Pulp-dentin biology in restorative dentistry. Part 2: Initial reactions to preparation of teeth for restorative procedures

Ivar A. Mjör, BSD, MSD, MD, Dr Odont

Pulpal complications involving inflammation, degradation, and necrosis are the result of a series of traumatic injuries. The restorative dentist must minimize the trauma to dentin and pulp inflicted during clinical procedures, including that inflicted during tooth preparation. Part II of this series discusses the structural and physiologic changes in the pulp-dentin complex that result from crown and cavity preparation and the clinical implication of these changes. (Quintessence Int 2001;32:537–551)

Key words: dentinal fluid, hybrid layer, pulp-dentin physiology, odontoblastic displacement, smear layer, tooth preparation

The effects of restorative procedures on dentin and pulp represent a combined response to the preparation and to the restoration. Long-term effects of preparation events alone are difficult to assess, because the preparation will have to receive a provisional or permanent restorative material or be left exposed to the oral environment. Because no restorative material exists that is truly inert in a biologic sense, and because preparations left open to the oral environment will accumulate debris and bacteria, the only way to evaluate structural changes in human dentin and pulp of a cavity or crown preparation is to extract the teeth immediately after the procedure is completed. Nondestructive, physiologic techniques may also be used in experimental studies on animals.

In 1955, a special experimental design was attempted to evaluate the long-term effect of cavity preparation. Cavity preparations with a separate central deep cavity were prepared in premolars in children. The deep part was covered by a gold plate sealed in with zinc phosphate cement. The teeth were extracted after observation periods ranging from 15 minutes to 4 weeks. Histopathologic examination of the pulp showed that the reactions subjacent to the deep cavity were the same as in teeth with cavities filled with zinc oxide–eugenol cement or gutta-percha.

The early reactions included displacement of odontoblastic nuclei into the dentinal tubules. After 4 weeks, reparative dentin had formed subjacent to the cavity. These results are considered to be a combined effect of two different procedures: restoration of a cavity with zinc phosphate cement and preparation of an open cavity. Application of current knowledge indicates that the initial observations may have resulted from the high interstitial fluid pressure in the pulp. Provided that the dentinal tubules are patent, cavity or crown preparations cut into the high-pressure area of the vital pulp can permit dentinal fluid to leak out. This leakage may be the most important effect of cavity and crown preparation, and it will be dealt with in some detail in this article.

Any pulpal and dentinal changes that result from the preparation can affect the evaluation of reactions to the entire restorative procedure, including possible toxic and allergic reactions to the restorative material or to bacteria and salivary components. Much attention has focused on bacteria present on the prepared surface and those at the tooth-restoration interface. What actions to take against these bacteria is a controversial topic, but it is generally accepted that bacteriostatic sealing of restorations is important in restorative dentistry to prevent bacterial leakage. However, extensive clinical experience has shown that contamination of dentin during cavity and crown preparations has no major effect on the outcome of the treatment, and it may stimulate defense mechanisms in the pulp-dentin organ. Long-term maintenance of a healthy pulp is a result of atraumatic preparation and the use of biologically acceptable restorative materials that can seal the tooth-restoration interface to prevent or minimize bacterial leakage.
Teeth that are to receive restorations have or have had primary caries lesions, are worn, or have fractured because of trauma; many restorations are placed because of failure of a previous restoration. All these conditions result in changes in the dentin and pulp. Intact teeth to be used for fixed partial denture abutments may also be involved. Thus, the condition of the teeth prior to cavity and crown preparation can be highly variable.

In a research setting, the evaluation of pulpal and dentinal responses to cavity or crown preparation must be based on those responses that occur after preparation of intact teeth from young individuals, preferably newly erupted teeth. This selection of teeth is necessary because the normal structure of these teeth is well established, and any deviation in structure observed after the preparation can then be attributed to the specific procedure. When a preparation technique that will not induce changes according to the method of evaluation employed has been established, this technique can be used to prepare cavities and crowns for subsequent testing of reactions to restorative procedures, including agents applied to the dentin, such as cleansers, disinfectants, acids, bonding agents, and restorative materials.

The initial reactions that will be described and discussed in this article will be limited to procedures immediately preceding the restorative phase of the treatment. Most studies on reactions to the cutting of dental hard tissues have been carried out with rotary instruments using different types of burs, but air abrasion and lasers have also been used. Such techniques have not received wide use in dental practice, but they will be briefly reviewed in this article as alternative preparation methods.

Histologic changes associated with cavity and crown preparation can be evaluated with microscopic techniques. Physiologic changes can be assessed with techniques such as histochemical demonstration of neurogenic components, blood flow measurements, or recording of interstitial tissue fluid pressure.

**FORMATION OF THE SMEAR LAYER**

The normal structure of dentin comprises mineralized intertubular and peritubular dentin and dentinal tubules (Figs 1 and 2) containing odontoblastic processes, or their remnants, and tissue fluid, often referred to as dentinal fluid. If the surface of cut enamel and dentin is examined after preparation with hand instruments or burs, no structural details such as cut dentinal tubules (Fig 3) or enamel prisms will be visible, even at high magnification. All such details are obscured by a covering layer of cutting debris from the mineralized tissues. This grinding debris consists of ground components of enamel and intertubular and peritubular matrix, including any content of the dentinal tubules, mixed with water, dentinal fluid, and often saliva. This layer is less than 2 μm thick and is termed the smear layer.

Because the dentinal substrate differs as a result of age-related changes, caries, dentinal sclerosis, and restorative procedures, the smear layer can vary in composition. If the prepared dentinal surface has open tubules, small plugs of debris may extend into any open dentinal tubule. The smear layer reduces the fluid flow from the dentin and decreases dentinal permeability.

The composition of the smear layer varies, depending not only on the substrate but also on the type of bur used. If a high-speed dental engine is used, the smear layer will be tightly burnished to the prepared surface. The smear layer cannot be completely removed by a water spray (Fig 4) or by scrubbing, but it will dissolve during acid-etching procedures. Acid etching demineralizes the smear layer and the peritubular and intertubular dentin of the prepared surface. It leaves the tubules wide open (Fig 5).

The smear layer may also be removed by the application of pumice to the prepared surface. This procedure removes the smear layer and leaves the smear plugs in the openings of the tubules in place (Figs 6 and 7). A similar selective removal of the smear layer, leaving the smear plugs intact, can be achieved by the use of ethylenediamine tetra acetic acid (EDTA) for cavity cleansing.

The formation of the smear layer is a physical process and not a biologic reaction per se. However, it does have clinical implications that must be dealt with in a biologic context.

The smear layer is not a stable structure, and it must be removed in order to obtain optimal chemical and mechanical bonding between restorative materials and tooth structures. This demineralization will allow resin to infiltrate the tubules and their branches, as well as the collagen mesh of the intertubular matrix and the collagen in the walls of the tubules exposed by the acid (Fig 8).

The presence of a smear layer can be beneficial by physically reducing the flow of fluid through dentin and thus decreasing its permeability. This reduced flow of dentinal fluid may have a protective effect on the pulp tissue. The smear layer may also impede the entry of bacteria into the cut dentinal tubules. An alternative to removal of the smear layer for bonding to mineralized dental tissues is to incorporate it as an integral part of the adhesive system. Materials for such bonding techniques have been marketed.

Routine restorative procedures that do not include acid etching are performed with the smear layer in
Fig 1 Scanning electron micrograph of fractured coronal human dentin showing a longitudinal view of one dentinal tubule with distinct peritubular dentin (PT) lining the tubule. Note the openings in the wall of the tubule for numerous branches from the odontoblastic process. (ID) Intertubular dentin. (Original magnification x7,400.)

Fig 2 Scanning electron micrograph of demineralized human dentin showing remnants of the odontoblastic process (OP) in a dentinal tubule. The peritubular dentin is lost during demineralization. (ID) Intertubular dentin. (Original magnification x1,250.)

Fig 3 Scanning electron micrograph of dentin subjected to high-speed cutting. Some loose debris is seen, but no dentinal tubules can be discerned. (Original magnification x3,000.)

Fig 4 Scanning electron micrograph of dentin subjected to high-speed cutting and subsequently washed with a water spray. No dentinal tubules can be discerned, but less debris is present than in Fig 3. (Original magnification x3,000.)

Fig 5 Scanning electron micrograph of the ground dentin surface after it has been treated with 35% phosphoric acid for 60 seconds and washed with a water spray. Note the open dentinal tubules. The peritubular dentin has been demineralized. (Original magnification x3,000.) (From Hørsted-Bindslev P, Mjör IA (eds). Modern Concepts in Operative Dentistry. Copenhagen: Munksgaard, 1988. Reprinted with permission.)

Fig 6 (left) Scanning electron micrograph of ground dentin after the surface has been polished with pumice in a rubber cup. Smear plugs (SP) are present in the openings of the tubules. One dentinal tubule (DT) does not have a smear plug; it was probably lost during preparation of the specimen. (Original magnification x3,000.) (From Hørsted-Bindslev P, Mjör IA (eds). Modern Concepts in Operative Dentistry. Copenhagen: Munksgaard, 1988. Reprinted with permission.)

Fig 7 (right) Scanning electron micrograph of undemineralized dentin, subjected to cavity preparation, showing a longitudinal view of a dentinal tubule (DT) with a smear plug (SP). (Courtesy of Dr. M. Ferrari; original magnification x7,000.)
Fig 8 Scanning electron micrograph of prepared and acid-etched dentin. Note the interwoven fibers on the cavity (CA) floor and in the wall of the dentinal tubule (DT). (Courtesy of Dr M. Ferrant; original magnification x7,500.)

place. Because a sterile technique is not used, it is likely that bacteria can be found in the smear layer, even if a rubber dam is employed. This situation has raised questions about the need to sterilize cavity preparations prior to restoration. Any antibacterial treatment applied to the prepared surface may alter the conditions for adhesion and may lead to pulpal reactions. Many liners, bases, and luting cements have antibacterial properties; it is also likely that the acid-etching procedure used in conjunction with adhesive restorative techniques exerts an antibacterial effect. These various agents are likely to be supplemented by antibacterial defense mechanisms in the pulp, because it has been claimed that vital dentin resists infection.

REATIONS TO CAVITY AND CROWN PREPARATION

Structural changes

It has long been established that preparation techniques are available that cause no or few histologic changes in teeth after evaluation of demineralized sections stained with hematoxylin and eosin (Fig 9). Adequate cooling of a bur cutting at high speed is essential to prevent histologic changes in the dentin and injury to the underlying odontoblastic region of the pulp. Temperature increases can cause severe injury to the pulp, and coolants should always be used during cavity and crown preparation. Care must be exercised to ensure that the water spray effectively cools the bur at the cutting surface. "Shadowing" effects by the tooth may prevent the water spray from reaching the bur (Fig 10). It is difficult to avoid histologic changes to the underlying pulp if a crown preparation is performed at high speed, even if an adequate water cooling system is employed. Intermittent cutting using light handpiece pressure can minimize temperature increases during cavity and crown preparation.

If histologic sections showing so-called harmless cavity preparations are scrutinized, a separation of the dentin and pulp is often found, localized to the tubules exposed by the cavity preparation (Figs 11 and 12). This separation is likely to be a histologic artifact, but because it is often limited to the tubules exposed by the cavity preparation, it is probable that some injurious changes that predispose to the separation have occurred in the dentin or in the pulp-predentin region.

The injury inflicted on dentin and pulp when cooling of the bur is inadequate during cavity and crown preparation of dentin can lead to displacement of odontoblastic nuclei into dentinal tubules (Figs 13 and 14). Similar histologic changes can occur if the dentin is dried excessively after the preparation is completed. Marked disorganization in the organelles of the odontoblasts and in the adjacent cells can also be observed (Fig 15). These responses must be regarded as gross reactions to injury. Overheating or burning of the dentin during crown and cavity preparation are the most common reasons for displacement of cells into the dentinal tubules and for disruption of the contents of the tubules.

Burning of the dentin was a frequent occurrence in the early days of restorative dentistry. Although low speed was used, considerable pressure on the bur produced frictional heat. Present-day high-speed equipment is designed to supply adequate cooling. However, care must be exercised to ensure that the water jet actually reaches the cutting edge of the bur at all times and that no part of the preparation prevents the water jet from reaching the cutting part of the bur, as seen in Fig 10. If dentin is overheated or burned during cavity or crown preparation, a color change will be visible in the margin of the preparation, as seen on histologic sections when certain stains are used (Fig 16).

Less dramatic changes than displacement of odontoblastic nuclei can be demonstrated by staining sections of prepared teeth to show the presence of glycosaminoglycans. These dyes stain components that are located intratubularly in a specific segment of the dentinal tubule in newly erupted teeth, and they may, therefore, be used as a marker for changes occurring in the content of the tubules (Fig 17). The application of these special stains to demineralized sections of newly erupted teeth can reveal distinct histologic
Fig 9 Photomicrograph of a demineralized section of a newly erupted premolar that was extracted immediately after cavity (CA) preparation with a bur supplied with an effective water cooling system. (dotted line)Extent of the tubules opened by the cavity preparation. Note the intact odontoblastic (O) layer and distinct cell-free zone adjacent to it. (Hematoxylin-eosin stain; original magnification ×220.)

Fig 10 Head of a contra-angled handpiece with a bur in place and with the water spray turned on. The water jet does not reach the working part of the bur because the tooth intervenes. (Courtesy of Dr K. Langeland.)

Fig 11 Photomicrograph of a cavity (CA) prepared prior to extraction of the tooth. (dotted line) Extent of the tubules opened by the cavity preparation. An intact odontoblastic (O) layer is present subjacent to the cavity, but the cell-free zone is not distinct. The separation (S) between the predentin (PD) and the odontoblastic layer is probably a histologic artifact; however, because it is limited to the tubules opened by the cavity preparation, it does signify that some changes had resulted from the preparation. (Hematoxylin-eosin stain; original magnification ×90.)

Fig 12 Higher magnification of the separation (S) between the predentin (PD) and the odontoblastic (O) layer as a result of cavity preparation similar to that shown in Fig 11. (dotted line) Extent of the dentinal tubules (DT) opened by the cavity preparation. (Hematoxylin-eosin stain; demineralized section; original magnification ×350.)
changes in dentin in which cavities have been prepared with a high-speed dental engine supplied with abundant water spray. This altered staining of the dentin occurs without displacement of odontoblastic nuclei into the tubules.

The teeth frequently used in such investigations are intact premolars that are to be extracted from children aged 10 to 14 years for orthodontic reasons. The specific change noted in these sections is based on the presence of intratubular reactive components that have shifted position following preparation of the dentin. The position of these reactive components after preparation indicates outward movement or displacement of the tubular contents (Figs 17 to 19). Such movements occur even if a so-called nontraumatic preparation technique is used.

The outward movement of the contents of the tubules is probably a result of the exposure of the dentin for the first time in an otherwise unaffected tooth. The preparation opens up into a high-pressure area because the normal interstitial tissue fluid pressure of the pulp is in the range of 5 to 20 mm Hg. It appears that this displacement of the contents of the tubules cannot be prevented when preparations are made in newly erupted, intact teeth. The movement of the contents of the tubules is dependent on the tubules' being open. No studies similar to those referred to on newly erupted teeth have been performed on intact teeth of adults or older individuals, in whom the tubules may be partly or completely obturated by growth of the peritubular dentin.

Cavity and crown preparations reaching dentin in newly erupted, intact teeth will expose tubules that are normally open. Protrusion of the contents beyond the tubules is sometimes observed in histologic sections (Figs 18 and 19). The reason that protrusion is not observed from all or most of the tubules may be that the reactive part of the contents has been completely extruded through the dentin. Furthermore, a smear layer may obturate the opening of the tubules and block or reduce extrusion of the contents (see Figs 3 and 4). The fact that the contents occasionally protrude beyond the cut tubules indicates that an active force has been applied, because capillary forces alone would fill, but not overfill, the tubules. These changes cannot be prevented, and they occur even where no displacement of odontoblastic nuclei takes place (Figs 20 and 21). Exudation of fluid from dentinal tubules after cavity preparation has also been shown through replica (impression) techniques.

The clinical significance of outward movement of the tubular contents has not been established. It has been suggested that the localized, reactive, and stainable contents of the tubules a short distance into the dentin from the dentin-predentin border are associated with secondary formation of peritubular dentin.
newly erupted teeth. Preparation and restoration of teeth may, therefore, have an effect on the secondary development and growth of peritubular dentin.

The reactive components within the dentinal tubules include cytoplasmic constituents. These constituents and any components present within the perithelial space, including tissue fluid, apparently become displaced. The disturbance and redistribution of these cellular constituents (Fig 15) will result in degeneration of the odontoblastic processes (Figs 22 and 23). If the preparation is restored, no reestablishment of normal staining reactions is observed (Fig 24). However, reestablishment of the normal staining pattern has been shown to occur if coronal dentin is exposed to the oral environment in shallow, self-cleansing facets for at least 7 days (Fig 25).

The clinical significance of any change following the displacement of odontoblastic nuclei and/or the contents of the tubules has not been fully established, but it is likely to have an effect on the physiology of the
Fig 20  (left) Photomicrograph of a demineralized section of a cavity (CA) preparation prepared with an abundant water cooling of the bur. The odontoblastic (O) layer subjacent to the cavity remained intact and no displacement of odontoblast nuclei into the dentinal tubules has occurred, (dotted line) Extent of the cavity preparation. (Hematoxylin-eosin stain; original magnification ×220.)

Fig 21  (right) Photomicrograph of the section adjacent to the one shown in Fig 20. Note the difference in staining of the dentin subjacent to the cavity (CA) preparation and that of unaffected dentin to the left of the dotted line, which delimits the extent of the cavity preparation. (Z) Zone with intratubular, stainable components as part of the normal staining pattern of dentin. (Toluidine blue stain; original magnification ×220.)

Fig 22  Electron micrograph of an undemineralized section showing a dentinal tubule (DT) with remains of a disintegrated odontoblastic process. (Ve) Vesicles coated with dark granules. (Courtesy of Dr O.B. Sveen; original magnification ×13,700.)

Fig 23  Electron micrograph of an undemineralized section showing a dentinal tubule (DT) with cellular fragments undergoing necrosis. The large, light, circular areas within the tubules may be lipid droplets. (Courtesy of Dr O.B. Sveen; original magnification ×11,200.)
affected dentin. The intratubular changes may be the start of a "dead tract" reaction. The formation of a dead tract may be dependent on the disturbance of the contents of the tubules and subsequent formation of tertiary dentin subjacent to the affected dentinal tubules. However, a certain degree of trauma to the odontoblasts and their processes must take place before a dead tract will develop, including the formation of an atubular "hyaline zone" between the physiologic secondary dentin and the tertiary dentin. This hyaline zone corresponds to the interfacial dentin, and the tertiary dentin compares to reparative dentin.

**Physiologic changes**

Immediate vascular responses have been demonstrated to result from the grinding of dentin. Olgart summarized the findings from a series of experiments on cats over a 25-year period that included common clinical procedures using neurophysiologic and hemodynamic techniques. These procedures comprised grinding of dentin and percussion of the teeth. Brief grinding (1 second, 3 times) of feline canines with a diamond bur flushed with saline at 6,000 rpm caused an instantaneous increase in blood flow (Fig 26). The blood flow in denervated contralateral teeth exhibited significantly smaller and much delayed responses. Grinding halfway into dentin caused a 53% increase in blood flow lasting for about 10 minutes. Further grinding into deeper layers of dentin caused only minor differences in the magnitude of the response. The effect of anesthesia on the blood flow was illustrated in a series of experiments using ultrasonic stimulation (Fig 21). The findings from these experiments were interpreted to support the concept that extensive branching of pulpal nerves is associated with functional connections to periodontal tissues.

In another experimental series, using teeth with intact enamel, a setup mimicking the percussion of teeth instantly produced a 30% increase in blood flow lasting about 2 minutes. The increase in blood flow following percussion was smaller than that after the exposure of dentin by grinding, perhaps because of the lack of exudation of dentinal fluid from the intact teeth. These investigations were not supplemented by histologic studies, which would have allowed correlation between the blood flow recordings and the degree of movement of the contents of the tubules, including...
displacement of odontoblastic nuclei into the tubules. Such displacement is more likely to occur following exposure of dentin than in teeth with intact enamel, because fluid flows through enamel much less than through exposed dentin.

Crown preparations made with a high-speed bur without water spray have been shown to decrease blood flow in the pulp of dog canines. The magnitude of the decrease in blood flow was dependent on the remaining dentin thickness. If the preparation reached the inner third of dentin, which was estimated to leave about 1 mm of remaining dentin, the blood flow was reduced by 90% after 1 hour. Preparation to the same depth had negligible effect on the pulpal blood flow when abundant water spray was used to cool the bur. Dry preparation halfway into dentin resulted in a significant increase in blood flow through shunt vessels, especially those in the apical part of the teeth.

Impressions of the prepared surfaces of rat teeth, which involved the use of a copper band with warm wax, caused severe fluctuations in blood flow; minimal changes were noticed if rubber-based impression materials were used. A further reduction in blood flow resulted from epinephrine in anesthetic solution. Thus, both the combination of dry preparation with high speed and the use of anesthetics with a vasoconstrictor are considered to be particularly harmful to the pulp. These investigations were not supplemented by histologic studies. Thus, no correlation with structural changes can be made. However, histologic changes in the pulp and dentin following complete crown preparation have been shown to occur, and they are considered difficult to avoid.

The vasoconstriction noted after cavities are prepared deep in dentin without a coolant may be due to inhibition of sympathetic nerve stimulation. It has also been shown that stimulation of cervical sympathetic nerves results in a significant decrease in fluid flow through dentin. Such changes in fluid flow may increase the rate of diffusion of agents from the dentinal surface to the pulp. Conversely, an increased flow from the tubules, eg, because of inflammation in the pulp, may prevent or reduce the diffusion of bacteria and toxic agents into the pulp.

It is evident that the dentinal fluid plays a central role in dentin physiology, including those changes that result from restorative procedures. The peripheral flow of this fluid following cavity preparation allows plasma proteins to enter the tubules. Clotting of these proteins will reduce the functional diameter of the tubules and reduce the permeability of the dentin. It was believed that fibrinogen caused the obstruction of the tubules, but the presence of fibrinogen has been difficult to demonstrate.
The presence of serum albumin in the tubules has been established.\(^9\)\(^{40}\) Cavity preparation into the inner third of the dentin in intact premolars from children causes an albumin flux. This exudation of albumin was markedly reduced after 2 days of exposure to the oral environment and after another 12 days following the placement of a zinc oxide–eugenol cement to seal the cavity.\(^4\) The exposed dentin was covered by a thin coat of Teflon to prevent the cement from blocking the tubules in these experiments. Histologic studies of the pulp showed good preservation of the pulpal tissue without cellular infiltration. Following bacteriologic challenge, marked cellular infiltration was found subjacent to the tubules exposed by the cavity preparation, including positive immunohistochemical reactivity for macrophages. Although the experimental procedures did not render the dentin impermeable, the reduction in permeability may be clinically important in preventing bacteria and toxic agents from diffusing into the pulp.

It is apparent that preparation, impression, and percussion of teeth may result in significant vascular changes in the dental pulp. These changes are transient and usually resolve without clinical complications. Whenever the blood flow is impeded in the pulp, locally or systemically, the reaction may be the start of an adverse process. If the vascular changes increase, the reaction may be looked on as a defense mechanism to initiate preparedness for subsequent insults.

The odontoblastic layer comprises closely packed cells that often appear pseudostratified in coronal dentin. A number of junctional complexes link the odontoblasts together. This layer of cells exhibits several characteristics similar to those of an epithelium.\(^4\) It may act as a barrier and provide a protective effect by preventing macromolecules from passing from the pulp into the dentin. This barrier is often disrupted during crown and cavity preparation and the physiologic reactivity in the region will change. It is likely that the junctional complexes become reestablished, but the nature and significance of this repair process are unclear.

**Mechanisms governing displacement of odontoblasts and tubular contents**

Displacement of odontoblastic nuclei into the dentinal tubules is a phenomenon that has long been recognized. It occurs regularly subjacent to marks on roots from the beaks of extraction forceps\(^5\) but may also occur for a variety of other reasons, including cavity and crown preparation. Considerable attention was paid to this phenomenon when high-speed dental engines were introduced in the late 1950s. The phenomenon has also been described as “aspiration” of odontoblastic nuclei into dentinal tubules.\(^4\)\(^4\)\(^1\) but the term displacement of odontoblasts\(^4\) has come into common use, because it is not suggestive of any specific mechanism for its occurrence. Other cells present subjacent to the tubules exposed by cavity preparation can also be displaced into the tubules under extreme conditions.\(^1\)

Provided that an adequate water spray is used during the cavity preparation, displacement of nuclei will not occur (see Figs 9 and 20). Intermittent, low-speed cutting of dentin with light pressure and without water spray is routinely performed, especially during removal of the final carious dentin in deep cavities. If performed with care, this “excavation” with a large round bur used without water spray is considered acceptable treatment, but cavity depth is an important modifying factor.\(^7\)\(^6\) Reduction in remaining dentin thickness makes the pulp more vulnerable to injury from cavity and crown preparation trauma.

Electron microscopic studies of the pulp-predentin interface after cutting of dentin\(^2\)\(^4\) have revealed displaced cellular contents and odontoblastic nuclei in some of the tubules. A number of morphologic changes have also been noted, including intracellular disorganization and rupture of the nuclear membrane (see Figs 15, 22, and 23). This process takes place quickly and causes disruption of the odontoblastic layer. Lysis of the cellular elements takes place over time, and an inflammatory reaction occurs in the adjacent pulpal tissue. After about 20 days in human teeth, the displaced cells will have disintegrated, and nuclei cannot be discerned in the dentin.\(^15\)

The mechanisms involved in displacement of odontoblastic cell bodies into the tubules and in displacement of the contents of the tubules are not fully understood. The displacement of nuclei is considered to be a more extreme reaction than that limited to movement of tubular contents. Many theories have been put forward to explain the displacement of nuclei into the tubules and the disorganization of the contents within the dentinal tubules. Because displacement of odontoblastic nuclei is regularly found corresponding to the forceps marks on the root following tooth extraction, mechanical distortion of the dentin is a likely explanation for the phenomenon in that context.

The distortion of teeth during extraction may be transmitted through the body of the pulp. If extraction forces are transmitted via the pulp, fluid flow is more likely through exposed tubules than through tubules covered by enamel and cementum. No such distortion occurs when animals are killed by an overdose of anesthesia and tissue blocks with the teeth in place are dissected after histologic fixation, but displacement of odontoblasts can still occur.\(^24\) Furthermore, a comparable distortion is unlikely to occur during the preparation of teeth and following excessive drying of the
prepared dentin. Thus, mechanical distortion of pulpal tissue alone cannot explain the phenomenon, but it may be a contributing factor.

Other theories for displacement of tubular contents include evaporation of fluid from the prepared surface, especially from heat generated during the preparation, marked differences in osmotic gradients, and chemotaxis from toxic agents on the dentinal surface. Evaporation of the contents of tubules occurs following preparation without adequate cooling of the bur or as a result of excessive drying of the prepared surfaces. Capillary forces will then replace lost dentinal fluid with the interstitial fluid in the pulp. A buildup of intrapulpal pressure due to inflammation has also been suggested, but histopathologic evidence of inflammation is not an immediate response to crown or cavity preparation. On the other hand, the increase in blood flow as an immediate reaction to the grinding of dentin is likely to increase the tissue fluid pressure locally.

More than one mechanism may be in operation to explain displacement of the contents of dentinal tubules, depending on the clinical situation. It is likely that the normal high interstitial fluid pressure in the pulp plays a role in displacing the tubular contents, at least in teeth where the dentin is exposed and the tubules are open and not obturated by mineralized deposits. Because extraction forceps denude the root dentin, the pressure gradient may also be a factor in this connection.

Irrespective of the mechanism involved, it is difficult to explain part of the movement of tubular contents induced by cavity preparation in vitro, both prior to and after fixation of the teeth for histologic preparation. These findings suggest that physical and possibly chemical forces play a major role in the displacement of the contents of the dentinal tubules.

The outcome of displacement of cytoplasm, nuclei, and other cellular components is a disintegration and degeneration of the contents of the tubules and debris. Waste products will cause some degree of inflammatory reaction in the pulp; based on histologic and clinical experience, the inflammatory response will usually be followed by healing. However, this type of additional trauma is unnecessary and should be prevented. In some teeth, cavity or crown preparation may be the additional trauma that results in pulpal complications in an already compromised pulp or hypersensitivity and discomfort for the patient after treatment.

A number of factors affect the pulp-dentin repair processes following restorative procedures, including remaining dentinal thickness, age of the patient, factors related to cavity dimensions, and possibly the release of growth factors. These issues will be discussed in detail in a later article on reactions to restorative procedures.

---

ALTERNATIVE PREPARATION METHODS

Rotary instruments with stainless steel, tungsten carbide, and diamond burs of different shapes and sizes are routinely employed to prepare cavities and crowns. Alternative cutting methods include air abrasion and lasers.

Air abrasion equipment that uses abrasive dust has been developed for cutting tooth structure, but for several reasons the clinical application of this technique never became popular. It does not allow tactile sense during the cutting procedure, and the abrasive dust obscured the field of operation. The dust may also be inhaled and therefore represents a potential health problem for the patient and the operator.

During the last few years, air abrasion equipment has been promoted for cleaning pits and fissures prior to the application of sealants. The need for such cleaning has not been demonstrated. On the other hand, cleaning of pits and fissures can aid in the diagnosis of occlusal caries. However, the inherent problem with dust management remains; because the cleaning procedure only calls for removal of debris, the equipment should be used intermittently and for short periods. The lack of tactile sense, therefore, is of minor importance.

Laser equipment is based on the use of beams of high light intensity, laser being an acronym for light amplification by stimulated emission of radiation. Light photons of characteristic wavelengths are produced, amplified, and filtered to make the laser beam. Carbon dioxide and neodymium:yttrium-aluminum-garnet lasers are most commonly used.

The main problem with laser cutting of hard dental tissues is the generation of heat. Increases in pulpal temperature of more than about 5°C may lead to damage. However, laser equipment is not used for cavity preparation but has a number of potential applications in dental practice, including coalescence of pits and fissures to eliminate retention sites for bacteria, desensitization of exposed root surfaces, roughening of hard tissue surfaces to promote bonding as an alternative or supplement to acid etching, vaporization of carious tissue, and endodontically for vaporization of organic tissue in the root canal. Limited research on pulpal reactions to laser cutting of dentin calls for caution in the use of this technology in restorative dentistry. The ability of such techniques to coalesce deep, narrow fissures is also questionable.

FORMATION OF THE HYBRID LAYER

Acid etching of enamel and dentin exposed by preparation, referred to as "the total-etch technique," has become routine treatment in conjunction with adhesive
techniques. Acid etching demineralizes hard tissues and exposes the organic matrix. The scanty organic matrix of enamel is lost during the demineralization and subsequent washing. The components of dentin are selectively demineralized. The most significant exposure of collagen occurs after acid treatment of the intertubular matrix of the dentin (see Fig 8).

The highly mineralized peritubular dentin demineralizes quicker than does the intertubular matrix. This demineralization widens the tubules, making them funnel shaped toward the surface. It exposes collagen on the wall of the tubules and also uncovers the openings of a large number of lateral branches that may be important for penetration of resin to achieve optimal bonding to dentin.56

The quality of the demineralized dentin is important for adhesion of resin, and the demineralization should not denature the collagen.57 Phosphoric acid and citric acid are the most commonly used acid etchants. The addition of 3% ferric chloride to 10% citric acid markedly enhances the adhesion to dentin by preventing the denaturation of collagen. The collagen exposed by acid etching forms an interwoven mesh of fibers that the resin will infiltrate (see Fig 8). This collagen mesh infiltrated by resin is referred to as the hybrid layer.58 It is about 5 to 10 μm thick. After polymerization, the resin-impregnated collagen, together with the resin in the dentinal tubules and their branches, constitutes the adhesion between the dentin and the resin.

The formation of the hybrid layer is basically a chemical process involving dissolution of primarily mineral salts and noncollagenous matrix components followed by diffusion of resin into the remaining collagen matrix. Because it has clinical implications, it is important that such treatment be considered within a biologic context. The chemical treatment of dentin may also release growth factors that may be important for subsequent reparative processes.59

Much attention has been focused on the degree of wetness of the hybrid layer at the time of application of the resin.60-62 If the hybrid layer becomes too dry, the collagen mesh will collapse and penetration of resin will be impaired. To obtain optimal bonding between the resin and the hybrid layer, the surface must have an adequate moisture content to prevent collapse of the collagen mesh. The ideal degree of wetness may vary from one resin-based product to another. The wetness will certainly differ on the various parts of the prepared surface because of the different densities and the structure of dentinal tubules in different locations on this surface.63 Thus, the instructions for use of resin-based materials must take these issues into consideration, and they must be followed closely to obtain the best possible clinical result. Further details related to the hybrid layer will be outlined in a discussion of adhesive restorative techniques later in this series of articles.

CONCLUDING REMARKS

Structural and physiologic changes resulting from crown and cavity preparation in vivo have been outlined in many experimental studies over the last 50 years. A number of biologic reactions have been shown to occur. Some reactions are of a physical or chemical nature, but they also have biologic and clinical implications. Although some of the reactions are clearly understood, for others the clinical implications are largely unknown, eg, the displacement of cell nuclei into dentinal tubules and the disruption of tubular contents following crown and cavity preparation. Restorative dentistry is possible even if these reactions are disregarded; however, if restorative dentistry is to evolve as a biologic science, they must receive attention, clinically as well as in continued research efforts. Pulpal complications involving inflammation, degradation, and necrosis are the result of a series of traumatic injuries. It is, therefore, the responsibility of the restorative dentist to minimize the trauma to dentin and pulp inflicted during all clinical procedures, including that occurring during the preparation phase.

ACKNOWLEDGMENTS

A Guest Research Fellowship from the Research Council of Norway, partly in support of the author’s Faculty Developmental Leave at NIOM, Scandinavian Institute of Dental Materials, is gratefully acknowledged.

The author would also like to thank Dr A. J. Smith, Professor and Chairman, and Dr P. E. Murray, Unit of Oral Biology, School of Dentistry, University of Birmingham, Birmingham, England, for reviewing the manuscript.

REFERENCES

New Frontiers in Adhesive Dentistry

HYBRIDIZATION OF DENTAL HARD TISSUES
Nobuo Nakabayashi and David H. Pashley

The hybridization of dentin—a process that creates a molecular-level mixture of adhesive polymers and dental hard tissues—gives clinicians a versatile new material, useful in a wide array of advanced dental treatments. As the first in-depth exploration of the subject, this book covers the development, present understanding, and future research areas of this multifunctional dental material. A thorough review of the current literature rounds out the text.

Valuable for students, researchers, and clinicians seeking a greater understanding of resin hybridization of tooth structure.

CONTENTS

1 Evolution of Dentin-Resin Bonding
2 Properties of Dentin
3 Acid Conditioning and Hybridization of Substrates
4 Characterization of the Hybrid Layer
5 The Quality of the Hybridized Dentin
6 Clinical Applications of Hybrid Layer Formation

129 pp: 80 illus (some in color);

To Order

Call Toll Free 1-800-621-0387
or Fax 1-630-682-3288

Visit our web site http://www.quintpub.com
Quintessence Publishing Co, Inc