Effect of Erbium, Chromium-Doped: Yttrium, Scandium, Gallium, and Garnet and Erbium: Yttrium-Aluminum-Garnet Laser Etching on Enamel Demineralization and Shear Bond Strength of Orthodontic Brackets

Abstract

Objective: The objective of this study was to compare the effect of two types of laser irradiation (erbium, chromium-doped: yttrium, scandium, gallium, and garnet [Er,Cr:YSGG] and erbium: yttrium-aluminum-garnet [Er:YAG]) and acid etching on enamel demineralization and shear bond strength (SBS) of orthodontic brackets. Materials and Methods: Ninety premolars were selected, scaled, and polished with no fluoridated pumice, and metal brackets were bonded to them. Then, they were randomly allocated to three groups based on the etching procedure: phosphoric acid etching, Er:YAG (100 mJ, 10 Hz) laser etching, and Er,Cr:YSGG (600 mJ, 20 Hz) laser etching. Teeth to be evaluated for demineralization and SBS were exposed to pH and thermal cycling, respectively. For SBS test, a universal testing machine was used, and adhesive remnant was index scored after debonding. Microhardness of enamel was evaluated with Vickers test. Data were analyzed statistically (α = 0.05). Results: The acid-etched group exhibited significantly higher SBS values compared to the laser groups (P < 0.05); however, the difference between the Er:YAG and Er,Cr:YSGG laser groups was not significant. Microhardness mean values in descending order were as follows: Er,Cr:YSGG, Er:YAG, and acid etched. There were significant differences between the laser and control groups (P < 0.001); however, the difference between the two laser groups was not significant (P = 0.320). There were no significant differences between the three groups in adhesive remnant index scores. Conclusion: Er:YAG and Er,Cr:YSGG laser etching resulted in clinically acceptable SBS; therefore, apart from its other advantages over acid etching, it can be a good appropriate alternative for bonding of orthodontic brackets.

Keywords: Lasers, orthodontic bracket, shear strength, solid state, tooth demineralization

Introduction

Phosphoric acid etching is the gold standard for etching the enamel in orthodontic treatment; however, the most important disadvantage of this technique is the demineralization of the enamel surface layer, making it susceptible to acid attacks and prone to caries, particularly in the area next to an orthodontic bracket.[1,2] Considering the high prevalence of white spot lesions in orthodontic patients,[2] and given the fact that white spot lesions can form as early as 4 weeks when there is poor oral hygiene,[3] it is of utmost importance to prevent enamel demineralization during orthodontic treatment. Furthermore, there are various steps in the acid-etched bonding technique; however, a simplified technique yielding a clinically functional bond is favorable. In recent years, erbium family lasers (erbium: yttrium-aluminum-garnet [Er:YAG] and erbium, chromium-doped: yttrium, scandium, gallium, and garnet [Er,Cr:YSGG]) have been reported to be alternatives for acid-etching technique for bonding orthodontic brackets[4-10] due to their ability to ablate enamel and dentin since their beams are properly absorbed by water and hydroxyapatite crystals.[10,11] Based on the histological studies, there is no pulp inflammation after tooth hard structures are exposed to Er,Cr:YSGG and Er:YAG laser beams.[11] Furthermore, it has been reported that laser-treated surfaces are resistant to caries because the calcium-to-phosphate ratio is altered, resulting in the formation of compounds that are less soluble by acid attack.[12-14] The prevention of enamel demineralization is of great importance during treatment.

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There have been ample attempts to find a method to decrease the incidence of white spot lesions in orthodontic patients. Recently, great attention is given to conditioning dental surfaces with laser light. The physical and chemical changes in laser-irradiated surfaces hold promise for the prevention of enamel demineralization. Although different laser systems have been used in previous studies for conditioning dental hard tissues, it is well clear that with available technology, only erbium family lasers (Er:YAG and Er,Cr:YSGG) are suitable for this purpose. The wavelength of Er:YAG laser is highly absorbed by water and hydroxyapatite, making it suitable for both hard- and soft-tissue ablation. Laser irradiation removes smear layer and creates surface roughness; both of them are favorable for monomer infiltration and adhesion process.

These effects of erbium family lasers pose the question whether it would be possible to apply laser etching on the enamel surface to prevent demineralization of enamel around brackets in routine clinical practice. However, it must be pointed out that success in orthodontic treatment depends on the bond strengths of orthodontic brackets to the enamel surface.

Recently, some studies have evaluated enamel demineralization and bond strength of brackets after application of these lasers. Nonetheless, no report is available on the use of an effective laser etching technique to prevent demineralization around brackets and at the same time to provide clinically favorable bond strength after application of Er:YAG and Er,Cr:YSGG laser beams with the use of similar adhesive systems.

Materials and Methods

In this in vitro study, 90 intact- and caries-free human premolars were used, after obtaining approval from the Research Ethics Committee of Hamadan University of Medical Sciences, Hamadan, Iran (ID: IR.UMSAH.REC.1396.139). Any remaining soft tissue was removed with a scaler, and the teeth were immediately stored in 0.1% thymol solution for not more than 1 week. The teeth were randomly assigned to three equal groups: the control group (etched with 37% phosphoric acid) and Er:YAG and Er,Cr:YSGG laser groups according to the etching procedure. The total spent time for this study in Hamadan University of Medical Sciences was 12 months.

Sample preparation

First, the buccal surfaces of the 90 tooth samples were cleaned with fluoride-free pumice and a rubber cup, followed by washing and drying. Nail varnish was applied to all the surfaces except for a 6 mm × 4 mm area on the mid-buccal surface. Then, the roots of the premolar tooth samples were embedded in self-cured acrylic resin 1–2 mm away from the cementoenamel junction, with the long axis of each tooth perpendicular to the resin block surface. The samples were subsequently stored in distilled water before bonding procedures.

Etching procedures

The enamel surfaces of the samples in the control group underwent an etching procedure with the use of 37% phosphoric acid (Resilient Ortho Technology, Florida, USA) for 15 s, followed by rinsing for 15 s and drying in moisture- and oil-free air to achieve an opaque white appearance. In the Er:YAG laser group, the enamel surfaces of the samples were irradiated with 2940-nm Er:YAG laser beams for 15 s, with the following laser parameters: a pulse energy per of 100 mJ, pulse repetition rate of 10 Hz, a mean output power of 1 W, a pulse duration of 100 μs, and 60% and 40% water and air levels, respectively. The laser beams were directed manually using a noncontact handpiece in a sweeping motion perpendicular to the tooth enamel surface. In the third group, Er,Cr:YSGG laser beams were used at 1.5-W output power for 15 s. The Er,Cr:YSGG laser operates at a wavelength of 2780 nm, a pulse duration of 140 μm, and a pulse repetition rate of 20 pulses/s (20 Hz). The air and water levels were 90% and 80%, respectively. The samples were then air-dried until a typical white opaque etched area was achieved, similar to that in the acid-etched group.

After etching, the orthodontic brackets were bonded as follows:

Bonding procedures

Etch-and-rinse system (Resilient Ortho Technology, Florida, USA) was used in this study. A total of 90, 0.018-slot-size premolar brackets (Dentaurum, Ispringen, Germany) were bonded with light-cured composite resin (Resilient Ortho Technology, Florida, USA); excess composite resin was removed carefully with an explorer. Then, the composite resin was light cured for 10 s from each mesial and distal aspect. Subsequent to bonding, all the samples were stored in distilled water for 24 h at room temperature and then evaluated for demineralization and shear bond strength (SBS).

pH cycling

After bonding, the samples underwent a pH cycling procedure to produce caries-like lesions. The samples were immersed in demineralizing and remineralizing solutions at 37°C for 6 and 17 h a day, respectively. The cycles began with a demineralizing solution (pH = 4.5) which consisted of 2.2 mmol/L of CaCl₂, 2.2 mmol/L of NaH₂PO₄, and 0.05 mol/L of acetic acid. Subsequently, the samples were rinsed with deionized water and immersed in the remineralizing solution (pH = 7.0) which consisted of 0.15 mol/L of KCl, 1.5 mmol/L of CaCl₂, and 0.9 mmol/L of phosphate ions (Na₂HPO₄). Both these solutions were refreshed daily. The samples underwent these cycles separately in separate glass containers for 14 days.

Thermal cycles and shear bond strength test

The samples underwent a 500-round thermocycling procedure at 5/55°C ± 5°C, with a dwell time of 20 s to
simulate warm and humid conditions of the oral cavity. The SBS was tested in a universal testing machine (Santam STM-20, Iran) at a crosshead speed of 1 mm/min. The samples were stressed oclusogingivally under the occlusal wings of the brackets and parallel to the long axis of each tooth. The SBS values in Newton were converted into MPa by dividing the value by the surface area of the bracket base.

Surface microhardness test
After the brackets were debonded, the adhesive remnant index (ARI) was scored by one investigator under ×10 magnification using the following scoring system:

1. The adhesive remained on the enamel surface completely
2. More than half of the adhesive remnant was observed on the surface of the enamel
3. More than half of the adhesive remnant was observed on the base of the bracket
4. The adhesive remained on the bracket base completely.

Vickers microhardness testing machine (Micromet 1, Buehler LTD, Lake Bluff, Illinois, USA) was used to assess microhardness using a 300-g load with a dwell time of 15 s. Three indentations were placed on a 2 mm × 4 mm nonbonded exposed surface of the enamel, and Vickers hardness number was recorded.

Statistical analysis
Data were analyzed with SPSS 23.0 (SPSS Inc., Chicago, IL, USA). Kolmogorov–Smirnov test was used to evaluate normal distribution of data. ANOVA and post hoc multiple comparison tests were used for two-by-two comparison of the SBS values between the groups. Kruskal–Wallis test and Mann–Whitney U-test with Bonferroni correction were used to analyze the microhardness values; Chi-squared test was used to analyze the ARI scores. All the tests were performed at a significance level of $P < 0.05$.

Results
The mean SBS values are presented in Table 1. There were significant differences in SBS values between the groups ($P < 0.001$). The control group exhibited the highest SBS values, followed by the Er:YAG and Er,Cr:YSGG laser groups in descending order. The acid-etched group exhibited significantly higher SBS values compared to the two laser groups ($P < 0.05$); however, the difference between the Er:YAG and Er,Cr:YSGG laser groups was not significant [Table 2].

Kruskal–Wallis test and Mann–Whitney U-test with Bonferroni correction were used to evaluate microhardness values. Microhardness mean values in descending order were as follows: Er,Cr:YSGG, Er:YAG, and acid etched. There were significant differences between the laser and control groups ($P < 0.001$); however, the difference between the two laser groups was not significant ($P = 0.320$) [Table 3].

Table 4 presents the results of ARI scores for ranking adhesive remnants on the enamel surfaces. According to Chi-squared test, there were no significant differences between the three groups in ARI scores. In the laser groups, <50% of adhesive remnants remained on the enamel, and in the acid-etched group, more than 50% of adhesive remnants remained on the enamel.

Discussion
Laser etching of enamel has attracted attention in recent years in orthodontic due to its user-friendly nature and formation of acid-resistant enamel surfaces after laser irradiation. To this end, erbium family lasers (Er:YAG and Er,Cr:YSGG) have been proposed as an alternative to acid etching for bonding of orthodontic brackets. These laser beams can ablate enamel and dentin because they are effectively absorbed by water and hydroxyapatite crystals. Therefore, it is very important to determine which lasers yield adequate bond strength and prevent demineralization because there are conflicting reports by most studies on the bond strength of brackets and enamel demineralization subsequent to the application of Er:YAG and Er,Cr:YSGG laser beams. Although different laser systems have been used in previous studies for conditioning dental hard tissues, it is well clear that with available technology, only erbium family lasers (Er:YAG and Er,Cr:YSGG) are suitable for this purpose. The wavelength of Er:YAG laser is highly absorbed by water and hydroxyapatite, making it suitable for both hard- and soft-tissue ablation. Laser irradiation removes smear layer and creates surface roughness; both of them are favorable for monomer infiltration and adhesion process.

The Er:YAG laser energy specifications in the present study were selected based on those used in previous studies which have shown that laser beams at 100–200 mJ and 10 Hz are appropriate for etching the enamel and significantly

| Table 1: Descriptive statistics including shear bond strength (MPa) values of the study groups |
|-----------------------------------------------|
| **Shear bond strength** | **Mean** | **SD** | **Minimum** | **Maximum** | **ANOVA test P** |
|--------------------------|----------|--------|-------------|-------------|-----------------|
| Acid-etched group (control) | 25.83    | 7.99   | 22.84       | 28.81       |                 |
| Er:YAG group             | 19.96    | 9.16   | 16.54       | 23.39       |                 |
| Er,Cr:YSGG group         | 16.65    | 6.36   | 14.27       | 19.02       | <0.001          |

SD: Standard deviation; Er:YAG: Erbium: yttrium-aluminum-garnet; Er,Cr:YSGG: Erbium, chromium-doped: yttrium, scandium, gallium, and garnet
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Maximum values of SBS were found for the Acid-etched group, with significantly higher values compared to the other groups, as shown in Table 2. The Tukey test revealed significant differences between the groups, with the Acid-etched group showing significantly higher mean SBS values than the Er:YAG and Er,Cr:YSGG groups. Therefore, the SBS values in the Er:YAG and Er,Cr:YSGG laser groups in the present study are clinically acceptable for orthodontic brackets (16–19 MPa).

In addition, the mean SBS values in the acid-etched groups were higher than those in the laser-treated groups, consistent with the results of studies by Yassaei et al.,[7] Von Fraunhofer et al.,[27] and Martinez-Insua et al.[28] but different from those reported by Visuri et al.[30] and Hibst and Keller.[23]

The lower bond strengths of laser-treated groups in the present study might be attributed to the technique used for laser etching; the hand control of sweeping motion of laser beams might be a possible explanation for poor etching of the enamel by application of laser beams.

Different direct and indirect methods are used to evaluate demineralization and remineralization of the enamel structure. In this context, the surface microhardness test is an indirect test for measuring changes in surface strength during demineralization and remineralization. Correa-Afonso et al.[32] reported that the Vickers hardness test provides precise evaluation due to the square shape of the indenter.

The results of the present study showed that the laser application methods used resulted in significantly higher surface microhardness subsequent to demineralization. The best of our knowledge, no study has compared surface microhardness values of teeth with brackets after etching with laser beams. However, Miresmaeili et al.[34] reported that irradiation with CO₂ laser beams at a wavelength of 10.6 mm resulted in higher surface microhardness and decreased enamel demineralization. Poosti et al.[35] reported that laser irradiation in conjunction with fluoride therapy prevented demineralization of the enamel and decreased surface microhardness. Ramalho et al.[36] reported that irradiation with CO₂ laser beams protected enamel against erosion after exposure to acid.

Patients at a high risk for caries, who want fixed orthodontic treatment, might benefit from the effects of Er:YAG and Er,Cr:YSGG laser beams as an etching agent for the enamel surface. We suggest further clinical trials to evaluate the inhibitory effect of erbium laser beams on the formation of white spot lesions on enamel surfaces.

Based on the ARI scores, the failure sites were mainly within the adhesive or bracket-adhesive interface. Some

### Table 2: Multiple comparisons of shear bond strength values between groups using Tukey test

| Paired comparison                  | Tukey post hoc test P |
|------------------------------------|-----------------------|
| Acid-etched group - Er:YAG group   | 0.014                 |
| Acid-etched group - Er,Cr:YSGG group | <0.001               |
| Er,Cr:YSGG group - Er:YAG group    | 0.243                 |

**Note:** Er:YAG: Erbium:yttrium-aluminum-garnet; Er,Cr:YSGG: Erbium, chromium-doped: yttrium, scandium, gallium, and garnet

### Table 3: Comparison of microhardness values (Vickers hardness number) by Kruskal-Wallis test and Mann-Whitney U-test

| Surface microhardness | Mean | SD  | Minimum | Maximum | Kruskal-Wallis U-test P | Multiple group comparisons P |
|-----------------------|------|-----|---------|---------|-------------------------|-----------------------------|
| Acid-etched group     | 305.36 | 85.44  | 155.00 | 405.66 | <0.001                  | Acid - Er:YAG <0.001        |
| Er:YAG group          | 418.14 | 43.81  | 330.33 | 515.33 |                         | Acid - Er,Cr:YSGG <0.001    |
| Er,Cr:YSGG group      | 423.59 | 29.17  | 345.50 | 512.00 |                         | Er:YAG Er,Cr:YSGG 0.320     |

**Note:** SD: Standard deviation; Er:YAG: Erbium:yttrium-aluminum-garnet; Er,Cr:YSGG: Erbium, chromium-doped: yttrium, scandium, gallium, and garnet

Er,Cr:YSGG showed that an increase in the power of Er:YAG laser beams from 1 to 2 W did not result in significant differences between the groups, with no positive effect on the prevention of enamel demineralization, which might be justified by the susceptibility of enamel surfaces roughened by higher beam energy to demineralization. Therefore, the laser parameters selected in the present study were as follows: energy/pulse: 100 mJ, pulse repetition rate: 10 Hz, mean output power: 1 W, and pulse duration: 100 µs. Er,Cr:YSGG laser beams etched the enamel surface at 1.5-W output power, a pulse duration of 140 µm, and a pulse repetition rate of 20 pulses/s (20 Hz). Based on a previous study, low-power laser beams (0.5, 0.75, and 1 W) cannot etch the enamel surface properly for bonding orthodontic brackets; however, 1.5- and 2-W laser beams might be as effective as conventional acid etching.[8]

Many studies have focused on bonding of orthodontic brackets to the enamel. Despite of various alternatives to acid etching, it is considered the gold standard for bonding resins to the enamel surface.[22,23] Enamel surface demineralization by the application of acid leads to its susceptibility to acid attacks and carries, especially when air bubbles and saliva interfere with the penetration of resin, with accumulation of plaque adjacent to brackets aggravating the condition.[24,25] Alternative techniques to replace phosphoric acid etching, such as the use of maleic and polyacrylic acids and sandblasting, have been proposed; however, they result in a weak bond strength.[24,25] Another alternative is to apply laser beams. According to previous studies, the minimum sample size necessary to obtain SBS and microhardness tests was 30 teeth in each group, that is, achieving a power ≥80%.[24]

The results of the present study showed significantly lower SBS values of brackets bonded with laser etching compared to those with acid etching. According to Reynolds,[26] bond strengths of 6–8 MPa are clinically acceptable. Therefore, the SBS values in the Er:YAG and Er,Cr:YSGG laser groups in the present study are clinically acceptable for orthodontic brackets (16–19 MPa).
Table 4: Adhesive remnant index score frequency and results of Chi-square comparison of the three groups

| ARI scores | 1, n (%) | 2, n (%) | 3, n (%) | 4, n (%) | Chi-square test P |
|------------|----------|----------|----------|----------|------------------|
| Acid       | 5 (16.6) | 13 (43.3)| 7 (23.3) | 5 (16.6) |                  |
| Er:YAG     | 6 (20)   | 6 (20)   | 12 (40)  | 6 (20)   | 0.412            |
| Er:Cr:YSGG | 6 (20)   | 6 (20)   | 13 (43.3)| 5 (16.6) |                  |

ARI: Adhesive remnant index; Er:YAG: Erbium:yttrium-aluminum-garnet; Er:Cr:YSGG: Erbium, chromium-doped: yttrium, scandium, gallium, and garnet

authors believe that bond failure at this site is more favorable than that at the enamel–adhesive interface because it might result in enamel fracture and crazing during the debonding procedure.[37] Furthermore, the time necessary for the removal of adhesives from the enamel mainly depends on the amount of remnant adhesive,[38] therefore, the less the adhesive remnants, the less the chair time. Although the failure occurred mainly at the enamel–adhesive interface, there was less adhesive remaining on the enamel surface in both laser groups, suggesting some decrease in chair time debonding compared to the acid-etched group. Sample preparation for collection of intact- and caries-free premolar teeth was the major limitation of this study.

Conclusion

Within the limitations of this study, the results suggest Er:YAG and Er:Cr:YSGG laser etching which presents a successful alternative to acid etching by providing higher demineralization prevention and comparable SBS values.

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Conflicts of interest

There are no conflicts of interest.

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