In recent years, there has been a growing debate on the use of lasers for conditioning enamel and dentin as a possible alternative to acid etching. Numerous studies have investigated the effects of Nd:YAG and Er,Cr:YSGG laser etching on the bond strengths of restorative materials to tooth structures.

Nd:YAG laser (yttrium-aluminum-garnet doped with neodymium, 1,064 nm) is ideal for a number of soft tissue procedures and can be used to remove incipient enamel caries, although not efficiently as can the Er,Cr:YSGG laser. Er,Cr:YSGG laser (yttrium-scandium-gallium-garnet doped with erbium...
and chromium, 2,780 nm) used with an air-water spray has several hard tissue applications such as enamel etching, caries removal, cavity preparation, bone surgery, and root canal preparation. The laser energy absorbed by the water microdroplets is believed to be partially responsible for the hard tissue cutting effects and has been designated a hydrokinetic system. Er,Cr:YSGG laser that is well absorbed by water and hydroxyapatite is able to mechanically ablate enamel, dentin, and alveolar bone, while Nd:YAG laser, which is not well absorbed by water, results in strong thermal reactions, such as carbonization, charring, and melting of organic tissue. Nd:YAG laser irradiation causes dentin to melt and recrystallize and results in occlusion of the dentinal tubules. Organic fraction of the dentin surface decreases while inorganic fraction increases. Er,Cr:YSGG laser irradiation produces cavities without signs of thermal damage on the surface and results in micro-irregularities and absence of a smear layer. The orifices of the dentinal tubules remain open. The morphologic structure produced by both lasers is thought to enhance bonding of adhesive restorations.

The contribution of organic solvents in the structure of adhesive systems is essential for achieving effective bonding to dentin. These solvents, such as acetone and ethanol, displace water from the moist collagen network, which promotes the infiltration of the adhesive through the dense collagen filigree. Studies have been published concerning the effect of solvent type on bond strength to dentin. Many studies, often with conflicting results, have evaluated the bond strength of composite restorations to enamel and dentin surfaces treated by laser compared to acid etching. However, to the authors’ knowledge, no study has yet assessed the effect of the solvent types of bonding agents on the bond strength of composite restorations on laser-etched tooth structures. Therefore, the present in vitro study aimed to evaluate the bond strength and adaptation of acetone- and ethanol-containing dentin bonding agents on Er,Cr:YSGG and Nd:YAG laser-irradiated versus acid-etched dentin surface.

**METHOD AND MATERIALS**

One hundred and forty-six extracted human permanent molars free of visible caries or other surface defects were used. The teeth were cleaned and subsequently stored in physiologic saline for no more than 6 months. All procedures were performed by a single operator (B.T.).

**Tooth preparation**

The radicular portions of 120 teeth were boxed in self-cured acrylic resin (Meliodent, Heraeus Kulzer) before preparation for bond strength testing. The mounted teeth were prepared with a water-cooled model trimmer (Rotaks-Dent) by removing the entire occlusal portion perpendicular to the long axis to expose middle dentin, creating a flat surface; no enamel covering the dentin was visible except at the periphery. The exposed surfaces were ground with a flat-ended cylinder diamond bur (Fig no 112, #12, coarse grit; Finzler, Schrock & Kimmel) to remove a thin layer of the surface under copious irrigation to produce bur-cut dentin surfaces.

**Surface treatment**

The specimens were randomly divided into 3 groups of 40 teeth each according to type of conditioning procedure. An area of 5 × 5 mm at the center of the prepared dentin surfaces was conditioned with 3 systems.

In the first group, the dentin surfaces were irradiated with Er,Cr:YSGG laser (Waterlase Millennium, Biolase Technology) at a wavelength of 2.78 µm, with a pulse duration of 140 microseconds and a repetition rate of 20 Hz in noncontact mode at a working distance of 2 mm in a circular manner. Laser irradiation was performed at 3 W (with air 60% and water 70%) pulse energy for 15 seconds. Laser energy was delivered through a fiber-optic system to a sapphire-tip terminal 600 µm in diameter. Dentin tissue was lased at a 90-degree angle to the previously flattened surfaces.

In the second group, the dentin surfaces were treated with Nd:YAG laser (ProPulse, American Dental Technologies) at a wavelength of 1.06 µm. Laser irradiation was performed with pulsed wave, 100 mJ, 20 Hz,
and 2 W. The fiber-optic probe, with a diameter of 300 µm, was used in a noncontact mode, 1 mm from the surface, and in a circular manner for 15 seconds.

In both groups, the laser beam was directed manually, without the use of a special holding device, to simulate clinical conditions as closely as possible.

Conditioning in the third group (control) was achieved using the conventional acid-etching method. Dentin surface was etched with 37% orthophosphoric acid gel (Total Etch, Ivoclar Vivadent) for 20 seconds, rinsed thoroughly with air-water spray for another 20 seconds, and air dried with oil-free compressed air for 2 seconds from a distance of 10 cm.

**Bonding procedure**

All restorative materials used in the study are listed in Table 1.

All groups were further subdivided into 2 groups according to the bonding agents applied. An acetone-based (Admira Bond) and ethanol-based (OptiBond Solo Plus) dentin bonding agent were used in this study.

The bonding agents were applied immediately after the conditioning procedure. For all groups, the adhesive systems were carefully applied to dentin surface with micro-brush disposable tips for 20 seconds and left undisturbed for 10 seconds. Excess solvent was removed with air syringe for 3 seconds from a distance of 10 cm. Bonding agents were then light cured for 20 seconds (Hilux Ultraplus, Benlioglu Dental). A power density of at least 600 mW/cm² was verified with a handheld radiometer.

Restorative resin rods 4 mm long × 4 mm wide (Admira, shade A3, for Admira Bond specimens; Prodigy Condensable, shade A3, for OptiBond Solo Plus specimens) were bonded to all dentin specimens using a Plexiglas mold. The mold was composed of 2 equal parts forming a cylindrical space with an inner diameter of 4 mm when attached together. The mold was placed on the exposed surface, and 2 2-mm increments of resin were then polymerized separately for 40 seconds each. The Plexiglas mold was then removed and specimens were stored in distilled water at room temperature for 1 day before bond strength testing.

**Bond strength testing**

The specimens were mounted onto a universal testing machine (Zwick Z010, Zwick), and tensile bond strength testing was accomplished at a crosshead speed of 0.5 mm/min using a 50-kgf load cell until the composite cylinder was dislodged from the dentin surface (Fig 1). The bond strength values were recorded and converted into megapascals.

### Table 1 Materials used in the study

<table>
<thead>
<tr>
<th>Material (manufacturer)</th>
<th>Material type</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Etch (Ivoclar Vivadent)</td>
<td>Etching gel</td>
<td>37% phosphoric acid in water. Contains inorganic fillers and a water-soluble polymer. (Standard composition—in wt %) Water distribution: 42.3; phosphoric acid (85%); 43.5; thickener: 14.0; pigments: &lt; 0.2; pH &lt; 1</td>
</tr>
<tr>
<td>Admira Bond (Voco)</td>
<td>Bonding agent</td>
<td>Bis-GMA, HEMA, organic acids complex, 3-dimensionally curing anorganic-organic copolymers, acetone</td>
</tr>
<tr>
<td>Optibond Solo Plus (Kerr)</td>
<td>Bonding agent</td>
<td>Bis-GMA, HEMA, GPDM, silica, barium, sodium hexafluorosilicate, glass, ethanol</td>
</tr>
<tr>
<td>Admira (Voco)</td>
<td>Ormocer-based composite resin</td>
<td>Bis-GMA, di-UDMA, TEGDMA, Ba-Al-B-silicate glass, SiO₂, 3-dimensionally curing anorganic-organic copolymers, additive aliphatic and aromatic dimethacrylates. Particle size: 0.04–1.2 µm (mean 0.7 µm); filler content: 56%vol; 78% wt</td>
</tr>
<tr>
<td>Prodigy Condensable (Kerr)</td>
<td>Packable composite resin</td>
<td>Bis-GMA, TEGDMA, EBA-DM, ceramic particles or pre-etched glass fibers. Particle size: 0.01–3.0 µm (mean 0.6 µm); filler content: 61% vol; 80% wt</td>
</tr>
</tbody>
</table>

(bis-GMA) bisphenol glycidyl methacrylate; (HEMA) hydroxyethyl methacrylate; (GPDM) glycerol phosphate dimethacrylate; (di-UDMA) diurethane dimethacrylate; (TEGDMA) triethylene glycol dimethacrylate; (EBA-DM) ethoxylated bis-phenol-a-dimethacrylate.
After bond strength testing, 3 specimens randomly selected from each subgroup were separated from the acrylic molds by cutting from the cervical regions. Using a diamond bur, grooves were prepared on the inferior surfaces, and the specimens were split to investigate the fractured and debonded surfaces under scanning electron microscopy (SEM; Jeol JSM-5910LV, Jeol).

The occlusal portions of the remaining 26 intact teeth were trimmed as described previously and separated from the root at the cervical third using a diamond disk. Twenty of the specimens were divided into 4 groups, prepared and conditioned by the same methods as for the bond strength tests (1 group of 5 remained untreated). These specimens were examined in SEM-EDS (electron dispersive system) to evaluate the alterations in calcium, phosphorus, magnesium, sulfur, calcium/phosphorus, and magnesium/calcium contents.

On the remaining 6 specimens, a thin layer of bonding agent was applied to the conditioned dentin surface, to which an approximately 1-mm–thick layer of restorative resin was placed and light cured. With a diamond bur, grooves were prepared on the inferior surfaces, and the specimens were fractured perpendicular to the resin-dentin interface for SEM investigations.

**Statistical analysis**

Data were analyzed with Statistical Package for Social Sciences for Windows 10.0 (SPSS), using 1-way analysis of variance (ANOVA) and Kruskal-Wallis tests. Results were calculated with 95% confidence intervals, and values of $P < .05$ were considered statistically significant.

**RESULTS**

Mean tensile bond strength values obtained with each dentin bonding agent for Er,Cr:YSGG laser–etched, Nd:YAG laser–etched, and 37% orthophosphoric acid–etched surfaces are shown in Table 2. The difference between the mean tensile bond strength values obtained with Admira Bond and OptiBond Solo Plus was statistically significant in the control group ($P < .001$). In Er,Cr:YSGG and Nd:YAG laser–etched groups there was no statistically significant difference between the adhesive agents ($P > .05$).

With both Admira Bond and OptiBond Solo Plus, highest mean tensile bond strength values were obtained in the control group followed by Er,Cr:YSGG and Nd:YAG laser groups, respectively. The differences among the 3 groups were statistically significant ($P < .001$).

SEM observation of the Er,Cr:YSGG laser–etched dentin surface revealed a rough surface with exposed orifices of dentinal tubules, and there was also a lack of smear layer (Fig 2). The adaptation of Admira Bond to Er,Cr:YSGG laser–etched dentin surface was observed to be better than that of OptiBond Solo Plus. Both in Admira Bond and OptiBond Solo Plus groups, resin tag formation was observed (Figs 3a and 3b). On the debonded surfaces, remnants of resin tags of both dentin bonding agents were seen in the dentinal tubules (Fig 4).

Nd:YAG laser irradiation on dentin surface resulted in crater formation, as well as significant surface melting. There were no exposed dentinal tubules, and resolidification after melting caused a spongelike appearance (Fig 5). On the debonded surfaces treated with Nd:YAG laser, there were no tubular
structures for the adhesive agents to penetrate, and only some remnants of the agents were seen on the surfaces. There was a visual superposition of resin over the dentin surface (Fig 6).

The dentin surfaces etched with 37% orthophosphoric acid revealed a lack of smear layer with funnel-shape opened orifices of dentinal tubules (Fig 7). Both dentin bonding agents showed better adaptation than laser-etched dentin surfaces and created resin tags by penetrating into opened dentinal tubules (Fig 8).

SEM-EDS analysis revealed no significant differences in the calcium, phosphorus, magnesium, sulfur, calcium/phosphorus, and magnesium/calcium contents among the groups ($P > .05$), and only the sulfur content in both laser-treated groups was found to be significantly lower than the untreated surface ($P < .05$) (Table 3).

**DISCUSSION**

The present study compared in vitro tensile bond strengths of 2 dentin bonding agents containing solvents on Nd:YAG and Er,Cr:YSGG laser–etched bur-cut dentin surface.

Shear or tensile bond strength tests are the most commonly used tests to screen performance of adhesives in laboratory.\(^2^6\),\(^2^7\) Although the easiest to perform are shear tests, there is a strong tendency to develop a bending moment in most of them. On the other hand, tensile tests are thought to develop more uniform stress distributions if there is a correct alignment between the specimen and the adherent.\(^2^8\) In the present study, a conventional tensile bond strength test was preferred. However, intraorally, restorations are subject to different forces such as tensile, shear, compressive, oblique, and combinations of these types. It is extremely difficult to

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**Table 2**

<table>
<thead>
<tr>
<th></th>
<th>Er,Cr:YSGG laser group</th>
<th>Nd:YAG laser group</th>
<th>Orthophosphoric acid group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admira Bond</td>
<td>$5.96 \pm 1.16$</td>
<td>$2.74 \pm 0.58$</td>
<td>$8.85 \pm 1.30$</td>
</tr>
<tr>
<td>OptiBond Solo Plus</td>
<td>$5.60 \pm 0.81$</td>
<td>$2.89 \pm 0.73$</td>
<td>$7.26 \pm 0.97$</td>
</tr>
</tbody>
</table>

* $P < .001$ (1-way ANOVA)
duplicate these forces in vitro because of the various movements of the mandible and masticatory patterns.

Although the authors tried to simulate clinical conditions as close as possible, some factors may have significant influence on the results of this study. Taking into consideration that changes occur in dentin after extraction were used in the experiments. The complex environment of the mouth with changing temperature, stresses, humidity, and acidity is impossible to simulate in laboratory. Short-term storage (24 hours in water at room temperature) of the specimens was used in this study. Perhaps different results could be obtained if long-term storage or thermocycling was performed.

### Table 3

<table>
<thead>
<tr>
<th>Groups</th>
<th>Ca</th>
<th>P</th>
<th>Mg</th>
<th>S</th>
<th>Ca/P</th>
<th>Mg/Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er,Cr:YSGG laser</td>
<td>70.13 ± 1.29</td>
<td>28.55 ± 1.22</td>
<td>1.17 ± 0.06</td>
<td>0.13 ± 0.16</td>
<td>2.46 ± 0.15</td>
<td>0.017 ± 0.001</td>
</tr>
<tr>
<td>Nd:YAG laser</td>
<td>68.51 ± 0.75</td>
<td>29.97 ± 0.56</td>
<td>1.33 ± 0.17</td>
<td>0.17 ± 0.12</td>
<td>2.28 ± 0.06</td>
<td>0.020 ± 0.003</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>68.97 ± 0.54</td>
<td>29.52 ± 1.42</td>
<td>0.98 ± 0.67</td>
<td>0.52 ± 0.35</td>
<td>*2.34 ± 0.12</td>
<td>0.014 ± 0.010</td>
</tr>
<tr>
<td>Bur-cut</td>
<td>68.96 ± 1.16</td>
<td>29.50 ± 1.13</td>
<td>1.18 ± 0.36</td>
<td>0.33 ± 0.15</td>
<td>*2.34 ± 0.13</td>
<td>0.017 ± 0.005</td>
</tr>
</tbody>
</table>

(Ca) calcium; (P) phosphorus; (Mg) magnesium; (S) sulfur.
Kruskal-Wallis test, *P > .05.

*P < .05 significantly decreased.
Most in vitro bonding tests are performed by preparing dentin surfaces with silicon carbide or aluminum oxide abrasive papers. Some studies report no significant differences between the bond strength values obtained by diamond burs or silicon carbide papers. Moreover, adhesive resins are clinically applied on dentin prepared with diamond burs. Taking these facts into consideration, diamond burs were used to prepare the experimental surfaces in this study. As bonding to dentin is a technique-sensitive procedure, for the most reliable results the clinical procedure recommended by the manufacturer should be followed meticulously. Accordingly, restorative resins from the same manufacturers as the respective adhesive systems were used in this study to avoid bonding agent incompatibility.

The so-called one-bottle adhesives combine the adhesive resin and primer into a single solution preceded by a separate etching step. They are mostly dissolved in acetone or ethanol, which displace water from the dentin surface. Many studies have investigated which is superior to the other. In some of these studies, solvent type was found not to be effective on the bond strengths. On the other hand, Carvalho et al. showed that the type of solvent could affect bonding ability to the dried dentin surface. In the studies of Moll et al., Mota et al., and Lopes et al., the highest bond strength values were obtained with the ethanol-based agents. In contrast, Toledo et al. reported that the bonding agents that resulted in higher bond strength values on dentin were acetone based. The conflicting results of the mentioned studies led us to use acetone- and ethanol-containing dentin bonding agents with different surface treatment methods in this study.

Generally, there is variability among the dentin bond strength values reported by various researchers that may be attributed to different testing methods and conditions, nature of dentin substrate, and the materials used. Because there are currently a few comparable studies using Er,Cr:YSGG laser, it will also be useful to consider the studies conducted using Er:YAG laser with similar effects on dental hard tissues and the resulting morphologic changes. In contrast to the results of Visuri et al., indicating that laser-irradiated samples had higher bond strength values compared with acid-etched controls, in many studies adhesion to dental hard tissues after Er:YAG laser etching was shown to be inferior to that obtained after acid etching and not to constitute an alternative to conventional acid etching.

Lee et al. reported that Er,Cr:YSGG laser irradiation adversely affected adhesion of resin to dentin and recommended acid etching following laser irradiation to increase bond strength values. Sung et al. suggested that primary dentin surfaces treated with Er,Cr:YSGG laser, with or without etching, may provide comparable or increased composite resin bond strengths depending on bonding agent used. Similar results were reported by Gurgan et al., although different substrates were used in these 2 studies.

A number of researchers reported that Nd:YAG laser etching of dentin did not produce superior bonding compared with the conventional acid etching and cannot be recommended as an alternative. Therefore, a different approach such as acid etching following laser irradiation is recommended in another study.

In the present study, in regard to solvent type used, acetone-based bonding agent attained significantly higher bond strength values than ethanol-based bonding agent on phosphoric acid–etched dentin surfaces. The solvent type was found to have no effect on the bond strength on laser-etched dentin surfaces. And, in regard to surface treatment method, the mean bond strength values obtained on both laser-irradiated dentin surfaces were significantly lower than those of the acid-etched surfaces. The highest mean bond strength values were attained on acid-etched surfaces by both bonding agents, although higher bond strength values were expected due to the irregular surface structure and opened tubule orifices with Er,Cr:YSGG laser. However, the bond strength values obtained with Er,Cr:YSGG laser were significantly higher than those obtained with Nd:YAG laser. These findings can be interpreted as indicating that conditioning method is more...
effective than the composition of the dentin bonding agent in bond strength.

SEM analyses of the Er,Cr:YSGG-lased surface revealed a rough or irregular structure. In addition, there was also the absence of a smear layer; the orifices of dentinal tubules were exposed. A careful Er,Cr:YSGG laser technique using a noncontact mode and under continuous water spray did not produce any carbonization of the dentin. The Nd:YAG-lased dentin showed a spongelike appearance because of the resolidification of the melted surface with obstruction of the dentinal tubules. However, on the acid-etched surfaces the smear layer was completely removed and the funnel-shaped dentinal tubules were clearly visible.

As in the present study, it has been shown in many studies that laser irradiation causes some changes in the surface structures of the dental hard tissues. The micro-irregularities created are increasing the surface area and producing a favorable surface for mechanical bonding.

In the present study, the bond strength values obtained with laser irradiation were lower than expected. This finding can be clarified by penetration of resin into the dentin on acid-conditioned surfaces, partial penetration on Er,Cr:YSGG laser–irradiated surfaces, and only visual superposition of resin over the dentin surface on Nd:YAG laser–treated surfaces. These findings supported the results of Oda et al. One of the reasons for the adverse effect on dentin adhesion with lasers might be that lasers could not selectively remove hydroxyapatite crystallites without having a harmful effect on the collagen fiber network. Thus, complete absence of hybrid layer and also thinner and cylindrical-shaped resin tags may not present a suitable surface for bonding mechanism.

**CONCLUSIONS**

Within the limits of this study, the following conclusions were drawn:

1. The solvent type of the dentin bonding agent was found to be influential on the acid-etched dentin surface, and acetone-containing adhesive system attained significantly higher bond strength values than ethanol-containing adhesive.
2. On the laser-etched dentin surface, the solvent type is not a determining factor on the bond strength.
3. The highest bond strength values were obtained in the acid-etched group for both bonding agents. Although Er,Cr:YSGG and Nd:YAG lasers cannot be an alternative to acid etching, Er,Cr:YSGG laser irradiation resulted in statistically higher bond strengths than Nd:YAG laser.

**REFERENCES**


