

DENTIN BONDING: PAST AND PRESENT

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Bonding to Tooth Structure

Historically, microleakage and post-treatment sensitivity have been persistent problems when composite resin is bonded to tooth structure. These problems are particularly common when bonding to dentin.

Marginal leakage, the more common of the two, can result in a host of problems. In addition to causing post-treatment sensitivity, leakage also contributes to marginal staining, recurrent caries, pulpitis, and even necrosis. The four main causes of microleakage are: the difference between the coefficients of thermal expansion of resin and tooth structure; polymerization shrinkage; the lack of a self-sealing mechanism; and occlusal loading.¹

An understanding of the role that polymerization shrinkage plays in causing marginal leakage and post-treatment sensitivity is helpful in explaining how dentin bonding agents can help reduce its detrimental effects.

Polymerization Shrinkage (PS)

Although PS of resin composites ranges from 1.5% to 5.5% by volume, most resins undergo a shrinkage of 2% to 3%. PS can result in the production of polymerization shrinkage stress (PSS) that pulls the resin away from tooth structure. It has been estimated that a resin to tooth structure bond of 17 MPa is necessary to offset this effect of PSS and prevent a microgap from forming between resin and tooth structure.²

Because the bond strength of resin to etched enamel ranges from 16 to 20 MPa^{3,4} (Erickson gives an average bond strength of 21 MPa⁵), PSS is insufficient to overcome this bond. However, when little or no enamel is available at the margin for etching, PSS can cause marginal gaps to develop because bonding to dentin produces a weaker bond than does bonding to etched enamel.

Lower bond strengths to dentin are the result of a number of factors:

1. dentin contains less mineralized tooth structure and more water than does enamel
2. the presence of the smear layer makes wetting of the dentin by the adhesive more difficult; even when good wetting does occur, PS can pull the smear layer away from the dentin and produce a microgap
3. fluid in the dentin tubules reduces the stability of

the composite resin to dentin bond

Until recently, these factors have compromised the clinical success of dentin bonding agents (DBAs). In the last few years, advances in dentin bonding have overcome many of these problems.

Classification of Dentin Bonding Agents

Historically, DBAs have been categorized into three generations of products based on chemistry and the manner in which they treat the smear layer.

The First-Generation products were early, largely unsuccessful attempts at producing a bond between dentin and resins. They essentially ignored the smear layer. The Second-Generation DBAs depended upon the smear layer for bonding while the Third-Generation agents characteristically remove or heavily alter the smear layer prior to bonding.

First-Generation Dentin Bonding Systems

These products ignored the smear layer. They included NPG-GMA (*N*-phenylglycine glycidyl methacrylate), the polyurethanes, and the cyanoacrylates. An example of an NPG-GMA bonding agent was S.S. White's Cervident which became available in 1965. The bond strength of this first-generation dentin bonding agent was on the order of 2 to 3 MPa.⁶ Clinical trials of these products were largely disappointing;⁷ one 6-month study reported a failure rate of 50%.⁸ Additional problems with them included loss in bond strength over time and a lack of stability of individual components during storage.

Second-Generation Dentin Bonding Systems

As already mentioned, these systems leave the smear layer largely, if not wholly, intact when used. Although second-generation bonding agents produced variable results, they generally performed better than first-generation bonding agents.⁹ They routinely produced bond strengths that ranged from approximately 4.5 to 6 MPa^{10,11} and exhibited clinical failure rates of 30% at one year. Many of these products were developed and marketed in the late 1970s and early 1980s. There were three types of second-generation products.

1. Etched tubule dentin bonding agents
 - attempted to achieve retention to dentin by etching the tubules with 25% citric acid and employing ethylmethacrylate to mechanically interlock with the etched tubules
 - representative brand: Dentin Bonding System (Den-Mat)
2. Phosphate ester dentin bonding agents
 - used analogs of BIS-GMA with attached phosphate esters
 - the phosphate group of the dentin bonding agent apparently

bonded with calcium in the tooth structure and the methacrylate end of the molecule bonded to the composite resin

- most systems of this type employed a mild cleanser to modify the smear layer

- bond strengths were approximately 10% to 30% as strong as etched enamel to resin bonds

- representative brands: Bondlite (SDS/Kerr), Creation Bond (Den-Mat), Prisma Universal Bond (Caulk), and Scotchbond (3M)

3. Polyurethane dentin bonding agents

- were based on the isocyanate group of the polyurethane polymer that bonds to various groups in dentin including carboxyl, amino, and hydroxy groups

- most used diisocyanates which simultaneously bonded to both the dentin and composite resin

- the polyurethane's setting reaction was unaffected by the presence of fluid in the dentin tubules or smear layer

- most of these systems left the smear layer intact, however some employed hydrogen peroxide for cleansing

- representative brand: Dentin-Adhesit (Ivoclar Vivadent)

Third-Generation Dentin Bonding Systems

These systems alter or remove the smear layer prior to bonding and produce bond strengths ranging from 16 to 26¹²⁻¹⁴ MPa. Some of the products produce bond strengths approaching those formed to enamel.¹⁵ Clinical retention rates of 100% at 2 years have been reported.¹⁶

Most products use a three-component system consisting of a conditioner, primer, and adhesive.

1. Conditioner (Cleanser, Etchant)

- is usually a weak organic acid (e.g., maleic acid), a low concentration of a stronger inorganic acid (e.g., phosphoric or nitric acid), or a chelating agent (e.g., EDTA).

Main Actions:

- *heavily alters or removes the smear layer

- *demineralizes peritubular and intertubular surface dentin and, thereby, exposes collagen fibrils

- demineralizes up to a depth of 7.5 microns

- depth of demineralization depends on type of acid, its concentration, and etching time

- more mineralized peritubular dentin is etched more deeply than the intertubular dentin

- *increases dentin permeability by 4 to 9 times¹⁷

2. Primer (Adhesion Promoter, Adhesion Enhancer, Bifunctional Monomer, Hydrophilic Monomer)

--is usually a bifunctional monomer in a volatile solvent such as acetone or alcohol; a bifunctional monomer is one that has a hydrophilic end (i.e., one with an affinity for water) and a hydrophobic end (one lacking an affinity for water); examples of bifunctional monomers include HEMA (hydroxyethyl methacrylate), NMSA (*N*-methacryloyl-5-aminosalicylic acid), NPG (*N*-phenylglycine), PMDM (pyromellitic diethylmethacrylate), and 4-META (4-methacryloxyethyl trimellitate anhydride).¹⁸

Main Actions:

- *links the hydrophilic dentin to the hydrophobic adhesive resin; is able to do this because of its bifunctional nature (i.e., primer's hydrophilic end bonds to the wet dentin and its hydrophobic end bonds to the adhesive resin)

- *promotes infiltration of demineralized peritubular and intertubular dentin by its own monomers and those of the adhesive resin

- *increases wettability of the conditioned dentin surface and increases contact between the dentin and resin

3. Adhesive (Bonding Resin, Sealing Resin)

--is an unfilled or partially-filled resin; may contain some component of the primer (e.g., HEMA) in an attempt to promote increased bond strength.

Main Actions:

- *combines with the primer's monomers to form a resin-reinforced hybrid layer (resin-dentin interdiffusion zone) from 1 to 5 microns thick⁹

- *forms resin tags to seal the dentin tubules

- *provides methacrylate groups to bond with the subsequently placed resin composite

To summarize, the application of third-generation dentin bonding agents involves three steps: etching with an acidic conditioner, priming with a bifunctional resin in a volatile solvent, and bonding with an unfilled or partially-filled resin.²⁰

Representative third-generation products include:

Scotchbond Multi-Purpose Adhesive (3M ESPE)

In July 1992, a new Scotchbond product was introduced, the Scotchbond Multi-Purpose Dental Adhesive System; 3M ESPE claims it forms strong bonds to both sclerotic and moist dentin and can be used for porcelain veneer bonding, porcelain and composite repairs, and bonding of composite to amalgam. Its application consists of three steps:

Step 1 apply etchant (10% to 12% maleic acid in polyvinyl alcohol and water) to both enamel and dentin for 15 seconds; rinse and dry.

Step 2 apply primer (HEMA, polycarboxylic acid, water) to enamel and dentin; dry.

Step 3 apply adhesive; light activate for 10 seconds.

In November, 1994, Scotchbond MPA was changed; the 10% maleic acid enamel/dentin etchant was replaced with a 35% phosphoric acid enamel/dentin etchant. This was done because clinicians felt uneasy after etching enamel with the maleic acid because it did not exhibit the usual frosted appearance. Also, research indicated that the resin-to-etched enamel bond strength was not as great when maleic acid was used as when phosphoric acid was used.

Another product was introduced at the same time, Scotchbond Multi-Purpose Plus Dental Adhesive System. This kit includes several components not found in the regular Scotchbond MPA kit such as an activator, ceramic primer (silanating solution), and catalyst. The purpose of this new kit is to provide the clinician with a true all-purpose bonding product that is dual-cured and will, therefore, be able to be used for amalgam bonding and for the luting of indirectly fabricated restorations such as composite resin, porcelain, and metal inlays and onlays.

OptiBond (SDS/Kerr)

--this product is a two-step system that gives the clinician the option of using a light-activated adhesive or a dual-activated adhesive.

Prime--HEMA, GPDM (glycerol phosphate dimethacrylate), mono (2-methacryloxy ethyl) phthalate, ethyl alcohol, and water; this solution is scrubbed onto the dentin surface, dried with air, and then light activated for 20 seconds.

Adhesive--UDMA (urethane dimethacrylate), TEG-DMA (triethylene glycol dimethacrylate), and GPDM; this is applied and light activated for 30 seconds.

--if a dual-activated adhesive is desired, the product comes with a liquid Activator and syringe-loaded Paste that are mixed, applied, and then light activated for 30 seconds. The dual-activated adhesive is 48% filled by weight and contains fluoride.

--it should be noted that although described above as a two-step system, SDS/Kerr recommends acid etching prior to bonding. The company includes a 37.5% phosphoric acid etchant for simultaneous etching.

A slightly different version of this product is also now available. It is called OptiBond FL and comes with the 37.5% acid etchant, prime, and a single-bottle, light-activated, filled bonding resin.

Fourth- and Fifth-Generation Dentin Bonding Agents

It is not uncommon to read about fourth-generation dentin bonding agents. One set of criteria used to distinguish fourth-generation products from earlier ones has been: ability to bond as strongly to dentin as to enamel, ability to bond strongly to moist dentin, and technique insensitivity.²¹ An additional criterion may be the ability to bond to many different types of substrates (e.g., enamel, dentin, porcelain, base and noble metals, amalgam). Being able to bond to these substrates generally means that the DBA enhances the strength of the bond of composite resin to them. The ability of DBAs to bond resin to metal has been demonstrated and commented upon by several researchers.²²⁻²⁵ Among the dentin bonding products that could be said to be fourth generation are All-Bond 2, OptiBond, and Scotchbond Multi-Purpose.

Recently, fifth-generation products have been introduced. These are essentially distinguished by being one-step or one-bottle products. This is a bit of a misnomer because these products are applied in two steps; first a 34% to 37.5% phosphoric acid etchant is applied to the tooth structure and then the dentin bonding agent is applied. The innovative aspect of these products is that the primer and adhesive resin are in one bottle. The first of these products was LD Caulk's Prime & Bond. When originally introduced, it was to be used only when placing direct composite resin restorations. Caulk now claims it can be used for most bonding applications. The instructions give the clinician the option of using an enamel-etch-only technique or a total-etch (enamel- and dentin-etch) technique. Recently, it underwent two changes and has been renamed Prime & Bond 2.1. The changes were addition of fluoride and inclusion of an elastomeric monomer to reduce the DBA's rigidity. Another fifth-generation product is Bisco's One-Step. It is a multi-substrate product but is not packaged with many of the components (e.g., silanating solution, metal opaquers, and luting resins) necessary to perform various types of bonding. Other fifth-generation products include OptiBond Solo (SDS/Kerr), Single Bond (3M ESPE), PQ1 (Ultradent), and Gluma One Bond (Heraeus Kulzer). In general, these products have limitations. Many require at least as much time to apply or even more time than three-component products and they lack many of the components necessary to perform multi-substrate bonding. It also appears important to apply multiple coats of these agents so that there is an adequately thick resin

layer on top of the hybrid layer. This helps protect the DBA from early failure when the resin composite shrinks during polymerization. Studies vary concerning their bond strength: in one study bond strengths produced by fifth-generation DBAs were lower than those of multi-component DBAs,²⁶ while another study found the values to be similar.²⁷ The micromorphology of the hybrid layer has been found to be similar to that produced by multi-component DBAs.²⁷

Newest Products

Nanofilled

Recently, bonding agents have been marketed that contain extremely small filler particles. These are called nanofilled DBAs and include the products Prime & Bond NT (Dentsply/Caulk) and Excite (Ivoclar Vivadent). Prime & Bond NT contains 7-nanometer fillers and purportedly has a greater concentration of resin and a smaller molecular weight resin that have been added. These changes, along with the small fillers, are said to make the DBA tougher, stronger, and able to cover adequately with a single coat; it is also claimed to penetrate dentin better, provide improved marginal integrity, and have a low film thickness. Ivoclar Vivadent's Excite contains 12-nanometer fillers and is packaged in a single-use capsule. It is very fast to apply, covers dentin in one coat, and comes with a graphics-only instruction card.

Self-Etching Primers

Another class of recently developed bonding agents are the self-etching primer products. Some clinicians and researchers label these as six-generation bonding agents. They use an acidified primer that is applied to the dentin and not rinsed off. Most self-etching primers are moderately acidic with a pH that ranges between 1.8 and 2.5²⁸. The primer acts to alter and penetrate the smear layer, demineralize surface dentin, expose collagen fibrils, and penetrate the treated area with resin. In effect, the solution etches and primes in one step; a separate adhesive resin is then applied. At least three self-etching primer products are available: Clearfil SE Bond and Clearfil Liner Bond 2V (Tokuyama/J. Morita), Simplicity (Apex Dental). It is claimed by the manufacturers of self-etching primer products that they reduce or eliminate post-treatment sensitivity because they etch and prime simultaneously. This is believed to reduce sensitivity because (1) they etch the dentin less aggressively than total-etch products (2) the demineralized dentin is completely infiltrated by resin during the etching process and (3) since the smear layer plugs are retained in the orifices of the dentin tubules, the tubules remain sealed. Products using self-etching

primers have been shown to form relatively thin (i.e., 1 to 2.6 micron-thick) hybrid layers compared to traditional three-step products.²⁹⁻³¹ Thickness of the hybrid layer, however, has not been shown to be necessary for obtaining good bond strengths.^{32, 33} Rather, it is the completeness of infiltration of the demineralized dentin by the resin monomers that affects bond strength. It is important to note that although self-etching primer products bond well to roughened or prepared enamel, they form a significantly weaker bond to unprepared enamel if the enamel is not first etched with a standard phosphoric acid etchant.³⁴

It is important to note that technically, self-etching primer products can be: two-step products, consisting of two solutions applied sequentially; or all-in-one bonding agents which consist of a single solution that is applied to the tooth.

Single-Solution

The latest type of bonding products have been single-solution agents such as those listed in the following table.

| Product Name | Filled/Unfilled | Manufacturer/Supplier |
|---------------------|------------------------|------------------------------|
| AQ Bond | Unfilled | Sun Medical, Japan |
| Etch & Prime | Unfilled | Degussa, Germany |
| FuturaBond | Unfilled | Voco, Germany |
| One-Up Bond F | Filled | Tokuyama, Japan |
| Prompt L-Pop | Unfilled | 3M ESPE, USA |
| Reactmer bond | Filled | Shofu, Japan |
| Touch & Bond | Unfilled | Parkell, USA |
| Xeno III | Filled | Dentsply/Caulk |
| iBond | Unfilled | Heraeus Kulzer |

Some researchers and companies call these single-solution or all-in-one products. The term single-solution appears more appropriate because they consist of a single solution when applied to the tooth structure. Many of the products above require mixing two separate components prior to use, but at the time they are actually applied to tooth structure, they consist of a single solution. The important thing to note about these products is that they accomplish all three traditional steps in the bonding process (etching, priming, bonding/sealing) with a

single solution. By definition, then, they are also self-etching primer products. As for the self-etching products mentioned earlier, some clinicians question the ability of the single-solution products to adequately penetrate the smear layer and demineralize underlying dentin. A recent study has found that the thickness of the smear layer does not adversely affect the bond strength of these products.²⁸

One of the single-solution products, Prompt L-Pop, is a good example of the simplicity in packaging that can be achieved by these straightforward products. Its packaging consists of a disposable, single, foil package with an attached applicator tip. Early studies have shown mixed results for Prompt L-Pop's bonding performance and ability to form a hybrid layer of traditional thickness. Other drawbacks are that it does not set when light activated with plasma arc curing lights and can not be used before luting restorations with dual-cured resin cements. It has recently been reformulated, however. The new version has a different photoactivator so it can be cured with all types of curing lights, and its instructions now make light curing mandatory instead of optional. One-Up Bond F comes as two solutions that are mixed at the time of use. They undergo a color change when mixed and also after light activation to enhance visualization of application. Touch & Bond is prepared immediately before use by activating its liquid using a chemical-impregnated pledget (i.e., sponge).

General Information

Excessive thinning of the adhesive resin component of current dentin bonding products using compressed air should be avoided because oxygen inhibition will prevent them from polymerizing;³⁵ this, in turn, will adversely affect adhesion. This is particularly true when the adhesive is less than 20 microns thick. 3M ESPE believed this to be enough of a problem that they recommended that their Scotchbond 2 adhesive be placed in a layer at least 75 to 100 microns thick. This is best accomplished by observing the bonding resin when it is air thinned. The adhesive should show ripples when air thinned; if not, it is too thin.

In the last decade, several trends have developed in the formulation and marketing of current dentin bonding agents in an attempt to simplify their application procedure and reduce the amount of time required to do it. One of the earliest identified trends was the development of combined enamel/dentin conditioners (i.e., those that are capable of etching enamel and dentin simultaneously). One of the first products that used this method for enamel and dentin treatment was Scotchbond Multi-Purpose Adhesive (which used 10% to 12% maleic acid). Scotchbond MPA and

most other current-generation products now use the same acid for etching dentin that they use for etching enamel (i.e., concentrations of phosphoric acid that range from 32 to 40%). This method of etching dentin with a 32 to 40% concentration of phosphoric acid is called the total-etch technique and was first discussed by Fusayama in 1977. It was slow to gain acceptance in the U.S., however, and only became popular after 1990 when All-Bond was introduced. Today, the total etch procedure is accepted by clinicians and researchers and is the standard for current dentin bonding agents.

Another trend was to reduce the number of components or bottles that make up the bonding agent. Combining components was done by combining the conditioner and the primer into one solution. These systems consist of two bottles (one is the acidified primer or self-etching primer and the other is the resin adhesive). It should be noted that some manufacturers introduced products that they claimed were two-component or two-bottle agents, but they really required a three-step application: the manufacturers just didn't provide the acid etchant. Instead, they provided only two bottles, the primer and the adhesive. From the true two-bottle products, however, we have progressed to the one-bottle products (i.e., fifth-generation DBAs). Unfortunately, these products are actually two-component or two-bottle products because they still require separate acid etching. As noted earlier, today we have the single-solution products that use just one solution for etching, priming, and bonding.

A final trend has been the production of unit-dose or single-use packaging. Traditionally, bonding agents have been a weak link in infection control because components have to be dispensed immediately before use, and few assistants or dentists overglove or deglove to do so. Now, several DBAs are provided in a unit-dose form. These include OptiBond Solo and OptiBond Solo Plus (SDS/Kerr), Excite (Ivoclar Vivadent), Prime & Bond NT (Dentsply/Caulk), Prompt L-Pop (3M ESPE), and iBond (Heraeus Kulzer).

Some manufacturers claim that their bonding systems are more compatible with particular resin composites.³⁶ This is believed to be the case because resin composites have different organic matrices (BIS-GMA or urethane dimethacrylate). Although one study indicates that different brands of composite bond to the same DBA with similar bond strengths,³⁷ another investigation suggests that type of composite (e.g., hybrid, microfill, etc.) may have a significant effect.³⁸ This study found that dentin bonding agents produced higher bond strengths when used with

hybrid composites than with microfills.

In general, it appears that cross compatibility between bonding systems and composite brands exists. In other words, different manufacturers' composites can be used with other manufacturers' DBAs without compromising the bond strength.³⁹

Anecdotal reports and some research⁴⁰ indicate that a lack of compatibility does exist between some dentin bonding agents (usually those using a self-etching primer) and self-cured resin composites and cements. The lack of compatibility results in debonding of the resin from the tooth. The reason for this incompatibility seems to be the low pH of the DBA's primer which interferes with polymerization of the resin composite or cement. This problem does not occur when these same bonding agents are used with light-cured resin composites or cements, because the light-curing process rapidly produces a huge number of free radicals which overwhelms the ability of the bonding agent's low pH to interfere with the continuing polymerization process.

Evidence indicates that when using certain bonding products (All-Bond 2, One-Step) dentin need not be dry during bonding; bond strengths of DBAs that contain alcohol- or acetone-based, hydrophilic monomers are actually higher when they are applied to moist dentin than to dry dentin.⁴¹ It is believed that this ability to bond to visibly moist dentin occurs for two reasons: first, the acetone chases water and enhances penetration of the bonding agent's monomers into the dentin for better micromechanical bonding. Also, the water keeps collagen fibrils from collapsing. This promotes better penetration and micromechanical bonding between resin and dentin. One practical way to ensure clinically that the proper moisture conditions exist for good bonding is to etch the tooth structure and then rinse well. Dry the enamel and dentin thoroughly. Then, remoisten the dentin using a small sponge or a fine-tipped brush. This technique results in a dry enamel surface and an adequately moist dentin surface. An alternative is to blot dry the dentin with a cotton roll prior to bonding so that it is glisteningly moist when the primer is applied. Research has shown that if the dentin is too moist during primer application, the quality of the hybrid layer is compromised.⁴²

With DBAs whose primers are water based (e.g., Scotchbond Multi-Purpose Adhesive, Amalgambond), the dentin can be dried before primer application because the water in the primer will rehydrate the dentin and provide an acceptable hybrid layer.⁴³ Evidence indicates that the demineralized, denatured collagen fibrils swell after application of the water-containing primers of these

products.⁴⁴ One study indicates that longer application times for these primers increase the resulting shear bond strength, presumably because the primers more effectively rehydrate the dentin.⁴⁵

Many clinicians wonder whether or not a DBA primer should be applied to enamel. Some studies indicate that this does not adversely affect the bond strength,^{46,47} while other others show that it reduces the strength.^{48,49} The most recent research, however, indicates that primer can be applied to etched, dried enamel and will have no effect on bond strength. If the enamel is left moist after etching, it must be treated with primer or the bond strength will be reduced.⁵⁰

Class V Cavity Preparation Guidelines When Using Dentin Bonding Agents:

- *Isolate the area well; although many current dentin bonding products bond well to moist dentin, this does not imply that they should be applied to tooth structure that has been contaminated by saliva, blood, or crevicular fluid
- *Bevel the enamel margin; this will reduce microleakage, improve esthetics, and increase bond strength
- *Roughen the dentin with a medium size diamond bur; this acts to remove debris, provide a more consistent bonding surface and provide mechanical retention; roughening the dentin has been shown to increase bond strengths from 10% to 75%;⁵¹ this may be of particular value when bonding to sclerotic dentin
- *Place a mechanical retention groove just inside the gingival cavosurface margin; note that recent work indicates that this design feature may not enhance clinical success if occlusal enamel is present⁵²
- *Etch the enamel (and dentin if directed by the instructions)
- *Place the dentin bonding agent exactly as the manufacturer recommends
- *Place and polymerize the composite resin incrementally to ensure completeness of polymerization and to reduce polymerization shrinkage stress (occlusal half first, then the gingival half)
- *If possible, try to minimize the amount of composite finishing that needs to be done; excessive finishing can cause crazing of the resin and may weaken the bond

Early work led many researchers to suggest that DBAs bonded to dentin chemically; those who believed this described the following possible modes of chemical bonding:

-bonding to the 45% mineralized or inorganic portion of the

dentin; ionic bonding occurs between the negative charges on the functional group and the Ca^{+2} of hydroxyapatite; the negative charges are usually provided by a phosphate group. This type of bonding is said to produce bond strengths of less than 10 MPa, but values vary greatly. Representative agents of this type include Scotchbond (3M ESPE), Prisma Universal Bond (Caulk), Bondlite (SDS/Kerr), and Creation Bond (Den-Mat).

-bonding to the 33% organic phase of the dentin; 90% of this organic phase is collagen and it is specifically to the pendant amino (NH_2) and hydroxy (OH^-) groups of the collagen that bonding occurs. An example of a DBA of this type was Ivoclar Vivadent's Dentin-Adhesit. Dentin-Adhesit was a polyurethane that contained functional isocyanate groups that bonded to the organic phase of the dentin.

The consensus that has recently developed is that bonding of current-generation DBAs to dentin is essentially mechanical in nature;^{35,53,54} this consensus is due, in part, to spectroscopic studies that showed no evidence of primary bonding by DBAs.^{55,56} Pashley believes that the mechanical bonding results from monomer flow into microscopic subsurface porosities in the intertubular dentin.⁵⁷ Erickson believes that it is due to monomer flow into demineralized intertubular dentin.⁵ This lends support to Duke's clinical observation that third-generation bonding agents did not bond well to nonsensitive, sclerotic erosion/abrasion lesions. The tubules in these cases contain calcified odontoblastic processes (which form as a final protective measure against trauma from advancing caries or toothbrush abrasion) and the tubule orifices are occluded by crystalline material. The intertubular dentin is also hypermineralized. In these situations, he suggests more aggressive dentin conditioning. The effect of dentin sclerosis on hybrid layer formation of a dentin bonding agent was evaluated by Prati et al⁵⁸ who found that sclerotic and old dentin showed a thinner hybrid layer with short resin tags and fewer lateral branches than normal dentin. Dentin bonding agents do retain resin composites well in sensitive, nonsclerotic erosion/abrasion lesions because the dentin in these areas contains open dentin tubules and less mineralized intertubular dentin. Resins flow easily into this type of dentin (after conditioning) and provide maximum mechanical retention. The two forms of dentin can be differentiated clinically because the sclerotic dentin appears heavily stained or translucent while the nonsclerotic dentin appears milky white or opaque.

Until recently, light-activated dentin bonding agents have been recommended only for direct restorative use while dual-activated bonding agents have been recommended for all purposes. The reason that light-activated products have not been used with

indirectly fabricated restorations is that they produce too thick a film thickness and prevent the restoration from fully seating. Recently, the light-activated, fifth-generation product One-Step has been recommended by its manufacturer for use in direct and indirect situations because it is purported to produce a low film thickness.

Three excellent uses for current-generation dentin bonding agents are:

1. prior to the luting of cast ceramic, porcelain, or composite restorations with resin cements when dentin is exposed; advantages may include increased bond strength, reduced microleakage, reduced post-treatment sensitivity, and increased fracture resistance of the luted restoration;⁵⁹ care must be taken, however, to use DBAs that produce a thin film thickness (e.g., Amalgambond, All-Bond 2)
2. as a dentin desensitizing agent
3. for the retention of resin-based restorative materials, particularly to nonsclerotic dentin

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