

A Historical Overview of the Development of the Acid-Etch Bonding System in Orthodontics

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Orthodontic treatment was revolutionized with the development of the acid-etch technique. This article will provide some historical perspectives of the evolution of orthodontic bonding as well as refer to some significant research contributions to the process. In addition current perspectives will be addressed. (Semin Orthod 2010;16:2-23.) © 2010 Published by Elsevier Inc.

The Early Years—An Era of Ideas and Significant Developments

Orthodontic treatment with fixed appliances requires the proverbial “handle on the teeth” to enable a force system to be applied to the teeth. Brackets, either welded to bands or bonded to enamel, provide these attachments to the teeth. This article presents an overview of the development of bonding over the last 50 years. It:

1. Uses the published data to demonstrate how laboratory and clinical testing has affected orthodontic treatment, and most importantly,
2. Encourages further investigations and discussions among clinicians and researchers alike.

Orthodontic Bands

The development of circumferential bands on teeth followed an interesting pathway. Edward H. Angle (1907)¹ introduced custom clamp bands of gold to provide attachment for his edgewise appliance. These were soon replaced by pinch-fit bands to simplify the arduous task of full-mouth banding. This task was further enhanced as stainless steel was introduced in the late 1920s and currently orthodontic bands are

manufactured from stainless steel. Throughout this process, dental luting cements for bands also evolved and the lineage went from Ames black copper phosphate cement, to polycarboxylate cement, zinc phosphate cement, zinc oxide eugenol cement, and currently the popular luting cement is glass ionomer cement (GIC) or some derivative of the latter.

A visual comparison of bands vs directly bonded attachments illustrates why direct bonding became popular (Fig 1).

Acid-Etching of the Enamel

Michael G Buonocore (1955)² revolutionized dentistry with his historical paper: “A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces” depicting the advantage of etching and bonding of acrylic to enamel.² It forever changed the practice of dentistry. Buonocore looked at the painting industry for his ideas about bonding to enamel. The painting industry relied on phosphoric acid and preparations containing this acid to treat metal surfaces, so as to obtain better adhesion of paint and resin coatings, remove surface and other contaminants, convert surface metal or oxides to phosphates, promote adsorption of phosphate groups on the metal, and eventually enhance this adhesion effect. In preparation of the dental enamel surface, Buonocore observed that various ions and saliva affect the superficial enamel surface making it different from the underlying enamel, and thus any receptivity of the superficial enamel surface for acrylic material is lost. Buonocore suggested a surface acid treatment of the enamel, similar to that used in the paint industry, which he believed would

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1073-8746/10/1601-0\$30.00/0

doi:10.1053/j.sodo.2009.12.002

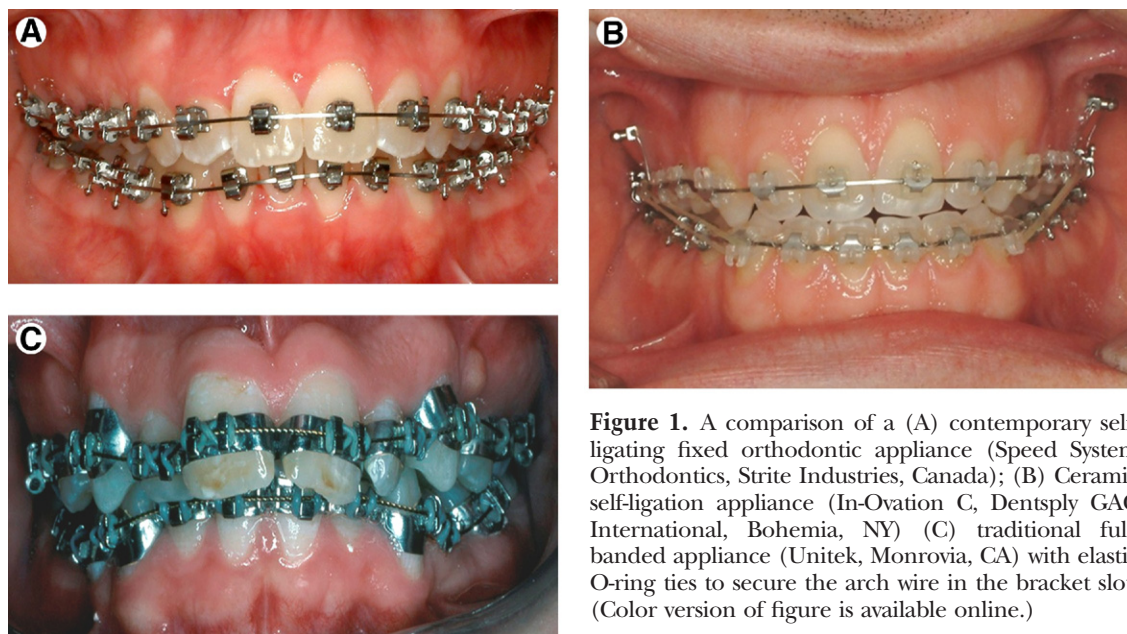


Figure 1. A comparison of a (A) contemporary self-ligating fixed orthodontic appliance (Speed System Orthodontics, Strite Industries, Canada); (B) Ceramic self-ligation appliance (In-Ovation C, Dentsply GAC International, Bohemia, NY) (C) traditional full-banded appliance (Unitek, Monrovia, CA) with elastic O-ring ties to secure the arch wire in the bracket slot. (Color version of figure is available online.)

render the enamel more receptive to adhesion in a similar manner as metals. He embarked on his bonding research in July 1954 by etching the enamel for 30 seconds with 85% phosphoric acid, and then rinsing the surface with water. Drops of acrylic were placed on the etched surface and compared with an unetched surface. The acrylic adhered for a long time on the etched surface; furthermore, it was noted that mechanical force was required to debond the acrylic material from the previously etched enamel surface. On the contrary, the acrylic spontaneously debonded from the unetched surface.

The acid-etch technique was thus developed—a contribution that would spearhead numerous additional developments to facilitate orthodontic treatment, a significant milestone in orthodontics.

The ease of the clinical management of the bonding process ensured that bonding was a viable clinical option irrespective of the occasional bond failure. Because replacing loose brackets is inefficient, time-consuming, and costly, the search for better bond strengths, better adhesives, simpler bonding procedures, as well as bonding in moist conditions is ongoing (Note: refer to the article on deproteinization in this issue of *Seminars in Orthodontics*).

It is imperative to execute the bonding process meticulously to achieve a low failure rate.

The contemporary bonding process to enamel includes the following steps:

1. A thorough prophylaxis to provide a clean bonding surface
2. A 37% phosphoric acid gel or aqueous solution applied for approximately 15 seconds to etch and provide a surface for mechanical retention/bonding (*see later in the text*)
3. Rinsing with copious amounts of water to remove all acid
4. Dry with moisture and oil-free air to show the frosty, chalky white demarcated etched enamel surface
5. Apply the sealant/primer (*preferably filled—see later in the text*)
6. Bond the bracket with composite cement under a dry field (autopolymerizing composites are still in use; however, light-cure or dual-cure are the preferred choice today)
7. Cure the composite; light-curing is the choice of most clinicians in the modern orthodontic clinic.

Note that the gel etch is available in different colors, which not only shows where the etch material is applied, but more importantly, it restricts the flow of the etch material. The gel and aqueous solutions show similar etch patterns on the enamel surface.

The Development of Bonding Materials

The basis of bonding materials, the bisphenyl A glycidyl dimethacrylate (Bis-GMA) resin, was introduced in 1956. It is better known as Bowen's resin and aptly named after its inventor, Rafael L. Bowen.³ Bowen launched his research in the 1950s and synthesized the Bis-GMA epoxy resin which led to the first successful production of a composite resin for filling teeth. Acrylic acid was discovered in 1843. The earlier acrylic fillings of the 1940s proved to have been unsatisfactory because they discolored, shrank, contributed to pulpal inflammation, and allowed extensive decay to recur. Bowen's product demonstrated more stable properties and better cosmetic qualities. Because Bis-GMA could be made to resemble the color of natural teeth, it proved especially useful for restorations in anterior teeth. In addition, the color was ideal for bonding orthodontic attachments to enamel. Bonding was a rapidly developing technology. Newman (1965)⁴ introduced direct bonding as a viable clinical technique in a progress report in the *American Journal of Orthodontics*. Subsequently, orthodontic bonding developed as an excellent alternative to banding, and its popularity increased significantly over the next years.

The 1970s brought clarification of bonding definitions.

Adhesion, Wetting, and Contact Angles

Retief et al (1970)⁵ emphasized that adhesion is the molecular attraction between surfaces or between molecules and that this attraction is enhanced by various forces; that is,

1. Physical adhesion by Van der Waal's forces and hydrogen bonds, and,
2. Chemical adhesion by covalent and electrovalent bonds.

These researchers also showed that surface contact was important in adhesion. Good surface contact between bracket base and enamel surface requires very short distances between the base and enamel surface, measured in Ångström units; thus, the smaller the distance the better adapted is the bracket base. Spontaneous adherence is thus possible at an atomic level if this close approximation occurs clinically when the surfaces are brought into contact. However,

tooth surfaces are not smooth surfaces and the molecular closeness for successful adhesion is subsequently achieved by introducing a liquid adhesive between the bracket and the enamel surface. This liquid can be micro- or macro-filled, and if attracting forces are strong, wetting occurs which is expressed as a very thin layer of liquid or cement distributed in all the surface crevices of the enamel and the bracket base. This liquid or cement forms a specific contact angle with the enamel surface. The smaller the contact angle the better the wetting, and thus the better the adhesion.

Bond Strength

Retief et al⁵ also illustrated that fresh adhesive outperformed a similar old sample; moreover, this research also emphasized that surface conditioning is essential for increased bond strengths to enamel. An interesting observation is the unit of bond strength used in this 1970 paper being pounds per square inch compared with today's standard unit, megapascal (MPa). The normal conversion would be 1 MPa = 145.038 lbs force per square inch. Bond strength using the MPa unit is thus a reflection of the debond force per unit area (bracket base area). Bond strength is often still measured in kilograms; thus, the MPa equivalent would be the kilogram force per unit area; that is 1 MPa = 1 kg/cm² × 0.098 07 or 1 kg/mm² = 9.807 MPa; also, 1 MPa = 1 N/mm² and 1 N/mm² = 100 N/cm². The modern universal testing apparatus will do all these conversions automatically with the provision that the unit area is provided and the MPa unit selected. Active treatment can be initiated shortly after the bonding process when light curing is used; however, with auto polymerizing or chemically cured materials one has to proceed more cautiously before applying a force to the bonded appliance as these materials normally take a maximum of 24 hours to reach maximum bond strength. Conventional laboratory bond strength testing has been described in numerous peer-reviewed manuscripts.⁶⁻⁹ It is important to review the methodology before applying the results of a project clinically. Bond strength studies, irrespective whether shear bond strength (SBS) or tensile bond strength (TSB), use the "mechanical mouth," better known scientifically as the Universal Testing Ma-

chine or by the manufacturer's name, Instron machine (Instron Corporation, Canton, MA), for testing. It uses a tooth-bracket specimen attached to a platform to which a force is applied until failure by a debonding apparatus, mostly a thin blade attached to a crosshead, at set speeds that is slow enough to provide standardized bond strength results (Fig 2). To provide bond strengths which can be compared between various studies, recordings are converted to the unit of choice, the MPa. As noted previously, the latter takes the base surface area in consideration when the bond strength is calculated. It is thus imperative to accurately obtain the base surface for this calculation to facilitate a comparison of bonding or debonding results among the various bracket sizes.

Bracket Mesh Pad

The bracket mesh pad development started in the 1970s (Fig 3) and bonding with "Durelon" (polycarboxylate) was described. A specially prepared zinc oxide powder mixed with acrylic or methacrylic acid resulted in this polycarboxylate cement, which adhered chemically to dental enamel and could also be used as a luting agent for bands as well as crowns in restorative dentistry. This polycarboxylate cement known as "Durelon" was introduced by Smith (1968).¹⁰

Bracket Base Size

An improved bonding technique enhances the ability for plaque removal by the patient; more-

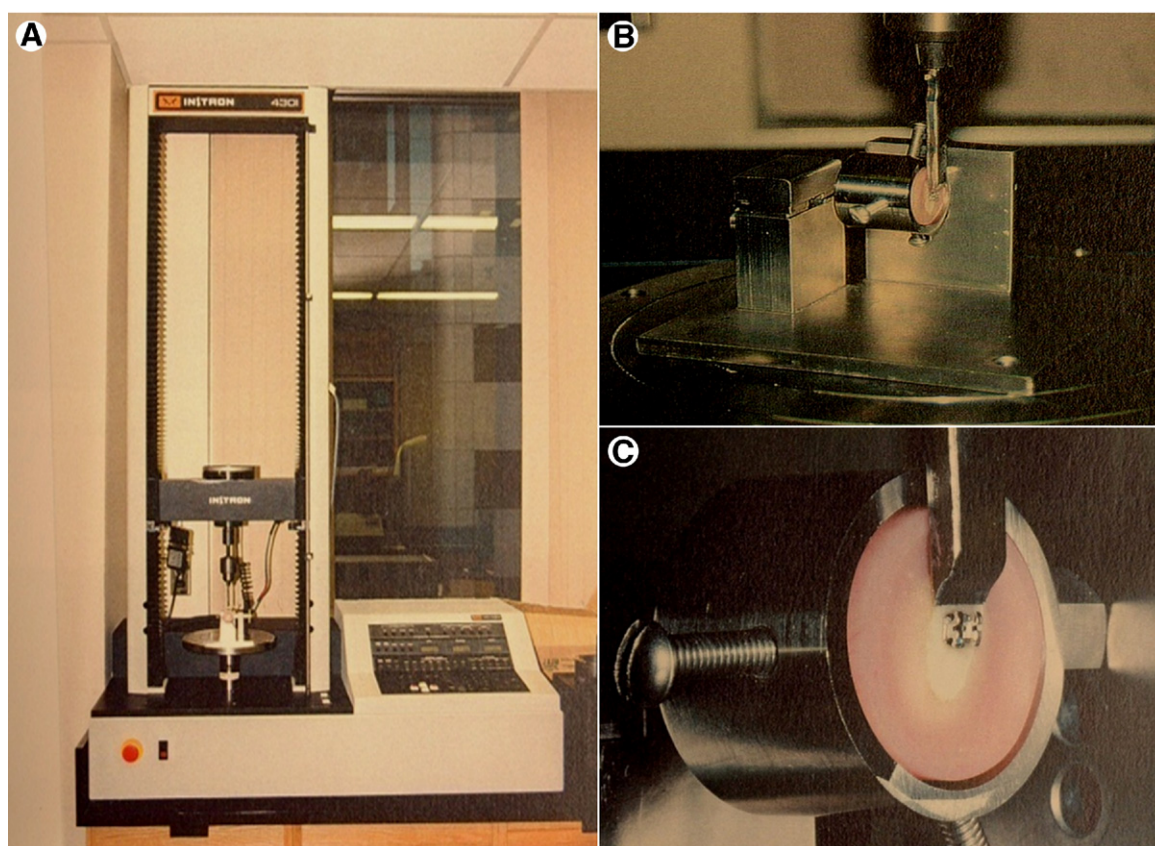


Figure 2. (A) The Universal testing machine represented by a model from the Instron Corporation (Instron, Canton, MA). The crosshead speed is usually in the range of 1-5 mm/min, and a 50 N load cell is used for this type of experiment. The bond strength is mostly measured in a shear debond mode (shear bond strength [SBS] obtained) and provided in unit of megapascals (debonding force per bracket base surface). (B, C) The debonding test in the figure shows a blade attached to the crosshead forcing the bracket to debond in an occluso-gingival direction similar to occlusal force in the mouth. (Color version of figure is available online.)

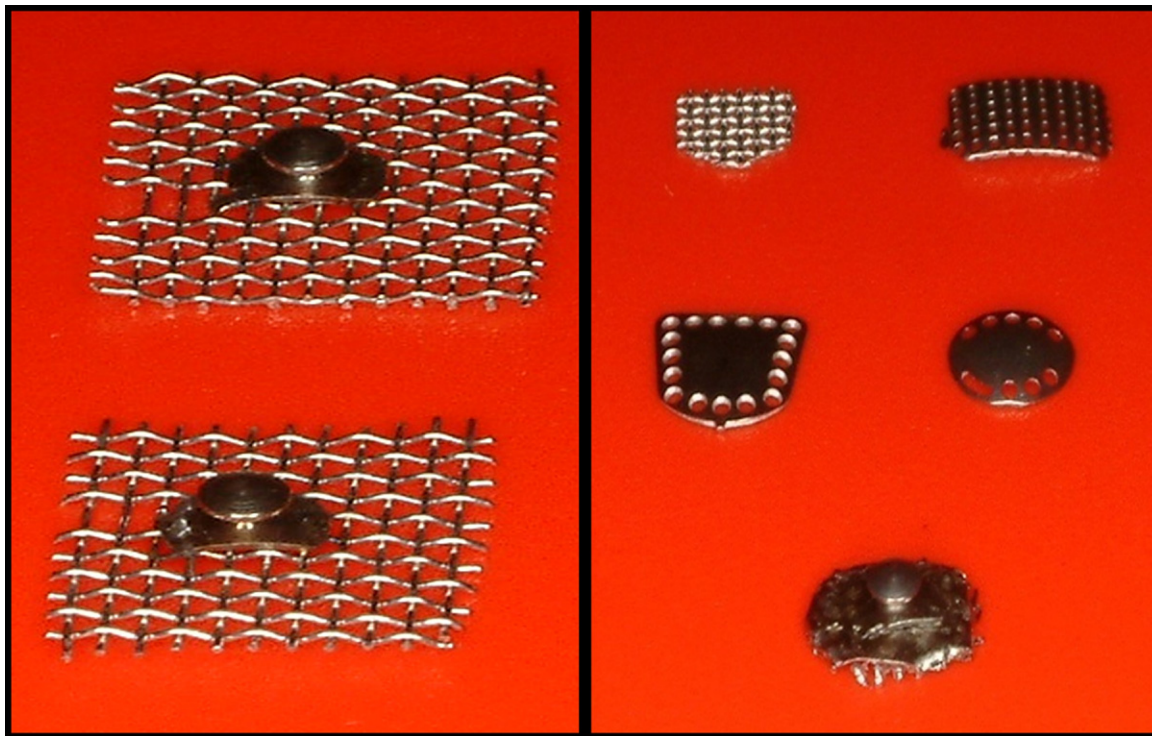


Figure 3. The mesh and early bonding base development circa 1970 (Courtesy: Dr PM Dallas, Campbell, TX). (Color version of figure is available online.)

over, soft-tissue irritation and hyperplastic gingivitis are also minimized. Research projects were initiated to study a reduction in bracket size (Fig 4). MacColl et al (1998)⁷ investigated the mean SBS vs base area reduction and surface preparation which included untreated, micro-etched, and sand-blasted surfaces. All 3 surfaces behaved similarly when the base area was reduced from 12.35 to 6.82 mm². The SBS remained fairly stable between 12.35 and 6.82 mm², but showed a significant reduction in SBS with further base area decreases. However, the SBS remained significantly higher for the 2 treated base surfaces compared with the untreated surface throughout the experimental ranges.

Correct bracket positioning enhances the occlusal outcome after treatment. There should be flexibility in the etch area to ensure that the brackets can be correctly positioned. Etching only a base size area limits bracket positioning. Clinical experience has shown that a larger etched area is not detrimental to the enamel; however, it is more important to ensure that the etched area is adequately sealed. Moreover, decalcification prevention regimens must be ad-

hered to and this includes fluoride use and removal of all plaque retentive areas, including removal of excess resin flash.

Gel and Aqueous Solution for Etching

The question is often posed as to which is ideal for etching of the enamel, gel or aqueous solutions. Urabe et al (1999)⁸ studied the effect of various acids on the bond strength of stainless steel, ceramic and plastic brackets. It was concluded that in general phosphoric and/or maleic acid provide similar bond strength. Moreover, certain combinations of acid and bracket bases proved to be ideal; for example, the combination of the stainless steel brackets and the aqueous acid solutions showed the highest bond strengths. In general, the 10% Maleic acid appeared to be an adequate etchant.

The adhesive remnant index (ARI) of Årtun and Bergland (1984)¹¹ is another evaluation method incorporated as part of contemporary bond strength studies (Fig 5). This ARI provides an assessment of failure site characteristics and is imperative for any bonding study. The ARI pro-

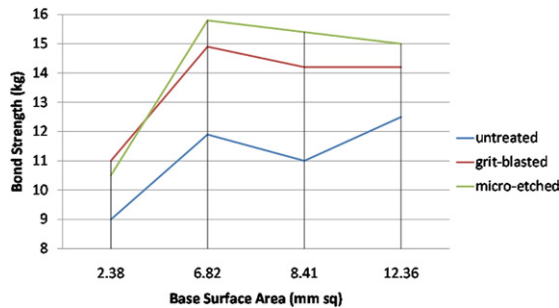


Figure 4. Mean SBS vs base area and surface preparation. The performance of the treated base surfaces, micro-etched (short interrupted line), and grit-blasted (long interrupted line) outperformed the untreated (solid line) base surfaces during the bonding experiment. As the base surfaces were reduced, the treated base surfaces maintained the edge over the untreated bases. It appears that when a critical small surface is attained, the SBS dropped significantly. (Adapted with permission from MacColl GA et al.⁷) (Color version of figure is available online.)

vides insight as to the resin-enamel and resin-bracket interface during debonding; that is, where the resin fracture occurs and thus information as to potential enamel damage (resin-enamel interface) or time required to remove the excess resin during the debonding process (resin-bracket interface). The ARI scale reads as follows: categories 0-3 (0 = no resin on enamel; 1 = <50%, 2 = >50%; 3 = all resin on enamel).

Ripley (1988)¹² and Bishara and Trulove (1990)¹³ proposed a variation of the ARI with an enhanced index for bracket debonding noting a range between 1 and 5; 1 indicates that all adhesive remained on the enamel surface through 5, indicating that no adhesive remained on the enamel surface. This index was proposed during a time when especially ceramic bracket use resulted in iatrogenic enamel fractures during debonding. The additional categories provided more detail with respect to the enamel-resin-bracket relationship.

Damage to Enamel

Damage to enamel during bonding and debonding is a clinical concern. The minimum damage with the maximum clinically useful bond strength is optimal. Questions of the optimal etching time and the appropriate acid concentration often arise. Reduction in etching time and acid concentration that produce an optimal bond should be strived for. Sadowsky et al (1990)¹⁴ showed no significant difference in the retention of bonded orthodontic attachments that occurred between etching times of 60 or 15 seconds, or between the acid concentrations 37% or 15% orthophosphoric acid (H_3PO_4). They thus suggested reducing both the etchant

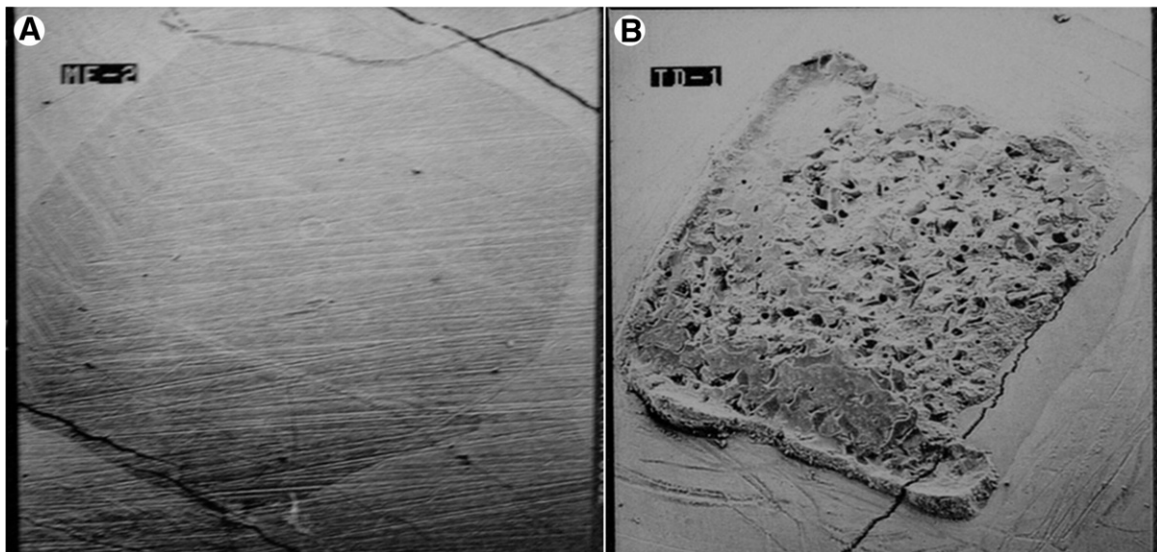


Figure 5. The adhesive resin index (ARI) is used to describe the fracture site after bracket debonding.¹¹ SEM (scanning electron microscopy) examples to show ARI interpretation; (A) ARI = 0, shows no resin remaining on enamel after debonding; (B) ARI = 2, more than 50% resin remains on the enamel surface. (Adapted with permission from Urabe H et al.⁸)

concentration and the duration of etching for orthodontic bonding.

Depth of the Etch

Legler et al (1990)¹⁵ measured the depth of etch after the use of:

1. acid concentrations: 37%, 15%, and 5% H₃PO₄
2. etching times: 60, 30, and 15 seconds, respectively.

Their calculated etch depths ranged from 27.1 μm with 37% H₃PO₄ for 60 seconds, and 3.5 μm with 5% H₃PO₄ for 15 seconds. Thus, the amount of calcium (enamel) dissolved from the subsurface zones was minimal with a 15-30 seconds etch and ensured an adequate bond strength with 37% phosphoric acid. Too long an etching time reduced the bond strength.

Enamel Loss

Zachrisson (2000)¹⁶ refers to Mannerberg (1960)¹⁷ when he reports that the normal enamel thickness where the bracket is bonded ranges between 1500 and 2000 μm . Enamel removal occurs during various processes. For example, abrasive wear removes approximately 2 $\mu\text{m}/\text{yr}$, routine etching 3-10 μm , enhanced mechanical interlocks remove another 25 μm . Thus, a total of approximately 35 μm is removed in the process of bonding and debonding; slightly more enamel can be removed depending on the instrument and procedure used for debonding. The superficial 100 μm of enamel is the fluoride-rich layer. It is apparent that most of the enamel loss is well within the fluoride-rich layer leaving adequate protection of the remaining enamel.¹⁶ Normal healthy enamel is not detrimentally affected by etching; in general, it is considered essentially a reversible process.¹⁴

Contaminants

Contaminants invariably affect bond strength. Rossouw et al (1996)¹⁸ evaluated the effect on bond strength of the obvious contaminants used during orthodontic treatment, which included dental wax, dust powder from gloves, sandblasting powder not properly removed, skin oil, and saliva. They noted a reduction in bond strength when bracket bases were exposed to these con-

taminants. Great care should be exercised in bracket base management during preparation for bonding to ensure a successful outcome of the orthodontic attachment bonding process.

Optimal Bond Strength

Retief (1974)¹⁹ highlighted the different factors with respect to optimal bond strength. He showed that enamel fractures can occur with bond strengths as low as 138 kg/cm² (13.53 MPa). It is comparable with the mean linear TBS of 148 kg/cm² (14.51 MPa) for enamel reported by Bowen and Rodriguez (1962).²⁰ The minimum clinically adequate TBS according to Reynolds (1975)²¹ appears to be between 60 and 80 kg/cm² (5.88-7.85 MPa). It was also shown by Bishara et al (1993)⁶ that a mean safe debonding strength should be less than 115 kg/cm² (11.28 MPa). The optimum range is thus between 5.88 and 13.53 MPa.

Bracket Failure

Esthetics and hygiene were the driving forces to produce smaller appliances (Fig 1). Smaller base areas were not necessarily better with respect to bond strength⁷ (Fig 4). The bond failure rate was recorded as between 5% (Keim et al, 2002),²² 21.6% (Dreyer and colleagues 1970)⁵ to 34% (Cavina, 1977).²³ Zachrisson (1977)²⁴ reported failure rates for the whole treatment period from 4% to 10% for central and lateral incisors, canines, and first premolars in both dental arches. A 5 year clinical review of bond failure with a light-cured resin adhesive by Millett et al (1999)²⁵ using data on 548 patients with 7118 bonded brackets was analyzed using a Survival Analysis. No significant differences were recorded between the categories of malocclusion. An overall failure rate of approximately 6% was measured for this British study which compared favorably with that noted in the United States.

Bond failures are the result of many factors:

1. Technique problems during the acid etching and bracket bonding procedure
2. Resin manipulation during bonding and curing
3. Bracket base design results in retention problems because of design defects or corrosion.^{5,9}

The specialty of Orthodontics is approaching 50 years of successful orthodontic bonding with a

mean bond failure rate of approximately 5% in the United States. The success rate has prompted most orthodontists to bond all teeth in the arch. Bonding also reduces arch length need when compared with banding of the teeth. Bands are occasionally used to attach appliances, such as the headgear or rapid palatal expander, with molar and premolar teeth being the most often used for this purpose. Some clinicians also prefer to band at least 1 tooth in each segment of the arch.

Bond Failure Reduced by Bracket Base Design

The influence of bracket base design or modification on bonding is of importance as the production of numerous different direct bonding attachments has increased significantly over the last 5 decades. Various reconditioning techniques were studied for increasing bond strength: conditioning by green stone, carbide bur, scaler, and sandblasting.²⁶⁻³³ Sandblasting, introduced in 1950s, uses a high speed stream of aluminum oxide particles propelled by compressed air to increase the roughness of the bracket bases.³⁴⁻³⁶ Conditioning in most instances enhances bond strength, but sandblasting in particular increases the bond strength.

Smith and Majier (1983)³⁷ introduced sintered porous metal-coated brackets (Fig 6), which appear to be an improvement in bracket base design with results showing 100% increase in bond strength compared with conventional mesh and fewer clinical failures. However, further development is needed.

Sharma-Sayal et al (2003)⁹ investigated the influence of orthodontic bracket base design on SBS. A variety of brackets with different base designs and gauge sizes were evaluated, which included untreated foil mesh, micro-etched foil mesh, metal alloy spray-treated bases, nickel-free injection molded 1-piece micro-etched bases, and integral 1 piece micro-etched bracket bases. These authors showed that bracket base design significantly affects SBS. Moreover, the results of this study also indicated that chair-side sandblasting significantly affects mean SBS.

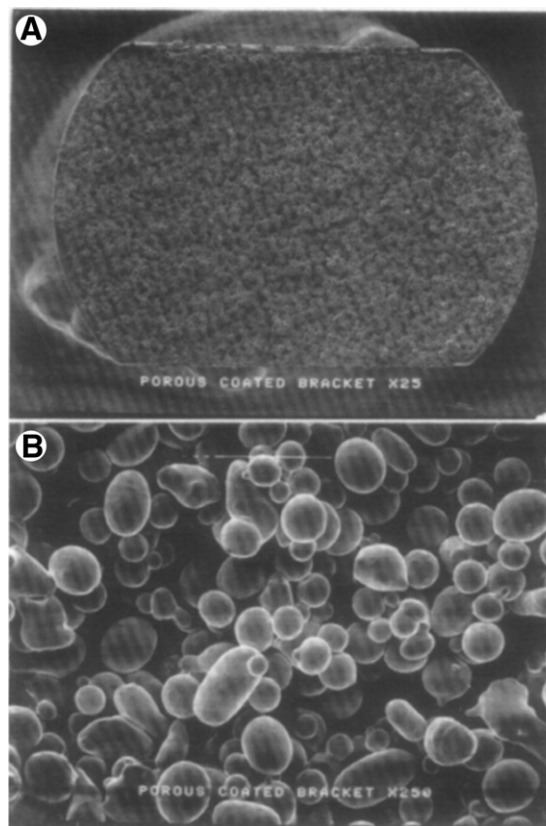


Figure 6. (A) Low-power SEM ($\times 25$) of a sintered porous coated bracket base, (B) higher magnification ($\times 250$) SEM image of the sintered base. (Adapted with permission from Smith DC and Majier R.³⁷)

Prevention of Decalcification or White Spot Lesions of Enamel

Enamel protection is important and a review of the published data about white spot lesion formation shows that they are visible within 1 month in the absence of fluoride treatment; 50% of orthodontic patients may show an increase in decalcification and maxillary laterals appear to have the highest incidence of white spot lesions.³⁸⁻⁴⁵ (A complete issue of *Seminars in Orthodontics* was devoted to this topic—Eser Tüfekçi [Guest Editor]: White spot lesions and enamel demineralization in orthodontics. *Semin Orthod* 14:173-226, 2008).

The frosty, white-etched unsealed surfaces are very obvious in contrast to the shiny, coated, and sealed surfaces. Zachrisson (1977)²⁴ referred to the advantages of sealants as a contribution to caries resistance, increasing bond strength, facili-

tation of moisture control, and aiding in debonding.

The question of whether sealants seal and, if so, which seals best was addressed by Joseph and Rossouw (1990)⁴⁶ in a study on the use of various fissure sealants in an endeavor to prevent decalcification. Brackets bonded to a sealant exhibited SBS equal to, if not higher than, the standard method of bonding. Moreover, the fracture sites of the fissure-sealed teeth also appeared more at the resin-enamel interface with an added advantage of less cleaning of the tooth surface after debonding. Scanning electron microscopy (SEM) images of the sealed enamel surfaces showed ample resin tags protruding into the etched enamel surface (Fig 7).⁴⁷ An interesting phenomenon was found by Joseph et al (1994).⁴⁸ The sealed surfaces in this latter study were treated with Transbond light-cured sealant (3 M Unitek, Monrovia, CA) and were compared with surfaces treated with an auto-polymerizing sealant. Only the light-cured surfaces were sealed. The auto-polymerizing sealant cured only where oxygen inhibition occurred in the deeper layers, the superficial or thin layers washed away and left the surfaces unsealed and exposed to decalcification agents.⁴⁷

Appropriate oral hygiene, enamel sealing, and fluoride application to a great extent prevent decalcification in contemporary orthodontics; however, irrespective of all these efforts to combat white spot lesions decalcification still occurs. Superficial decalcification may disappear

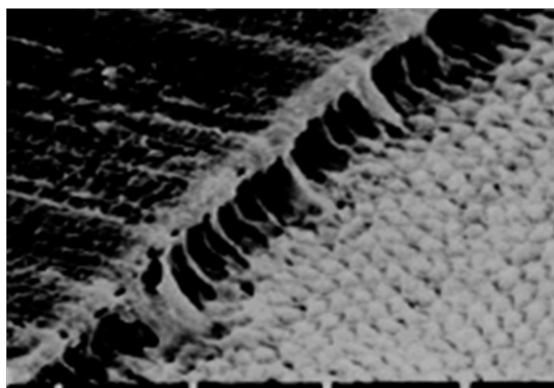


Figure 7. SEM image of a sealed enamel surface. Note resin tags showing after acid treatment to remove enamel. The classic etch pattern of the enamel surface is visible where the enamel was not sealed. (Adapted with permission from Joseph VP et al.⁴⁷)

over time; the mineral of the dental enamel is in equilibrium with its environment and saliva contains all the necessary elements for hydroxyapatite crystal growth. In the natural state, demineralization and remineralization takes place continuously. An excellent example of this is the maturation of tooth enamel that occurs shortly after a tooth erupts. Examination of a group of 9 years old children revealed 72 carious white lesions, which were carefully recorded.⁴⁹ Backer-Dirks (1966)⁴⁹ reevaluated the sample 6 years later; 50% of those lesions had disappeared, inferring that remineralization had taken place. Remineralization varies considerably from subject to subject, and from site to site in the mouth.

These studies have shown an average remineralization of 20%-30% over 2 weeks (measured as percent mineral change). Sometimes the amount of remineralization cannot totally overcome the amount of demineralization even with an effective agent present. Wilmott (2008)⁵⁰ showed that after removal of a fixed orthodontic appliance, some regression of postorthodontic lesions is known to occur provided other etiologic factors are favorable. Moreover, Joseph et al (1992)⁵¹ indicated that removal of white spot lesions can be facilitated by conservative superficial acid stripping which has been proven to be a safe procedure. This procedure is an adjunct development of the acid-etching procedure. Polishing with up to 10 5-second applications per clinical session (the number depends on the extent of the superficial white spots) using an acid and pumice slurry showed adequate elimination of superficial white spot lesions; a total less than 50 seconds (5 seconds $\times$ 10 applications as noted) ensured decalcified enamel removal well within the fluoride-rich 100- μ m outer layer. The esthetic outcome of this technique revealed normal enamel without the decalcification or white spot lesions.

Studies on the development and management of decalcification were undertaken by numerous researchers during the era of the advancement of orthodontic bonding.

Bryant et al (1985)⁵² showed that after application of the topical fluorides, acidulated phosphate fluoride (1.23%; Luride Phosphate, Davies Rose, Needham, MA), freshly prepared 8% stannous fluoride (SnF_2), topical fluoride varnish (Duraphat; Woelm Pharma, Eschwege, Germany), or Fluor Protector (Vivadent, Schaan, Liechtenstein) enamel surfaces acquired fluo-

ride from the topical fluoride agents, and the bond strengths to these surfaces were not significantly different. These authors concluded that the application of topical fluoride 7 days before bonding will not have an adverse effect on bond strength. Moreover, Thornton et al (1986)⁵³ showed that fluoride in the etching solution resulted with similar enamel etch patterns as etching solutions without fluoride, and thus did not affect the bond strength. A fluoride-releasing resin was used by Underwood et al (1989).⁵⁴ The latter indicated a 93% reduction in the first stages of enamel alteration and the resin also served as a promising fluoride exchanging medium which could serve as a caries prevention agent.

A recent study by Benham et al (2009)⁵⁵ used a highly filled (58%) pit and fissure clear sealant Ultraseal XT Plus (Ultradent Products, Jordan, Utah) to evaluate the sealant's efficiency of protecting against demineralization. The sealant provided a significant reduction in enamel demineralization during fixed orthodontic treatment, and the authors recommended that clinicians should consider the use of a filled sealant before bracket bonding to minimize white spot lesions. In addition, the authors concluded that the highly filled light-cured sealant effectively resisted mechanical abrasion and remained well-attached throughout the treatment. Moreover, Van Bebber (2009) evaluated 3 different filled sealants and a control (no sealant; 18%; 30% and 50% filled) applied to enamel surfaces exposed to toothbrush abrasion and acid exposure (phosphoric acid similar to that in soft drinks), and also showed that filled sealants provided enamel protection.⁵⁶

Other Methods of Enamel Conditioning

Other methods of enamel conditioning were investigated in an effort to replace acid-etching and thus reduce enamel loss during etching.

- a) Enamel air abrasion showed significantly lower bond strength and thus was not advocated as an enamel conditioner to replace acid etching.⁵⁷
- b) The phenomenon of crystal growth (Fig 8) was examined by several researchers.⁵⁸⁻⁶² Potential advantages of the crystal growth technique included minimal loss of surface

enamel shown by SEM, and debonding and cleanup were greatly facilitated. Årtun and Bergland (1984) used the conventional acid-etching pattern after an application of 37% H_3PO_4 to show the significant difference of the crystal growth pattern after crystal growth conditioning with an ion solution containing 1% sulfuric acid buffered to pH 1.5 and 15% anhydrous sodium sulfate for 90 seconds.¹¹ However, Årtun and Bergland (1984)¹¹ concluded that it is a very sensitive procedure and not a viable bonding option. Nearly all the brackets came loose during the first 2 weeks. An interesting observation was noted by Majijer and Smith (1986)⁶² who claimed that the solution used by Årtun and Bergland (1984)¹¹ was not according to their prescription, hence, the disappointing results. Majijer and Smith⁶² used 40% polyacrylic acid with 3.8% sulfate ions applied to the enamel for 4 minutes. This solution resulted in the growth of calcium sulfate dehydrate crystals. The crystals in turn retained the resin adhesive. However, the bond strength was relatively low. This technique was not clinically practical and never gained popularity.

- c) Combined acid and primer or the "lollipop method" was tested by Bishara et al (1998).⁶³ Their results showed debonding forces comparable to both phosphoric acid (11.8 ± 4.1 MPa) and maleic acid (10.9 ± 4.4 MPa). Fracture sites showed less residual adhesive remaining on the tooth, which is an advantage to the clinician as it requires less time to clean the teeth after debonding.
- d) Direct bonding provided the clinician with so many options that many clinicians bonded all the teeth; however, the second molar areas in particular created moisture-control problems in many instances. The need for a moisture-insensitive bonding material existed. Silverman et al (1995)⁶⁴ and Coups-Smith et al (2003)⁶⁵ used glass ionomer cements (GIC) and resin reinforced GICs to test bonding in moist environments. GIC serves as a reservoir of fluoride, thus reducing the cariogenic potential of plaque. These studies showed that clinically sufficient SBSs can be obtained using the GIC in a wet environment. Wet or dry bonding was better when conditioned with polyacrylic acid before bonding. Fricker (1992)⁶⁶ conducted a clinical trial compar-

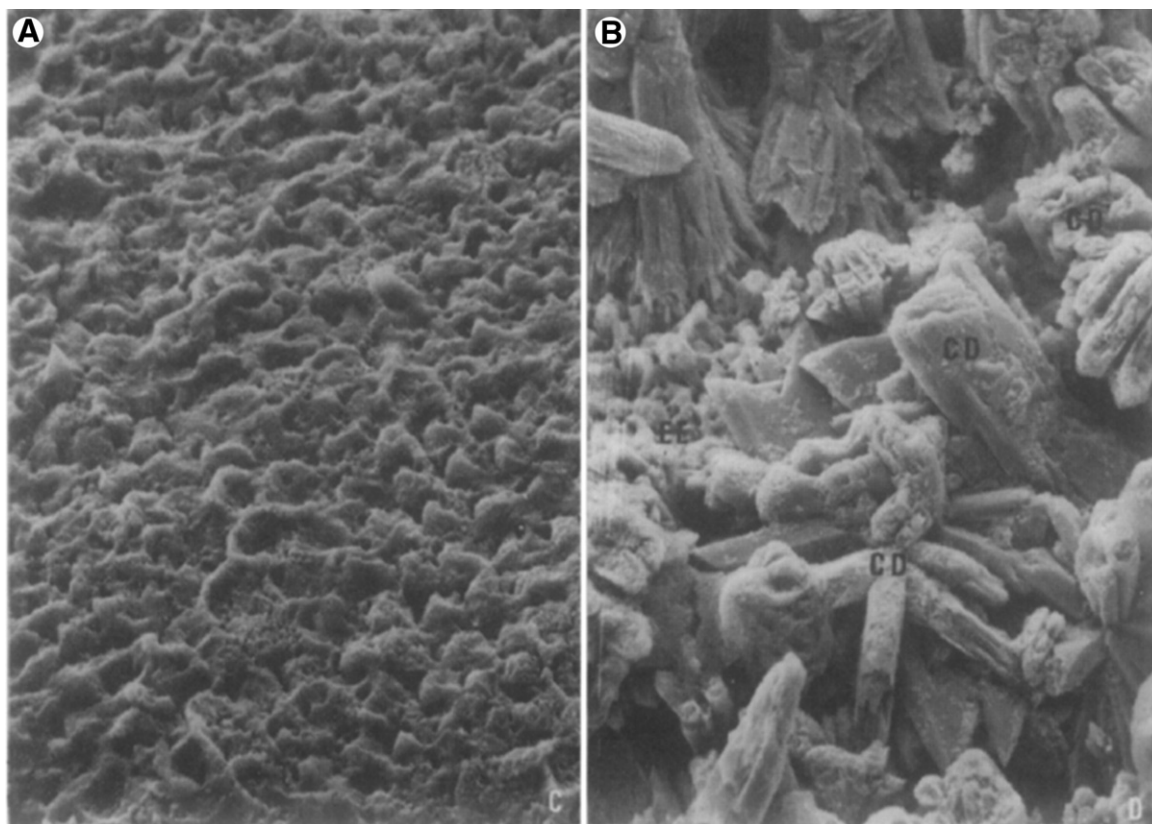


Figure 8. A comparison of crystal growth to conventional acid etch-SEM appearance $\times 1000$ after the 2 conditioning methods: (A) after acid etching 37% H_3PO_4 ; (B) after crystal growth conditioning with an ion solution containing 1% sulfuric acid buffered to pH 1.5 and 15% anhydrous sodium sulfate for 90 seconds. (Adapted with permission from Årtun J and Bergland S.¹¹)

ing a conventional composite bonding adhesive with a GIC for direct bonding of orthodontic attachments. After 12 months, he recorded a failure rate of 20% for the GIC and 5% for the composite cement.

Enamel Bleaching

Esthetic dentistry developed as rapidly as the direct bonding procedure as patients pursued straighter and whiter teeth. The question was posed whether enamel bleaching is acceptable before bonding. Miles et al (1994)⁶⁷ reported that bleaching before bonding reduced bond strengths and is not recommended. They recommended that bleaching should be discontinued at least 1 week before bonding to avoid bond failures. In contrast to their results, Bishara et al (1993, 2005, respectively)^{68,69} reported that

home-bleaching or in-office application do not appear to affect the SBS of orthodontic brackets.

Oral Hygiene

Orthodontic bracket systems are consistently improving with the addition of the smaller direct bonding appliances, including self-ligating appliances (MacColl et al 1998).⁷ These small self-ligating appliances have less plaque retention areas and also eliminate the plaque attracting elastic ties to entrap the arch wire (Fig 1). In addition, bonding techniques have significantly improved in an effort to enhance the hygiene process. Direct bonding of orthodontic brackets has thus, in general, resulted in an improved oral environment.^{5,70-74} Furthermore, the ability for plaque removal by the patient is enhanced,

minimizing soft-tissue irritation and hyperplastic gingivitis.^{5,75}

Regardless of all the efforts to provide adequate hygiene care, compliance with the hygiene protocol is still neglected and decalcification remains a problem. White spot lesion and/or decalcification development still occurs frequently. Filled sealants, as previously noted, withstand the effects of mastication and abrasives in toothpaste during tooth brushing. Therefore, it is essential to protect the enamel surface against decalcification throughout the orthodontic treatment period with this procedure of filled sealant protection as the treatment period often extends beyond 2 years.^{55,56}

Cytotoxicity

Thompson et al (1982)⁷⁶ observed that significant amounts of unpolymerized material remained in cured orthodontic bonding resins which could readily leach out by aqueous solutions, such as saliva, water, soda water, and ethanol solutions. Direct-bonding agents thus inadvertently come in contact with skin, oral mucosa, and gingiva. However, they noted that resin monomers were not leached from cured specimens by aqueous solutions containing citrate. Thompson et al⁷⁶ evaluated the resin materials extracted by test solutions and demonstrated using ultraviolet spectrophotometry that ethanol and dimethyl sulfoxide preferentially extracted material which absorbed light in the range of 265-280 nm. They further used animal studies to determine whether the components of orthodontic bonding resins could pose a real hazard to either the clinician or the patient. The unpolymerized material extracted from cured orthodontic bonding resin was analyzed and under certain conditions, substantial amounts of the material (approximately 14%) were leached from bracketed teeth. Allergy sensitivity to especially the unpolymerized resin is a reality.⁷⁶⁻⁸¹ The enforcement of gloves as part of clinical practice has reduced this resin skin sensitivity problem for the clinician and staff.

The possible carcinogenicity of these unpolymerized materials was also noted by Thompson et al. It was thus concluded that it is essential to ensure that all resin is completely cured. Jonke et al (2008)⁸² evaluated the cytotoxicity of 4 resin systems. The chemically cured orthodontic

adhesive showed a high cytotoxic potential, whereas the light-cured bonding systems had a cell toxicity potential at a level significantly lower. After 7 days of preincubation, all systems were significantly less cytotoxic than fresh specimens ($P < 0.001$). All bonding systems showed a clinically satisfactory bond strength higher than 10 MPa, with the chemically cured system showing the lowest SBS. They also experimented again with a 2-step bonding system with a self-etching primer and because etching liquid was unnecessary, concluded that the application of the 2-step bonding system is safer for the patient.⁸²

Light-Cure Bonding

Light-cure bonding with its light-polymerized adhesives was introduced by Tavas and Watts (1979, 1984).^{83,84} Their laboratory trials concluded that light-cured materials compared favorably with chemically cured adhesives. The newest addition to the various light sources is the light-emitting diode (LED) devices.^{85,86} Stahl et al (2000)⁸⁷ described the advantages of LEDs, which included light emitted in narrow wavelengths ideally matched that of camphorquinone (470 nm); no light emitted in the ultraviolet or infrared range, thus no filters or fans required; LEDs are cordless and thus easy to handle; the LED lights are resistant to vibration which secure long life spans, and little power degradation (mW). Light curing increased the efficiency and predictability of the bonding process and in addition introduced new terminology to the orthodontic dictionary. Fujibayashi et al (1998)⁸⁸ pointed out that the LED at a wavelength of 470 nm produced a deeper cure and greater hardness than a quartz-tungsten halogen (QTH) light source at 10, 20, 40, and 60 seconds when both were adjusted to 100 mW/cm². Moreover, more conversion of monomer to polymer occurred with the LED than with QTH. In a power density comparison of light sources, Dunn and Taloumis (2002)⁸⁵ and Bishara et al (2003)⁸⁹ showed that the LED unit of lower intensity was more efficient than QTH units of the same or higher intensity. No statistically significant difference was found in mean SBS.

Gronberg et al (2006)⁹⁰ evaluated the mean SBS vs curing time (5-40 seconds) and distance from the curing light source (1-10 mm).⁹⁰ No

distance effect was detected, but a significant time effect was noted. The SBS increased in a curvilinear manner; that is, fewer increases occurred at higher exposure times. All the recorded SBS exceeded the minimum clinically acceptable levels of bond strength. Reynolds²¹ reported a minimum bond strength for clinical success to be 6 MPa.

Bonding to Old and Young Teeth

Bond strength to younger and older permanent teeth was evaluated using etching times of 15 and 60 seconds.⁹¹ Sheen et al (1993)⁹¹ observed no significant difference in TBS between 15 and 60 seconds in younger or older permanent teeth. However, regardless of etching time, the bond strength of the older permanent teeth was greater than that of the younger teeth. No statistically significant differences in the debonding interface were noted among younger and older permanent teeth with 15- or 60-second etching. Enamel detachment was found only at etching times of 60 seconds. The authors recommended that to reduce enamel destruction and save chair time, 15-second etching on either younger or older permanent teeth appears adequate.

Bonding to Nonenamel Surfaces

Bonding to gold and porcelain (Fig 9) was enhanced by silane coupling agents. Wood et al (1986)⁹² showed that porcelain conditioned with silane-coupling agents produced bond strengths similar to mechanical retention obtained by acid-etching of enamel. Various metal bond enhancers are available today which enhance bonding to gold and amalgam surfaces. There are no reservations in roughening these surfaces before bonding as both, and especially gold, are easily and highly amenable to repolishing; moreover, diamond paste restores the “original” finish.

Bond strength to amalgam can exceed that to enamel, as illustrated in a study by Sperber et al (1999).⁹³ It was especially the restorative type resins, such as Panavia EX (J Morita USA, Inc., Tustin, CA) bonded to a sandblasted amalgam surface that showed the strongest SBS (Fig 10). This type of bonding is often experienced in the

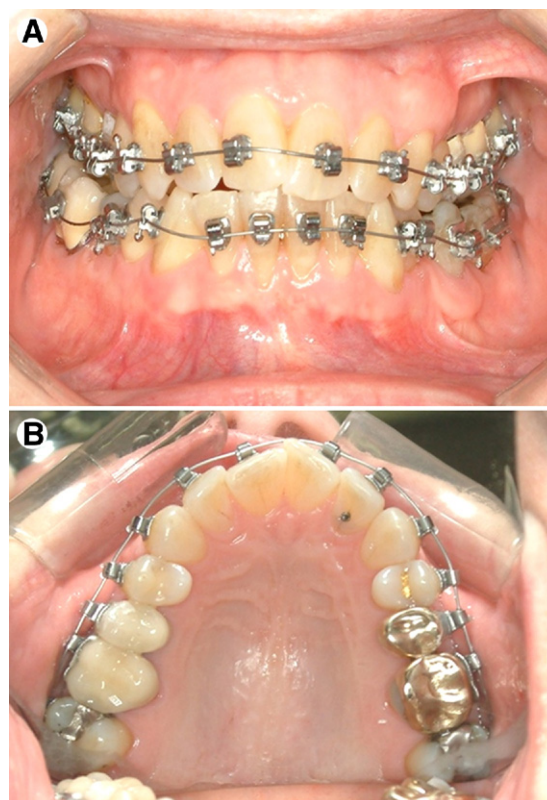


Figure 9. (A) Frontal and (B) occlusal views of fixed appliances bonded directly to enamel, porcelain, and gold. (Color version of figure is available online.)

adult patient who has had extensive restorative treatment.

Orthodontic Bracket Removal—Debonding

In the earliest studies, methods such as application of a few drops of chloroform was sufficient to dislodge the brackets for removal after bonding with an epoxy-resin adhesive.⁵ Debonding mechanisms and procedures have significantly evolved over the years. Orthodontic bracket removal using conventional (mechanical) and ultrasonic debonding techniques can lead to enamel loss, and according to Krell et al (1993)⁹⁴ it is also time-consuming. Electrothermal debonding was presented as an option by Lee-Knight et al (1997)⁹⁵; moreover, they showed that it provided predictable debonding with no ceramic veneer damage and minimal risk to the pulp when debonding ceramic brackets. However, the best

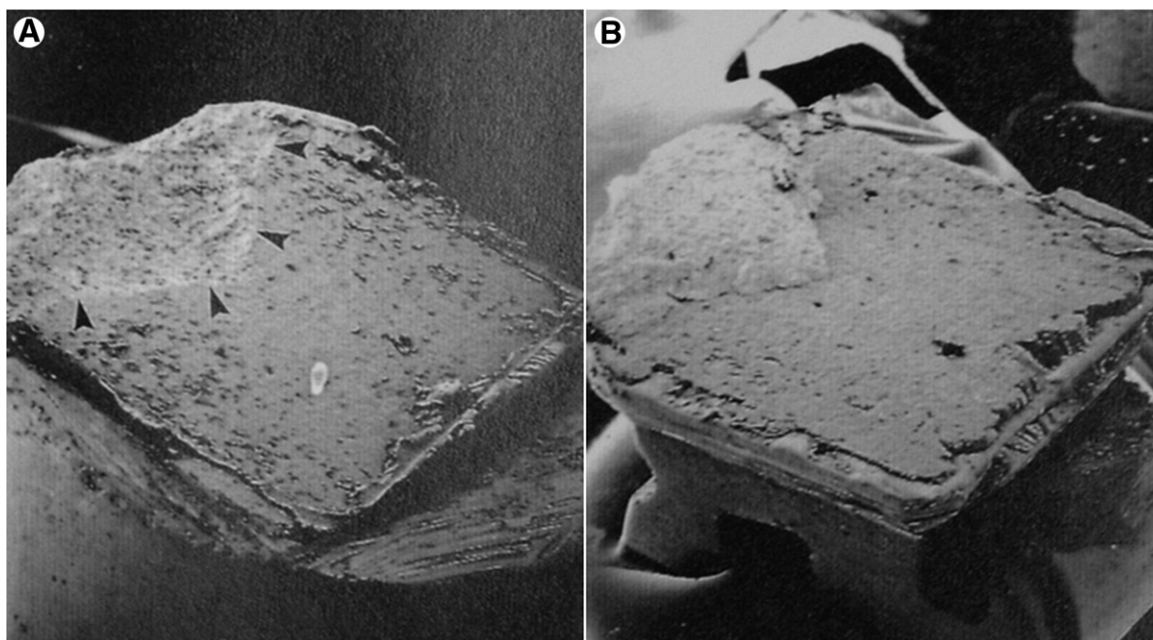


Figure 10. Bonding to amalgam can be successfully accomplished as shown by Sperber et al (1999).⁹³ The illustrations portray the adhesion/cohesion fracture of the amalgam surface. (A) Note the triangular amalgam lesion illustrates a cohesive fracture within the amalgam, (B) with the mirror image attached to the bracket base surface. This strong bond to amalgam was attained by grit-blasting the surface of the amalgam followed by bonding using a restorative resin material (Panavia EX, J Morita USA, Inc., CA).

and safest results are normally attained following the manufacturer's recommended instructions for debonding. This process is well described by Theodorakopoulou et al (2004)⁹⁶ in their debonding study producing safe and effective debonding of the esthetic brackets Clarity (3 M Unitek, CA) using a pair of Weingart pliers as well as a special debonding instrument for Inspire (Ormco, CA)

brackets. Rossouw and Terblance (1995)⁹⁷ used the finite element analysis to illustrate how debonding decisions should be made. Their study recorded the Von Mises stress distribution in enamel after debonding (Fig 11). The shear-torquing debonding showed the least traumatic effect on enamel versus tremendous opportunity for enamel trauma during tensile debonding.

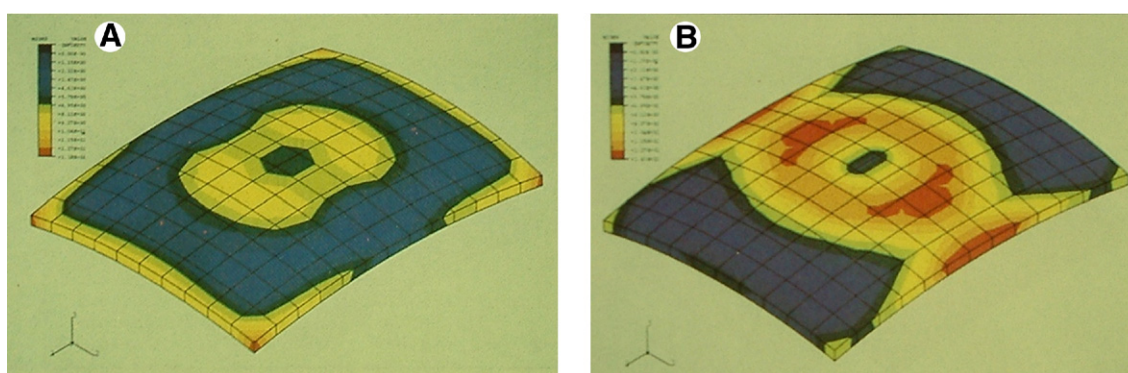


Figure 11. (A) Von Mises stress distribution in enamel after a shear debonding procedure. Note the absence of any red coloring which normally shows the high iatrogenic debonding stress resulting in possible enamel fracture.⁹⁷ (B) Von Mises stress distribution in enamel after tensile debonding. Note the red color areas indicating stress areas which are possible enamel fracture areas.⁹⁷ (Color version of figure is available online.)



Figure 12. (A) Lower incisor crowding is a natural occurrence which is also seen following orthodontic treatment where individuals neglected to adhere to a retainer protocol. (B, C) A bonded fixed retainer is a common method to maintain lower incisor alignment; however, (C) hygiene maintenance can be problematic. (Color version of figure is available online.)

After successful debonding, the enamel surface often shows resin remnants. The enamel surface can easily be damaged after removal of this residual resin after debonding. Tungsten carbide fluted burs are recommended for finishing. Retief and Denys (1979)⁹⁸ used a 12-bladed tungsten carbide bur at high speed to

remove the excess resin followed by graded polishing disks and a water slurry of pumice to restore the enamel glaze. Rouleau, et al (1982)⁹⁹ recommended a tungsten ultra fine carbide bur at high speed with water spray to provide the smoothest enamel surface. Campbell (1995)¹⁰⁰ provided a clinically useful pro-

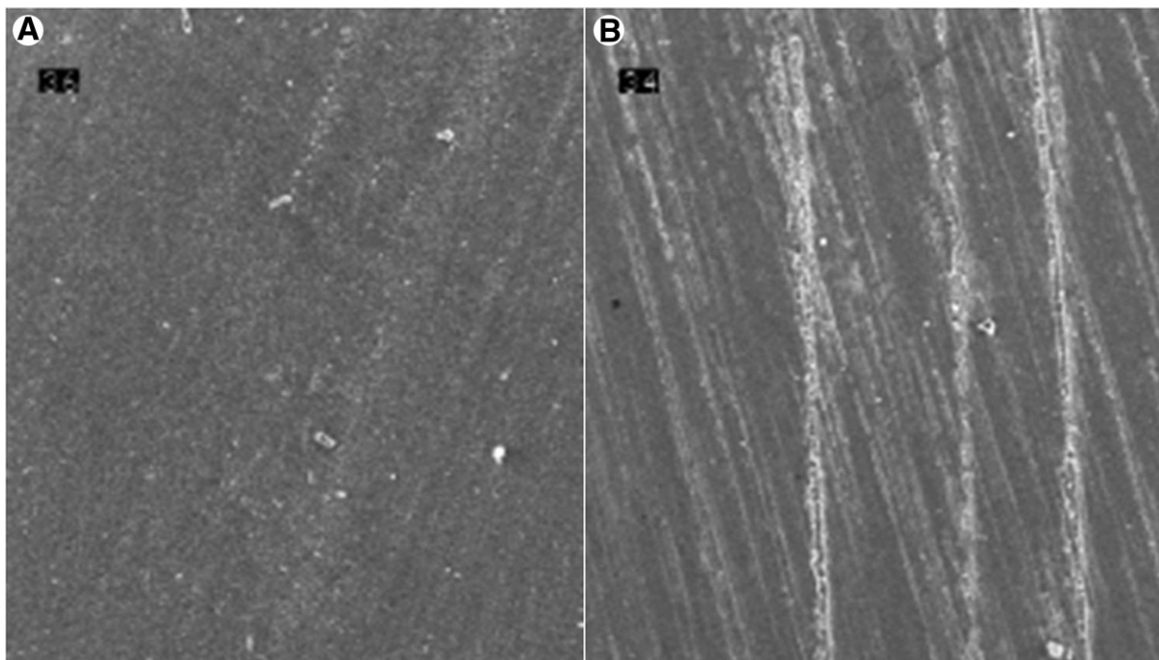


Figure 13. In the instance where posttreatment revision is required the incisor irregularity as shown in Figure 12A can be corrected by a combination of space creation through interproximal enamel reduction and orthodontic alignment. (A) The acid-etch technique assists in obtaining a smooth enamel surface (B) after the enamel removal. Enamel polishing with diamond disks and 3M disks versus the use of the latter disks and addition of 37% phosphoric acid to the polishing procedure is illustrated in the SEM images. Note the enamel smoothness after the acid-etch procedure.^{104,105}

protocol following the outcome of his study comparing the 30- vs 12-fluted carbide finishing bur. The enamel surfaces after orthodontic bracket debonding were evaluated using scanning electron micrographs. The protocol included using the 30-fluted tungsten carbide bur in a high speed hand piece to remove excess resin, followed by Enhance points and cups (Caulk/Dentsply, Milford, DE) to remove gross scarring, and then a water slurry of fine pumice to smooth the surface with a subsequent series of brown and green cups (Brasseler, Savannah, GA), then dry for a highly finished polished surface. The ultimate goal is to attain a smooth enamel surface resembling the original surface. Eliades et al (2004)¹⁰¹ also pursued this goal and tested an 8 bladed carbide bur versus an ultra fine diamond bur to remove the remaining composite after removal of the orthodontic fixed appliances. Eliades et al showed no significant difference between the two methods because both resulted with a smooth enamel surface as an outcome. However, they reported that they took half the time to reach the same result with the ultra fine diamond bur.

Other Roles of Acid-Etching in Orthodontics Besides Bracket Bonding

Mandibular incisor crowding after correction needs to be maintained by either fixed bonded retainers or removable retainers (Fig 12 A and B). Bonding a fixed retainer is selected by many clinicians; however, the fixed bonded retainer often has hygiene concerns, such as calculus deposits (Fig 12B). Appropriate hygiene and long-term maintenance of the fixed retainer is thus important. Eslambolchi et al (2008)¹⁰² showed that mandibular incisor irregularity seems to be a phenomenon that occurs throughout life and particularly in the post-treatment occlusion. Interproximal enamel stripping or reapproximation (IPR) is often used to obtain space during post-treatment revision of the alignment of irregular lower incisors. The IPR ensures that space is created; however, the procedure results in scratches remaining on the enamel surface. Acid-etching can be an addition to the IPR procedure to assist in providing a smooth surface after the initial abrasive procedure.¹⁰³ Joseph et al (1992)¹⁰³ and Rossouw and Tortorella (2003)^{104,105} used diamond

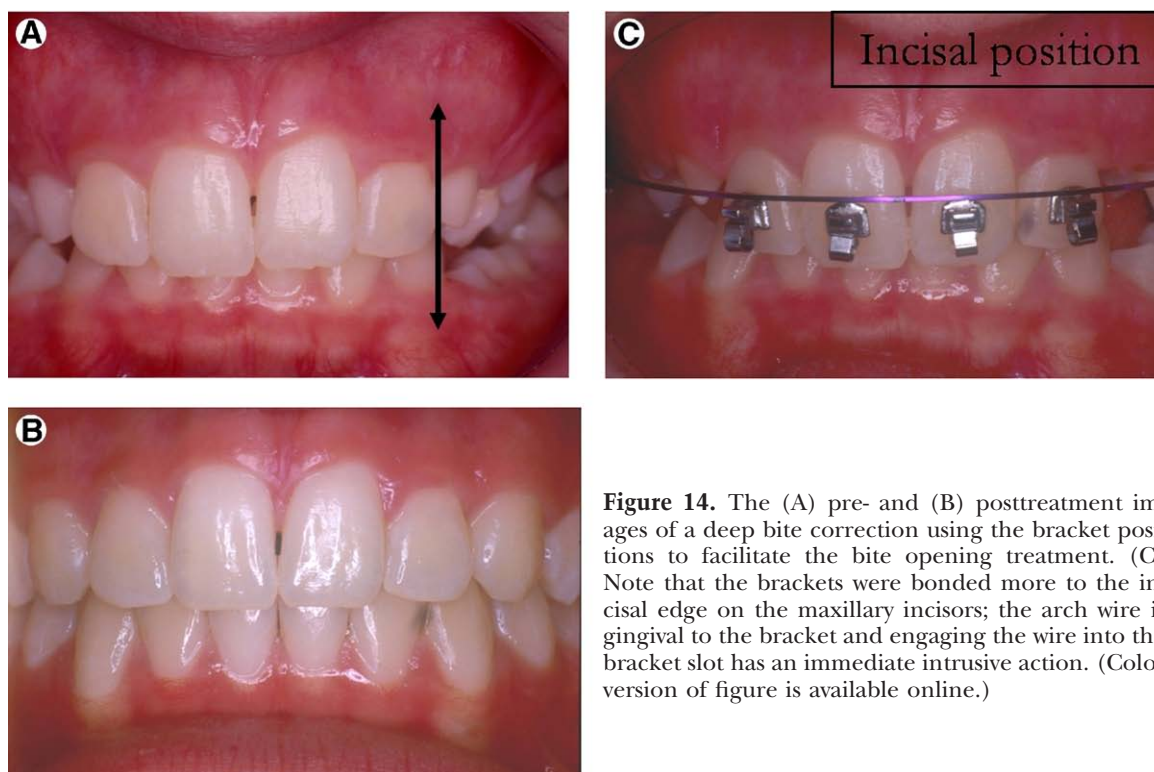


Figure 14. The (A) pre- and (B) posttreatment images of a deep bite correction using the bracket positions to facilitate the bite opening treatment. (C) Note that the brackets were bonded more to the incisal edge on the maxillary incisors; the arch wire is gingival to the bracket and engaging the wire into the bracket slot has an immediate intrusive action. (Color version of figure is available online.)

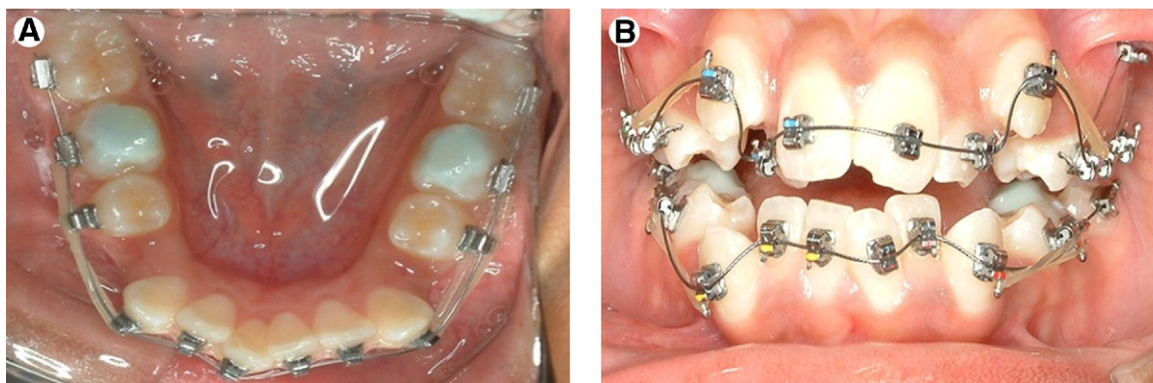


Figure 15. Use of the chemical bond characteristic of glass-ionomer cements to enamel. (A) No etching is necessary, the glass ionomer cement is placed on the enamel surface followed by light-cure. (B) It serves as a bite block to open the bite during cross-bite correction, vertical control in combination with mini-screw implants, and as a bonus it serves as a fluoride reservoir to store and leech fluoride for prevention of enamel decalcification during treatment. (Color version of figure is available online.)

disks and 3M disks (3M Unitek, CA) for the IPR plus an etchant, 37% phosphoric acid, to ensure a smooth enamel surface as an outcome of the enamel-stripping procedure. The authors also used another method where the mechanical removal was enhanced by an abrasive powder in a water-soluble gel combined with a mildly concentrated form of hydrochloric acid (Prema enamel microabrasion kit, Prema Dental Products, King of Prussia, PA). All the experimental samples with the added etchant showed during a SEM assessment that the treated enamel surfaces were equal to that of a smooth normal enamel surface (Fig 13). It is recommended that clinicians follow the recommended enamel-stripping method of teeth by fluoride application.

Biomechanics has been enhanced by the development of the acid-etch technique. A few examples from the numerous adjunctive treatments include the following:

1. The acid-etch-bracket-bonding technique provides flexibility in bracket placement; thus, a bracket can be bonded in any predetermined position on the enamel to aid in planned tooth movement; for example, more incisal bonding for intrusive tooth movements (Fig 14).
2. Bite opening treatment can be facilitated where GIC can be used as a bite block in place of a laboriously produced biteplate to open the bite to correct a cross bite (Fig 15). GIC can be chemically bonded to the occlusal



Figure 16. (A, B) Peg-shaped maxillary lateral incisors were esthetically restored using the acid-etch technique to restore the anatomy through resin bonding after orthodontic treatment (Courtesy: Dr Lenny Arenson, Richmond Hill, ON, Canada). (Color version of figure is available online.)

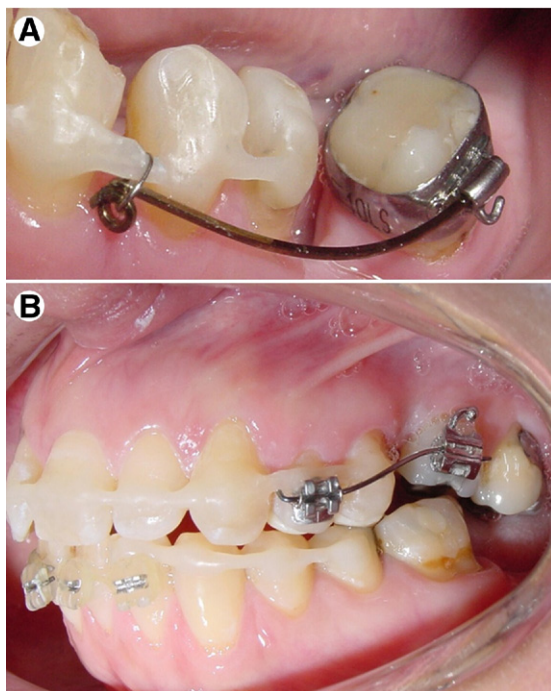


Figure 17. (A) A resin band bonded as anchorage to the lower canine and bicuspid allows a cantilever spring to be attached to the anchor unit with subsequent uprighting, distalizing, intrusion, or mesializing of the molar without affecting the other teeth; (B) similar objective pursued for the maxillary molar. Note the resin band used to provide anchorage (Courtesy: Dr C. Burstone, Farmington, CT).¹⁰⁷ (Color version of figure is available online.)

surface after a prophylaxis of the surface. This procedure is accomplished without any additional etching because of the characteristics of the cement. Moreover, the cement wears away over time without any detrimental effect on the enamel, and following its usefulness can be removed by polishing, similar to bracket debonding.

3. Bonding sections of teeth to harmonize anatomical relations and thus enhance the smile esthetics after the completion of the active treatment (Fig 16 A and B); tooth size reduction using interproximal enamel reduction—a procedure which also corrects tooth-size discrepancies (Bolton, 1958).¹⁰⁶
4. Anchorage in orthodontic treatment can be attained by various applications. One such method is to use the projected root surfaces of teeth to provide the needed resistance against reciprocal movement of the anchor

unit; that is, larger surfaces may be used as anchorage against which smaller surfaces may be moved. Anchorage reinforcement can thus take the form of grouping teeth together to further enlarge the projected root surfaces and thus increase anchorage. Such a system can be created by using the acid-etch technique to bond a resin band to secure groups of teeth for Anchorage use (Fig 17).¹⁰⁷

The Future

Many areas of orthodontics will undergo great development in the future. Bonding to non-enamel surfaces allows clinicians to bond attachments directly to mini-implant temporary anchorage devices, a procedure well illustrated by Kyung et al (2005).¹⁰⁸ The latter adjunct treatment will greatly enhance orthodontic outcomes in the future. In the pursuit of more esthetic appliances, patients often request from orthodontists the consideration of clear aligners (Invisalign, CA) from orthodontists. Certain tooth movements using clear aligners are facilitated with the addition of various shapes of bonded attachments. Each attachment is shaped to provide a specific type of movement, such as for axial inclination correction, intrusion, and rotation movements. Thus, more sophisticated tooth movement may be a possibility with this relatively simple appliance using the acid-etch-bonding technique. Decalcification still remains a concern today and although such procedures as sealants^{55,56} are used to combat these white spot lesions, developments are underway to enhance treatment. New developments include remineralizing agents (Dunn, 2007),¹⁰⁹ development and testing of an amorphous calcium phosphate containing orthodontic resin cement (Sehgal et al, 2007),¹¹⁰ and a recently released antibacterial agent Selenium (ClassOne Orthodontics, Lubbock, TX) incorporated into the bonding materials. These products are in their infancy and more testing is required. However, they will affect the future of orthodontic treatment.

Conclusions

The acid-etch technique has greatly affected orthodontic treatment. In a survey of orthodontists in the United States, Gorelick (1979)¹¹¹

found that 93% used bonding of orthodontic brackets; approximately 17% used indirect bonding. A later survey in the United States by Keim et al (2002)^{22,112} showed that not only the failure rate of bonding was low, but also that more than 90% clinicians use direct bonding, approximately 10% indirect bonding, 75% replaced 1- or 2-paste self-cure systems with light-cure bonding resins, and the most used etchant is phosphoric acid.

The purpose of this review was to show how the development of bonding to enamel influenced research, enhanced treatment, provided evidence for appropriate clinical decision-making, and will continue to affect the future of orthodontics.

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