Erbium Lasers and Adhesion to Tooth Structure

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Abstract: In 1997, the FDA cleared the Er:YAG laser for caries removal, cavity preparation, and laser etching of enamel. The clearance of the first Er:YAG (2.94 µm) laser focussed on the ability of this wavelength to create Class I, II, II, IV, and V dental preparations, and its role in restorative dentistry was established. An extensive number of studies were completed investigating adhesion and seal in association with Er:YAG, and evaluating whether laser cavity preparation and/or laser cavity conditioning could replace the acid-etch procedure or the classic pretreatment procedures prior to resin composite or glass-ionomer restoration. This review presents an overview of the literature regarding adhesion and sealing efficacy of different (pre)treatment protocols in association with Er:YAG laser preparation. It is concluded that at present, it is advisable to respect the conventional pretreatment procedures prescribed by the adhesive materials. Although the majority of present day reports show that microleakage and bond strength values are negatively influenced by laser (pre)treatment as compared to conventional preparation, contradictions remain on how adhesion is best achieved on Er:YAG-lased surfaces. An explanation for the disparate statements is the heterogeneity in the parameters used when preparing dental tissue with a laser. Based on these findings, it has to be emphasized that there is a need for "golden standards" regarding energy output in order to eliminate surface and subsurface alterations of dental substrate which negative influence adhesion and seal.

Keywords: Er:YAG laser, adhesion, resin composite, glass-ionomer cement, microleakage, tensile bond strength.

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To date, newer technologies for preparing dental hard tissue, such as laser irradiation, have become widespread. The most promising wavelength has been the Er:YAG laser at 2.94 µm, which has been advocated especially to prepare microcavities in keeping with "microdentistry", "minimally invasive dentistry" or "minimal intervention dentistry".

Although all adhesive materials and procedures are developed to act on tooth substrate prepared by conventional techniques, new investigations search for alternative techniques that could produce better effects than acids. Among the innovations for substrate surface treatment, the role of the Er:YAG laser has also been highlighted. This laser, applied to dental surfaces, results in a rough microretentive pattern that can help in the retention of restorative materials. As a consequence, the use of acid etching and a dentin primer to promote infiltration of resin within the hydrophilic organic tissue is no longer recommended by some researchers. This different approach is also recommended by a number of laser manufacturers. Some dentists have also started using the Er:YAG laser at low-energy settings for conditioning both enamel and dentin in place of conventional acid etching as pretreatment for adhesive procedures. This means that three different (pre)treatment procedures involving laser are available nowadays: (1) Er:YAG cavity preparation without any pretreatment procedure, (2) Er:YAG cavity preparation and laser conditioning prior to placement of an adhesive restoration, and (3) Er:YAG cavity preparation in association with the conventional adhesive approach (acid etching for resin or conditioning for glass ionomer + adhesive procedure).

The aim of the present overview was therefore to review the bonding and sealing effectiveness of adhesive restorative materials (resin composites and glass-ionomer cements) in Er:YAG-prepared cavities in association with the three previously described pretreatment procedures or their combinations: no pretreatment, laser conditioning, and conventional conditioning procedure as prescribed by the adhesive material of choice.

LASER PROCEDURES ON DENTAL HARD TISSUES – A HISTORICAL REVIEW

Cavity preparation using lasers remains an area of major research interest since lasers were initially developed in the early 1960s.[1] Goldman et al[2] and Stern and Sognaes[3] carried out the original research in that period with hard-tissue treatment including caries therapy and cavity preparation. Basic studies with Nd:YAG and CO_2 lasers followed in the 1970s. As a result of these investigations, unavoidable disadvantages such as damage to the dental pulp, carbonization of dentin, and crack formation in enamel were discussed as limitations in cavity preparation. In 1974, Stern[4] concluded that unless heat-related structural changes and damage to the surrounding dental tissues could be reduced, laser technology could not replace conventional dental rotating instruments.

Although high-powered photothermal lasers can be used effectively to cut and coagulate soft tissue, they are not ideal for hard tissue interactions. They compromise tooth structure and create a pathological condition. The thermal ablation efficiency or the thermal effects were too high, or both. In 1988, Paghdiwala[5] tested for the first time the ability of the Er:YAG laser to ablate dental hard tissues. He successfully created cavities in enamel and dentin with low energies. Without any water cooling, the prepared cavities showed no cracks and little or no charring, whereas the mean rise of temperature in the pulpal cavity was 4.3°C, well within the margin of pulpal safety.

Studies between 1988 and 1991 by Hibst et al[6,7] and Keller et al[8] showed that tooth structure could be removed by the Er:YAG wavelength without causing any measurable degree of thermal damage. Moreover, in a prospective study, it was shown that when the Er:YAG laser was used in conjunction with an adequate water spray for cooling during cavity preparation, it was a comfortable (relatively little pain was felt by the patient) alternative to conventional mechanical preparation.[9] Although preparation time for the laser procedure was approximately twice that of a high-speed handpiece, pulp vitality was maintained. Ablation of tooth structure was about one order of magnitude lower than for soft tissue and about two to four times lower than for bone.[10]

The safety and the value of using the Er:YAG wavelength for preparation of hard tissues was investigated during the mid-1990s.[11-15] A common finding in these studies was that tooth structure could be ablated without thermal damage when the Er:YAG was used with water. Ablation rates in enamel of 20 to 50 µm per pulse were obtained. Typical microcracks and other thermal damage such as carbonization were seen when the wavelength was used without water spray.

In 1997, the FDA cleared the Er:YAG laser for caries removal, cavity preparation, and laser etching of enamel. The clearance of the first Er:YAG (2.94 µm) laser focussed on the ability to create Class I, II, III, IV, and V dental preparations, and its role in dentistry was established.[16]

At present, several laser types with similar wavelengths in the middle infrared region of the electromagnetic spectrum are used commonly for cavity preparation and caries removal. The Er:YAG, Er:YSSG and Er,Cr:YSGG lasers operate at wavelengths of 2.940 µm, 2.790 µm, and 2.780 µm. These wavelengths correspond to the peak absorption range of water in the infrared spectrum. However, the absorption of Er:YAG laser (13,000 cm^{-1}) is much higher than that of the Er:YSGG (7,000 cm^{-1}) and Er,Cr:YSGG (4,000 cm^{-1}).[17,18] The efficiency of ablation is thus greatest for the Er:YAG laser.

Other non-erbium laser-based cavity preparation systems have been tested during the last three decades. To date, alternative laser systems, including super-pulsed CO_2, Ho:YAG, Ho:YSGG, Nd:YAG, Nd:NLF, diode lasers, and excimers, have not been proven feasible for cavity preparation in general practice settings.[1]

TISSUE INTERACTION – Er:YAG vs Er,Cr:YSGG

Both wavelengths have the highest absorption in water of any dental wavelength and have a high affinity for hydroxyapatite.[6,19,20] The laser energy couples into the hydroxyl radical in the apatite crystal and into the water that is bound to the crystalline structures of the tooth. The vaporization of the water within the mineral substrate causes the surrounding material to literally explode away.[21] The free-running pulse mode provides the peak power to facilitate the explosive expansion, and laboratory studies indicate that the pulpal temperature of the treated tooth may decrease by as much as 5°C during laser treatment.

Removal of tooth substance is characterized by a typical popping sound. Both the pitch and resonance of sound relate to the propagation of an acoustic shock wave within the tooth, and vary according to the presence or absence of caries. This feature assists the user in determining whether caries removal has been completed.[22]

In contrast to the popping sound during caries removal, the Er,Cr:YSGG laser system creates a loud snapping sound even when not in contact with any structure in the mouth. This seeming paradox can be explained by an effect termed "plasma de-coupling" of the beam, in which incident laser energy heats the air and water directly in front of the laser handpiece. In the Er,Cr:YSGG laser, this is done intentionally in order to deliver energy onto the rear surface of atomized water molecules, with the aim of accelerating them to a higher speed, known as "hydrokinetic cutting".[23]

High-speed photography and the scientific literature cannot give any credence to the "hydrokinetic effect" as being a viable means of how laser ablation occurs.[24-26] The mechanism by which enamel is removed is thus basically the same for both laser systems: explosive subsurface expansion of interstitially trapped water.[26] Freiberg and Cozean also concluded that "if the proposed hydrokinetic effect exists, it is not effective on hard materials, which are void of water, and it does not contribute in any significant degree in the ablation of dental enamel."[26]

The preparations produced by the Er:YAG and Er,Cr:YSGG lasers have a characteristic chalky surface when used on enamel. Micromorphology of the laser-treated dentin depicts a retentive pattern similar to acid-etched enamel and preservation of the anatomical features of enamel rods.[27,28] In dentin, a crater-like surface often accompanied by good definition of the exposed orifices of the dentinal tubules is seen. Most of the tubules remain open after ablation. Surfaces are generally clean, without cracks and with very little to no smear layer. Vaporization of intertubular dentin is greater than of peritubular dentin, showing a protrusion of the dentinal tubules with a cuff-like appearance. Scanning electron microscopic images show that laser irradiation produces a surface that increases the restorative material retention.[29]

PRESENT-DAY ADHESION TO DENTIN AND ENAMEL

The basic mechanism of bonding to enamel and dentin is essentially an exchange process involving replacement of minerals removed from the hard dental tissue by resin monomers which, upon setting, become micromechanically interlocked in the created porosities.[30] Based upon the underlying adhesion strategy, three mechanisms of adhesion are currently in use with modern adhesives.[31,32]

The Etch-and-Rinse Approach

The etch-and-rinse technique is definitely still the most effective approach to achieve efficient and stable bonding to enamel. Retention is the result of (1) formation of resin tags through in situ polymerization of resin within the etched pits and (2) envelopment of the exposed hydroxyapatite crystals.

Diffusion-based mechanisms are the basis of dentin bonding. Hybridization or micromechanical interlocking of resin within the exposed collagen fibril scaffold should be achieved.

For this approach, a conditioning step (etching with 30% to 40% phosphoric acid) should be followed by (1) a priming step and application of the adhesive resin, ie, a three-step application (two-bottle adhesives), or (2) primer and adhesive are combined into one application, ie, a simplified two-step etch-and-rinse application (one-bottle adhesives).

The Self-etching Adhesives

A nonrinse acidic monomer simultaneously conditioning and priming the dentin and enamel is used. This approach eliminates the rinsing phase.

There are two types of self-etching adhesives: mild and strong. Strong self-etching adhesives have a rather low pH (<1) and exhibit a bonding mechanism (primarily diffusion based) and interfacial ultramorphology in dentin resembling that produced by etch-and-rinse adhesives. Mild self-etching adhesives (pH around 2) dissolve the dentin surface only partially, so that a substantial number of hydroxyapatite crystals remain within the hybrid layer. Adhesion is obtained micromechanically through shallow hybridization and by additional chemical interaction of specific carboxyl/phosphate groups of functional monomers with residual hydroxyapatite.[33]

Glass-ionomer Cements and Glass-ionomer Adhesives

Glass-ionomer cements are the only materials that are self-adhering to tooth tissue.[34] A two-step approach is needed: conditioning and cleaning of the surface, eliminating the need for acid etching with polyalkenoic acid, in order to remove the smear layer and to expose the collagen fibrils up to about 0.5 to 1 µm deep.[35] Therein glass-ionomer components will then interdiffuse and establish a micromechanical bond following the principle of hybridization.[31,36] Consequently, chemical bonding is obtained by ionic interaction of the carboxyl groups of the polyalkenoic acid with calcium of hydroxyapatite that remains attached to the collagen fibrils.[34] A two-fold bonding mechanism similar to that of mild self-etching adhesives is achieved. It should be emphasized that the infiltration capacity of glass ionomers is limited by the high molecular weight of the polycarboxyl-base polymer, so that only shallow hybrid layers are formed.

DEVELOPMENT OF RESIN DENTIN ADHESIVES AND THEIR CLASSIFICATION

Successful bonding to enamel was achieved with ease. The development of predictable bonding to dentin, however, has been more problematic. The chronological method of classifying dentin bonding systems is called the “general system” and refers to different generations.[37]

As research on adhesion in Er:YAG laser dentistry only started in 1990s, especially 4th and 5th generation adhesives have been investigated. Nowadays, with the introduction of one-step self-etching or so-called all-in-one adhesives, a limited number of studies have already evaluated the 6th generation adhesives.

Fourth-generation Adhesives

It was only in the early- to mid-1990s that a significant advance in adhesive dentistry was made with the development of multistep dentin adhesive systems. With these systems, the obligatory pretreatment of dentin with conditioners and/or primers that made the heterogeneous and hydrophilic dentin substrate more receptive to bonding was mandatory. The pretreatment procedure was followed by the application of a low-viscosity adhesive resin, unfilled or semifilled, that copolymerized with the primed dentinal surface layer and simultaneously offered bonding receptors for copolymerization with the restorative resin composite.

Fifth-generation Adhesives

The fourth-generation adhesives were characterized by the complexity of number of steps or compounds involved. The intended purpose of the fifth-generation adhesives was to achieve similar or improved bonding and sealing, but with fewer bottles and/or in less time. Not all of these fifth-generation adhesives have fulfilled these requirements: bonding strength was comparable, clinical performance was not as good as or comparable to the fourth-generation adhesives. On the other hand, improvement of these systems still continues.

Sixth-generation Adhesives

This generation refers to simplification of the systems and the introduction of true single-bottle systems or all-in-one systems. In this “war of the bottles”, the idea of self-etching adhesives is not new. Already in the early 1990s, the concept of self-etching primers was introduced with Scotchbond 2 (3M). The self-etching adhesives nowadays provide monomer formulations for simultaneous conditioning and priming of both enamel and dentin. Next to the classification on the number of application steps, self-etching adhesives should also be subdivided into mild and strong self-etching adhesives, depending on their pH and thus etching potential.

ADHESION TO DENTIN AND ENAMEL IN LASER DENTISTRY

Since the report of Buonocore,[38] the standard approach for enamel pretreatment has been acid etching. Effective adhesion to enamel has been achieved with relative ease and has repeatedly proven to be a durable and reliable clinical procedure for routine applications in modern adhesive restorative dentistry.[39] The formation of a hybrid layer and resin tags is essential to the establishment of a strong bond at the dentin level.[40,41] One way of achieving this is by a complete dissolution of the smear layer and the demineralization of intertubular and peritubular dentin by means of acid etching, resulting in an exposed collagen matrix that is infiltrated by resin that polymerizes in situ.

With the introduction of the Er:YAG laser, in contrast to other available lasers, it became possible to remove dentin and enamel more effectively.[8,42,43] Moreover, cavity pretreatment with Er:YAG laser (laser etching) was proposed by some as an alternative to acid etching of enamel and dentin: laser irradiation of enamel and dentin has been reported to yield an anfractuous surface (fractured and uneven) and open tubules, both apparently ideal for adhesion.[44] Roughened dentin surfaces with open tubules without smear layer production were reported by others.[45-51]

Next to cavity preparation, the ablative effect of Er:YAG light in healthy enamel and dentin could also be used for modifying the dental surfaces and eliminating the need for acid etching. Some researchers have explored the use of lasers to modify the surfaces of teeth intentionally and to improve bonding of restorations.[28,50-53]

When referring to the previously mentioned mechanisms of adhesion, it must be clear that there is a contradiction between the adhesion approach promoted after laser preparation without conventional conditioning (etching or the use of a glass-ionomer conditioner) and the well-established pretreatment for adhesive procedures with present-day composites and glass-ionomer cements after conventional cavity preparation with the bur.

The question remains of how appropriate adhesion can be achieved in lased cavities. Indeed, the ablation process does not leave hydroxyapatite-depleted collagen on the dentin surfaces, in contrast to acid etching which exposes a microporous, demineralized collagen fibril network that can be hybridized using conventional resin-based adhesives.[31] Consequently, when the laser-conditioned tissue is not separately acid etched, collagen is not exposed, and consequently no hybrid layer can be formed.[54] Even the use of a dentin primer to promote infiltration of resin within the hydrophilic organic tissue is no longer recommended.[55] Despite this different approach, laser manufacturers commonly continue to maintain that at low-energy settings, enamel and dentin can be conditioned with the Er:YAG in place of conventional acid-etching procedures as pretreatment for adhesive procedures.

OBJECTIVE OF THE REVIEW

Present-day adhesive dentistry in general is confronted with the following shortcoming: adhesive restorations have a limited durability in vivo[56] as a result of loss of retention and marginal adaptation.[57,58] It has been shown that the immediate bonding effectiveness of contemporary adhesives is quite favorable, regardless of the approach. In the long term, however, the bonding effectiveness of some adhesives drops dramatically, whereas the bond strengths of other adhesives are more stable.[59] In a recent systematic review of current clinical trials evaluating the clinical effectiveness of contemporary adhesives,[30] the following conclusions were drawn:

- Glass-ionomer cements bond most effectively and durably to tooth tissue.
- Three-step etch-and-rinse adhesives and two-step self-etching adhesives show a clinically reliable and predictably good clinical performance.
- The clinical effectiveness of two-step etch-and-rinse adhesives was less favorable, and an ineffective clinical performance was noted for the one-step self-etching adhesives.
- Simplification of the application procedure appears to induce loss of effectiveness.
- The simplified adhesives might be faster and easier to use clinically, the resultant technique-sensitivity rises rapidly.

In the light of laser adhesive dentistry, the aim of this paper was then to review the literature on:

- The effectiveness of contemporary adhesives and adhesive materials (including glass-ionomer cements) in association with Er:YAG-lased cavities and to compare the data with those of the adhesive efficacy in conventionally (bur-) prepared cavities;
- The added value of laser pretreatment in order to eliminate conventional pretreatment procedures.

ADHESION: BOND STRENGTH AND MARGINAL SEALING ABILITY

1. Bond Strength

Resin Composites

Different bond strength tests have been developed.[60,61] Currently, the shear and microtensile bond strength test methods are the most frequently used.[59] The fact that there is evidence that the smear layer is absent when dental hard tissue is irradiated by the Er:YAG laser[7,42] has supported the view that there is no need to acid etch (phosphoric acid) the enamel and dentin in association with Er:YAG laser preparation for smear layer removal prior to bonding. The latter is a requirement when burs are used, for rotating instruments always produce a smear layer.[37,62]

First hypothesis: laser irradiation is as effective as traditional acid-etching procedures to pretreat enamel and dentin

In general, studies on bonding to laser-treated teeth have been reported using 4th and 5th generation bonding agents.[44,63-82] No studies after the year 2000[67-82] could substantiate the hypothesis that laser irradiation was equally effective as traditional acid-etching procedures to pretreat enamel and dentin for bonding. Moreover, acid etching laser-conditioned enamel and dentin significantly improved the bonding effectiveness of the total-etch adhesive. Thus, the conclusion was reached that (1) an Er:YAG laser created a laser-modified layer that adversely affected adhesion to dentin and therefore could not constitute an alternative bonding strategy to conventional etching,[72] and (2) there were subsurface changes in Er:YAG-lased dentin and enamel which could also result in subsurface fissuring that is unfavorable to adhesion.[68]

Second hypothesis: preparation of tooth substrate with Er:YAG laser or diamond bur is equally effective in terms of bond strength

A second hypothesis was that preparation of tooth substrate with Er:YAG laser or diamond bur is equally effective in terms of bond strength. With the introduction of the 6th generation self-etching self-priming bonding systems, this hypothesis has been advanced more than before. In the meantime, there is evidence that this hypothesis should be rejected not only for the 4th and 5th generation adhesive systems, but also for the self-etching and self-priming bonding systems.[83,84]

An explanation can be found in surface alterations due to laser irradiation. For example, Nd:YAG laser is known to create an acid-resistant layer on the surface of dentin and enamel, which might be useful as a preventive measure against dental caries.[85,86] The underlying process is not clearly understood, but may be due to grain growth of apatite crystallites induced by heating effects of the laser irradiation. At subablative energy densities, the Er:YAG laser decreases the water amount in dentin, which later can be partly restored by water uptake. Relative decrease of organic tissue within the dentin was detected as well, which may indicate that the Er:YAG laser selectively removes organic tissues.[87] In addition, Kataumi et al[54] observed cracks below the hybrid layer, indicating that subsurface damage was caused by Er:YAG irradiation. These findings were confirmed by Fe-SEM examination in the study of De Munck et al, demonstrating significantly more microcracks in laser-irradiated than in fractured dentin surfaces.[73]

Hybridization is a requirement for effective dentin adhesion. Surface alteration as a result of laser irradiation may therefore interfere with dentin adhesives even when laser irradiation is followed by acid etching. The more acid-resistant laser irradiated surface might have reduced the acid effectiveness, especially in those situations where less acidic self-etching adhesives are used. Next to an increased acid resistance, there is also less collagen left for hybridization after Er:YAG irradiation. Moreover, the subsurface damage can also exceed the thickness of the hybrid layer, leaving a weakened substrate without resin reinforcement underneath. This finding, among others, explains the cohesive fractures of dentin and enamel frequently observed.[67,68,71,73] The theory of subsurface damage and insufficient hybridization with self-etching adhesives, resulting in low tensile bond strengths, is substantiated in studies where the superficial layer of the lased cavity is acid etched or removed by air abrasion[70,74] or additionally pretreated with glutaraldehyde.[73] It seems that the formation of an interdiffusion zone similar to that obtained when the dentin is prepared conventionally and acid etched is difficult to create.[88-90]

Besides these structural changes, the phenomenon of vitrification has not yet been addressed. Vitrification means the recrystallization of the dentinal apatite and a formation of an additional phase of calcium phosphate. This phenomenon increases hard tissue resistance to acid demineralization, dental hardness, and dental abrasion, and also seals the dentinal tubules to a depth of up to 4 µm, thus reducing permeability and dentinal hypersensitivity.[91-93] These structural alterations which modify the qualities of dentin and enamel surfaces can prevent the restorative materials from successfully bonding to the tooth. Moreover, hard-tissue cohesive microfractures can be found in the areas below the irradiation target.[68]

The process of vitrification is associated with the amount of laser energy on the dental substrate, and laser energy is also associated with heat. The heat generated by the laser beam might induce an intense and rapid temperature increase in dentin located under the irradiated area.[94] Due to the low coefficient of thermal diffusion in dentinal tissue, heat is not scattered but contained within a restricted area below the lased surface. A rapid and substantial heat output from the laser therefore produces an intense thermal expansion of the dentin below the lased surface. This is followed by a rapid contraction during the subsequent cooling phase, resulting in high internal tensions. In addition, light energy can be transmitted to the underlying dentinal layers as a collision wave. This mechanical solicitation as well as the internal tensions may be responsible for the presence of microfractures in lased dentinal tissue.

Even the enamel etched by the laser shows fractures where the course is perpendicular to the bonded surface, probably as a result of the direction of the enamel prisms and anisotropic characteristics.[68] The application of an energy output under 200 mJ using the Er:YAG laser is advised.[94] The lack of golden standards for energy output in relation to the type of tooth substrate needs to be highlighted. This makes it more difficult to interpret and compare the findings of all previously mentioned studies with their heterogeneous energy output.

CONCLUSION

- Total-etch and self-etching adhesives bond significantly less effectively to Er:YAG-lased than to bur-cut enamel/dentin.
- The acid-etching technique remains mandatory even after laser conditioning for both dentin and enamel.
- There is a reduced thickness of the hybrid layer in association with Er:YAG-lased dentin and acid etching.
- To date, it is not advisable to use all-in-one or self-etching systems in association with Er:YAG-lased cavities.
- Subsurface damage initiated by Er:YAG ablation is probably the major reason for the decrease in bond strength and cohesive failure in the sub-bonding layer in dentin and enamel.
- There is a need to further clarify the effects of enamel and dentin laser conditioning on adhesive bonding.
- There is a need for further research of the micromorphological alterations of dental surface and the substrate/restorative-material interface.
- Golden standards are mandatory for the energy output in relation to the different types of tooth substrate in order to avoid vitrification and surface alterations which might negatively influence adhesive strength.

GLASS-IONOMER CEMENTS

For the purpose of clarity in this review, adhesive restorative materials are classified into four major groups. It is still common to refer to some materials as glass ionomers. These materials have compositional elements of glass-ionomer cements, but the typical acid-base reactions which characterize the glass-ionomer cement are lacking.

The glass-ionomer category includes both conventional (or conventionally setting) and resin-modified materials. The basic composition, setting chemical reactions, and structures are compared in Table 1.

There are different types of conventional glass-ionomer cements (GICs).[95]

1. GICs for direct restoration: these are typical acid-base reaction materials, generally consisting of a calcium aluminosilicate glass powder, a liquid containing polyalkenoic acid, and an acid serving as a complexing agent.
2. Metal-reinforced GICs: the powder contains fluoroaluminosilicate glass and a silver alloy, or the glass is sintered with silver.
3. Highly viscous GICs: as stated, these materials are more viscous than the classic GICs and were designed as an alternative to amalgam for posterior preventive restorations.
4. Low-viscosity GICs: developed as liners, fissure protection materials, sealing materials for hypersensitive cervical areas, and endodontic materials.

Resin-modified glass-ionomer cements (RM-GIC) are defined as materials that undergo both polymerization and acid-base reaction. The basic components of the liquid are polycarboxylic acid, water, and HEMA. It may also contain a small amount of cross-linking material. The composition and structure of the fluoroaluminosilicate glass for RM-GICs are basically similar to those of conventional cements.

Polyacid-modified resin composites (PAM-RC) were the result of a search for new materials where an acid monomer could polymerize in the presence of fluoroaluminosilicate glass. A PAM-RC or compomer is mainly a resin composite with fluoride-releasing potential. The

Table 1 Classification of glass-ionomer cement compomer and resin composite according to Saito et al[95]

Material	Basic composition	Setting reaction	Structure of set material
Glass-ionomer cement	Powder: fluoroaluminosilicate glass Liquid: polyacrylic acid, polybasic carboxylic acid, Water	Acid-base reaction	Filler: fluoroaluminosilicate glass powder Matrix: polyacid salt
Resin-modified glass-ionomer cement	Powder: fluoroaluminosilicate glass Liquid: polyacrylic acid, water-soluble methacrylate monomer (HEMA, etc, ...), catalyst	Acid-base reaction Polymerization	Filler: fluoroaluminosilicate glass powder Matrix: polymer acid salt, methacrylate powder
Compomer	Paste: filler (containing fluorine, etc, ...), methacrylate monomer, acidic monomer, catalyst	Polymerization	Filler: filler containing fluorine Matrix: methacrylate polymer, acidic polymer
Resin composite	Paste: filler (oxide filler, etc, ...), methacrylate monomer, catalyst	Polymerization	Filler: oxide filler Matrix: methacrylate powder

fluoride-releasing characteristic should not be overemphasized. The material has no potential to self-adhere to tooth structure.

Laser dentistry and glass-ionomer adhesion

Glass ionomers are auto-adhesive to dental tissue through combined micromechanical and chemical bonding. Er:YAG laser creates a rough microretentive pattern, which could aid in retention of this material. The determination of tensile bond strength with conventional glass ionomers is not easy, as these are brittle materials and failure during testing occurs frequently cohesively within the cement.[96] The RM-GICs, due to their resinous content, are more suited for tensile bond strength tests. It has been shown that they have higher tensile bond strength for enamel and dentin than the conventional cements.[97] Data on the tensile bond strength of GIC in association with laser dentistry are very scarce. To our knowledge, there is only the study by Corona et al,[98] investigating the influence of Er:YAG laser on the adhesion of RM-GICs (Vitremer R, 3M, St Paul, MN, USA; and ProTec CEM, Vivadent, Schaan, Liechtenstein) to dentin. The authors found that Er:YAG laser influenced the adhesion of RM-GICs, mainly Vitremer R, and that the application of primer or conditioner after Er:YAG laser irradiation of dentin provided better adhesion between the tested cements and the substrate. More research, however, is needed to draw conclusions in this matter.

CONCLUSION

- The investigation of the bond strength has been limited to resin-modified glass-ionomer cements. Information is too scarce to draw conclusions.
- No information is available yet on the influence of Er:YAG-lased dental tissue on the bond strength of conventionally setting glass-ionomer cements.

2. LEAKAGE

In terms of adhesion, dental restorations have to fulfill two requirements: retention through adhesion and sealing through adhesion. A good seal is important to prevent further decay and exposure of the dentin to the oral environment, and to prevent pulpal damage. Voids created during insertion and function may lead to ingression of oral fluids along the tooth/restorative-material interface. Two types of leakage can be distinguished on the basis of the size of the voids:

1. microleakage when large voids are present; here, water, large molecules, and bacteria can migrate along the cavity walls;
2. nanoleakage when small voids are present which can only be penetrated by water and small molecules.

MICROLEAKAGE

Studies so far have only investigated microleakage in association with Er:YAG-lased cavities. It should also be mentioned that all current adhesives appear incapable of completely sealing the restoration margins and thus preventing microleakage.[99-103] Furthermore, all resin-based restorative materials show volumetric shrinkage during polymerization, resulting in imperfections at the interface of restorative material and the cavity wall.

There are many techniques for the assessment of microleakage, and as a result there is also a considerable variance in data.[103] The oldest and the most common method used for detecting leakage in vitro is the one using organic dyes as tracers. Many dyes can be used with different particle sizes and affinity for substrates, but this does not appear to influence the test results significantly.[103] The main disadvantage, however, of this type of microleakage evaluation is that it is a qualitative method. As a consequence, the results obtained in each study group render interpretation and especially comparison of the results difficult.

RESIN COMPOSITES

To etch or not to etch?

Data on the quality of the margins of composite fillings in relation to the use of Er:YAG laser for hard tissue preparation have been discussed. Controversial results regarding the quality of the margins of composite restorations conditioned conventionally by acid etching, those remaining unconditioned after Er:YAG lasing, and those acid etched after Er:YAG lasing have been reported.[29,46,48-53,64,104-108] Laser etching next to cavity preparation and as an option for cavity conditioning prior to resin composite adhesion was investigated in a limited number of studies.[29,51,52,106]

All studies on microleakage evaluating the use of an Er:YAG laser have in common that adhesion to the gingival wall appeared to be more difficult to achieve than to the occlusal (enamel) walls. These observations coincide with the greater technique- and substrate-sensitivity of the dentin as compared to enamel.[31] It was demonstrated that laser irradiation seemed to be associated with more leakage than acid treatment at enamel margins (in bur-cut as well as in Er:YAG-prepared cavities), and was not advised for promoting a bond between resin composite materials and enamel in cavities both with[29,52] and without a bevel.[29,104,106,107] In the study by Delmé et al,[29] SEM analysis of the enamel surfaces demonstrated that laser irradiation as well as additional laser-etching rounded off the enamel irregularities, resulting in a less retentive surface than that provided by acid etching. This might explain the poorer seal. A similar effect was also noted on the surface of lased dentin samples. In general, it is thus recommended to acid etch enamel margins whatever type of cavity preparation was performed.

At the gingival walls, none of the procedures (Er:YAG lased, Er:YAG lased and laser etched, Er:YAG lased and acid etched, conventionally prepared and acid etched) completely eliminated microleakage irrespective of the composite formulation and associated adhesive system. There was a tendency towards a better seal when Er:YAG-lased cavities were acid etched. Conventional preparation and acid etching appeared to be superior to Er:YAG preparation and acid etching of the gingival walls. When the gingival walls were Er:YAG lased but not etched, the quality of the marginal seal of resin composites appeared to be dependent on the resin composite and associated three-step adhesive system used.[29] The ethanol-water based system produced a better seal than the water based system. The explanation put forward was that leakage is influenced by the nature of the composite and adhesive. A good penetration capability has been described for adhesive systems, although remaining water in the water-based systems may hamper resin penetration/polymerization.[31] This finding also coincides with the previously described sub-surface damage, water evaporation in the superficial layer, and the alteration of the superficial layer of lased tooth structure.[65,73,87-90]

What about 6th generation adhesives or all-in-one systems?

As far as bond strength was concerned, it was not advised to use all-in-one or self-etching systems. Research on microleakage with the all-in-one systems in Er:YAG-lased cavities is scarce.[109] The study by Palma Dibb et al[109] showed that Etch and Prime 3.0 (Degussa, Düsseldorf, Germany) showed a 7- to 50-fold higher microleakage (in %) at the enamel margins as compared to a filled single-bottle acetone-based adhesive (Bond-1, Jeneric/Pentron, Wallingford, CT, USA) and an unfilled acetone-based single-bottle adhesive (Prime & Bond NT, Dentsply/Caulk, Milford, DE, USA), both with 37% phosphoric acid etching for 15 s following laser conditioning. The all-in-one systems showed a microleakage value of 77.8% (± 20.7%) vs 0% for Prime & Bond NT, and 71.6% (± 24.3%) at the gingival dentin/cementum margins.

Influence of Er:YAG laser energies on microleakage

Most of the studies investigating the microleakage of resin-based materials following cavity preparation with the Er:YAG laser have, to date, investigated three areas: cavity preparation and dental-tissue conditioning with the laser, cavity preparation with the laser and conventional etching with phosphoric acid, and conventional cavity preparation with a high-speed diamond bur in an air-rotor handpiece and laser conditioning.[110] The results, as previously shown, were conflicting. An explanation can be found in the large number of variables involved, such as the choice of laser parameters, restorative material, and cavity shape. Although they did not give clear cut trends, there appeared to be agreement that the conventionally prepared, beveled and etched cavity walls produced a better resin-based composite/dental tissue seal compared to margins of laser-prepared cavities (pulse energies within the range of 200 to 300 mJ);[111,112] cavities with a high C-factor were also found to exhibit the worst leakage. Furthermore, investigations on the quality of the seal of resin-based composite restorations in dentin highlighted the importance of the choice of dentin bonding agent:[113] using the same microfilled resin composite and laser parameters of 250 mJ at 2 Hz, two of the seven dentin bonding agents tested exhibited significantly lower microleakage scores for lased cavities when compared to conventional preparation. Two others showed no difference, and the efficacy of the remaining three agents (one of which Scotchbond Multipurpose, 3M, St Paul, MN, USA) was reduced when compared to that achieved with conventional cavity preparation. On the basis of this study, Roebuck et al[110] evaluated the influence of three Er:YAG laser energies on the microleakage of Class V resin-based composite restorations. They concluded that optimum sealing was achieved with energies of at least 240 mJ at the enamel margin and with energies no higher than 200 mJ to finish the dentin margin. However, while all the pulse energies compared favorably to the control group in enamel, a similar result was found only using 300 mJ, with 100 mJ to finish, at dentin margins. Hence, care must be taken with the choice of pulse energy.

CONCLUSION

- Microleakage with total-etch and self-etching adhesives is in general significantly higher in association with Er:YAG-lased enamel/dentin as compared to conventional preparation.
- The acid-etching technique thus remains mandatory even after laser conditioning for both dentin and enamel.
- To date, the information on the sealing ability of all-in-one systems in Er:YAG-lased cavities is insufficient. The data on bond strengths in association with these systems on enamel and dentin surfaces suggest that these systems should still be avoided.
- Care must be taken with the energy output, which emphasizes the need for standards for laser energy output in relation to the different tooth substrates.

GLASS-IONOMER CEMENTS

Glass-ionomer cements chemically adhere to dental structure by bonding of the cement's carboxylic groups to calcium and phosphate ions in the tooth; micromechanical interlocking of the glass ionomer and dental tissue also provides retention. In RM-GICs, the resinous components lead to the formation of a hybrid layer[114,115] that minimizes the occurrence of the microleakage phenomenon.[116] Although RM-GICs show superior bond strength to tooth substrates compared to conventional GICs, they undergo substantial shrinkage due to the polymerization of HEMA, which is incorporated as a resin component.[117]

The previously mentioned research makes it clear that pretreatment procedures are necessary for all restorative materials with resinous components. Conventional GICs possess a coefficient of thermal expansion closely approximating that of dental tissues and a low setting shrinkage; they are reported to provide good marginal sealing, show little microleakage at the restoration-tooth interface, and have a high retention rate.[116] Providing the cavity surface is cleaned of debris and smear layer through proper conditioning prior to placement of the glass-ionomer material, there will be an immediate ion exchange between the cement's carboxylic groups and the calcium and phosphate ions of the tooth. For conditioning of the bur-prepared dentin, pretreatment with weak acid solutions such as polyacrylic acid have been strongly advised.[118-120] As Er:YAG-lasing of enamel and dentin results in smear layer-free surfaces, the question may rise whether conditioning of enamel and dentin surfaces is necessary in order to improve marginal adaptation.

The study of microleakage in association with conventional glass ionomers is limited to Quo et al[121] and Delmé et al.[122] Quo et al[121] demonstrated that Er:YAG laser provided an equivalent method of substance removal when evaluated for microleakage of GIC materials (Fuji II LC and Fuji II) compared to a high-speed handpiece, and that the RM-GIC had significantly more leakage compared to the conventional GIC. In the study by Delmé et al,[122] it was concluded that the application of KetacFil Plus (3M ESPE, St Paul, MN, USA) to laser-prepared enamel and dentin resulted in a better and more reproducible seal compared to conventionally prepared tooth surfaces. When using the more viscous Fuji IX (GC, Tokyo, Japan) Er:YAG lasing did not improve marginal adaptation.

Microleakage of RM-GIC restorations has been investigated in a limited number of studies.[121, 123-125] On the basis of these and due to the heterogeneous set-up of the studies, it is difficult to draw final conclusions. However, the 4 studies had in common that pretreament procedures as prescribed for adhesive materials were required for better adhesion. In addition, the use of Er:YAG laser for cavity preparation and surface treatment tended to result in higher microleakage scores than when cavities were conventionally prepared.

All studies on microleakage in association with GICs concluded that GIC, both pure and resin modified, did not prevent microleakage, whether the mode of tooth-substance removal was by Er:YAG or the high-speed handpiece, and that leakage at the gingival (dentin/cementum) margin was in all cases higher than at the occlusal enamel margins.

CONCLUSION

- Research on the sealing ability of glass-ionomer cements in Er:YAG-lased cavities is scarce.
- Adhesion with resin-modified glass ionomers has to be achieved in the same way as with resin composites due to their resinous components: the pretreatment procedure using acid etching or conditioner is therefore mandatory in order to obtain good bonding and consequently, a good seal.
- More research is needed on the sealing ability of conventional glass ionomers, as the information is very scarce. The available information suggests that because of the smear layer-free surfaces, pretreatment conditioning might not be necessary.

GENERAL CONCLUSION

Studies in the beginning of the 1990s showed that there was in general no difference between tensile bond strength values and microleakage scores for resin composites in teeth where tooth substrate was Er:YAG lased or conventionally prepared and acid-etched. More recent studies have not substantiated the hypothesis that laser irradiation was equally effective as traditional acid etching procedures for pretreating enamel and dentin for bonding. A second hypothesis that preparation of tooth substrate with Er:YAG laser or diamond bur was equally effective in terms of bond strength was also not substantiated. Recent research has shown that lasing of dentin and enamel may result in surface and sub-surface alterations negatively influencing both adhesion and seal. Based on these findings, the energy output using Er:YAG laser should be emphasized: the advised output energy in the past was regularly too high. It is currently important to establish golden standards for optimal enamel and dentin preparations, as well as for conditioning of these surfaces.

The effectiveness of the currently favored three-step etch-and-rinse adhesives and the two-step etch-and-rinse adhesives in Er:YAG lased cavities is also greater than the newer all-in-one systems. The data on bond strengths in association with these systems on enamel and dentin surfaces suggest that it is still better to avoid usage of the latter systems. In the present-day studies, acid etching of lased surfaces is also advised.

Studies on glass-ionomer cement adhesion in Er:YAG laser dentistry are scarce. When glass ionomers are investigated, studies are confined to resin-modified formulations. As these cements are resin based, the findings coincide with those of the resin composites. Pretreatment procedures enhance adhesion and seal in Er:YAG-lased cavities.

REFERENCES

1. Walsh LJ. The current status of laser applications in dentistry. Austr Dent J 2003;48:146-155.
2. Goldman L, Gray JA, Goldman J, Goldman B, Meyer R. Effects of laser impacts on teeth. J Am Dent Assoc 1965;70:601-606.
3. Stern RH, Sognaes RF. Laser beam on dental hard tissues. J Dent Res 1964;43:873.
4. Stern RH. Dentistry and the laser. In: Wolbarsht ML (eds). Laser applications in Medicine and Biology, vol II. New York: Plenum Press, 1974:361-387.
5. Paghdiwala A. Application of the Erbium:YAG laser on hard dental tissues: Measurement of the temperature changes and depths of cut. Laser Res Med Surg Dent ICALEO 1988;64:192-201.
6. Hibst R, Keller U, Steiner R. Die Wirkung gepulster Er:YAG Laserstrahlung auf Zahngewebe. Laser Med Surg 1988;4:163-165.
7. Hibst R, Keller U. Experimental studies of the application of the Er:YAG on dental hard substances. I. Measurement of the ablation rate. Lasers Surg Med 1989;9:338-344.
8. Keller U, Raab WH, Hibst R. Pulp reactions during erbium YAG laser irradiation of hard tooth structure. Dtsch Zahnartzl Z 1991;46:158-160.
9. Keller U, Hibst R, Geurtsen W, Schilke R, Heideman D, Klaiber B, Raab WH. Erbium:YAG laser application in caries therapy: Evaluation of patient perception and acceptance. J Dent 1998; 26:649-656.
10. Nuss RC, Fabian RL, Sarkar R, Puliafito CA. Infrared laser bone ablation. Lasers Surg Med 1988;8:381-91.
11. Paghdiwala AF, Vaidyanathan TK, Paghdiwala MF. Evaluation of Erbium:YAG radiation of hard dental tissues: analysis of temperature changes, depth of cuts and structural effects. Scanning Microsc 1993;7:989-97.
12. Burkes EJ, Hoke J, Gomes E, Wolbarsht M. Wet versus dry ablation by Er:YAG laser. J Prosthet Dent 1992;67:847-851.
13. Dostalova T, Krejsa O, Jelinkova H, Hamal K. The evaluation of the cavity margins after Er:YAG laser ablation of the enamel and dentine. In Bown SG, Escourrou J, Frank F, editors. Medical applications of lasers. II. Proc SPIE 1993;1880:132-139.
14. Hoke JA, Burkes EJ Jr, Gomes ED, Wolbarsht ML. Erbium:YAG (2.94 µm) laser effects on dental tissue. J Laser Appl 1990;2:61-65.
15. Li Z, Code JE, Van De Merwe WP. Er:YAG laser ablation of enamel and dentine of human teeth: determination of ablation rates at various fluences and pulse repetition rates. Lasers Surg Med 1992;12:625-630.
16. Van As G. Erbium lasers in dentistry. Dent Clin North Am 2004;48:1017-1059.
17. Stock K, Hibst R, Keller U. Comparison of Er:YAG and Er:YSGG laser ablation of dental hard tissues. SPIE 2000;3192:88-95.
18. Belikov AV, Erofeev AV, Shumilin VV, Tkachuk AM. Comparative study of the 3 micron laser action on different hard tissue samples using free running pulsed Er-doped YAG, YSGG, YAP and YLF lasers. SPIE 1993;2080:60-67.
19. Eversole LR, Riziou IM. Peliminary investigations on the utility of an erbium, chromium YSGG laser. J Calif Dent Assoc 1995; 23:41-47.
20. Hossain M, Nakamura Y, Yamada Y, Kimura Y, Matsumoto N, Matsumoto K. Effects of Er,Cr:YSGG laser irradiation in human enamel and dentin. J Clin Laser Med Surg 1999;17:105-109.
21. Rechmann P, Goldin D, Henning T. Er:YAg lasers in dentistry: an overview. SPIE 1998;3248:1-13.
22. Clark J, Symons AL, Diklic S, Walsh LJ. Effectiveness of diagnosing residual caries with various methods during cavity preparation using conventional methods, chemo-mechanical caries removal, and Er:YAG laser. Austr Dent J 2001;46(suppl):S20.
23. Riziou I, Kimmel A. Atomized fluid particles for electromagnetically induced cutting. US Patent 1998 5,741,247.
24. Hibst R. Lasers for caries removal and cavity preparation: state of the art and future directions. J Oral Laser Applic 2002;2:203-212.
25. Fried D, Ashouri N, Breunig T, Shori R. Mechanism of water augmentation during IR laser ablation of dental enamel. Lasers Surg Med 2002;31:186-193.
26. Freiberg RJ, Cozean C. Pulsed erbium laser ablation of hard dental tissue: the effects of atomized water spray versus water surface film. Lasers in dentistry VIII. Proc SPIE 2002;4610:74-84.
27. Tratjenberg CP, Pereira PNR, Powers JM. Resin bond strength and micromorphology of human teeth prepared with an Erbium:YAG laser. Am J Dent 2004;17:331-336.
28. Delmé KIM, De Moor RJG. A scanning electron microscopic comparison of different caries removal techniques for root caries treatment. J Oral Laser Applic 2003;3:235-242.
29. Delmé KIM, Deman PJ, De Moor RJG. Microleakage of class V resin composite restorations after conventional and Er:YAG laser preparation. J Oral Rehab 2005;32:676-685.
30. Peumans M, Kanumilli P, De Munck J, Van Landuyt K, Lambrechts P, Van Meerbeek B. Clinical effectiveness of contemporary adhesives: a systematic review of the current clinical trials. Dent Mater 2005;21:864-881.
31. Van Meerbeek B, Vargas S, Inoue S, Yoshida Y, Peumans M, Lambrechts P, Vanherle G. Adhesives and cements to promote preservation dentistry. Oper Dent 2001;26:S119-S144.
32. Van Meerbeek B, De Munck J, Yoshida Y, Inoue S, Vargas M, Vijay P, et al. Buonocere memorial lecture. Adhesion to enamel and dentin: current status and future challenges. Oper Dent 2003;28:215-235.
33. Yoshida Y, Nagakane K, Fukuda R, Nakayama Y, Okazaki M, Shintani H. Comparative study on adhesive performance of functional monomers. J Dent Res 2004;83:454-458.
34. Yoshida Y, Van Meerbeek B, Nakayama Y, Fujitani M, Shinatni H, Wakasa K. Evidence of chemical bonding at biomaterial-hard tissue interfaces. J Dent Res 2000;79:709-714.
35. Inoue S, Van Meerbeek B, Abe Y, Yoshida Y, Lambrechts P, Vanherle G, Sano H. Effect of remaining dentin thickness and the use of conditioner on micro-tensile bond strength of a glass-ionomer adhesive. Dent Mater 2001;17:445-455.
36. Lin A, McIntyre N, Davidson R. Studies on the adhesion of glass ionomer cements to dentin. J Dent Res 1992;71:1836-41.
37. Van Meerbeek B, Inoue S, Perdigao J, Lambrechts P, Vanherle G. Enamel and dentin adhesion. In: Summitt JB, Robbins JW, Schwartz RS (eds). Fundamentals of Operative Dentistry. A contemporary approach. Chicago: Quintessence, 2001:178-235.
38. Buonocore MG. A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces. J Dent Res 1955; 34:849-853.
39. Nakabayashi N. Adhesive bonding with 4-MEAT. Oper Dent 1992;17 (Suppl. 5):125-130.

40. Nakabayashi N, Kojima K, Masuhara E. The promotion of adhesion by the infiltration of monomers into tooth substrates. J Biomed Mater Res 1982;16:265-273.
41. Van Meerbeek B, Inokoshi S, Braem M, Lambrechts P, Vanherle G. Morphological aspects of the resin-dentin interdiffusion zone with different dentine adhesive systems. J Dent Res 1992;71:1530-1540.
42. Keller U, Hibst R. Experimental studies of the application of the Er:YAG laser on dental hard substances - II. Light microscopic and SEM investigations. Lasers Surg Med 1989;9:345-351.
43. Hibst R, Keller U. The mechanism of Er-YAG induced ablation on dental hard substances. ProcSPIE 1993;1880:156-162.
44. Visuri SR, Gilbert JL, Wright DD, Wigdor HA, Walsh JT Jr. Shear strength of composite bonded to Er:YAG laser-prepared dentin. J Dent Res 1996;75:599-605.
45. Aoki A, Ishikawa I, Yamada T, Otsuki M, Watanabe , Tagami J. Comparison between Er:YAG laser and conventional technique for root caries treatment in vitro. J Dent Res 1998;77:1404-1414.
46. Niu W, Eto JN, Kimura Y, Takeda FH, Matsumoto K. A study of microleakage after resin filling of class V cavities prepared by Er:YAG laser. J Clin Laser Med Surg 1998;16:227-231.
47. Armengol V, Jean A, Rohanizadeh R, Hamel H. Scanning electron microscopic analysis of diseased and healthy dental hard tissues after Er:YAG laser irradiation: in vitro study. J Endod 1999;25:543-546.
48. Shigetani Y, Tate Y, Okamoto A, Iwaku M, Abu-Bakr N. A study of cavity preparation by Er:YAG laser - effects on the marginal leakage of composite resin restoration. Dent Mater J 2002;21:238-249.
49. Liberman R, Segal TH, Nordenberg D, Serebro LI. Adhesion of composite materials to enamel: comparison between the use of acid and lasing as pretreatment. Lasers Surg med 1984;4:323-327.
50. Cooper F, Myers ML, Nelson DG, Mowery AS. Shear strength of composite bonded to laser-pretreated dentin. J Prosthet Dent 1988;60:45-49.
51. Ceballos L, Osorio R, Toledano M, Marshall GW. Microleakage of composite restorations after acid or Er:YAG laser cavity treatments. Dent Mater 2001;17:340-346.
52. Setien VJ, Cobb DS, Denehy GE, Vargas MA. Cavity preparation devices: effect on microleakage of class V resin-based composite restorations. Am J Dent 2001;14:157-162.
53. Wright GZ, McConnell RJ, Keller U. Microleakage of class V composite restorations prepared conventionally with those prepared with an Er:YAG laser: a pilot study. Pediatr Dent 1993;15:425-426.
54. Kataumi M, Nakajima M, Tamada T, Tagami J. Tensile bond strength and SEM evaluation of Er:YAG laser irradiated dentin using dentin adhesive. Dent Mater J 1998;17:125-138.
55. Armengol V, Jean A, Weiss P, Hamel H. Comparative in vitro study of the bond strength of composite to enamel and dentine obtained with laser irradiation or acid-etch. Lasers Med Sci 1999;14:207-215.
56. Van Meerbeek B, Perdigao J, Lambrechts P, Vanherle G. The clinical performance of adhesives. J Dent 1998;26:1-20.
57. Mjör IA, Gordan VV. Failure, repair, refurbishing and longevity of restorations. Oper Dent 2002;27:528-534.
58. Mjör IA, Shen C, Eliasson ST, Richter S. Placement and replacement of restoratoions in general dental practice in Iceland. Oper Dent 2002;27:117-123.
59. De Munck J, Van Landuyt K, Peumans M, Poitevin A, Lambrechts P, Braem M, Van Meerbeek B. A critical review of the durability of adhesion to tooth tissue: methods and results. J Dent Res 2005;84:118-132.
60. Pashley DH, Sano H, Ciucchi B, Yoshiyaa M, Carvalho RM. Adhesion testing of dentin bonding agents. Dent Mater 1995;11:117-125.
61. Pashley DH, Carvalho RM, Sano H, Nakajima M, Shono Y, Fernandes CA, et al. The microtensile bond test: a review. J Adhes Dent 1999;1:299-309.
62. Nordenvall KJ, Brannstrom M, Malgren O. Etching of deciduous teeth and young and old permanent teeth. Am J Orthod 1980;78:99-108.
63. Keller U, Hibst R. Effects of Er:YAG laser on enamel bonding of composite materials. Topographical Lasers Orthoped Dent Vet Med II SPIE 1993;1880:163-168.
64. Moritz A, Gutknecht N, Schoop U,Goharkay K, Wernish J, Sperr W. Alternatives in enamel conditioning: a comparison of conventional and innovative methods. J Clin Laser Med Surg. 1996;14:133-136.
65. Moritz A, Schoop U, Goharkhay K, Szakacs S, Sperr W, Schweidler E, Wernish J, Gutknecht N. Procedures for enamel and dentine conditioning: a comparison of conventional and innovative methods. J Esthet Dent 1998;10:84-93.
66. Lin S, Caputo AA, Riziou I, Eversole LR. Topographical characteristics and shear bond strength of tooth surfaces cut with a laser-powered hydrokinetic system. J Prosthet Dent 1999;82:451-455.
67. Kameyama A, Kawada E, Takizawa M, Oda Y, Hirai Y. Influence of different acid conditioners on the tensile bond strength of 4-META/MMA-TBB Resin to Er:YAG laser-irradiated bovine dentin. J Adhes Dent 2000;2:297-304.
68. Martinez-Insua A, da Silva-Dominiquez L, Guitian-Rivera F, Santana-Penin UA. Differences in bonding to acid-etched or Er:YAG laser-treated enamel and dentin surfaces. J Prosthet Dent 2000;84:280-287.
69. Burnett LH, Conceiçao EN, Pelinos JE, de Paula Eduardo. Comparative study of inlfuence on tensile bond strength of a composite to dentin using Er:YAG laser, Air abrasion, or air turbine for preparation of cavities. J Clin Laser Med Surg 2001;19:199-202.
70. Eguro CT, Maeda T, Tanabe M, Otsuki M, Tanaka H. Adhesion of composite resins to enamel irradiated by the Er:YAG laser: application of the ultrasonic scaler on irrdiated surface. Lasers Surg Med 2001;28:365-370.
71. Kameyama A, Oda Y, Hirai Y, Kawada E, Takizawa M. resin bonding to Er:YAG laser-irradiated dentin: combined effects of pre-treatments with citric acid and glutaraldehyde. Eur J Oral Sci 2001;109:354-360.
72. Ceballos L, Osario R, Toledano M, Tay bFR, Marshall GW. Bonding to Er:YAG laser treated dentin. J Dent Res 2002;81:119-122.
73. De Munck J, Van Meerbeek B, Yudhira R, Lambrechts P, Vanherle G. Microtensile bond strength of two adhesives to Erbium:YAG-lased vs. bur-cut enamel and dentin. Eur J Oral Sci 2002;110:322-329.
74. Eguro T, Maeda T, Otsuki M, Nishimura Y, Katsuumi I, Tanaka H. Adhesion of er:YAG laser-irradiated dentin and composite resins: application of various treatments on irrdiated surface. Lasers Surg Med 2002;30:267-272.
75. Gonçalves M, Corona SAM, Borsatto MC, Silva PCG, Pecora JD. Tensile bond strength of dentin-resinous system interfaces conditioned with Er:YAG laser irradiation. J Clin Laser Med Surg 2002;20:89-93.

76. Ramos RP, Chimelloe DT, Chinelatti MA, Nonaka T, Pecora JD, Palma Dibb RG. Effect of Er:YAG laser on bond strength to dentin of a self-etching primer and two single-bottle adhesive systems. Lasers Surg Med 2002;31:164-170.
77. Otsuki M, Eguro T, Maeda T, Tanaka H. Comparison of the bond strength of composite resin to Er:YAG laser irradiated human enamel pre-treated with various methods in vitro. Lasers Surg Med 2002;30:351-359.
78. GonçalvesM, Corona SAM, Pecora JD, Palma-Dibb RG. Influence of the frequency of Er:YAG laser on the bond strength of dental enamel. J Clin Laser Med Surg 2003;21:105-108.
79. Tratjenberg CP, Pereira PNR, Powers JM. Resin bond strength and micromorphology of human teeth prepared with an Erbium:YAG laser. Am J Dent 2004;17:331-336.
80. Chimello -Sousa DT, de Souza AE, Chinelatti MA. Influence of Er:YAG laser irradiation distance on the bond strength of a restorative system to enamel. J Dent 2005;7;Epub.
81. Dunn WJ, Davis JT, Bush AC Shear bond strength and SEM evaluation of composite bonded to Er:YAG laser-prepared dentin and enamel. Dent Mater. 2005;21:616-24.
82. Oliveira DC, Manhaes LA, Marques MM, Matos AB. Microtensile bond strength analysis of different adhesive systems and dentin prepared with high-speed and Er:YAG laser: a comparative study. Photomed Laser Surg. 2005;23:219-224.
83. Van Meerbeek B, De Munck J, Mattar D, et al. Microtensile bond strengths of an etch&rinse and self-etch adhesive to enamel and dentin as a function of surface treatment. Oper Dent. 2003; 28:647-660.
84. de Souza AE, Corona SAM, Palma Dibb RG, Borsatto MC, Pecora JD. Influence of Er:YAG laser on tensile bond strength of a self-etching system and a flowable resin in different dentin depths. J Dent 2004;32:269-275.
85. Kinney JH, Haupt DL, Balooch M, White JM, Bell WL, Marshall SJ, Marshall GW Jr. The threshold efffects of Nd and Ho:YAG laser-induced surface modification on deminerlaisation of dentin surfaces. J Dent Res 1996;75:1388-1395.
86. Yamamoto H, Sato K. prevention of dental caries by Nd:YAG laser irradiation. J Dent Res 1980;59:2171-2177.
87. Bachmann L, Diebolder R, Hibst R, Zezell DM. Changes in chemical composition and collagen structure of dentine tissue after erbium laser irradiation. Spectrochim Acta A Mol Biomol Spectrosc. 2005;61:2634-2639.
88. Schein MT, Bocangel JS, Nogueira GE, Schein PAL. SEM evaluation of the interaction pattern between dentin and resin after cavity preparation using Er:YAG laser. J Dent 2003;31:127-135.
89. Bertrand MF, Hessleyer D, Muller-Bolla M, Nammour S, Rocca JP. Scanning electron microscope evaluation of resin-dentin interface after Er:YAG laser preparation. Lasers Surg Med 2004; 35:51-57.
90. Sassi JF, Chimello DT, Borsatto MC, Corona SAM, Pecora JD, Palma-Dibb RG. Comparative study f the dentin/adhesive systems interface after treatment with Er:YAG laser and acid etching using scanning electron microscope. Lasers Surg Med 2004; 34:385-390.
91. Fowler BO, Kuroda S. Changes in heated and in laser-irradiated human tooth enamel and their probable effects on solubility. Calcif Tissue Int 1986;38:197-208.
92. Oho T, Morioka T. A possible mechanism of acquired acid resistance of human dental enamel by laser irradiation. Caries Res 1990;24:86-92.
93. Rohanizadeh R, Legeros RZ, Fan D, Jean A, Dacalsi G. Ultrastructural properties of laser irradiated and heat-treated dentine. J Dent Res 1999;78:1829-1835.
94. Giachetti L, Scaminaci Russo D, Scarpelli F, Vitale M. SEM analysis of dentin treated with the Er:YAG laser: a pilot study of the consequences resulting from laser use on adhesion mechanisms. J Clin Laser Med Surg 2004;22:35-41.
95. Saito S, Tosaki S, Hirota K. Characteristics of glass-ionomer cements. In: Davidson CL, Mjör IA (eds). Advances in Glass-ionomer cements. Chicago: Quintessence, 1999:15-50.
96. Papacchini F, Goracci C, Sadek FT, Monticelli F, Garcia-Godoy F, Ferrari M.. Microtensile bond strength to ground enamel by glass-ionomers, resin-modified glass-ionomers, and resin composites used as pit and fissure sealants. J Dent. 2005;33:459-467.
97. Pereira LC, Nunes MC, Dibb RG, Powers JM, Roulet JF, Navarro MF. Mechanical properties and bond strength of glass-ionomer cements.J Adhes Dent. 2002;4:73-80.
98. Corona SAM, de Menezes M, Borsatto MC, et al. Influence of er:YAG Laser on Tensile Bond Strength of Resin-modified Glass-ionomer Cements in Dentin. JOLA 2003;3:21-25.
99. Pilo R, Ben-Amar A. Comparison of micro-leakage for three one-bottle and three multi-step dentin bonding agents. J Prosthet Dent 1999;82:209-213.
100. Bouillaguet S, Duroux B, Ciucchi B, Sano H. Ability of adhesive systems to seal dentin surfaces: an in vitro study. J Adhes Dent 2000;2:201-208.
101. Grobler SR, Oberholzer TG, Rossouw RJ, Grobler-Rabie A, Van Wyk Kotze TJ. Shear bond strength, micro-leakage, and confocal microscopy of 4 amalgam alloy bonding agents. Quintessence Int 2000;31:501-508.
102. Hilton TJ. Can modern restorative procedures and materials reliably seal cavities? In vitro investigations. Part 1. Am J Dent 2002;15:198-210.
103. Hilton TJ. Can modern restorative procedures and materials reliably seal cavities? In vitro investigations. Part 2. Am J Dent 2002;15:279-289.
104. Keller U, Hibst R. Ultrastructural changes of enamel and dentin following Er:YAG laser irradiation on teeth. Proc. SPIE 1990;1200:408-415.
105. Araujo RM, Eduardo CP, Duarte SL Jr, Araujo MA, Loffredo LC. Microleakage and nanoleakage: influence of laser in cavity preparation and dentin pretreatment. J Clin Laser Med Surg. 2001; 19:325-332.
106. Corona SAM, Borsatto MC, Palma Dibb RG, Ramos RP, Brugnera A, Pecora JD. Microleakage of class V resin composite restorations after bur, air-abrasion or Er:YAG laser preparation. Oper Dent 2001;26:491-497.
107. Armengol V, Jean A, Enkel B, Assoumu M, Hamel H. Microleakage of class V composite restorations following Er:YAG and Nd:YAP laser irradiation compared to acid-etch: an in vitro study. Lasers Med sci. 2002;17:93-100.
108. Gonzalez Bahillo J, Ruiz Pinon M, Rodriguez Nogueira J, Biedma BM, Patino PV, Munoz FM, et al. A comparative study of microleakage through enamel and cementum after Er:YAG instrumentation in class V cavity obturations, using scanning electron microscopy. J Clin Laser med Surg 2002;20:197-201.
109. Palma Dibb RG, Corona SAM, Borsatto MC, Ferreira KC, Ramos RP, Pecora JD. Assessing microleakage on class V composite resin restorations after Er:YAG laser preparation varying the adhesive systems. J Clin Laser Med Surg 2002;20:129-133.

110. Roebuck EM, Saunders WP, Whitters CJ. Influence of Erbium/YAG laser energies on the microleakage of Class V resin-based composite restorations. Am J Dent 2000;13:280-284.
111. Hofmahn N, Haller B, Klaiber B, Käsdorf A. Füllungsrandschluss nach laserpräparation. Dtsch Zahnäztl Z 1992;47:711-713.
112. Hibst R, Keller U. Sealing quality of composites after Er:YAG laser enamel conditioning. In: Anderson RR, Katzir A. Lasers surgery: Advanced characterization, therapeutics and systems IV. Proceeding of Biomedical Optics Conference. Los Angeles. 1994:260-266.
113. Haller B, Hofmann N, Klemen J, Klaiber B. Er:YAG-Laserpräparation und Komposit-Dentinhaftung in vitro. Dtsch zahnärtzl Z 1993;48:707-712.
114. Pereira PNR, Sano H, Ogata M, Zheng L, Nakajima M, Tagami J, Pashley DH. Effect of region and dentin perfusion on bond strengths of resin-modified glass ionomer cements. J Dent 2000;28:347-354.
115. Pereira PNR, Yamada Y, Inokoshi S, Burrow MF, Sano H, Tagami J. Adhesion of resin-modified glass ionomer cements using resin bonding systems. J Dent 1998;26:479-485.
116. Mount GJ. Buonocore Memorial Lecture Glass ionomer cements: Past, present and future. Oper Dent 1994;19:82-90.
117. Attin T, Bucalla W, Kielbassa AM, Helwig E. Curing shrinkage and volumetric changes of resin-modified glass ionomer restorative materials. Dent Mater 1995;11:359-362.
118. Inoue S, Abe Y, Yoshida Y, et al. Effect of conditioner on bond-strength of glass-ionomer adhesive to dentin/enamel with and without smear layer interposition. Oper Dent 2004;29:685-692.
119. Glasspoole EA, Erickson RL, Davidson CL. Effect of surface treatments on the bond strength of glass ionomers to enamel. Dent Mater 2002;18:454-462.
120. Arweiler NB, Auschill TM, Reich E. Does pretreatment of cavities effectively promote good marginal adaptation of glass-ionomer cements? J Adhes Dent 2000;2:289-295.
121. Quo BC, Drummond JL, Koerber A, Fadavi S, Punwani I. Glass ionomer microleakage from preparations by an Er:YAG laser or a high-speed handpiece. J Dent 2002;30:141-146.
122. Delmé KIM, Deman P, De Moor RJG. Microleakage of class V glass ionomer restorations after conventional and Er:YAG laser preparation. J Prosthet Dent 2006 accepted.
123. Khan MF, Yonaga K, Kimura Y, Funato A, Matsumoto K. Study of microleakage at Class I cavities prepared by Er:YAG laser using three types of restorative materials. J Clin Laser Med Surg 1998;16:305-308.
124. Corona SA, Borsatto MC, Pecora JD, De Sa Rocha RAS. Assessing microleakage of different class V restorations after Er:YAG laser and bur preparation. J Oral Rehab 2003;30:1008-1014.
125. Chinelatti MA, Ramos RP, Chimello DT, Borsatto MC, Pecora JD, Palma-Dibb RG. Influence of the use of Er:YAG laser for cavity preparation and surface treatment in microleakage of resin-modified glass ionomer restorations. Oper Dent 2004;29:430-436.

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