dentin, suggestive of negative staining; these may represent regions that were highly mineralized before the specimen was fixed, demineralized, and stained.

FIG 2. *Transmission electron micrograph of demineralized and stained cross section of dentin surface that had been cut and abraded. A relatively amorphous zone is visible in the surface of the outer dentin shown at the top. Its thickness, which varies, has a maximum of about 1 μm. The lumina of dentinal tubules nearer the surface are partly filled with stainable amorphous substance; in these, the peritubular dentin remains more nearly intact than the peritubular dentin of the empty tubules farther removed from the cut and abraded surface of dentin. X3300; width of field about 22 μm.*

Scanning electron micrographs and transmission electron micrographs of smeared dentin surfaces treated with ferric oxalate solutions are remarkably different.

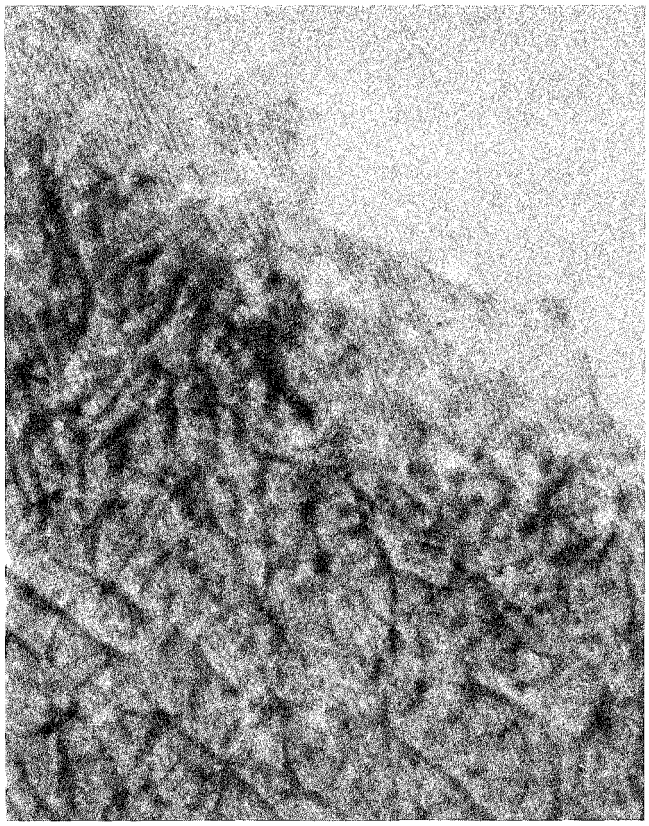

FIG 3. *Transmission electron micrograph at higher magnification of demineralized and stained section of dentin transverse to the dentin surface that was cut and abraded before fixation and processing. The relatively amorphous region is seen to vary in thickness between about 1.3 and 1 μm of the surface of the outer dentin (at top); lower, the banded collagen fibrils appear undenatured. The small white features throughout may correspond to regions where mineralization was sufficiently high to virtually exclude stainable organic matrix. X15 200; width of field about 4.9 μm.*

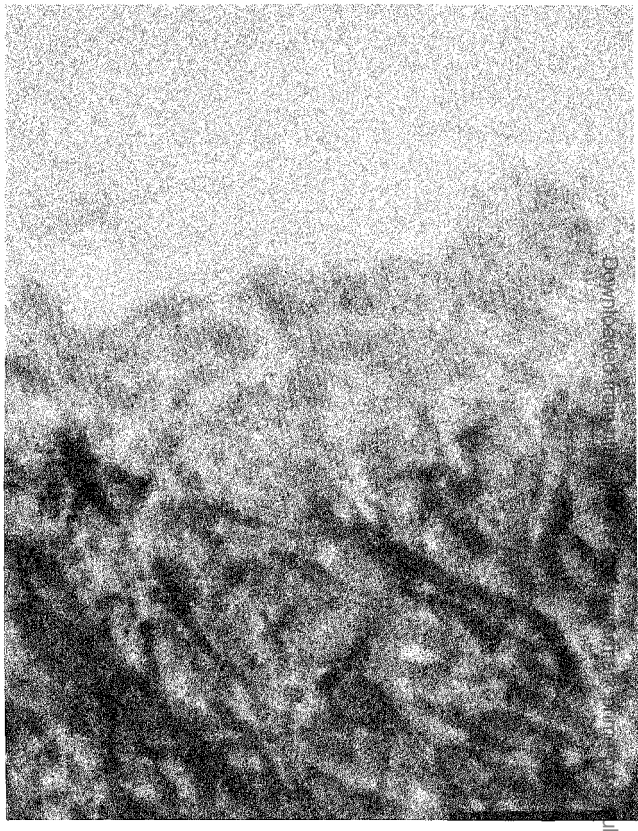

FIG 4. *Transmission electron micrograph at further magnification of a smeared surface of dentin. This shows an amorphous outer region slightly less than 1 μm in depth. There is a relatively abrupt transition between the denatured and the deeper undenatured collagen fibrils. The irregularity of the surface is probably due to the direction of the grooves and ridges, produced by the abrasive particles, being perpendicular to the plane of the section. X25 000; width of field about 3 μm.*

DISCUSSION AND CONCLUSIONS

The features seen in Figures 1-4 are provisionally interpreted as being representative of smeared dentin. This combined study by SEM and TEM suggests that smeared dentin, when cut and abraded as in this experiment, has an altered structure ranging 0-3 μm in depth. The depth is not uniform. Greater depths of structural alteration might be expected, depending on the way the surface is cut or abraded. Intertubular collagen appears to be denatured in this region of altered surface to a depth up to about 1 μm. The surface layer of adhering debris has been described as 0.1 - 1.0 μm in thickness (Arends, 1977, unpublished).

There was some evidence of microcracking of surface material up to 2 or 3 μm below the outermost disturbed surface. There may have

been some loosening or lifting of surface material, which would correspond to the edge of flakes as seen in Figure 1. Organic stainable material was seen in the lumina of dentinal tubules near the disturbed surface.

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Smear Layer: Pathological and Treatment Considerations

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Bacteria in the Smear Layer under Restorations

The pathological consequences of the smear layer and whether it should be present or absent under restorations are rather complicated questions. To a great extent they seem to be related to the presence of bacteria under the restoration. We had to answer many questions when we first discovered the growth of bacteria under silicate and composite resin restorations 14 years ago (Brännström & Nyborg, 1971). One question was: Is it possible that bacteria entrapped in the smear layer survive and multiply under these restorations?

We tried to answer this in a study two years later (Brännström & Nyborg, 1973). Facial cavities were prepared in 20 contralateral pairs of human premolars. One cavity, randomly selected after preparation, was cleaned with water spray, while the other was cleaned with an antiseptic detergent. Both cavities were then filled with composite and allowed to set. In both teeth, the outer part of the filling was removed and replaced with zinc oxide and eugenol or Cavit cement. In this way we prevented the growth of bacteria into the contraction gap between the resin and the cavity walls. The teeth were extracted after three to six weeks. They were coded and histologic evaluation was made by two observers.

The histologic evaluation revealed that in 17 of the water-cleaned cavities, with the smear layer remaining, numerous bacteria were present; in the antiseptically cleaned cavities, bacteria were absent. These results were highly significant and showed that a few bacteria entrapped in the smear layer may survive and multiply. There was also pulpal inflammation under these cavities. Using a similar technique we have found that bacteria may also survive and multiply in the smear layer under silicate, though not as frequently as under composite resins (Brännström, Vojinovic & Nordenvall, 1979).

The fact that bacteria may multiply on cavity walls even if there is no appreciable communication to the oral cavity seems to indicate that certain microorganisms get sufficient nourishment from the smear layer and dentinal fluid. This view is also supported by the results from

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our experiments with inlays cemented with phosphate cements without any protective lining of the cavity walls (Brännström & Nyborg, 1960, 1974, 1977). We used inlays made of lead because it is soft and more easily adapted to the margins of the cavity. In this way we got a good seal and minimal communication to the oral cavity. We had 59 inlays cemented in antiseptically cleaned cavities, and in almost all teeth there were no bacteria on cavity walls and no inflammation in the corresponding pulp, not even when there was a pulpal exposure.

On the other hand, when the cavities had been cleaned only with water before cementation, a high frequency of inflammation was found in 22 of 25 teeth and in 10 teeth the inflammation was moderate to severe. There were also indications that in these teeth bacteria were present. These considerations favor the opinion that most of the smear layer should be removed and any smear layer remaining, for instance at the tubule apertures, should be antiseptically treated before the application of a lining or a luting cement. The presence of a smear layer may also affect the retention of a lining and of luting cements. Their retention is obtained mainly through mechanical interlocking into micro undercuts in the dentin (Øilo, 1978). It is possible that the presence of a superficial smear layer will weaken mechanical retention between the lining and the surface of the cut dentin.

It has been suggested that bacteria are not present in freshly prepared smear layers (Mjör, 1974). This suggestion was based on stained sections of freshly cut intact teeth. It seems clear that histologic techniques cannot reveal a few bacteria entrapped within a smear layer. They must multiply for some time, form a thicker layer, replace the smear layer, and become attached to the cut dentin if we are to find them with certainty on the stained sections, because, during the demineralization of freshly cut and unprotected dentin in preparation for cutting sections, not only enamel but also the smear layer disappears. At the same time, microbes entrapped within the smear layer disappear as well.

It is true that a smear layer without bacteria can be produced when intact teeth are cut experimentally. On the other hand, in normal clinical procedures, especially when operating on carious teeth, usually with low-speed or hand instruments in the final preparation, we must consider the great risk of bacteria surviving in the smear layer. Bacteria may even be left in the narrow gap between the enamel and dentin at the lateral walls, as well as in single tubules in mineralized dentin underneath. There is no evidence that common permanent restorative materials are sufficiently antibacterial to kill bacteria entrapped within the smear layer, especially when a fluid-filled contraction gap, 5 – 20 μm wide, separates the restoration from the smear layer.

Using the same experimental technique described earlier (Brännström & Nyborg, 1973), we have found that bacteria may also enter from the tooth surface into the fluid-filled contraction gap around silicate and composite restorations. This had been confirmed in experiments using a microbiologic technique at the University of Michigan (Bergenholtz & others, 1982). These authors also found that microbial invasion occurred frequently around amalgam restorations. These observations seem to favor the recommendation that all cavity walls should not only be cleaned and antiseptically treated but also protected with a thin lining. This lining, applied to all cavity walls, should not be placed over a superficial smear layer on the surface of cut enamel and dentin, as a thin lining may be insufficiently antibacterial (Brännström, 1982; Brännström, Nordenvall & Glantz, 1983; Brännström, 1984). Moreover, for adequate retention of the lining to the cut enamel and dentin, a superficial smear layer must not be present.

Bases of zinc oxide and eugenol and calcium hydroxide may have good antiseptic effects but, unfortunately, under permanent restorations these bases cannot be placed on all cavity walls. Also, bases of calcium hydroxide, such as Dycal, may disappear when leakage occurs, leaving a fluid space for bacteria to enter. This has been demonstrated in experiments (Brännström, 1984). In small cavities, or large but shallow cavities—and they too need a lining—thick bases take up too much space. Bases of fast-setting calcium hydroxide may attach poorly to the cut surface and there is the risk that a fluid-filled gap may develop on both sides of the lining. Pure calcium hydroxide is an excellent antibacterial temporary dressing and should be applied under temporary fillings. This has been confirmed in many studies of pulp capping. It is also possible—but not proved—

that calcium hydroxide may reinforce the remaining smear plugs in the outer apertures of dentinal tubules.

Smear Layer on Dentin Exposed to the Oral Cavity

Another question concerns what may happen to the smear layer on surfaces exposed to the oral cavity and left unrestored, for example, in root planing, after superficial grinding, or under poorly fitting temporary crowns. We have found that when a smear layer is produced experimentally on human dentin, and left exposed, it disappears after a couple of days and is replaced by bacteria, and after a week almost all tubules are opened and some even widened (Brännström, 1982). There may be 10 000 – 20 000 tubules per square millimeter exposed on a superficial, hypersensitive exposure. The consequence is the invasion of bacteria. In single tubules they can be found to have penetrated rather deeply (Lundy & Stanley, 1969; Olgart, Brännström & Johnson, 1974). Bacteria may plug the apertures of the tubules. After two weeks, however, we have occasionally seen a mineralized pellicle blocking the apertures of the tubules (Brännström, 1982).

Removal of the Smear Layer under Restorations

We cannot expect a mineralized pellicle to develop under a restoration where saliva does not circulate. However, we know that the outward flow of fluid in dentinal tubules and around fillings may be reduced with time. The pulpal ends of the tubules may be partly blocked by irregular dentin. As reported by Pashley (1984), accumulation of solids in tubules and at their outer apertures may contribute to a reduced flow of fluid. Under favorable conditions a mineralized pellicle may develop at the outer aperture of the contraction gap. The same has been observed in the apertures of tubules of cut dentin left unprotected.

Little research is available to indicate what happens to the smear layer left under a restoration. The smear layer may be detached and follow the outward flow of fluid in the contraction gap. In a vital tooth this flow is directed outward due to the pressure gradient—a higher pressure of fluid in the pulp. The size of the gap around the restoration may vary from 5 to 20 μm. In one study we noticed that parts of the smear layer had been removed from the floor of a cavity containing a poorly fitting temporary restoration of gutta percha for three days (Johnson & Brännström, 1971). We can imagine what may happen under a poorly fitting temporary crown with a gap filled with fluid and bacteria. It is not surprising that the dentin is often hypersensitive when such a temporary crown is removed after a couple of weeks. Certain bacteria may directly dissolve enamel and the highly mineralized peritubular dentin (Brännström, 1982; Brännström & Mejàre, unpublished data). We may also expect that certain bacteria may remove at least parts of the smear layer. Histologic sections sometimes reveal that the bacterial layer is closely oriented to the surface of the cut dentin; the bacteria have, in other words, occupied the smear layer.

Before sectioning of a tooth in the laboratory, a composite or amalgam restoration is removed. If we use the scanning electron microscope (SEM), we may observe the bacterial layer attached also to the inner surface of the restoration (Brännström, 1982). Sometimes the whole bacterial layer is detached from the cavity and no bacteria are seen in the dentinal tubules because of the presence of smear plugs in the tubule apertures. This is one reason why we may not always find a correlation between pulpal inflammation and the presence of bacteria on cavity walls. Inflammation may be present in the pulp, but a bacterial layer may not appear on the actual sections because it has been detached. Another reason for this failure is that usually the sections examined in the microscope cover only a small part of the total area of cavity walls. Bacteria may multiply on a lateral wall and the concentration of toxins may increase in the fluid-filled gap, but in the area sectioned, or microbiologically sampled, the bacteria may not be attached to the dentin. Conversely, bacteria may be present on the sections but no inflammation seen in the corresponding pulp because of the presence of atubular, irregular dentin blocking the pulpal ends of the tubules. This "reparative" dentin may develop after two weeks in monkeys and dogs, animals often used in experimental studies. In humans usually two to three months

are needed for developing this barrier. This fact, which makes it difficult to interpret results from such animal experiments and correlate them with the clinical situation in humans, has been discussed elsewhere (Brännström, 1982).

The Protective Effect of Smear Plugs in Tubule Apertures and the Consequence of Removing the Plugs

In a study 11 years ago we found that etching the cavity prior to the placement of composite resin resulted in a massive invasion of bacteria in dentinal tubules (Vojinovic, Nyborg & Brännström, 1973). This was seen in all teeth after three to four weeks. The corresponding cavities, cleaned by water and with the smear layer left, had a bacterial layer on cavity walls but practically no invasion into the dentinal tubules. Obviously smear plugs in the apertures of the tubules had prevented bacterial invasion. Inflammation was present under all infected cavities, being somewhat more pronounced under the etched cavities, but the difference was not great. Thus, another conclusion from this study was that smear plugs did not prevent bacterial toxins from diffusing into the pulp. This has been confirmed by Bergenholtz (1977). The degree of inflammation in the pulp seems to depend on the amount and type of toxin, from both live and dead bacteria, reaching the pulp, rather than the presence of bacteria within the tubules. However, toxins, sometimes in combination with an unduly intense reaction, may lead to a local necrosis. From opened tubules, bacteria may easily reach the pulp and multiply (Brännström, 1982). Therefore, removal of smear plugs should be avoided. Pashley (1984) has also demonstrated that smear plugs reduce permeability of dentin.

Another important consequence of etching and the removal of smear plugs and peritubular dentin at the surface is that the area of wet tubules may increase from about 10 to 25% of the total (Garberoglio & Brännström, 1976; Johnson & Brännström, 1974). Subsequently it is difficult to get the dentin dry because fluid continues to be supplied from below through the tubules. This moisture would not seem to favor adhesive or mechanical bonding to dentin. When a resin varnish, liner, or restoration is allowed to set slowly, droplets and "lakes" may appear on the inner surface of the resin (Nordenvall, 1978). Drying is not a problem in eroded or abraded dentin, where the tubules usually are occluded by sclerosis. However, in sensitive dentin, the tubules are open all the way. It is better to keep them occluded with disinfected smear and with peritubular dentin preserved at the surface. The permeability is reduced and the cut dentin can be more easily desiccated with a blast of air.

Pulpal Irritation Due to Removal of the Smear Layer

We have found that an application of 50% citric acid or 37% phosphoric acid for even five seconds is sufficient to remove smear plugs and peritubular dentin at the surface (Brännström & Johnson, 1974; Nordenvall & Brännström, 1980). Other investigations have shown that even weaker acids may have the same capacity, especially if applied for 30 – 60 seconds (Bowen, 1978; Pashley, Michelich & Kehl, 1981). In several experiments we have found that 37% phosphoric acid or 50% citric acid applied for 15 seconds or one minute does not result in any appreciable pulpal reaction, inflammation, or necrosis. This is true even if we are very near the pulp or apply the acid to an exposed pulp for 15 seconds (Brännström & Nordenvall, 1978; Nordenvall, Brännström & Torstenson, 1979; Torstenson, Nordenvall & Brännström, 1982).

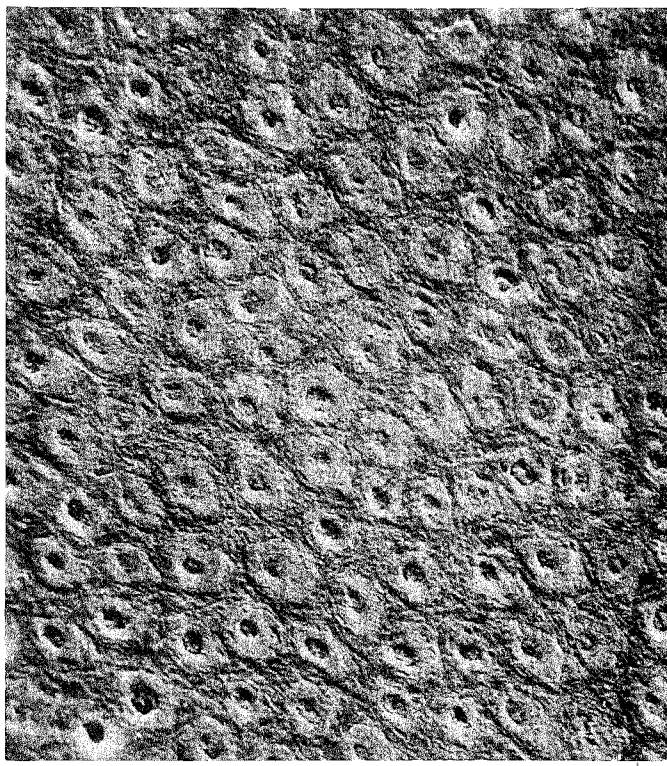
In one study we restored the cavities of 62 human teeth with a composite (Clearfil Bond System-F; Kuraray Co, Ltd, Osaka, Japan). No lining was used. Some cavities had pulpal exposures. All cavities were etched for 15 seconds with 40% phosphoric acid and then rinsed with water and treated for one minute with an antiseptic detergent (Tubulicid; Dental Therapeutics AB, Nacka, Sweden) before drying for several seconds with a blast of air. The outer part of the cavity was sealed with zinc oxide and eugenol cement to avoid bacterial invasion from the surface of the tooth. There was no inflammation or damage to the pulp, except for the loss of some primary odontoblasts, when infection was prevented, despite very deep cavities or pulpal exposures to which acid, detergent, and resin had been applied.

The results from many experiments includ-

ing hundreds of human teeth have pointed to the same conclusion. Acid etchants, detergents, a thin mix of phosphate cement, silicate, glass-ionomer cement, and resins do not produce any appreciable damage and inflammation to the pulp, not even when applied to exposed pulps (Brännström, 1982, 1984). However, for reasons already mentioned the cut dentin should not be treated with acid or EDTA in such a way that the tubules become open and widened. Therefore, the discussion of the possible pulpal irritation from such solutions seems to be academic.

When we started our research on the removal of the smear layer more than 10 years ago, we found that common cleansing procedures such as peroxide followed by 95% alcohol, or other solvents, did not remove the superficial smear layer (Brännström & Johnson, 1974). Only various acids and EDTA were capable of removing the smear layer but, unfortunately, they also removed the smear plugs and peritubular dentin. Several investigations were performed to find a suitable cleanser that would retain the smear plugs and remove only the superficial smear layer (Brännström, Glantz & Nordenvall, 1979; Brännström & others, 1980). A detergent should remove the superficial smear layer, so that an antiseptic component in the cleanser can reach and kill any bacteria present in smear plugs (see figure). One acceptable solution contained a surfactant combined with 0.2% EDTA and benzalkonium chloride to which 1% sodium fluoride was added (Tubulicid, Red Label). Fluoride in this concentration is antibacterial and we may get a fluoride impregnation of cavity walls and remaining smear plugs.

It should be added that this cleanser did not irritate the pulp. The problem of cleansing prepared surfaces has been discussed and reviewed elsewhere (Brännström, Nordenvall, & Glantz, 1982; Brännström, 1982).



An SEM of surface of dentin ground with a diamond cylinder high speed and then cleaned with a detergent (Tubulicid, Blu Label) for one minute five seconds by rubbing with a cotton pell soaked with the solution. The smear layer is removed, the per tubular dentin intact, and amorphous material remains in th apertures of the tubules. X1800.

Smear Layer in Root Canals after Reaming

In reaming root canals we produce a smear layer similar to that in cavities. This has been demonstrated in many studies with SEM (Baker & others, 1975; McComb, Smith & Beagrie, 1976; Lester & Boyde, 1977; Goldman & others, 1982).

The morphology of the canal wall is of interest in this context. In adult teeth the wall may be partly covered with atubular, irregular dentin and thus the tubules are blocked in the same way as under erosion and abrasion. Infection may not be seen in the tubules in such an area. However, in many adult teeth and especially in young teeth we may have large areas with primary dentin facing the root canal. From a necrotic and infected canal, bacteria enter the dentin and can be found rather deep in the tubules. Infected tubules with fluid communication to the exterior may cause pathological complications such as external resorption of roots and periapical pathosis.

In the treatment of infected roots there is a good reason to remove smear plugs from the apertures of the tubules by using, for instance, EDTA. In this way the bacteria within the tubules at some distance can be more easily

destroyed by an intracanal dressing. On the other hand, if the asepsis or the sealing is poor, we may run the risk of reinfecting dentinal tubules opened and widened by treatment with EDTA. The situation is similar to that for cavities.

The absence of superficial smear may facilitate good contact between the sealing material and the wall of cut dentin. This has been noticed in a recent study by Cameron (1983). Lester & Boyde (1977) found that treatment for three days with 5% sodium hypochlorite did not remove smear plugs from apertures of tubules and may not diffuse into the dentinal tubules sufficiently to take care of microbes that have penetrated deeper into the dentinal tubules. However, Cameron (1983), using an ultrasonic technique, found that 3% sodium hypochlorite combined with ultrasound for three to five minutes removed not only the superficial smear layer but also the smear plugs; but one minute of ultrasound removed only the superficial smear layer. In this method we may have a selective technique that can modify the effect of an irrigating solution. As suggested by Yamada and others (1983), an alternative would be a combination of irrigants. They found the combined use of 10 ml of 17% EDTA, followed by 10 ml of 5% sodium hypochlorite effective. There are no reasons to believe that a short application of these solutions would have any deleterious effects on periapical tissues already replaced by granulation tissue.

To reduce the risk of reinfection, but also to avoid the development of secondary caries, in permanent coronal restorations of root-filled teeth the cavity should be treated in the same way as cavities in vital teeth, that is, a proper cleansing and lining of all cavity walls.

Summary and Conclusion

In cavities and on surfaces of dentin prepared for restorations and abutments, the superficial smear layer should be removed and the remaining smear plugs treated antiseptically. The advantage of this is that:

- The surface is easier to dry with a blast of air as outward flow of fluid is avoided;
- Improved adaptation is obtained for lining material and luting cements;
- There is a reduced risk of bacteria multiplying in the smear layer and in a fluid gap between the lining and the surface of cut dentin.

Demineralizing cleansers that remove smear plugs and widen the tubule apertures should be avoided. The dentin will be wetter and in the case of bacterial contamination there will be an invasion of bacteria into dentinal tubules. Furthermore, the surface will become several times more permeable to toxins diffusing to the pulp.

The problem is similar for smear produced by reaming root canals, though the removal of smear plugs with demineralizing solutions may have both positive and negative effects; it depends on the infectious situation in the root, the morphology of the dentin of the root, and the way the treatment is performed.

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