
Impact of Er,Cr:YSGG laser and bonding protocols on enamel surface integrity and bracket bonding strength: an *in vitro* study

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ABSTRACT

Adequate enamel conditioning is vital for reliable bracket bonding. Laser-assisted alternatives to conventional acid etching exist, but their impact on shear bond strength (SBS) remains highly controversial. This study aimed to evaluate the effect of Er,Cr:YSGG laser enamel conditioning on the SBS of orthodontic brackets bonded using different composite materials in the presence or absence of a bonding agent. Thirty-six extracted human premolars and molars were randomly allocated into four groups (n=9). Group A received Er,Cr:YSGG laser conditioning followed by bonding with 3M Universal Bonding Agent (3M ESPE, St. Paul, MN, USA) and 3M composite (3M ESPE, St. Paul, MN, USA). Group B (control) received conventional phosphoric acid etching followed by bonding with 3M Universal Bonding Agent and 3M composite. Group C received Er,Cr:YSGG laser conditioning followed by bonding with Nova composite (Imicryl, Konya, Turkey) without a bonding agent, while Group D received conventional phosphoric acid etching followed by bonding with Nova composite without a bonding agent. SBS testing was performed using a universal testing machine, and failure patterns were qualitatively assessed using the Adhesive Remnant Index (ARI). Artificial intelligence technology of IBM SPSS Statistics software (IBM Corp., Armonk, NY, USA) was used for the statistical analysis. The mean SBS values were 13.06±4.20 MPa, 15.29±9.52 MPa, 13.20±8.04 MPa, and 11.41±6.22 MPa for Groups A, B, C, and D, respectively. One-way analysis of variance (ANOVA) revealed no statistically significant difference among the four groups ($F_{(3,32)}=0.428$, $p=0.734$). Although Group B demonstrated the highest mean SBS and Group D the lowest, substantial overlap in standard deviation (SD) values was observed among all groups. The qualitative ARI assessment indicated that the predominant failure mode corresponded to score 2. No significant difference in orthodontic bracket SBS was observed between Er,Cr:YSGG laser conditioning and conventional phosphoric acid etching.

Key words: bonding; shear bond strength; Er,Cr:YSGG; brackets.

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Received: 31 July 2026.

Accepted: 28 September 2026.

Laser Therapy

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Licensee PAGEPress, Italy
Laser Therapy 2026; 33:443
doi:10.4081/ljt.2026.443

Introduction

The success of orthodontic treatment relies heavily on creating a secure and durable bond between orthodontic brackets and the outer tooth enamel. Adequate bond strength is essential for withstanding masticatory and orthodontic forces, minimizing bracket failure, and avoiding prolonged treatment time. At the same time, bracket debonding should occur without causing enamel damage, making the optimization of adhesive performance clinically significant.^{1,2}

Conventional enamel conditioning with phosphoric acid etching remains the reference standard for orthodontic bonding because it creates enamel microporosities that enhance micromechanical retention.³ Despite its effectiveness, acid etching may contribute to enamel demineralization, surface loss, and increased moisture sensitivity, highlighting the need for alternative surface conditioning methods that preserve enamel integrity while maintaining adequate bond strength.^{3,4}

Among emerging alternatives, laser-assisted enamel conditioning has gained increasing attention. Infrared lasers such as CO₂, Nd:YAG, Ho:YAG, Er:YAG, and Er,Cr:YSGG have been explored in dentistry for hard tissue applications. Erbium lasers, particularly Er:YAG and Er,Cr:YSGG systems, are commonly employed for their capacity to effectively ablate enamel and dentin through interactions with water and hydroxyapatite.⁵⁻⁷ Unlike conventional mechanical preparation, laser techniques provide a non-contact approach, minimizing vibration and allowing for more conservative tissue modification.^{6,7}

The Er,Cr:YSGG laser has shown significant potential as a method for enamel surface preparation because laser irradiation can alter enamel morphology, producing micro-irregularities and surface roughness that may enhance adhesive retention.^{6,7} However, the effect of laser conditioning on orthodontic bracket bonding remains controversial. Past literature has yielded conflicting results regarding shear bond strength (SBS), with outcomes varying with laser settings, conditioning protocols, and adhesive systems used.⁸

Specifically, research indicates that the laser output power of 1 W frequently generates insufficient enamel porosity, yielding lower SBS values that occasionally drop below the conventional clinical threshold of 6 to 8 MPa.⁹

Conversely, optimizing the operational parameters within the range of 1.5-2 W for 15 seconds produces micromechanical retention patterns and clinical bond strengths

that are statistically equivalent to those achieved with conventional 37% phosphoric acid etching, the gold standard.¹⁰⁻¹²

Furthermore, the introduction of combined laser-acid regimens or nanoparticle-modified adhesives has added to this disparity by producing vastly superior bond strength compared to laser irradiation alone.¹³

In addition to enamel conditioning, adhesive strategies play a critical role in bracket retention. Orthodontic composites are commonly used because of their favorable handling properties and adaptability to enamel surfaces and bracket bases. Furthermore, the use of bonding agents may enhance resin penetration and adhesive stability, thereby influencing bond strength outcomes.^{8,14} Although universal adhesives provide clinical flexibility through either self-etch or etch-and-rinse application strategies, their ultimate performance relies heavily on how the substrate is prepared and the application protocol used.^{10,14}

SBS is one of the most common mechanical methods used to assess how well orthodontic adhesives perform. Although the precise threshold for clinical success is still a topic of ongoing discussion, multiple studies indicate that a minimum value between 5.9 and 7.8 MPa provides adequate resistance against both orthodontic and masticatory forces.¹⁵ In addition to SBS, evaluation of the Adhesive Remnant Index (ARI) offers clinically relevant insights into the exact site of bond failure, whether at the enamel-adhesive or bracket-adhesive interface, and may minimize the likelihood of cracking or chipping the enamel surface when the brackets are eventually detached.¹⁶ In the present study, the nanohybrid composite resin Nova Compo SF (Imicryl, Konya, Turkey) was selected because of its favorable flow properties, ease of application, and ability to achieve reliable adhesion to enamel surfaces. Its potential use without a separate bonding agent offers a simplified bonding protocol, making it clinically attractive for orthodontic applications. Additionally, its reported bonding performance makes it a suitable material for evaluating the effect of different enamel conditioning techniques on the SBS of orthodontic brackets under controlled laboratory conditions.^{14,16}

Despite growing interest in laser-assisted enamel conditioning, evidence regarding the effect of Er laser irradiation on orthodontic bracket bond strength remains inconclusive.^{3,14} Moreover, limited evidence exists regarding the interaction between laser-conditioned enamel, different composite systems, and the use or omission of bonding agents.^{8,10,17} Therefore, further analysis is re-

quired to verify whether laser conditioning can provide bonding performance comparable to conventional acid etching and whether bonding agents are necessary to achieve reliable adhesion.^{3,4,10}

The null hypothesis (H_0) of the present study was that neither the enamel conditioning protocol, composite material, nor the use of a bonding agent would significantly affect the SBS of orthodontic brackets. The alternative hypothesis (H_1) was that at least one of these factors would significantly influence SBS.

Consequently, this research investigated the effects of Er,Cr:YSGG laser conditioning on enamel surface characteristics and the SBS of orthodontic brackets bonded with various flowable composite systems, both with and without bonding agents. SBS testing and ARI evaluation were analyzed to determine the efficacy of laser-conditioned enamel in achieving clinically acceptable bracket adhesion performed.^{1,16}

Materials and Methods

This *in vitro* experimental study was conducted following approval from the Research Ethics Committee of Ajman University for Science and Technology, United Arab Emirates (Approval No. D-F-H-26-05-20). The study aimed to evaluate the effect of Er,Cr laser irradiation (Waterlase MD, BIOLASE Technology, San Clemente, CA, USA) on enamel surface conditioning and the SBS of metal orthodontic brackets bonded using different composite materials, with or without the application of a bonding agent.

A total of 36 freshly extracted human premolars and molars obtained from patients undergoing orthodontic extractions were collected and handled in accordance with accepted laboratory biosafety procedures.¹⁸ All specimens were anonymized through numerical coding to ensure confidentiality. Experimental procedures were standardized throughout the study to minimize variability related

to tooth selection, cleaning, conditioning, bonding, curing, mounting, and mechanical testing.

Teeth were selected according to predetermined inclusion and exclusion criteria to ensure standardization of enamel quality. Only teeth with intact buccal enamel surfaces free from caries, fluorosis, restorations, cracks, abrasions, attrition, or developmental defects were included. Teeth exhibiting enamel defects, demineralization, restorations, or other structural abnormalities were excluded from the study.

Immediately after extraction, all teeth were cleaned of soft tissue remnants and stored in 1% thymol solution to prevent microbial contamination and preserve enamel integrity until use. Prior to bonding procedures, the buccal surfaces were polished with non-fluoridated pumice paste for approximately 15 seconds, rinsed thoroughly with water, and dried using oil-free compressed air to remove debris and contaminants and to standardize the enamel surface. Each specimen was subsequently embedded vertically in self-cure acrylic resin using polyethylene molds. The teeth were positioned with their long axes perpendicular to the base, ensuring complete exposure of the buccal surface to facilitate standardized bracket placement and uniform force application during SBS testing.

The 36 specimens were randomly divided into four experimental groups ($n=9$). Group A received Er,Cr:YSGG laser conditioning followed by bonding with 3M Universal Bonding Agent (3M ESPE, St. Paul, MN, USA) and 3M composite (3M ESPE, St. Paul, MN, USA). Group B served as the control group and received conventional phosphoric acid etching (B&E Dental Co., South Korea) followed by bonding with 3M Universal Bonding Agent and 3M composite. Group C received Er,Cr:YSGG laser conditioning followed by bonding with Nova composite (Imicryl, Konya, Turkey) without a bonding agent,^{8,17} while Group D received conventional phosphoric acid etching followed by bonding with Nova composite without a bonding agent (Table 1). All specimens received metal orthodontic brackets (3M Gemini brackets,

Table 1. Samples in groups.

Group	Experimental procedure
A	Tooth irradiated with Er,Cr:YSGG laser; bracket bonding with 3M Universal Bonding Agent and 3M composite
B	Tooth without laser irradiation; bracket bonding with 3M Universal Bonding Agent and 3M composite
C	Tooth irradiated with Er,Cr:YSGG laser; bracket bonding Nova composite without a bonding agent
D	Tooth without laser irradiation; bracket bonding Nova composite without a bonding agent

McLaughlin-Bennett-Trevisi prescription, 0.022-inch slot; 3M Unitek, Monrovia, CA, USA).

Laser-treated groups (Groups A and C), enamel conditioning was performed using the erbium-doped yttrium aluminum garnet (Er,Cr:YSGG laser; Waterlase MD, BIOLASE Technology, San Clemente, CA, USA) with standardized parameters of 2,780 nm, 150 mJ energy, 20 Hz frequency, 1.5 W power output, and a 10-second exposure time per tooth (Table 2).^{10,11,19} The laser tip was maintained at approximately 1 mm from the enamel surface and moved in a square-shaped scanning pattern with 80% water cooling to ensure uniform irradiation while minimizing thermal damage. For the conventionally treated groups (Groups B and D), enamel surfaces were conditioned with 37% phosphoric acid etching gel for 15-30 seconds, then rinsed with a water spray for approximately 10 seconds and dried with oil-free compressed air until a frosted enamel appearance was achieved.

Metal orthodontic brackets were bonded to the center of the buccal tooth surface approximately 3.5 mm from the occlusal edge to ensure standardized positioning. For Groups A and B, a 3M Universal Bonding Agent was applied according to the manufacturer's instructions before adhesive placement. Depending on the group allocation, either the 3M composite or the Nova composite was applied to the bracket base. The bracket was then positioned on the enamel surface using gentle pressure to achieve optimal adaptation, and excess adhesive around the bracket margins was carefully removed before polymerization. Polymerization was carried out using an LED light-curing unit at an intensity of 1,200 mW/cm² for 20 seconds. Light was applied from the mesial, distal, occlusal, and gingival aspects to ensure complete curing of the adhesive material.

Following bonding, all specimens were incubated at 37°C for 3 days to simulate oral environmental conditions and allow adequate maturation of the adhesive

interface before mechanical testing. After incubation, SBS testing was performed using a universal testing machine (Figure 1). A load was applied parallel to the bracket base at a crosshead speed of 1 mm/min until the bracket debonded (Figure 2). The maximum force required to cause bond failure was recorded, and the SBS values were calculated and expressed in MPa.^{8,17}

Following debonding, the amount of residual adhesive remaining on the enamel surface was evaluated using the ARI under a stereomicroscope at ×10 magnification. ARI scores were assigned according to the following criteria:

Score 0: No adhesive left on the tooth surface; all adhesive remained on the bracket.

Score 1: Less than 50% of adhesive left on the tooth surface; most adhesive remained on the bracket.

Score 2: More than 50% of adhesive left on the tooth surface; most adhesive remained on the tooth.

Score 3: All adhesive left on the tooth surface; all adhesive remained on the tooth.

Table 2. Laser parameters.

Parameter	Value
Wavelength	2780 nm
Energy	150 mJ
Power	1.5 W
Frequency	10 Hz
Exposure time	10 s



Figure 1. Universal testing machine.

Lower ARI scores, specifically 0-1, were interpreted as bond failure predominantly occurring at the tooth-adhesive interface and were considered to be associated with a greater risk of enamel damage. Higher ARI scores, specifically 2-3, indicated failure at the bracket-adhesive interface and were considered more favorable in terms of enamel safety.¹⁶

Statistical analysis

Artificial intelligence technology of IBM SPSS Statistics software (IBM Corp., Armonk, NY, USA) was used for the statistical analysis. Descriptive statistics were calculated and reported as mean $\pm$ standard deviation (SD). Differences in mean SBS values among the four experimental groups were analyzed using one-way analysis of variance (ANOVA). Statistical significance was established at $p < 0.05$.

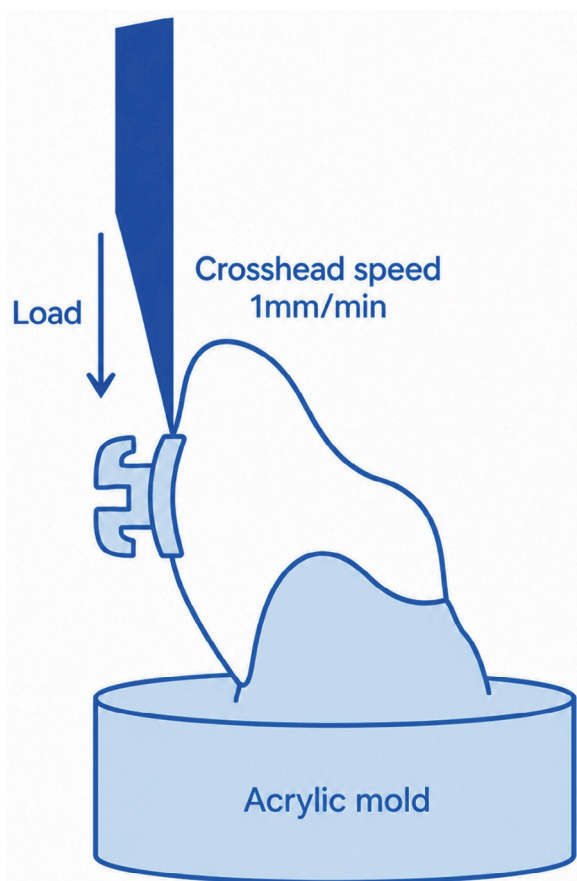


Figure 2. Shear bond test.

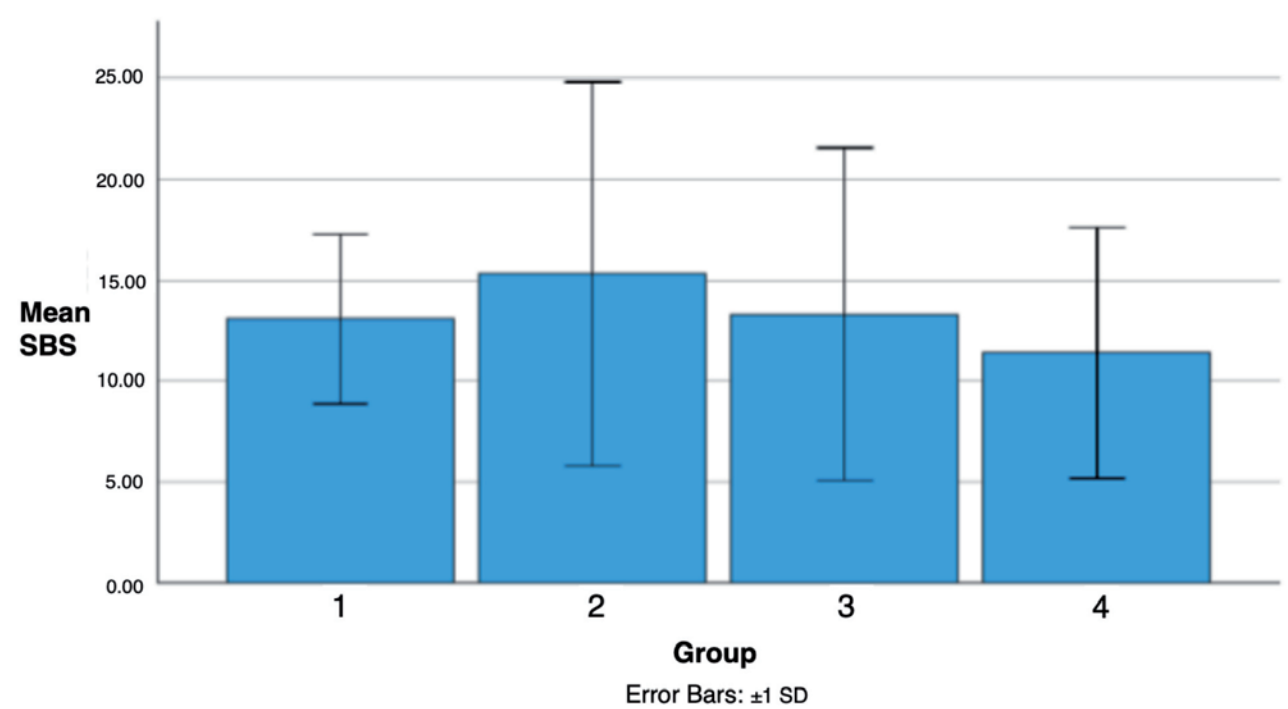
Results

The mean SBS values for Groups A, B, C, and D were 13.06 ± 4.20 MPa, 15.29 ± 9.52 MPa, 13.20 ± 8.04 MPa, and 11.41 ± 6.22 MPa, respectively. Group B demonstrated the highest mean SBS value, whereas Group D displayed the lowest mean SBS value; one-way ANOVA was performed to compare the mean SBS among the four experimental groups. The analysis revealed no statistically significant difference in SBS between the groups ($F_{(3,32)} = 0.428$, $p = 0.734$). The effect size was small ($\eta^2 = 0.039$), indicating that the treatment protocol accounted for only a small proportion of the variability in SBS values (Figure 3).

These findings suggest that neither the enamel conditioning method nor the composite/bonding protocol produced a statistically significant effect on the SBS of orthodontic brackets under these experimental conditions. Figure 3 illustrates the mean SBS (MPa) of the four experimental groups. Error bars represent ± 1 SD. Although minor differences in mean SBS values were observed among the groups, substantial overlap of the error bars was evident, consistent with the absence of statistically significant differences, regardless of the enamel-conditioning method, composite material, or use of a bonding agent. Qualitative stereomicroscopic evaluation of representative debonded specimens demonstrated that the predominant failure pattern corresponded to ARI score 2. In most of the examined samples, more than 50% of the adhesive stayed on the enamel surface after bracket removal, demonstrating that bond failure was primarily observed at the bracket-adhesive interface (Figure 4).

Discussion

The primary objective of this *in vitro* study was to assess the efficacy of Er,Cr:YSGG laser conditioning on tooth surface preparation and its influence on the SBS of orthodontic brackets bonded using different composite systems with and without a bonding agent. The results demonstrated that although slight variations in mean SBS values were noticed among the four tested groups, these variations were not statistically significant. This indicates that neither the method of enamel conditioning nor the type of composite/bonding protocol had a measurable effect on bracket bond strength under these experimental conditions.



SBS, shear bond strength; SD, standard deviation.

Figure 3. SBS values.

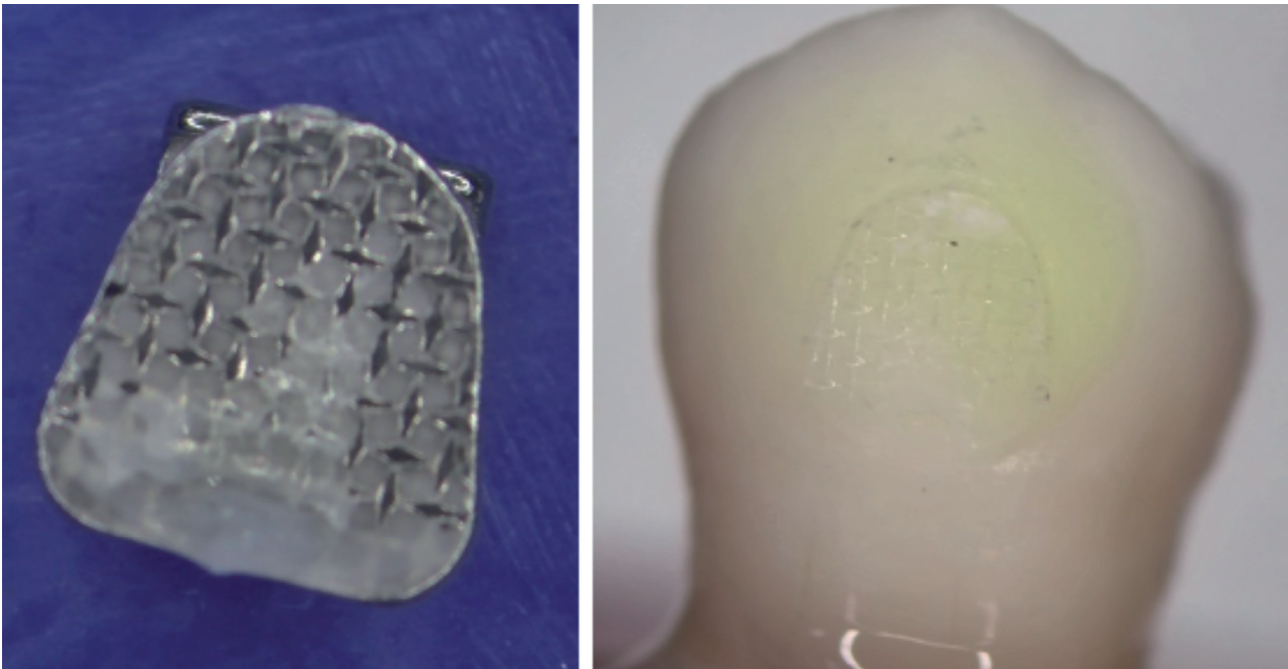


Figure 4. Failure mode.

These findings align with several contemporary studies evaluating erbium-family lasers as alternative enamel surface conditioners. Lopes *et al.* demonstrated that when laser parameters are optimized, the resulting micromechanical retention yields SBS scores that are statistically indistinguishable from those obtained through conventional 37% phosphoric acid etching.²⁰

In the current investigation, laser-conditioned groups showed bond strength comparable to that of conventionally acid-etched groups. Group B (acid-etch with bonding agent and 3M composite) demonstrated the highest mean SBS, while Group D (acid-etch with Nova composite without bonding agent) showed the lowest value; however, these differences did not reach statistical significance. These findings suggest that Er,Cr:YSGG laser irradiation at the parameters used provides enamel conditioning that is clinically similar to phosphoric acid etching in terms of bracket retention.

The ablation process of the Er,Cr:YSGG laser (wavelength 2,780 nm) works *via* micro-explosions targeting water and hydroxyapatite, which generate a micro-fractuous, irregular topography well-suited for composite resin tag penetration.²¹ Furthermore, the data revealed a high degree of uniformity across all tested groups, regardless of whether a bonding agent was used, suggesting that the macro- and micro-retention provided by modern composite systems is sufficient to adequately adapt to laser-conditioned enamel.^{6,7}

Consistent with earlier literature, no significant variation in SBS was observed between laser-treated and acid-etched enamel surfaces, indicating that erbium lasers may be a viable alternative for enamel conditioning in orthodontic bonding procedures.^{6,8} This similarity in bonding performance may be attributed to the ability of Er,Cr:YSGG laser irradiation to modify enamel surface morphology and create micro-roughened areas that may enhance micromechanical retention of adhesive resins.^{6,7} However, the effectiveness of laser conditioning is known to be highly dependent on irradiation parameters, including power output, energy density, exposure time, and cooling settings, which may explain variations in outcomes across different studies.^{22,23}

Laser etching of enamel has been shown to produce microcracks that facilitate resin penetration into the substrate.^{6,7} In addition, treating enamel surfaces with lasers enhances their ability to withstand acid dissolution. This protective effect occurs because the laser alters the calcium-to-phosphate ratio, driving the development of

highly stable chemical compounds that do not dissolve easily in acid. Consequently, the enamel becomes significantly less vulnerable to tooth decay.^{5,24} Furthermore, an additional clinical advantage of laser etching is that it eliminates the need for water spraying and air drying, thereby reducing overall chairside time.^{6,7} From a clinical standpoint, this reduction in procedural time may also improve bonding outcomes by decreasing the likelihood of salivary contamination during enamel preparation.^{3,10} In contrast, other investigations have reported either lower or more inconsistent bond strength values for laser-treated enamel than for acid-etched enamel. These discrepancies may be related to the heterogeneous nature of laser-induced surface morphology, where areas of insufficient ablation may coexist with over-irradiated regions, leading to non-uniform bonding substrates. Acid etching, on the other hand, produces a more homogeneous “honeycomb-like” microporous pattern that enhances predictable resin infiltration and may explain the slightly higher, although not statistically significant, SBS observed in the acid-etch group in the present study.^{3,6,25}

Another important finding of this study is that the use of a bonding agent did not significantly influence SBS values when comparing laser- or acid-etch groups. This is supported by previous studies showing that universal adhesives may have variable effects depending on the substrate and conditioning method.^{4,8,17} This suggests that both Nova Compo SF and 3M composite achieved adequate enamel adhesion under the tested conditions, regardless of the adhesive strategy.

The variability observed in SBS values, particularly the relatively large SDs in all groups, may be attributed to inherent differences in tooth morphology, enamel composition, and structural variability among extracted human teeth. Despite strict inclusion criteria and standardized storage protocols, biological variation remains an unavoidable factor in *in vitro* bonding studies and may contribute to dispersion in bond strength results.²⁶ The mean SBS values for all tested protocols surpassed the clinically acceptable range of 5.9-7.8 MPa recommended by Reynolds.¹⁵ These results demonstrate that all of the tested conditioning methods deliver adequate bond strength for clinical orthodontic use. These findings demonstrate that Er,Cr:YSGG laser conditioning maintains clinical bonding efficacy, making it an effective substitute to traditional phosphoric acid etching. Furthermore, the ARI evaluation, provides in-

sight into the mode of bond failure. Lower ARI scores reflect a bond failure between the enamel and the adhesive, while higher scores signify a failure between the bracket and the adhesive, making the latter clinically preferable. All tested bonding protocols generated SBS values exceeding the lower limit considered acceptable for clinical orthodontic use. In addition, the predominance of ARI score 2 indicated a favorable mode of bond failure, with most adhesive remaining on the enamel surface post-debonding, suggesting a reduced risk of enamel damage.

In this study, ARI distribution suggests that most failures occurred within acceptable limits, indicating a balanced adhesion between enamel and bracket interfaces.^{14,16}

It is also important to acknowledge that laboratory-based SBS testing does not fully replicate intraoral conditions. In the intraoral environment, brackets are exposed to complex combinations of tensile, shear, and rotational forces, as well as thermal fluctuations, humidity, salivary enzymes, and microbial activity.¹⁴ Therefore, although SBS testing provides valuable comparative data, clinical trials are required to confirm the long-term reliability of laser-assisted enamel conditioning.

Overall, the research demonstrates that conditioning enamel with Er,Cr:YSGG laser conditioning is an effective substitute for traditional acid etching when bonding orthodontic brackets. However, given the lack of statistically significant advantages and the observed data variance, acid etching remains a reliable and predictable method for enamel preparation.

With respect to the experimental boundaries of this *in vitro* study, the irradiance of the light-curing unit was not measured before and after photopolymerization of the samples. However, further investigations incorporating larger sample sizes, artificial aging procedures, surface morphology analysis, thermal cycling, and extended clinical evaluation are required to ensure the durability and clinical viability of this bonding approach.

Conclusions

In conclusion, Er,Cr:YSGG laser conditioning provides bracket bond durability similar to traditional phosphoric acid etching. Furthermore, neither the enamel conditioning method nor the use of a bonding agent significantly alters bond strength across the experimental groups.

Contributions: Ahmed El Gamal: conceptualization, design, data acquisition; Maria Micheal Morise Mahrous, Haima Aamir Nadhim Alkhafaji, Rawnaq Atheer Alju-boori, Raghad Fahmi: data collection, analysis, and interpretation, writing – original draft; Mohammed Naji, Majd Naji: revision. All authors have read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Conflict of interest: the authors declare no conflict of interest.

Ethics approval and consent to participate: this study was conducted following approval from the Research Ethics Committee of Ajman University for Science and Technology, United Arab Emirates (Approval No. D-F-H-26-05-20). Written consent to participate was obtained from all study participants.

Funding: this study received no specific funding.

Acknowledgments: the authors would like to express their sincere appreciation to Ms. Dalya Sharaf, Research Laboratory Engineer, Faculty of Dentistry, Ajman University, for her valuable technical assistance and contribution throughout this study.

Declaration of generative artificial intelligence and artificial intelligence-assisted technologies in the writing process: artificial intelligence technology of IBM SPSS Statistics software (IBM Corp., Armonk, NY, USA) was used for the statistical analysis.

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