Orthodontic materials research and applications: Part 1. Current status and projected future developments in bonding and adhesives

Theodore Eliades
Thessaloniki, Greece

The purpose of this opinion article, to be presented in 2 parts, is to project immediate future developments expected in orthodontic materials research and applications. Analysis of the material is structured around 2 axes: presentation of evidence summarizing the current status in various fields, and formulation of a hypothesis for short-term future developments. This first part of the article deals with advances and developments in bonding to enamel. Projected adhesive developments include greater use of high-energy lamps for polymerization in light-cured systems, universal application of molar tube bonding, widespread use of self-etching primers, broader acceptance of glass ionomers in their conventional and modified modes, and elimination of 2-phase adhesives in favor of no-mix and light-cured adhesives. Long-term future adhesive applications might also include biomimetic approaches, adopting mechanisms used by living organisms to adhere to surfaces. (Am J Orthod Dentofacial Orthop 2006;130:445-51)
emphasis on the mechanical, physical, and biological properties, and the potential alterations induced by intraoral aging and their implications in mechanotherapy. The purposes of this opinion article were to review the current status of orthodontic materials and their applications, and to project the development expected in the next decade in a wide range of research trends and clinical applications. This first part presents the status and potential changes in bonding to enamel and adhesives. The second part will include a brief overview of the advancements projected in brackets, archwires, and elastomerics along with a review of new strategies in assessing the biological properties of materials in response to regulations set by national and international organizations.

The assessment of the overall advancement of materials and techniques in orthodontics during the past decades and the projection of future developments are based on the author’s overview and therefore are subjective. Also, some claims made in this article might not hold true for a global application of materials to orthodontic therapy and should serve only as working arguments for the immediate specialty outlook in this field. The references indicate only the subjects discussed because the many topics and materials described in this article necessitate the citation of an enormous amount of literature; this would have resembled a bibliographical index.

**BONDING**

Advances in bonding to enamel during the last decade have shown a whole new set of materials and techniques. More options are now available for enamel preparation before bonding, ie, acid etching and non-etching mediated bonding, whereas at the same time the direction of assessing these materials’ performance has departed from the largely presumptuous character of laboratory tests to include clinical trials. This trend seems to correlate well with the overall changes in orthodontic research, which has adopted modern instrumentation, advanced analytic techniques, and more thorough statistical methods.
Enamel preparation: acid etching, Crystal growth, laser, or air abrasion?

Much literature published in the past decade deals with the techniques of enamel treatment for orthodontic bonding. Studies have documented that enamel etching with orthophosphoric acid provides similar bond strength with much lower acid concentrations than the original 37%\(^7\) as well as reduced etching times.\(^8\) Also, enamel pumice before etching has been found of limited value when the tooth surfaces are free from visible plaque precipitation and might not be an integral part of the etching process, since neither bond strength nor enamel surface etch pattern is altered by pumicing clean enamel.\(^9\)

Many studies have focused on the inevitable side effects of etching on enamel. These articles have shown the irreversible alterations of enamel arising from the retention of resin tags, the alterations during fixed appliance therapy, and the potential risk of enamel damage during debonding.\(^10-15\) Enamel surface roughness and color alterations were found to be affected similarly by both etching and nonetching mediated (glass ionomer) bonding.\(^16,17\) The studies reporting this effect concluded that the surface structure and the optical properties of enamel were affected mainly by the debonding process involving rotary instruments and not by the infiltration of enamel by resin, as evidenced by the lack of difference of enamel parameters between postdebonded glass ionomer-bonded and resin-bonded enamel. Nonetheless, some evidence suggests that resin tags can discolor because of the absorption of colorants and the oxidation of orthodontic adhesives,\(^18\) and, therefore, the long-term color alterations of labial tooth surfaces have yet to be validated.

The considerable amount of data on the effect of bonding on enamel stimulated the development of alternative methods of appliance retention onto enamel. Among the techniques and materials tried, the most prominent was the Crystal growth system. This method, originally developed by Maijer and Smith at the University of Toronto, attempted to reduce the depth penetration of treatment into enamel (Fig 2); however, the bond strength provided by this system was considered inadequate at that time.\(^19,20\)

Other research efforts focused on developing new techniques or adopting materials from restorative dentistry and transferring them to orthodontic bonding. Thus, the feasibility of air abrasion, Scotchbond primers, and various acids such as maleic were tested, but these applications did not find wide acceptance, although the results looked promising.\(^21\)

Laser etching with laser ablation was also assessed, although this method involves additional costs of the apparatus.\(^22\) Lately, self-etching primers have received wide interest, and their use has gained popularity. During the past 5 years, more than 30 studies have been conducted on the efficiency of these systems, which were adopted from restorative dentistry.\(^23-28\) Etching with self-etching compounds has proven effective despite the morphologic variation of the interfacial properties of conventional and self-etching enamel. Scanning electronic microscopic studies showed that self-etching yields shorter resin tags, which nonetheless might be adequate for orthodontic bonding, because resin tag length is not a determinant of bond strength (Fig 3).\(^29\) Overall, self-etching primers have been found to perform acceptably during treatment\(^30\); however, contradicting evidence still exists on this issue,\(^31-33\) and more research is needed to establish the degree of cure and potential cytotoxicity of primers. Because of the retention of the acidic primer in the polymer structure, care should be exercised during application of primers to avoid mucosal irritation (Fig 4).

Projected short-term future developments in enamel preparation

- The already widespread use of self-etching and molar tube bonding will be expanded even more.
- Lower concentrations of acid and short-time acid etching will be universal.
- Nonetching mediated bonding protocols will be greatly improved.
Photo-initiation: halogen, plasma, or light-emitting diode?

A fascinating improvement in orthodontic bonding has been the introduction of novel powerful light sources, which greatly reduce the irradiation time of adhesives for the initiation of polymerization. Light-emitting diode (LED), argon laser, and plasma arc light-curing units have become commercially available in recent years. Although plasma and argon laser substantially decrease the time required to reach comparable bond strength with conventional halogen,\textsuperscript{34-40} these lamps are costly, but the expense can be partially cancelled by their longer lives. Irradiation with LED curing units requires similar times as those used with halogen, but new types of these lamps show promising results with significantly reduced times.\textsuperscript{41} Irradiation of adhesives with an overwhelmingly high energy rate might accentuate their defects, which become apparent during setting. These defects include the encapsulation of unreacted monomer in the polymer network and high stresses because of polymerization contraction. Although these defects might not be of concern in orthodontic bonding because there are no cavity walls involved to preclude relaxation of these stresses as in operative dentistry applications, the rate of polymerization is a critical determinant of the material properties.\textsuperscript{3} The rate of polymerization might not actually alter the bond strength directly; a decreased cure would be expected to have adverse effects on the long-term hydrolytic degradation of the material, with unknown effects on the release of degradation species.

A new perspective emerged from the research on the effect of irradiation light on tissues. Apart from the effects on the retina, evidence suggests that blue light can form intracellular reactive oxygen species, thereby affecting cell functions. Wataha et al\textsuperscript{42} hypothesized that, if the biologic effects of blue light are redox-mediated, antioxidants might be used to reduce the undesirable effects on tissues during clinical use, although there might be a therapeutic approach related to modulating the redox-sensitive cell signaling responses. Because most available research examined the effects of conventional halogen lights, the conclusions drawn should not be generalized to the new, powerful light-curing
units, and additional research is necessary to assess these possible effects.

Projected short-term future developments in light-curing sources

- Use of plasma and LED lamps will become widespread.
- Research will focus more on basic materials properties that remain unexplored, such as degree of cure and leaching; standard bond-strength experimental protocols will gradually decline.

Adhesives: 2-phase, no-mix, or light-cured?

During the past decade, adhesives with antimicrobial properties and moisture-resistant or water-activated features were also introduced, and the literature has also dealt with varnishes and fluoride-releasing materials to inhibit microbial colonization around brackets and reduce the risk of decalcification. Glass ionomers and resin-modified glass ionomers have been used for that purpose with relatively high success.

The 2-phase products were the first to be tried by orthodontists in the early days of bonding. Handling and applying these materials is problematic, time-consuming, and cumbersome, and they are gradually being eliminated from active orthodontic practices. Mixing the 2 components introduces potentially critical defects such as surface porosity and air voids in the bulk material, because of the prolonged exposure to air and the inevitable entrapment of air bubbles, which adversely affect polymerization because of the inhibition of the reaction by the oxygen in the atmospheric air. Studies have shown that light-cured composites, intentionally mixed as if they were chemically cured materials, had severely porous surfaces and air voids in the bulk material (Fig 5). Bond strength data probably cannot reflect these structural defects because bond-strength values largely depend on base mesh design and enamel preparation. However, the long-term effects of porosity have detrimental implications for the integrity of the polymer network, which shows degradation and release of monomers.

The principle of inhomogeneous polymerization was introduced in orthodontics with the development of the no-mix adhesives, which were intended to minimize the mixing-induced defects and reduce the steps required for placement of the material. In these systems, a catalyst gradient is established from the primed enamel surface toward the brackets, by means of a diffusion process. Under these conditions, resin strength is decreased by the establishment of a disturbed cross-linked network, which nonetheless can facilitate bond strength, similar to conventional systems.

In light-cured adhesives, for a given monomer system, the extent of polymerization depends on exposure time, photoinitiator concentration, light intensity of the curing unit at the peak absorbance wavelength of the photoinitiator, and filler volume fraction, which can induce refraction and scattering of light, thereby reducing its intensity in the bulk material. The spectral distribution of the light source significantly affects the polymerization of the material, and thus the intensity given by the manufacturer should be read at the peak absorbance wavelength of the initiator, which for most systems is 468 nm (Fig 7).

The widespread use of light-cured adhesives, the gradual decline of 2-phase systems, and the develop-
ment of moisture-insensitive primers, water-activated adhesives, and antimicrobial properties are the main developments over the past 10 years.

Projected short-term future developments in adhesives
- Glass ionomer and compomer bonding will become more frequent.
- Two-phase chemically cured systems will be gradually abandoned.
- Fluoride-releasing adhesives with long-term release capacity, rather than the current nonstandardized adhesives, will be introduced.
- Adhesives with antimicrobial properties or microbial-repellent actions might be adopted.
- Antimicrobial varnishes might be introduced as the standard means of prophylaxis.

CONCLUSIONS

Long-term developments in adhesive materials will probably involve biomimetic approaches, adopting mechanisms found in living organisms. In this promising field, research efforts have already proven fruitful in developing bonding mechanisms for both dry and wet substrates. Dry bonding in associated research efforts has copied the ability of animals such as geckos to suspend their bodies from vertical or horizontal surfaces by the retentive forces of a network of fibrils attached to their feet. Scientists discovered that the mechanism underlying this phenomenon relates to the formation of van der Waals forces. They were then successful in formulating a network of carbon nanotubes, grown on silicon substrates and embedded in a polymer matrix, which resembled the foot-hair morphology of the animal.47

Likewise, wet bonding research used models imitating the capacity of mussels to attach to various surfaces such as metals, polymers, and ceramics with the aid of specific proteins. Isolation of these proteins showed that the main molecule responsible for this effect was 3,4-dihydroxyphenylalanine (dopa); incorporation of this into a polypeptide resulted in the synthesis of adhesives, which are functional in many wet material surfaces.48

REFERENCES


