Shear bond strength and SEM evaluation of composite bonded to Er:YAG laser-prepared dentin and enamel

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KEYWORDS
Lasers;
Ablation;
Adhesion;
Dentin bonding;
Acid etching

Summary
Objectives. The purpose of this study was to evaluate dentin and enamel bond strength to resin composite following high-speed rotary or Er:YAG laser preparation using a total etch adhesive system. The microstructure of resin-tooth interfaces was also investigated.

Methods. Human dentin and enamel specimens were prepared with a high-speed handpiece (KaVo) or Er:YAG laser (DELIGHT) at manufacturer’s recommended settings and etched with either 37\% H\textsubscript{3}PO\textsubscript{4}, laser etched, or not etched. Composite rods (Z-250, 3M/ESPE) were bonded to specimens with an adhesive (Adper Scotchbond Multi-Purpose, 3M/ESPE). After thermocycling, specimens were tested in shear to failure.

Results. Two-factor ANOVA detected significant differences in the main effects of preparation and etch type, and interaction (\(p<0.001\)). Post hoc analyses showed that in both dentin and enamel, only the acid-etched specimens had significantly higher mean bond strengths, with rotary-prepared specimens having significantly higher mean bond strengths versus laser prepared specimens. Within each preparation type, in both dentin and enamel, acid etch was better than laser etch, and laser etch was better than no etch. Scanning electron microscopy of laser-ablated specimens demonstrated significant surface scaling and subsurface fissuring beyond normal resin penetration depth.

Significance. Adhesion to laser-ablated or laser-etch dentin and enamel was inferior to that of conventional rotary preparation and acid etching.

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Introduction

In 1960, Maiman [1] developed the method of light amplification by the stimulated emission of
radiation, now commonly known by its acronym, LASER. Five years later, Goldman et al. [2] investigated the application of the laser beam on dental hard tissues. Clinicians were concerned about possible adverse pulpal responses [3], but subsequent investigations demonstrated that lasers cause little thermal damage [4,5], especially if used in conjunction with water spray [6]. Lasers have demonstrated some analgæsic effect which could increase patient acceptance of certain procedures [7]. Advancements in laser technology have led to multiple dental applications such as periodontal soft tissue plastic surgery [8], gingivectomy [9], soft tissue crown lengthening [10], gingival retraction for prosthodontics [11], composite photopolymerization [12], frenectomy [13], tooth whitening [14], treatment of apthous ulcers [15], endodontic procedures [16], and caries removal with increased precision, improved hemostasis and sterility, with minimal post operative pain and swelling [6,7,17].

The first dental lasers cleared by the FDA were used exclusively for soft tissue procedures and included the carbon dioxide (CO2) laser, Neodymium-Yttrium-Aluminum-Garnet (Nd:YAG) laser, argon laser, and the semiconductor diode laser. The CO2 laser was the first dental laser approved by the FDA and has been successfully used in soft tissue surgeries such as gingivectomies, frenectomies, removal of benign and malignant lesions, and excisional and incisional biopsies [18]. The Nd:YAG laser uses a fiberoptic delivery system that penetrates wet tissue more easily than the CO2 laser. There has been interest in using the Nd:YAG laser on mineralized tissue to possibly enhance the bond strength of composite to dentin [19], but the Nd:YAG laser is still not approved for hard tissue applications. The argon laser can be used for soft tissue procedures and is approved for photopolymerization of light-activated materials [20]. Semiconductor diode lasers perform the same soft tissue procedures as the CO2 and Nd:YAG lasers and have also been used to enhance the effects of bleaching discolored teeth [21]. Other approved systems include the Erbium–Chromium–Yttrium–Scallium–Gallium–Garnet (Er, Cr:YSGG) laser and the Erbium doped Yttrium–Aluminum–Garnet (Er:YAG) laser. These systems can be used for soft tissue procedures but most of the interest in Erbium lasers has been focused on hard tissue applications such as caries removal and endodontic cleaning and shaping of the root canal system [22].

The Er:YAG laser, originally developed by Zharkov et al. [23] in 1975, was approved by the FDA in 1997 for caries removal, forming cavity preparations, and modifying dentin and enamel prior to etching [24]. The Er:YAG laser has compared favorably with the high-speed rotary dental handpiece in some scanning electron microscopic (SEM) and histological studies [6]. The Er:YAG laser has also been shown to be more comfortable for patients than conventional preparation with a high-speed rotary handpiece [7]. In endodontic studies the Er:YAG laser has demonstrated effective cleansing and antimicrobial properties [16,25]. Use of the Er:YAG laser has been suggested for nonsurgical periodontal therapy, soft tissue surgery [26], and possibly subgingival scaling [27]. Tooth preparation using the Er:YAG laser has not demonstrated any significant thermal elevation compared with a rotary dental handpiece [28]. Takamori [29] demonstrated that tooth preparation with the Er:YAG laser may lead to pulpal repair faster than with rotary preparation. The Er:YAG laser produces minimal thermal effect on the tooth during preparation in comparison to other dental lasers [3].

The cutting effect of the Er:YAG laser on enamel, dentin, carious dentin, and composite varies according to the water content of the material being prepared. The beam can ablate, or remove by melting or vaporization, carious dentin with an energy level of 250 mJ at 2 Hz, sound dentin with 300 mJ at 2 Hz, and enamel with 350 mJ at 3 Hz [30]. In theory, this allows for the selective preparation of a particular type of substrate or material. For example, during operative procedures carious dentin would be selectively removed while sparing healthy dentin, or composite would be selectively removed without damaging tooth structure following orthodontic bracket removal [31]. Microleakage and bond strength studies following Er:YAG preparation report highly variable results [24,32–36]. Visuri et al. [32] reported a significantly higher shear bond strength of composite to dentin prepared with an Er:YAG laser. In contrast, Sakikbara et al. [24] and Ceballos et al. [35] reported a decrease in bond strength to laser-irradiated dentin, and Armengol et al. [30] and Kataumi et al. [33] found no difference between laser-irradiated and non-irradiated specimens. Improvements in laser technology and the increased interest in their potential for hard tissue applications warrant the further investigation of Er:YAG laser-prepared teeth and adhesion with resin-based composite. The purpose of this study was to evaluate dentin and enamel bond strength to resin-based composite following high-speed rotary handpiece preparation or Er:YAG laser preparation with a multi-step, total etch adhesive system. The microstructure of resin-dentin and resin-enamel interfaces was also investigated. The hypothesis tested was that there would be no difference in the mean shear bond strength between composite and
tooth surfaces prepared by high speed rotary instrumentation or laser ablation, etched with phosphoric acid, laser-etched, or not etched.

Materials and methods

Two hundred and forty human molar teeth were collected and stored in 0.5% chloramine-T solution no more than 6 months from time of extraction to inclusion in the study. The teeth were free of visible caries and other surface defects. For the dentin portion of the study the occlusal surfaces of 120 teeth were abraded with 120-grit silicon carbide (SiC) paper (Buehler Ltd, Lake Bluff, IL, USA) until a uniform layer of peripheral dentin was observed. Dentin specimens were then sequentially polished with 240, 400, and 600 grit SiC paper on a water-cooled polishing lathe (Buehler Ltd). The roots were notched and embedded in type IV dental stone (WhipMix Corporation, Louisville, KY, USA) in acrylic molds (Mark V Laboratories, East Granby, CT, USA) with the polished occlusal surfaces extending 2-mm above the level of the stone. The dentin specimens were randomly divided into six groups (n=20), representing the six different surface treatments to be investigated.

Group 1D: high-speed, #57 bur, no etch, Adper Scotchbond Multi-Purpose DBA
Group 2D: high-speed, #57 bur, 37% H$_3$PO$_4$ etch, Adper Scotchbond Multi-Purpose DBA
Group 3D: high-speed, #57 bur, laser etch, Adper Scotchbond Multi-Purpose DBA
Group 4D: Er:YAG laser preparation, no etch, Adper Scotchbond Multi-Purpose DBA
Group 5D: Er:YAG laser preparation, 37% H$_3$PO$_4$ etch, Adper Scotchbond Multi-Purpose DBA
Group 6D: Er:YAG laser preparation, laser etch, Adper Scotchbond Multi-Purpose DBA

Approximately 0.5-mm of dentin was removed from the occlusal surface of specimens in groups receiving high-speed rotary preparation with a #57 straight fissure tungsten carbide bur (Brasseler USA, Savannah, GA) at approximately 200,000 rpm with air/water coolant. A high-speed handpiece (KaVo America, Lake Zurich, IL, USA) was secured to a surveying instrument to insure that tooth surfaces were prepared in a standard fashion, flat and parallel to the floor. The mounted dentin specimens in groups 4-6D were prepared with an Er:YAG dental laser (DELight laser system, Continuum, Santa Clara, CA, USA) in a focused, non-contact mode, at a setting of 30 Hz/140 mJ, a spot size of 0.6-mm, a working distance of 1-mm, and a repetition rate of 30 Hz. The DELight laser system is an Er:YAG laser that emits a pulsed laser beam with a wavelength of 2940 nm. After appropriate instrumentation with either the high-speed handpiece or the Er:YAG laser, Groups 3D and 6D were laser-etched in a focused, non-contact mode at a setting of 10 Hz/35 mJ. The dentin surface was cooled throughout irradiation with water to avoid cracking and fusion. The laser beam was directed manually without using a fixed support to simulate clinical conditions. Following appropriate preparation with either the high speed handpiece or the Er:YAG laser, Groups 2D and 5D were chemically etched were etched with 37% phosphoric acid for 20 s, and then rinsed with sterile water for 20 s. Specimens were blotted with tissue, leaving a moist dentin surface for bonding, but with no pooling of water.

Adper Scotchbond Multi-Purpose (3M ESPE, St Paul, MN, USA, lot# 20030329, exp. 12/2005), a multi-step, total etch dentin bonding agent, was used as the adhesive for all specimens. The primer was applied for 20 s, and then gently blown with clean, dry, compressed air for 5 s until the primer rippled. The adhesive was then applied and photopolymerized for 20 s with an Optilux 501 light-curing unit (Demetron Research Corporation, Danbury, CT, USA). A power density of at least 600 mW/cm$^2$ was verified with a hand-held radiometer (Model 100, Demetron Research Corporation). A 3-mm long by 3-mm wide composite rod (Z-250 shade A1, 3M ESPE) was bonded to all dentin specimens using a split teflon mold with an inner diameter of 3-mm. The mold was secured to the specimen, and then two 1.5-mm increments of composite were polymerized separately for 40 s each. The teflon mold was removed and specimens were stored in water at 37°C for 1 day, and then thermocycled for 500 cycles between 5 and 55°C with a dwell time of 30 s each.

The remaining 120 teeth were used to fabricate the enamel specimens. The roots were removed using an Isomet low speed precision saw (Buehler Ltd). The crowns were embedded in dental stone (WhipMix Corporation) in acrylic molds (Mark V Laboratories) with buccal enamel surfaces extending 2-mm above the level of the stone. The enamel specimens were randomly divided into six groups, similar to the dentin specimens, each representing a different surface treatment for enamel bonding.

Group 1E: high-speed, #57 bur, no etch, Adper Scotchbond Multi-Purpose adhesive
Group 2E: high-speed, #57 bur, 37% H$_3$PO$_4$ etch, Adper Scotchbond Multi-Purpose adhesive
Group 3E: high-speed, #57 bur, laser etch, Adper Scotchbond Multi-Purpose adhesive
Group 4E: Er:YAG laser preparation, no etch, Adper Scotchbond Multi-Purpose adhesive
Group 5E: Er:YAG laser preparation, 37% H$_3$PO$_4$ etch, Adper Scotchbond Multi-Purpose adhesive
Group 6E: Er:YAG laser preparation, laser etch, Adper Scotchbond Multi-Purpose adhesive
Group 3E: high-speed, #57 bur, laser etch, Adper Scotchbond Multi-Purpose adhesive
Group 4E: Er:YAG laser preparation, no etch, Adper Scotchbond Multi-Purpose adhesive
Group 5E: Er:YAG laser preparation, 37% H₂PO₄ etch, Adper Scotchbond Multi-Purpose adhesive
Group 6E: Er:YAG laser preparation, laser etch, Adper Scotchbond Multi-Purpose adhesive

Approximately 0.5-mm of enamel was removed from buccal surfaces of specimens receiving high-speed rotary instrumentation with a #57 tungsten carbide straight fissure bur. The handpiece was secured to a paralleling device described earlier to ensure standardized, flat enamel surfaces parallel to the base of the stone. Surfaces were inspected for a flat bonding area of at least 4×4 mm with no dentin exposed. The dentin surfaces of groups 4E-6E were laser-prepared with the Er:YAG dental laser in a focused, non-contact mode, at a setting of 25 Hz/240 mJ, a spot size of 0.6-mm, a working distance of 1-mm, and a repetition rate of 30 Hz. Groups 3E and 6E were laser-etched with the Er:YAG dental laser in a focused, non-contact mode at a setting of 10 Hz/35 mJ. The surface was kept wet to avoid drying and cracking. Groups to be chemically etched were etched with 37% phosphoric acid for 20 s, rinsed with water for 20 s, and then dried with clean, compressed air for 10 s as recommended by the manufacturer. Adper Scotchbond Multi-Purpose was applied to specimens in Groups 2E and 5E in the same manner as the dentin samples, except surfaces for enamel specimens were kept dry.

Composite rods were bonded to enamel specimens in the same manner as the dentin specimens. Enamel specimens were then stored in water at 37 °C for 1 day, and then thermocycled for 500 cycles between 5 and 55 °C with a dwell time of 30 s each. Shear bond testing was accomplished using a wire loop secured to a Universal Testing Machine (Model 1541S, Instron Corporation, Canton, MA, USA) at a crosshead speed of 0.5-mm/s. The force to failure was recorded for each specimen. The mean shear bond strength in megapascals (MPa) was determined for each group. Fractured specimens were observed with a stereomicroscope (Nikon SMZ-1B, Osaka, Japan) at 20× magnification for determination of failure modes, which were classified as cohesive, adhesive, or mixed. Data were subjected to a two-factor analysis of variance (ANOVA) to examine the effects of preparation type and etch type on each of the two substrates (enamel and dentin) separately. All statistical analyses were performed at α=0.05. Twelve caries free human third molars were used for scanning electron microscopic (SEM) evaluation. Each tooth represented one of the six enamel or six dentin groups and was prepared and bonded with a composite rod according to the group’s protocol as previously described. These specimens were cross-sectioned in a low speed precision saw (Isomet, Buehler Ltd) in a mesio-distal direction through the composite rod and then lightly polished with 600 and 1200 grit SiC paper under running water in a polishing lathe. The specimens were mounted on aluminum stubs, desiccated, sputter coated with gold/palladium, and examined in a scanning electron microscope (LEO, model #435VP, Cambridge, UK). In addition, several dentin and enamel specimens were acid-etched, lased, or acid-etched and lased and fixed in glutaraldehyde for SEM observation.

Results

Mean shear bond strength data of composite bonded to rotary-prepared or Er:YAG laser-prepared dentin and enamel, etched with either 37% phosphoric acid, laser-etched at 10 Hz/35 mJ, or not etched, are presented in Table 1. For dentin specimens the ANOVA detected statistically significant main effects (p<0.001) as well as a significant interaction (p<0.001) between preparation type and etch type, so no direct conclusion can be drawn regarding the main effects of either factor.

For enamel specimens the ANOVA also detected statistically significant main effects (p<0.001) in addition to a statistically significant interaction (p<0.001) between preparation type and etch type, so again, no direct conclusion may be drawn regarding the main effects of either factor.

Tukey’s post-hoc analyses of preparation type showed that among both the dentin and enamel specimens, only the acid-etched specimens had statistically significantly different (p<0.001) mean bond strengths, with the rotary-prepared specimens having much higher mean bond strengths versus the laser prepared specimens. There were no statistically significant differences within the other etch types with regard to preparation type, as might be expected by the significant interaction term. In other words, the acid-etched rotary-prepared specimens demonstrated higher mean bond strength than the acid-etched laser-prepared specimens. The laser-etched, rotary-prepared specimens were not statistically different from
the laser-etched, laser-prepared specimens, nor were the non-etched, rotary-prepared specimens different from the non-etched, laser-prepared specimens. This observation was noted for both dentin and enamel.

Tukey’s post-hoc analyses demonstrated that within each preparation type, all of the differences among the three etch types were statistically different from each other (acid etch better than laser etch better than no etch). These differences were found to be significant ($p < 0.001$). Fracture patterns of dentin and enamel specimens are presented in Table 2.

Scanning electron microscopy of rotary-prepared, acid-etched dentin (Fig. 1A) revealed a smooth surface with tubule orifices devoid of smear plugs. The intertubular dentin is undisturbed. Cross section of the bonded composite rod to rotary-prepared, acid-etched dentin revealed intimate contact between composite and dentin, suggesting good hybridization. In contrast, SEM of a cross-section of laser-ablated, laser-etched dentin showed a highly irregular surface and fissuring. Areas of poor hybridization between composite and dentin suggest poor hybridization, or no hybridization. Laser-prepared dentin revealed surface scaling and flaking, along with peritubular cuffing (Fig. 1B). Acid-etching after laser ablation appeared to decrease some of the surface scaling and flaking (Fig. 1C). Laser ablated, acid-etched dentin demonstrated areas of detachment from both the resin adhesive and the unaffected subsurface dentin (Fig. 3). Scanning electron microscopic images of enamel surfaces bonded with composite revealed similar findings to that of dentin.

Table 1 Mean shear bond strength (MPa) of dentin and enamel groups.

<table>
<thead>
<tr>
<th>Group</th>
<th>Preparation type</th>
<th>Etchant</th>
<th>Shear bond strength</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dentin specimens</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1D</td>
<td>Rotary</td>
<td>Acid</td>
<td>19.8</td>
<td>3.6</td>
</tr>
<tr>
<td>2D</td>
<td>Laser</td>
<td>6.1</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>None</td>
<td>3.4</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>4D</td>
<td>Laser</td>
<td>Acid</td>
<td>10.2</td>
<td>2.8</td>
</tr>
<tr>
<td>5D</td>
<td>Laser</td>
<td>7.4</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>6D</td>
<td>None</td>
<td>4.6</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Enamel specimens</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1E</td>
<td>Rotary</td>
<td>Acid</td>
<td>25.6</td>
<td>5.1</td>
</tr>
<tr>
<td>2E</td>
<td>Laser</td>
<td>12.1</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>3E</td>
<td>None</td>
<td>4.6</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>4E</td>
<td>Laser</td>
<td>Acid</td>
<td>17.6</td>
<td>3.4</td>
</tr>
<tr>
<td>5E</td>
<td>Laser</td>
<td>12.5</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>6E</td>
<td>None</td>
<td>5.4</td>
<td>3.6</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Fracture patterns of tooth specimens.

<table>
<thead>
<tr>
<th>Group</th>
<th>Preparation type</th>
<th>Etchant</th>
<th>Cohesive failure</th>
<th>Adhesive failure</th>
<th>Mixed failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dentin specimens</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1D</td>
<td>Rotary</td>
<td>Acid</td>
<td>4 (20%)</td>
<td>6 (30%)</td>
<td>10 (50%)</td>
</tr>
<tr>
<td>2D</td>
<td>Laser</td>
<td>8 (40%)</td>
<td>4 (20%)</td>
<td>8 (40%)</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>None</td>
<td>2 (10%)</td>
<td>14 (70%)</td>
<td>4 (20%)</td>
<td></td>
</tr>
<tr>
<td>4D</td>
<td>Laser</td>
<td>Acid</td>
<td>6 (30%)</td>
<td>6 (30%)</td>
<td>8 (40%)</td>
</tr>
<tr>
<td>5D</td>
<td>Laser</td>
<td>11 (55%)</td>
<td>3 (15%)</td>
<td>6 (30%)</td>
<td></td>
</tr>
<tr>
<td>6D</td>
<td>None</td>
<td>10 (50%)</td>
<td>5 (25%)</td>
<td>5 (25%)</td>
<td></td>
</tr>
<tr>
<td>Enamel specimens</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1E</td>
<td>Rotary</td>
<td>Acid</td>
<td>2 (10%)</td>
<td>11 (55%)</td>
<td>7 (35%)</td>
</tr>
<tr>
<td>2E</td>
<td>Laser</td>
<td>12 (60%)</td>
<td>3 (15%)</td>
<td>5 (25%)</td>
<td></td>
</tr>
<tr>
<td>3E</td>
<td>None</td>
<td>1 (5%)</td>
<td>13 (65%)</td>
<td>6 (30%)</td>
<td></td>
</tr>
<tr>
<td>4E</td>
<td>Laser</td>
<td>Acid</td>
<td>11 (55%)</td>
<td>3 (15%)</td>
<td>6 (30%)</td>
</tr>
<tr>
<td>5E</td>
<td>Laser</td>
<td>12 (60%)</td>
<td>2 (10%)</td>
<td>6 (30%)</td>
<td></td>
</tr>
<tr>
<td>6E</td>
<td>None</td>
<td>11 (55%)</td>
<td>2 (10%)</td>
<td>7 (35%)</td>
<td></td>
</tr>
</tbody>
</table>
Lased dentin and enamel, subsequently acid-etched, demonstrated an improvement in contact intimacy between the composite material and the tooth surface interface. Acid-etched enamel is seen in Fig. 2A. A loss of surface area for resin penetration occurs during laser ablation of enamel (Fig. 2B). If laser-ablated enamel is subsequently acid-etched, a unique etch pattern is seen (Fig. 2C); this etch pattern resulted in specimens that had higher bond strength than laser ablation alone, but did not improve to the bond strength levels of conventional rotary-prepared, acid-etched enamel.

Discussion

Although some previous investigations have reported that the bond strength of composite to laser-irradiated dentin was higher than that of
acid-etched dentin, data from our study demonstrate that bond strengths are significantly weaker when tooth surfaces are prepared with the Er:YAG laser. The results of this study agree with the findings of Ceballos et al. [35], Kameyama et al. [37], Martinez-Insua et al. [38], and Aoki et al [39].

In contrast, Keller and Hibst [40], Visuri et al. [32], and Stiesch-Scholz and Hanning [41] postulated that the lased dentin surface possessed an advantage because of an apparent enlarged surface area for adhesion based on the scaly and flaky surface appearance following Er:YAG irradiation. This scaly surface appearance of laser ablated dentin, along with the cuff-like appearance of peritubular dentin described by Aoki et al. [39], was also evident in the SEM images from the current study (Fig. 1b). The unusual appearance of laser-irradiated dentin can be explained by understanding the process of laser ablation. Li et al. [42] explained that the Er:YAG laser thermomechanically ablates hard tissues by causing micro-explosions within inorganic structures in teeth. Initially, the Er:YAG laser vaporizes water and other hydrated organic components until internal pressure causes the destructive explosion of the inorganic component before the melting point is reached. Aoki et al. [39] determined that intertubular dentin was selectively ablated more than peritubular dentin, leaving a cuff of more highly mineralized dentin around dentin tubule orifices. The higher water content of intertubular dentin compared to peritubular dentin can explain this.

Ceballos et al. [35] proposed that the ablation of dentin fused collagen fibrils together resulting in a lack of interfibrillar space, restricting resin diffusion into the subsurface intertubular dentin. Cross sectional observation of resin bonded to laser-ablated dentin revealed a lack of penetration of the resin, and even peeling of the resin layer from the ablated dentin surface (Figs. 3 and 4), supporting the theory of resin restriction. The lack of resin penetration in laser-ablated dentin is the most likely explanation for lower bond strengths. Data from the current study substantiate the observation that laser ablated dentin results in significantly lower shear bond strength compared with rotary-prepared, acid-etched specimens (Table 2). These data are in agreement with the fracture pattern findings of Martinez-Insua et al. [38] and Kameyama et al. [37]. The cohesive dentin failures may be explained by the lack of penetration of resin into Er:YAG irradiated dentin, creating a weak subsurface zone just below the interface.

The prospect of laser etching enamel surfaces was welcomed because of potential disadvantages with enamel acid etching. Acid demineralization with 37% phosphoric acid can make enamel surfaces more susceptible to caries, especially if resin impregnation is incomplete or defective [38]. It was thought that laser etching might reduce caries risk because demineralization would not occur, and that water and organic components would be

![Figure 3](image3.png) Separation of resin adhesive and unaffected subsurface dentin from laser-ablated, then acid-etched dentin.

![Figure 4](image4.png) Resin adhesive peeling away from the laser-ablated dentin surface.
reduced [46]. However, the extensive fissuring and subsurface cracking that occurs with the Er:YAG laser on enamel surfaces negates any possible advantages and precludes its use. Enamel specimens that were irradiated with the Er:YAG laser demonstrated significantly lower mean bond strengths compared to rotary-prepared, acid-etched specimens. These results are in agreement with Martinez-Insua et al. [38].

Acid etching of enamel surfaces removes approximately 10 μg of the enamel surface and creates a microporous layer from 5 to 50 μg deep which is readily filled with resin [47]. The laser irradiated enamel surface (Fig. 2B) produced surface fissuring and a union or blending of the distinctive etch pattern normally seen in acid-etched enamel (Fig. 2A). This blending effect likely prevented the penetration of resin into the enamel, resulting in lower enamel bond strength values. Interestingly, the subsequent addition of acid etchant to laser ablated enamel created a delicate etch pattern that assumed the appearance of a more retentive surface (Fig. 2C) than that created by laser etching alone. Bond strength data from the present study appear to support this observation (Table 1), but the values still do not reach those of acid-etched enamel. Fracture patterns of composite rods bonded to laser ablated enamel specimens reveal a high incidence of cohesive enamel failures, suggesting that the Er:YAG laser produces subsurface fissuring that goes beyond resin penetration.

When dentin and enamel specimens were acid etched after they were laser irradiated, a significant improvement in shear bond strength from laser etching alone was observed. In contrast, Kameyama et al. [38] postulated that acid treatment following laser irradiation amplified the deleterious effects to dentin. Fig. 1C demonstrates that the subsequent use of phosphoric acid after laser irradiation eliminates some of the surface scaling and flaking that typifies the laser-ablated dentin surface (Fig. 1B). However, it appears that the thermo-mechanical effects of laser irradiation extend into the subsurface in both dentin and enamel, compromising the integrity of the tooth-restoration bonded interface and decreasing the resulting shear bond strength. Still, the highest bond strengths are obtained when dentin or enamel is prepared by a rotary handpiece and then etched with 37% phosphoric acid.

Within the limits of this study, the null hypothesis that there would be no difference in mean shear bond strength between composite and tooth surfaces prepared by high speed rotary instrumentation or laser ablation, etched with acid, laser etched, or not etched, must be rejected. Our observations suggest that the deleterious effects of Er:YAG laser irradiation on dental hard tissue goes beyond normal resin penetration depth. Any purported advantage of Er:YAG laser treatment on dental hard tissues must be seriously challenged in light of the results of this study. Er:YAG laser irradiation has an adverse effect on dental hard tissues and is not a viable alternative to conventional acid etching. Further studies examining the effects of Er:YAG irradiation and the structural changes in teeth that result are required before Er:YAG laser use can be established as a reliable operative technique in dentistry.

References


