

牙體復形學 Operative dentistry

## Enamel and Dentin Adhesion

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### 學習目標

■ 期許同學在瞭解病患的需求及材料的特性後，能依據所學善加利用，做到不僅是幫病患解決病痛的牙醫師，同時也是個讓病患永遠也忘不了的藝術家。

1. 牙齒的生理，解剖形態
2. 齲齒的生理，診斷及治療計劃
3. 窩洞的修形及材料的選擇
4. 窩洞的充填方式及其修飾
5. 美觀性材料的選擇及其運用
6. 變色牙的修飾

### 參考資料

1. Sturdevant's art and science of operative dentistry. 4th edition. Theodore M. Roberson.
2. Fundamental of operative dentistry. A contemporary approach 3rd edition, James B. Summitt.

### Summary

Operative dentistry is the basic science in clinical dental practices. It included dental physiology, morphology, cariology, tooth preparation for restoration. The purpose of Operative dentistry is to complete the function and create the aesthetic outlook.

After observing the industrial use of phosphoric acid to improve adhesion of paints and resin coatings to metal surfaces, Buonocore, in 1955, applied acid to teeth to "render the tooth surface more receptive to adhesion." Buonocore's pioneering work led to major changes in the practice of dentistry. Today, we are in the age of adhesive dentistry. Traditional mechanical methods of retaining restorative materials have been replaced, to a large extent, by tooth-conserving adhesive methods. The concepts of large preparations and extension for prevention, proposed by Black in 1917, have gradually been replaced by concepts of smaller preparations and more conservative techniques.

### Advantages of Adhesive Techniques

Bonded restorations have a number of advantages over traditional, nonadhesive methods. Traditionally, retention and stabilization of restorations often required the removal of sound tooth structure. This is not necessary, in many cases, when adhesive techniques are used. Adhesion also reduces microleakage at the restoration-tooth interface. Prevention of microleakage, or the ingress of oral fluids and bacteria along the cavity wall, reduces clinical problems such as postoperative sensitivity, marginal staining, and recurrent caries, all of which may jeopardize the clinical longevity of restorative efforts.

Adhesive restorations better transmit and distribute functional stresses across the bonding interface to the tooth and have the potential to reinforce weakened tooth structure. In contrast, a traditional metal intracoronal restoration may act as a wedge between the buccal and lingual cusps and increase the risk of cuspal fracture. Adhesive techniques allow deteriorating restorations to be repaired and debonded restorations to be replaced with minimal or no additional loss of tooth material.

Adhesive techniques have expanded the range of possibilities for esthetic restorative dentistry. Today's patient pays more attention to esthetics than ever before, and teeth are a key consideration in personal appearance. Tooth-colored restorative materials are used to esthetically restore and/or recontour teeth with little or no tooth preparation. Advances in dental adhesive technology have enabled the dentist to improve facial esthetics in a relatively simple and economic way.

### **Expanding Indications for Adhesive Dentistry**

Adhesive techniques with resin composites were initially used for the replacement of carious and fractured tooth structure or for the filling of erosion or abrasion defects in cervical areas. Modern adhesive techniques also enable restorative material to be added to the tooth for the correction of unesthetic shapes, positions, dimensions, or shades. Resin composite can be placed mesiodistally to close diastemas, incisally to add length, or buccally to mask discoloration. Because of the alleged mercury toxicity associated with silver amalgam substantial research is currently focused on the development of alternatives to amalgam. Posterior resin composites can be directly or indirectly bonded into Class 1 and Class 2 preparations.

Adhesive techniques are also used to bond anterior and posterior ceramic restorations, such as veneers, inlays, and onlays, with adhesive luting composites. Adhesives can be used to bond silver amalgam restorations; to retain metal frameworks; to adhesively cement crowns and fixed partial dentures; to bond orthodontic brackets; for periodontal or orthodontic splints; to treat dentinal hypersensitivity; and to repair fractured porcelain, amalgam, and resin restorations. Pit and fissure sealants utilize adhesion as part of a preventive treatment program. Adhesive materials are often used with core buildup foundations.

### **Principles of Adhesion**

The word adhesion is derived from the Latin word *adhaerere*, which is a compound of *ad*, or to, and *haerere*, or to stick. Cicero used the expression *haerere in equo*, to stick to a horse, to refer to keeping a firm seat.

In adhesive terminology, adhesion or bonding is the attachment of one substance to another. The surface or substrate that is adhered to is termed the adherend. The adhesive or adherent, or in dental terminology the bonding agent or adhesive system, may then be defined as the material that, when applied to surfaces of substances, can join them together, resist separation, and transmit loads across the bond. The adhesive strength or bond strength is the measure of the load-bearing capability of the adhesive. The time period during which the bond remains effective is referred to as durability.

Adhesion refers to the forces or energies between atoms or molecules at an interface that hold two phases together. In debonding tests, adhesion is often subjected to tensile or shear forces, and the mode of failure is quantified. If the bond fails at the interface between the two substrates, the mode of failure is referred to as adhesive. It is cohesive if failure occurs in one of the substrates, but not at the interface. The mode of failure is often mixed.

**Four theories have been advanced to account for the observed phenomena of adhesion:**

1. Mechanical theories state that the solidified adhesive interlocks micromechanically with the roughness and irregularities of the surface of the adherend.

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2. Adsorption theories encompass all kinds of chemical bonds between the adhesive and the adherend, including primary (ionic and covalent) and secondary (hydrogen, dipole interaction, and London dispersion) valence forces (Table 8-1). London dispersion forces are almost universally present, because they arise from and solely depend on the presence of nuclei and electrons. The other bond types require appropriate chemical groups to interact.

**Four theories have been advanced to account for the observed phenomena of adhesion:**

3. Diffusion theories propose that adhesion is the result of bonding between mobile molecules. Polymers from each side of an interface can cross over and react with molecules on the other side. Eventually, the interface will disappear and the two parts will become one.

**Four theories have been advanced to account for the observed phenomena of adhesion:**

4. Electrostatic theories state that an electrical double layer forms at the interface between a metal and a polymer, making a certain, yet obscure, contribution to the bond strength.

An important requirement for any of these interfacial phenomena to occur is that the two materials being joined must be in sufficiently close and intimate relation. Besides an intimate contact, sufficient wetting of the adhesive will occur only if its surface tension is less than the surface-free energy of the adherend. Wetting of a surface by a liquid is characterized by the contact angle of a droplet placed on the surface. If the liquid spreads completely on the solid surface, this indicates complete wetting, or a contact angle of 0 degrees (Fig 8-1).

According to this theory of wetting and surface free energies, adhesion to enamel is much easier to achieve than is adhesion to dentin. Enamel contains primarily hydroxyapatite, which has a high surface-free energy, whereas dentin is composed of two distinct substrates, hydroxyapatite and collagen, and dentin has a low surface-free energy. In the oral environment, the tooth surface is contaminated by an organic saliva pellicle with a low critical surface tension (28 dynes/cm) which impairs adequate wetting by the adhesive. Likewise, instrumentation of the tooth substrate during cavity preparation produces a smear layer with a low surface-free energy. Therefore, the natural tooth surface should be thoroughly cleaned and pretreated before bonding procedures to increase its surface-free energy and hence to render it more receptive to bonding.

Several, if not all, of the mechanisms of adhesion described contribute to some extent to bond strength. Glass-ionomer cement is the only restorative material that has been reported to possess an intrinsic self-adhesive capacity to bond to tooth tissue without any retreatment. Other restorative materials with adhesive potential, such as resin composites, require the application of an intermediate resin to unite the tooth substrate with the restorative material. In the case of adhesion to enamel, a resin bonding agent is bonded primarily by micromechanical interlocking with the surface irregularities of the etched substrate. A micromechanical type of bonding is also largely involved in bonding to dentin. Although there is some controversy about the contribution of primary chemical bonds to the resin-tooth attachment, secondary, weak London-van der Waals forces may play a contributing role because of the intimate contact between the resin and tooth substrate.

### Factors Affecting Adhesion to Tooth Tissue

The strength and durability of adhesive bonds depend on several factors. Important factors may include the physicochemical properties of the adherend and the adhesive; the structural properties of the adherend, which is heterogeneous; the formation of surface contaminants during cavity preparation; the development of external stresses that counteract the process of bonding and their compensation mechanisms; and the mechanism of transmission and distribution of applied loads through the bonded joint. Furthermore, the oral environment, which is subject to moisture, physical stresses, changes in temperature and pH, dietary components, and chewing habits, considerably influences adhesive interactions between materials and tooth tissues.

### Compositional and Structural Aspects of Enamel and Dentin

Because the composition and structure of enamel and dentin are substantially different, adhesion to the two tooth tissues is also different. The inorganic content of mature enamel is 95% to 98% by weight (wt%) and 86% by volume (vol%); the primary component is hydroxyapatite. The remainder consists of water (4 wt% and 12 vol%) and organic material (1 to 2 wt% and 2 vol%) (Fig 8-2). The major inorganic fraction exists in the form of submicron crystallites, preferentially oriented in three dimensions, in which the spread and contiguous relationship of the crystallites contribute to the microscopic unit, called the rod or prism. The natural surface of enamel is smooth, and the ends of the rods are exposed in what has been described as a keyhole pattern (Fig 8-3). Operatively prepared surfaces expose rods in tangential, oblique, and longitudinal planes. Enamel is almost homogeneous in structure and composition, irrespective of its depth and location, except for some aprismatic (prismless) enamel at the outer surface, in which the crystallites run parallel to each other and perpendicular to the surface.

Unlike enamel, dentin contains a higher percentage of water (12 wt%) and organic material (18 wt%), mainly type I collagen, and only about 70 wt% hydroxyapatite (Fig 8-2). Structurally more important to adhesion are the volumes occupied by the dentinal components. There is, combined, as much organic material (25 vol%) and water (25 vol%) as there is inorganic material (50 vol%). In addition, these constituents are unevenly distributed in intertubular and peritubular dentin (Fig 8-4), so the dentinal tissue is heterogeneous.

Numerous dentinal tubules radiate from the pulp throughout the entire thickness of dentin, making dentin a highly permeable tissue. These dentinal tubules contain the odontoblastic processes (Fig 8-5) and form a direct connection to the vital pulp. In contrast to enamel, dentin is a vital and dynamic tissue that is able to develop specific defense mechanisms against external injuries. The diameter of the tubules decreases from 2.5  $\mu\text{m}$  at the pulp side to 0.8  $\mu\text{m}$  at the dentinoenamel junction. Likewise, the number of tubules decreases from about 45,000/ $\text{mm}^2$  near the pulp to about 20,000/ $\text{mm}^2$  near the dentinoenamel junction. With an average of 30,000 tubules/ $\text{mm}^2$  in the middle part of cut human dentin, a considerable volume of dentin consists of their lumina. Each tubule is surrounded by a collar of hypermineralized peritubular dentin (Fig 8-6). Intertubular dentin is less mineralized and contains more organic collagen fibrils. Besides an odontoblastic process in the deepest one third of the total tubule length, the tubules are filled with tissue fluid or so-called dentinal fluid, an organic membrane structure called lamina limitans, and intratubular collagen fibrils of yet unknown origin and function (Fig 8-7).

Because of the fan-shaped radiation of dentinal tubules (Fig 8-8), 96% of a superficial dentinal surface is composed of intertubular dentin; only 1% is occupied by fluid in the dentinal tubules, and 3% by peritubular dentin. Near the pulp, peritubular dentin represents 66% and intertubular dentin only 12% of the area of a cut surface, while 22% of the surface area is occupied by water. Similar data demonstrate that 3% of the area of a cut surface consists of dentinal tubules in superficial dentin and 25% in deep dentin. A mean diameter of dentinal tubules ranging from 0.63 to 2.37  $\mu\text{m}$ , depending on depth, has been determined by image analysis of transmission electron microscopic and scanning electron microscopic (SEM) micrographs. Hence, dentin is an intrinsically wet tissue. Dentinal fluid in the tubules is under a slight, but constant, outward pressure from the pulp. The intrapulpal fluid pressure is estimated to be 25 to 30 mm Hg or 34 to 40 cm water.

### Changes in Dentinal Structure

Dentin is a dynamic substrate subject to continuous physiologic and pathologic changes in composition and microstructure. Dentin that has been violated by caries or has undergone abrasion (Fig 8-9) or erosion (Fig 8-10) may be quite different from unaffected sound dentin. Dentin undergoes physiologic dentinal sclerosis as part of the aging process and reactive sclerosis in response to slowly progressive or mild irritations, such as mechanical abrasion or chemical erosion. Tertiary, or reparative, dentin is produced in the pulp chamber at the lesion site in response to insults such as caries, dental procedures, or attrition. Hypermineralization, obstruction of tubules by whitlockite crystalline deposits (Fig 8-11), and apposition of reparative dentin adjacent to the pulp are well documented responses to caries. Less is known about the compositional and morphologic modifications of dentin that accompany the development of cervical abrasions and erosions.-

Dentinal sclerosis, or the formation of transparent, glasslike dentin, which occurs in the cervical areas of teeth, has several common characteristics. Sclerosis is reported to result from the obstruction of dentinal tubules by apposition of peritubular dentin and precipitation of rhombohedral mineral crystals. The refractive index of the obstructed tubules is similar to that of intertubular dentin, resulting in a glasslike appearance.

Sclerotic dentin usually contains few, if any, patent tubules and, therefore, has low permeability and tends to be insensitive to external stimuli. The odontoblastic processes associated with sclerotic dentin often exhibit partial atrophy and mineralization. Heavily sclerotic dentin has areas of complete hypermineralization without tubule exposure, even when etched with an acid (Fig 8-12). Some areas show abundant mineral sclerotic casts, which extend from the tubule orifices above the dentinal surface and probably represent mineralized odontoblastic processes (Fig 8-13).

All of these morphologic and structural transformations of dentin, induced by physiologic and pathologic processes, result in a dentinal substrate that is less receptive to adhesive treatments than is normal dentin.

### The Smear Layer

When the tooth surface is altered by rotary and manual instrumentation during cavity preparation, cutting debris is smeared over the enamel and dentinal surfaces, forming what is termed the smear layer (Figs 8-14a and 8-14b). The smear layer has been defined as "any debris, calcific in nature, produced by reduction or instrumentation of dentin, enamel or cementum, or as a "contaminant" that precludes interaction with the underlying pure tooth tissue. This iatrogenically produced layer of debris has a great influence on any adhesive bond formed between the cut tooth and the restorative material.

It has been suggested that the burnishing action of the cutting instrument generates considerable amounts of frictional heat locally and shear forces, so that the smear layer becomes attached to the underlying surface in a manner that prevents it from being rinsed off or scrubbed away. In an in vivo study, ethylenediaminetetraacetic acid (EDTA) was found to be the most potent conditioner for removing the smear layer and opening the orifices of the dentinal tubules. Acidic conditioners include, in order of increasing potential to remove the smear layer, citric, polyacrylic, lactic, and phosphoric acids. Cavity cleansers, such as Tubulicid (Dental Therapeutics) and hydrogen peroxide, were found to have only a slight effect.

The morphologic features, composition, and thickness of the smear layer are determined to a large extent by the type of instrument used, by the method of irrigation employed, and by the site of dentin at which it is formed. Its composition reflects the structure of the underlying dentin, mainly pulverized hydroxyapatite and altered collagen, mixed with saliva, bacteria (Fig 8-14a), and other grinding surface debris. The thickness of the smear layer has been reported to vary from 0.5 to 5.0  $\mu\text{m}$ . Although smear debris occludes the dentinal tubules with the formation of smear plugs, the smear layer is porous and penetrated by submicron channels, which allow small amounts of dentinal fluid to pass through (Figs 8-14b and 8-15). The smear layer is reported to reduce dentinal permeability by about 86%.

### Internal and External Dentinal Wetness

The dentinal permeability and, consequently, the internal dentinal wetness depend on several factors, including the diameter and length of the tubule, the viscosity of dentinal fluid and the molecular size of substances dissolved in it, the pressure gradient, the surface area available for diffusion, the patency of the tubules, and the rate of removal of substances by pulpal circulation (Fig 8-16). Occlusal dentin is more permeable over the pulp horns than at the center of the occlusal surface, proximal dentin is more permeable than occlusal dentin, and coronal dentin is more permeable than root dentin. High dentinal permeability allows bacteria and their toxins to easily penetrate the dentinal tubules to the pulp, if the tubules are not hermetically sealed.

The variability in dentinal permeability makes dentin a more difficult substrate for bonding than enamel. Removal of the smear layer creates a wet bonding surface on which dentinal fluid exudes from the dentinal tubules. This aqueous environment affects adhesion, because water competes effectively, by hydrolysis, for all adhesion sites on the hard tissue. Early dentin bonding agents failed primarily because their hydrophobic resins were not capable of sufficiently wetting the hydrophilic substrate. In addition, bond strengths of several adhesive systems were shown to decrease as the depth of the preparation increased, because dentinal wetness was greater. No significant difference in bond strengths is observed between deep and superficial dentin when the smear layer is left intact. Bond strengths of more recent adhesive systems that remove the smear layer appear to be less affected by differences in dentinal depth, probably because their increased hydrophilicity provides better bonding to the wet dentinal surface. In addition to internal dentinal wetness, external dentinal wetness, or environmental humidity, has been demonstrated to negatively affect bond strengths to dentin (Fig 8-16).

### Wetting of the Adhesive

An ideal interface between dental restorative material and tooth tissue would be one that simulates the natural attachment of enamel to dentin at the dentinoenamel junction. Intimate molecular contact between the two parts is a prerequisite for the development of strong adhesive joints. This means that the adhesive system must sufficiently wet the solid surface, have a viscosity that is low enough to penetrate the microporosities, and be able to displace air and moisture during the bonding process. In one study; the wetting characteristics of six adhesives were compared and judged to be sufficient with contact angles of less than 15 degrees (see Fig 8-1). Primers in currently available systems usually contain hydrophilic monomers, such as 2-hydroxyethyl methacrylate (HEMA) (see list of abbreviations), as surface-active agents to enhance the wettability of the hydrophobic adhesive resins. In addition, solvents in modern primers, such as ethanol or acetone, ensure adequate removal of air and liquid by rapid evaporation.

From polymer chemistry, it is known that polarity and solubility characterize molecular interactions that determine many physical properties, such as wetting behavior. If an adhesive monomer has a polarity and a solubility similar to those of a polymer substrate, the monomer may act as a solvent for the polymer and infiltrate it. If both parameters are sufficiently different, the monomer and polymer are immiscible.

In dental adhesive technology, the collagen phase of dentin is a polymer, and both the primer and adhesive resin contain monomers that penetrate the exposed collagen layer to form a micromechanical bond. If a given conditioner conveys to the dentinal surface a specific polarity and solubility, the primer must match these to achieve penetration. The same is true for the adhesive resin applied to the primed dentinal surface.

### **Polymerization Contraction of Restorative Resins**

The dimensional rearrangement of monomers into polymer chains during polymerization inevitably leads to volume shrinkage. Although high filler loading of the restorative resin matrix reduces polymerization contraction, current resin composites shrink 2.9 to 7.1 vol% during free polymerization. Contraction stresses within resin of up to 7 MPa have been reported.

In clinical situations, the curing contraction is restrained by the developing bond of the restorative material to the cavity walls. This restriction induces polymerization contraction stress, which counteracts the developing resin-tooth bond by pulling the setting resin composite material away from the cavity walls (Fig 8-17). If the weakest link is the bonding interface with the tooth, the resin-enamel bond may survive the shrinkage, but the weaker resin-dentin interface may not. No dental resin composite material currently available is free of shrinkage during polymerization, however, research is underway to develop nonshrinking materials. A double ring-opening polymerization process, based on high-strength expandable resin composites used in industry, is being evaluated.

### **Compensation for Polymerization Contraction Flow**

Throughout the entire polymerization process, plastic deformation, or flow, of the resin composite occurs and may partially compensate for the induced shrinkage stress. This irreversible plastic deformation takes place during the early stages of the setting process, when the contraction stress exceeds the elastic limit of the restorative resin. As the setting proceeds, contraction and flow gradually decrease because stiffness increases. Fast-setting light-curing resin composites exhibit less flow-related stress relief, while self- or autocuring resin composites give the developing adhesive bond to dentin more time to survive. Only a fraction of the final stiffness is reached by most self-curing resin composites 10 minutes after mixing. Consequently, the combination of a slow curing rate and rapid formation of an adhesive bond is considered favorable for the preservation of marginal integrity.

The apparently superior marginal adaptation of autocuring resin composites can also be explained by the presence of air bubbles, which contribute to the amount of free surface and eventually increase the flow capacity of the resin composite.

Restriction of flow is affected by the configuration of the restoration, known as the C-factor. The C-factor is the ratio of bonded (flow-inactive) to unbonded or free (flow-active) surfaces. An increase in the number of bonded surfaces results in a higher C-factor and greater contraction stress on the adhesive bond. Only the free surface of a resin restoration, which is not restricted by bonding to the cavity walls, can act as a reservoir for plastic deformation in the initial stage of polymerization. The higher the ratio of bonded to free resin surfaces, the less flow may compensate for contraction stress (Fig 8-18). For example, to improve marginal integrity of resin composite in a Class 5 restoration, a flatter and more wedge-shaped cavity design would be preferred to the typical butt-joint, five-walled preparation. Carrying this a step farther, the use of a base material, such as glassionomer cement, within the cavity preparation (providing a so-called "sandwich" restoration) decreases the volume of the resin composite portion of the restoration, thus generating more free restorative surface relative to the smaller amount of resin.

Other methods have been used to compensate for polymerization contraction. Bowen has reported that the placement of glass or ceramic blocks into soft resin composite before light curing, displacing as much of the resin composite as possible, results in reduced microleakage. The improvement exhibited by megafilled resin composite restorations was attributed to a decrease in the overall curing contraction of the limited amount of resin composite and a decrease in the coefficient of thermal expansion of the restoration containing the inserts.

Prepolymerized resin composite inserts may also be used to help offset polymerization contraction. One example is the addition of prepolymerized resin pieces in the manufacture of microfilled resin composites. At the other extreme are resin composite inlays, which are cemented in the cavity with a luting resin. The use of inlays avoids the direct adverse effect of polymerization contraction on the developing resin-tooth bond. However, the flow-active free surface of the luting resin composite is relatively small at the narrow inlay-tooth marginal gap, yielding a high C-factor. Consequently, the luting resin composite is not likely to provide enough compensation for the shrinkage stress induced by polymerization of the luting resin. Nevertheless, the incorporation of pores by mixing of the two components and the slow autocuring rate of the dual-cured luting resin may still allow sufficient stress relaxation by flow.

Another strategy to slow curing and thus allow more flow to compensate for shrinkage stress is the so-called soft-start or ramped light-curing technique. Curing lights designed for this technique produce low-intensity light (400 mW/cm<sup>2</sup> or less) during a period of about 10 seconds, after which the light intensity is immediately or exponentially increased to about 800 mW/cm<sup>2</sup> or more.

The introduction of laser and xenon arc high-powered light-curing technology, a contrasting approach, has elicited much controversy. The theory behind this high-intensity light-curing technology is that curing times can be reduced to 1 to 3 seconds without a decrease of physicochemical material properties. Advocates of this new light-curing technique recommend placement of small resin composite increments to ensure sufficient polymerization. Evolution of curing technology is expected to continue. The recent development of long-lasting, high-intensity light-emitting diodes (LEDs) may become a useful adjunct to existing curing methods

### **Hygroscopic Expansion**

The effect of polymerization shrinkage is somewhat tempered by fluid absorption, which causes resin composite to swell and may offset the residual elastic stress. Again, the configuration of the cavity determines the effectiveness of this compensation mechanism. Overcompensation may even transform contraction stress into expansion stress. Microfilled resin composites have been shown to absorb nearly two and a half times more water than macrofilled materials because of the greater volume of resin in the micro fills.

However, hygroscopic expansion occurs during the days and weeks immediately following placement of the resin composite restoration, after the dentin bonding may already have failed. When this has occurred, hygroscopic expansion may force a Class 5 resin composite restoration to expand beyond the margin of the preparation.



## Elasticity

If the resin-tooth bond remains intact, the final stiffness or rigidity of a resin composite may play a compensating role in coping with remaining polymerization contraction stress. Stiffness is quantified by Young's modulus of elasticity, which represents the resistance of a material to elastic deformation. The lower the Young's modulus of a restorative resin, the greater its flexibility and the more capacity it has to reduce remaining contraction stress. Resin composites with a high filler content have a higher Young's modulus of elasticity, which will reduce volumetric contraction (because of the higher filler content relative to the lower resin content), but have higher remaining contraction stress, which may affect the resin-dentin interface.

Viscous adhesive resins produce a rather thick resin bonding layer between the stiff dentinal cavity wall and the shrinking restorative resin composite. Stretching of this intermediate layer (with a low Young's modulus) may provide sufficient elasticity to relieve polymerization contraction stresses of the restorative resin composite (Fig 8-19). Based on this theory, an "elastic bonding concept" has been advanced. It has been determined that a bonding layer thickness of 125  $\mu\text{m}$  reduces shrinkage stresses below dentin bond strengths, preserving the bond. A flexible intermediate resin layer may also better transmit and distribute stresses induced by thermal changes, water absorption, and occlusal forces across the interface. Also, a thick adhesive resin layer permits limited inhibition of polymerization by oxygen without impairing the resin-dentin bond.

Support for the elastic bonding concept is provided by in vitro experiments conducted with Gluma (Bayer) resin. When Gluma was prepolymerized in a relatively thick layer, less microleakage occurred than when it was left uncured prior to application of the resin composite. Lack of such a built-in polymerization contraction relaxation mechanism might have largely accounted for the high clinical failure rates recorded for Gluma, two experimental total-etch systems, and Gluma.

## Cervical Sealing

Sealing of the cervical marginal gaps with an unfilled low-viscosity resin, after the restorative resin has been cured, is another technique that has been described to overcome the negative effects of polymerization shrinkage and obtain sealed cervical restorations. Use of a restorative resin with high elasticity and low curing contraction in combination with such a low-viscosity resin layer may provide sufficient strain relief to compensate for the small curing contraction of the unfilled resin layer. However, this technique is laborious and prone to failure in the event of contamination with blood or saliva.

## Initial Polymerization

Initiation of polymerization at the resin-tooth interface, directing the shrinking resin material toward the cavity wall rather than away from it, is advantageous. Contraction has always been claimed to occur toward the light source in light-curing resin composites, whereas initial setting has been said to occur in the center of the bulk of material in self-curing resin composites (see Fig 8-17). For both light-curing and self-curing systems, tensile stresses operate across the resin composite-dentin interface, pulling the material away from the cavity walls. Countering the theory that contraction occurs toward the curing light in light-curing systems, a recent study using finite element analysis showed that the direction of polymerization shrinkage was not significantly affected by the orientation of the incoming curing light. Instead, the cavity shape and the bond quality determined the direction of the polymerization vectors. That study concluded that the contraction patterns between auto- and photocuring composites were similar.

For many years, Fusayama has argued that the initial setting of autocuring resins starts at the dentinal wall because body heat accelerates the chemical reaction. In other words, the shrinking restoration is pulled toward, rather than away from, the cavity base. Evaluation of premolar restorations in vivo showed that the use of chemically cured resin composite did not result in reduced gap formation relative to gaps produced when light-cured composites were used. This study could not confirm the supposed stress-relieving effect of self-curing resin composites.

For light-initiated resin composite polymerization, there is general agreement that the unbonded resin material at the free surface of the restoration sets first when it is exposed to the light source; thus, its flow relaxation capacity is considerably diminished. Incremental layering techniques have been used to minimize the negative effects of light polymerization to increase the actual resin-free area relative to the resin-bonded area (see Fig 8-17). This disciplined application technique promotes sufficient polymerization of the deepest material, in contrast to that achieved with the limited light penetration that occurs with bulk placement. The incremental technique has also been hypothesized to result in less stress caused by polymerization contraction, because the flow relaxation capacity is higher and can be used to direct polymerization shrinkage of each increment toward the cavity walls. But the theory that an incremental placement technique reduces stress effects of resin composite shrinkage is debated. Completeness of cure, adequate adaptation to the cavity walls, and adequate bond formation may still be reasons to use a composite layering technique. Furthermore, improved marginal adaptation of the critical gingivoproximal border of Class 2 resin composite restorations has been described with the use of a three-sided light-curing technique with laterally light-reflecting wedges. Once again, however, the benefit of this directed curing technique is no longer generally accepted.

Some adhesive systems are also designed so that chemical polymerization is initiated at the surface of dentin. For example, the simplified Gluma 2000 System attempts to impregnate the dentinal surface with an amine part of the catalytic system in the form of glycine, which is claimed to establish a chemical bond to collagen. Because camphoroquinone is incorporated as the other part of the catalytic system, and selected methacrylic monomers, such as HEMA and bisphenol glycidyl methacrylate (bis-GMA), are included in the adhesive resin, the polymerization was expected to be initiated at the adhesive interface. This simplified pretreatment technique has proved to be highly effective in reducing the marginal gap in cavities in both enamel and dentin. However, several *in vivo* and *in vitro* reports on the use of amino acids have yielded contradictory results.

A water-triggered polymerization has been described for the 4-methacryloxyethyl trimellitate anhydride/methyl methacrylate-tri-*n*-butyl borane (4-META/MMA-TBB) systems, such as Super-Bond D-Liner (Sun Medical) or AmalgamBond (Parkell). Although water and oxygen, which are omnipresent in dentin, are normally expected to affect the polymerization process of bonding resins, they may apparently also act as coinitiators of the polymerization reaction. Effective water-triggered polymerization in deep, tubule-rich dentin has been suggested to direct resin shrinkage toward the dentinal surface itself. Imai et al hypothesized that the application of ferric chloride with these adhesive systems to acid etch dentin might promote and initiate resin polymerization at the interface. More research is needed to explore these mechanisms to initiate polymerization at the interface.

### **Thermal Expansion Coefficient And Thermal Conductivity**

Because the coefficient of thermal expansion of resin is about four times that of tooth structure, any bonded resin restoration is likely to suffer from marginal gap formation. The microfilled resin composites have a higher coefficient of thermal expansion than do hybrid-type resin composites. However, Harper et al suggested that the dimensional change that occurs in the clinical restoration as a result of temperature fluctuations may not be as great in magnitude as its relatively high coefficient of thermal expansion would suggest. The temperature transfer through resin composite restorations is slower, and the rate of temperature change is lower than in amalgam restorations. Nevertheless, marginal adaptation and microleakage studies have shown that prolonged thermocycling induces percolation under resin composite restorations.

### **Transmission of Stress Across the Restoration-Tooth Interface**

The adhesive bond between a restorative material and tooth has a biomechanical role in the distribution of functional stress throughout the whole tooth. A true bond will transmit stress applied to the restoration to the remaining tooth structure, and bonded restorations may strengthen weakened teeth. Displacement and bending of the cusps may compensate for the contraction stress in Class 2 resin composite restorations but polymerization contraction may also induce cuspal fracture. In general, high masticatory stresses are known to reduce the longevity of adhesively bonded restorations.

A similar concept of "tooth flexure" has been reported by Heymann et al. It has been suggested that microfilled resin composites compress rather than dislodge during tooth flexure. A high correlation between the modulus of elasticity and marginal leakage was found by Kemp-Scholte and Davidson. They reported that the higher the modulus of elasticity of the resin composite used, the greater the number of cervical gaps. Therefore, microfilled resin composites have commonly been preferred for restorations in wedge-shaped cervical lesions. However, in recent clinical trials, performance of microfilled resin composites was comparable to that of hybrid resin composite materials in Class 5 noncarious cervical lesions at 2 years. These findings cast some doubt on the advantages of flexible resin composites in stress-induced cervical lesions, though benefits may yet appear after a longer term.

## Biocompatibility

To the physicochemical aspects of dentin and resin composite restorative materials must be added the biologic concern of pulpal compatibility. The dissemination of residual monomer molecules to the pulp chamber via the dentinal tubules has been reported to involve a significant degree of cytotoxicity, even in low concentrations. However, in vivo biocompatibility studies have demonstrated that resin composites, whether fully or partially cured, cause little pulpal irritation if the cavities are sealed to prevent ingress of bacteria from the oral environment. Fusayama has argued that the fundamental factor involved in pulpal irritation is separation of the resin from dentin (see Fig 8-17). When debonding occurs, thermal and mechanical stresses on the restoration exert a pumping action on the fluid in the gap, pressing irritants or bacterial toxins into the tubules.

Some general health concerns have been expressed related to the use of resin composite systems. One concern is that leakage of bisphenol-A from bis-GMA-based resin composites and sealants may have estrogenic effects. Soderholm and Mariotti concluded that, considering the dosages and routes of administration and the modest response of estrogenic-sensitive target organs, the short-term risk of estrogenic effects from treatment using bisphenol A-based resins is insignificant and therefore should not be of concern to the general public. Long-term effects need to be investigated further. A "three-finger" syndrome, or a contact allergy, at the fingertips of clinicians or dental assistants has been described, although there is currently little experimental data available. A "noncontact" handling of diverse monomer-based materials, specially primers and adhesive resins, is therefore strongly advised.

Although the biologic evaluation of dentin adhesive systems has received a considerable amount of attention, the results and conclusions of these biocompatibility tests vary widely and do not cover all systems. Therefore, conclusions about the influence of chemical irritants on postoperative sensitivity must be considered premature.

The use of acids on vital dentin has traditionally been avoided because of the fear of pulpal irritation, confusion over the protective function of the smear layer, and the lack in efficacy of the bonding agents. Stanley et al reported that acid etching of dentin causes pulpal reactions when the remaining dentin is less than 1.0 mm thick, but other histopathologic studies have shown that acid etching dentin has no adverse effects. Fusayama has stated that, in the case of carious dentin, diffusion of penetrating acid is largely limited to 10  $\mu\text{m}$ , because of the blocking action of odontoblast processes in the tubules of vital teeth and intertubular crystals.

## Adhesion to Enamel And Dentin

Concepts in restorative dentistry have been continually changing during the last four decades, and adhesive technology has become steadily more important. Today, clinicians are confronted with a continuous and rapid turnover in adhesive materials. The trend toward adhesive dentistry started in the mid-1960s with the advent of the first commercial restorative resin composites, followed in the early 1970s with the introduction of the acid-etch technique in clinical practice.

Since then, there has been continuous progress in developing more refined and diversified restorative composites along with steady improvement in bonding agents. Effective adhesion to enamel was achieved with relative ease and has repeatedly proven to be a durable and reliable clinical procedure. Although adhesion to dentin is not yet as reliable as that to enamel, today's adhesives produce superior results in laboratories, along with an improved clinical effectiveness,<sup>332,336</sup> and the performance of dentin bonding has approached that of enamel bonding.

Early one-step dentin bonding agents became multistep systems with more complicated, time-consuming, and technique-sensitive application procedures. Today, so-called universal, all-purpose, or multipurpose adhesive systems are available that purportedly bond to enamel, dentin, amalgam, metal, and porcelain. In the early 1990s, the selective enamel-etching technique was replaced by a total-etch concept. Since then, universal enamel-dentin conditioners are simultaneously applied to enamel and dentin. Now that total-etch adhesives have reached an acceptable bonding effectiveness, most recent efforts have been to simplify the multistep bonding process and to reduce its sensitivity to errors in clinical handling.

Bonding to tooth tissue can also be achieved directly with glass-ionomer cements. Glass-ionomer-based materials have an auto-adhesive capacity due to their specific chemical formula and structural nature. Parallel with the progress made in resin-based adhesives, glass-ionomer technology has undergone many improvements and modifications to the original chemistry, developed in the early 1970s by Wilson and Kent. A recent trend in adhesive material development has been to combine glass-ionomer and resin composite technology in new adhesive systems and restorative materials with mixed characteristics.

### Enamel Acid-Etching Technique

Adhesion to enamel is achieved through acid etching of this highly mineralized substrate, which substantially enlarges its surface area for bonding. This enamel-bonding technique, known as the acid-etching technique, was the invention of Buonocore in 1955. He demonstrated a 100-fold increase in retention of small buttons of polymethylmethacrylate to incisors *in vivo* when enamel was etched with 85% phosphoric acid for 2 minutes. Further research into the underlying mechanism of the bond suggested that taglike resin extensions were formed and micromechanically interlocked with the enamel microporosities created by etching.

Enamel etching transforms the smooth enamel surface into an irregular surface with a high surface-free energy (about 72 dynes/cm), more than twice that of unetched enamel. An unfilled liquid acrylic resin with low viscosity, the enamel bonding agent, wets the high-energy surface and is drawn into the microporosities by capillary attraction. Enamel bonding agents are commonly based on bis-GMA, developed by Bowen in 1962, or urethane dimethacrylate (UDMA) (Fig 8-21). Both monomers are viscous and hydrophobic and are often diluted with other monomers of higher hydrophilicity and lower viscosity, such as triethylene glycol dimethacrylate (TEG-DMA) and HEMA (Fig 8-21). The bond between enamel and the restorative material is established by polymerization of monomers inside the microporosities and by copolymerization of remaining carbon-carbon double bonds with the matrix phase of the resin composite, producing strong chemical bonds. In addition, the potential for chemical interaction between specific monomers and the etched enamel surface cannot be excluded.

Acid etching removes about 10  $\mu\text{m}$  of the enamel surface and creates a microporous layer from 5 to 50  $\mu\text{m}$  deep. Three enamel-etching patterns have been described. These include type I, in which there is predominant dissolution of the prism cores; type II, in which there is predominant dissolution of the prism peripheries; and type III, in which no prism structures are evident (Figs 8-22a to 8-22c). Two types of resin tags have been described. Macrotags are formed circularly between enamel prism peripheries; microtags are formed at the cores of enamel prisms, where the monomer cures into a multitude of individual crypts formed where hydroxyapatite crystals have dissolved (Fig 8-23). Microtags probably contribute most to the bond strength because of their greater quantity and large surface area.

The effect of acid etching on enamel depends on several parameters:

- ~ The kind of acid used
- ~ The acid concentration
- ~ The etching time
- ~ The form of the etchant (gel, semigel, or aqueous solution)
- ~ The rinse time
- ~ The way in which etching is activated (rubbing, agitation, and/or repeated application of fresh acid)
- ~ Whether enamel is instrumented before etching
- ~ The chemical composition and condition of enamel
- ~ Whether enamel is on primary or permanent teeth
- ~ Whether enamel is prism-structured or prismless
- ~ Whether enamel is fluoridated, demineralized, or stained

An acid gel is generally preferred over a liquid because its application is easier to control. This enamel etching technique has proven to be a durable and reliable clinical procedure for routine applications in modern restorative dentistry.

Complete removal of the etchant and dissolved calcium phosphates, and preservation of the clean etched field without moisture and saliva contamination, are crucial to the longevity of the resin-enamel bond. For this reason, isolation with a rubber dam is preferred over isolation with cotton rolls .

Historically, some controversy existed about the concentration of phosphoric acid that would provide 194 optimal etching efficacy, because some acids have been reported to form precipitates on the surface that might interfere with resin bonding. One study showed that 50% phosphoric acid applied for 60 seconds on enamel produces a precipitate of monocalcium phosphate monohydrate that can be rinsed off. A precipitate of dicalcium phosphate dihydrate produced by etching with a less than 27% phosphoric acid was found not to be easily removable. Calcium dissolution and etching depth increase as the concentration of phosphoric acid increases until the concentration reaches 40%; at higher concentrations, a reverse effect is obtained. Although most commercial enamel etchants have concentrations between 30% and 40%, lower concentrations are often used without compromising enamel bond strengths.

### **Phosphoric Acid Etchants**

Generally, use of a phosphoric acid concentration between 30% and 40% (Fig 8-24), an etching time of not less than 15 seconds, and washing times of 5 to 10 seconds are recommended to achieve the most receptive enamel surface for bonding.

The etching time has also been reduced from the traditional 60-second application with 30% to 40% phosphoric acid to etching times as brief as 15 seconds. Several laboratory and clinical studies have demonstrated bonding effectiveness to be equivalent with etching times from 15 to 60 seconds. Adequate rinsing is an essential step. Rinsing times of 1 to 3 seconds on flat surfaces have been shown to provide for adequate bond and seal. For preparations with more geometric form, a rinse time of 5 to 10 seconds is recommended. The use of ethanol to remove residual water from the etched pattern has been reported to enhance the ability of resin monomers to penetrate the etched enamel surface irregularities. Modern primers frequently contain drying agents, such as ethanol or acetone, with a similar effect.

In addition to phosphoric acid, other inorganic and organic acids (Fig 8-24) have been advocated for acid etching enamel (and dentin), as they were supplied with specific commercial adhesives.