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Research Article

EFFECTS OF SINTERING PROTOCOL AND ER:YAG LASER APPLICATION MODE ON THE BOND STRENGTH OF MONOLITHIC ZIRCONIA

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ABSTRACT

Objective: To evaluate the combined effects of slow and rapid sintering protocols and Er:YAG laser application modes (non-contact and slight-contact) at different power settings on the microshear bond strength (μSBS) of monolithic 5Y-TZP zirconia to resin cement.

Materials and Methods: Eighty rectangular 5Y-TZP zirconia specimens were fabricated and randomly assigned to two sintering protocols: slow and rapid (n = 40 each). Specimens were further subdivided into five surface treatment groups (n = 8): control, 3 W non-contact, 5 W non-contact, 3 W slight-contact, and 5 W slight-contact Er:YAG laser irradiation. Following surface treatment, a 10-MDP-containing universal adhesive was applied, and composite resin cylinders were bonded. μSBS testing was performed using a universal testing machine. Data were analyzed using two-way ANOVA and Bonferroni post hoc tests (α = 0.05).

Results: Both sintering protocol ($p < 0.001$) and surface treatment procedure ($p < 0.001$) significantly influenced bond strength, whereas their interaction was not significant ($p = 0.758$). Rapid sintering yielded significantly higher μSBS values than slow sintering. The highest bond strength was observed in the 5 W slight-contact laser group following rapid sintering (156.2 ± 10.5 MPa), whereas the lowest values were recorded in the 3 W non-contact laser group with slow sintering (85.42 ± 4.5 MPa). The 5 W slight-contact laser group showed the highest bond strength among surface-treatment groups ($p < 0.05$).

Conclusion: Both sintering protocol and laser application mode significantly affect zirconia-resin bond strength. Slight-contact Er:YAG laser irradiation may improve bonding performance, particularly under rapid sintering conditions.

Keywords: Adhesion, Lasers, Sintering, Zirconia

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INTRODUCTION

All-ceramic restorations are widely used in contemporary esthetic dentistry due to their favorable biocompatibility and optical properties (1). Within this material category, zirconia ceramics have expanded the clinical applicability of fixed restorations because of their high flexural strength and superior fracture resistance (1,2). In conventional 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP), these mechanical properties are primarily attributed to stress-induced transformation toughening, which contributes to resistance against crack propagation during functional loading (1,2). However, the relatively opaque appearance of 3Y-TZP often necessitates veneering to fulfill esthetic expectations, and this layered design may increase the risk of chipping or veneer-interface complications (1,3).

To address the esthetic limitations of conventional zirconia, zirconia systems with higher yttria content, particularly 5 mol% yttria-stabilized zirconia (5Y-TZP), have been introduced. In these materials, the increased cubic phase fraction reduces light scattering at grain boundaries due to the optically isotropic nature of the cubic structure, thereby enhancing translucency (3). Nevertheless, this compositional modification reduces transformation toughening and compromises fracture toughness compared with conventional 3Y-TZP. Consequently, the clinical performance of high-translucency zirconia may depend more heavily on manufacturing parameters and surface treatment approaches (2).

Reliable adhesion to zirconia remains challenging because this polycrystalline ceramic lacks a silica-based glassy matrix, rendering conventional hydrofluoric acid etching ineffective. Surface-conditioning methods, such as airborne-particle abrasion and tribochemical silica coating, are commonly used to enhance micromechanical retention; however, these approaches may also induce surface flaws, microcracks, or tetragonal-to-monoclinic phase transformation. Such undesirable effects may be particularly critical in 5Y-TZP, given that its fracture resistance is already lower than that of conventional 3Y-TZP (4).

Laser-assisted surface conditioning has emerged as a promising alternative for generating controlled surface roughness on zirconia surfaces. The Er:YAG laser emits radiation at a wavelength of 2940 nm, which exhibits high absorption by water molecules (5). Although zirconia itself does not contain an intrinsic water phase, laser energy may still interact with adsorbed moisture, hydroxyl groups, and surface contaminants. Once the ablation threshold is exceeded, localized micro-explosive events and surface alterations may occur (6). At higher energy settings, micro-melting or disruption at grain boundaries may also take place. Therefore, the resulting surface morphology is determined not only by the wavelength but also by the mode and intensity of laser energy delivery (7).

The mode of laser application may substantially affect the effectiveness of surface conditioning. Non-contact irradiation delivers laser energy without direct physical interaction with the substrate, potentially allowing a broader and more homogeneous energy distribution. In contrast, slight-contact irradiation positions the tip closer to the zirconia surface, which may increase localized energy concentration and mechanical interaction (6). Although this approach may enhance surface roughening and micromechanical retention, it may also increase the risk of excessive surface modification, localized melting, or microstructural damage. For high-translucency zirconia, the optimal balance between retentive surface topography and structural integrity remains unclear (8,9).

Laser power represents another critical determinant of the zirconia surface response, as it directly influences energy density and the extent of material modification. Lower power settings may promote mild surface roughening with minimal thermal effects, whereas higher settings may improve ablation efficiency while simultaneously increasing the risk of surface melting, microcrack formation, grain-boundary disruption, and phase transformation (9). Excessive thermal stress may compromise zirconia stability by inducing tetragonal-to-monoclinic phase transformation. Therefore, laser parameters should be carefully optimized to improve micromechanical retention while minimizing undesirable structural alterations (10).

In addition to surface treatment, the sintering protocol is an important determinant of the microstructural characteristics of 5Y-TZP zirconia. Parameters such as temperature profile, holding time, and heating rate influence densification behavior, grain growth, and the distribution of cubic and tetragonal phases (11). Rapid sintering protocols, which are increasingly incorporated into CAD/CAM workflows, offer considerable reductions in processing time compared with conventional sintering schedules. However, accelerated thermal cycles may also alter grain-boundary development and phase stability. Such microstructural alterations may influence surface energy, laser-material interactions, and the chemical affinity of zirconia for functional monomers such as 10-

MMDJ
MEANDROS MEDICAL AND DENTAL JOURNAL
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MDP (12). Consequently, these changes may ultimately affect both the mechanical performance and adhesive behavior of zirconia.

Although the effects of sintering conditions and Er:YAG laser treatment have been investigated individually, evidence regarding their combined influence on bonding to 5Y-TZP zirconia remains limited. Variations in sintering speed may alter the interaction between laser energy and the zirconia surface, potentially affecting surface morphology, phase stability, and zirconia-resin adhesion in ways that cannot be fully predicted from independent evaluations. Therefore, clarifying the combined effects of sintering protocol and laser application parameters is essential for establishing a more predictable adhesive strategy for high-translucency zirconia restorations (13).

Accordingly, the present study aimed to evaluate the combined effects of conventional and rapid sintering protocols together with non-contact and slight-contact Er:YAG laser irradiation at different power settings on the microshear bond strength of monolithic 5Y-TZP zirconia bonded to resin cement. The null hypothesis was that neither the sintering protocol nor the laser application mode would significantly affect zirconia-resin bond strength.

MATERIALS AND METHODS

Specimen Preparation

Ethical approval was not required for this study since no human participants or animals were involved. The sample size was determined a priori using G*Power software (version 3.1.9.2) based on F tests, ANOVA: Fixed effects, special, main effects and interactions, for a 2 × 5 factorial design. Using an effect size of f = 0.40, an alpha level of 0.05, and a statistical power of 0.80, the minimum required sample size was calculated as 80 specimens. A schematic representation of the experimental workflow is presented in Figure 1. Eighty rectangular specimens were prepared from high-translucency monolithic zirconia blocks (Copran Zr-i Monolith Zirconia Blank, A2 shade; White Peak Dental Solutions, Essen, Germany). The blocks were sectioned under water cooling and vacuum support with a low-speed precision cutting unit (Micracut 201, Metkon

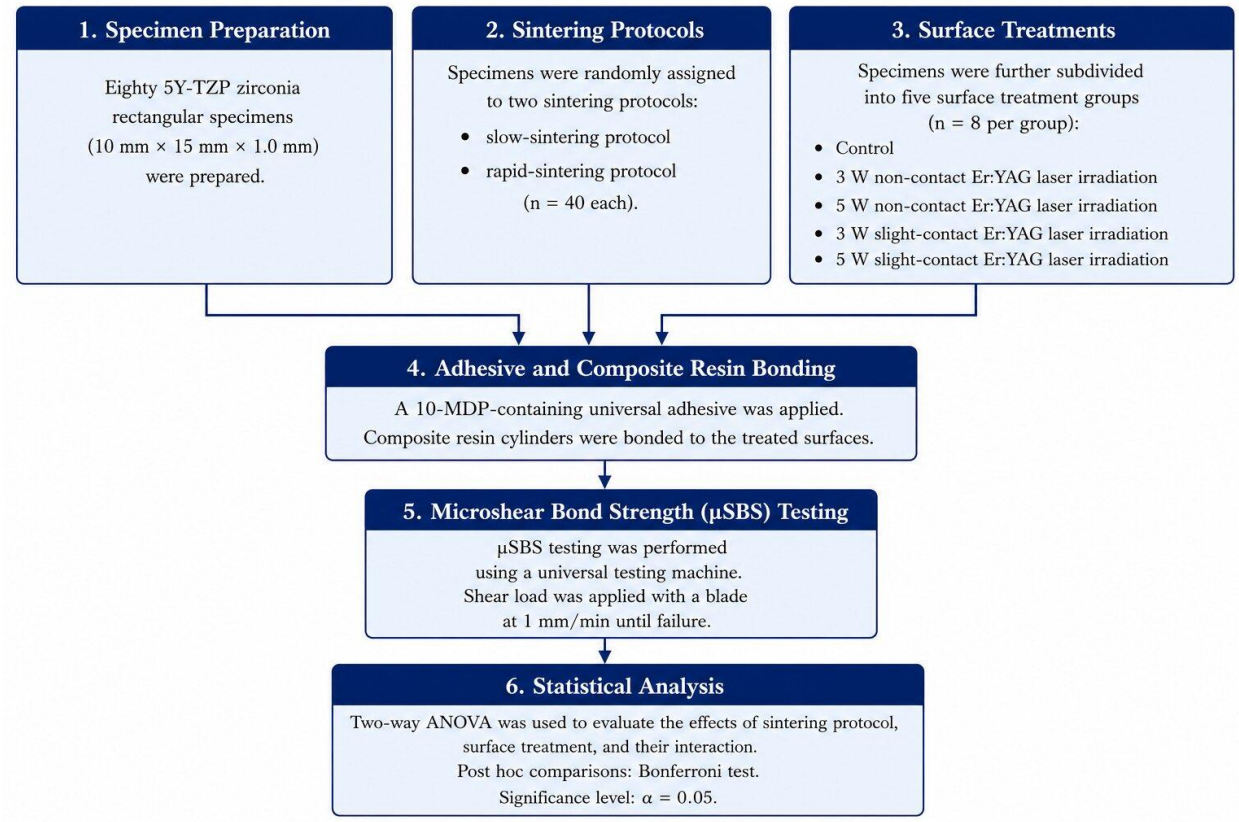


Figure 1. Schematic representation of the experimental workflow.

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MEANDROS MEDICAL AND DENTAL JOURNAL
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Instruments Inc., Bursa, Türkiye) to obtain dimensions of 10 mm × 15 mm × 1.0 mm.

Sintering Protocols

Sintering procedures were carried out using a zirconia sintering furnace (Ceramill Therm 3 / Ceramill Therm DRS, Amann Girrbach, Koblach, Austria) in accordance with the manufacturer's recommended protocols. A total of 80 zirconia specimens were randomly allocated into two experimental groups (n = 40 per group) based on the sintering program applied. For the slow sintering protocol, the temperature was first increased at a rate of 5 °C/min until reaching 950 °C, followed by a heating rate of 2 °C/min up to the final temperature of 1500 °C. The specimens were then maintained at this peak temperature for 120 minutes. In the rapid sintering protocol, the furnace temperature was raised at 50 °C/min to 1100 °C and subsequently increased at 20 °C/min until reaching 1500 °C. A holding time of 30 minutes was applied at the final temperature. Following completion of the sintering cycles, all specimens were allowed to cool slowly inside the furnace to minimize the risk of thermal stress formation. After sintering, each specimen was embedded in autopolymerizing acrylic resin (Integra Self Cure Acrylic; Birleşik Grup Dental, Ankara, Türkiye). To obtain standardized bonding surfaces, zirconia specimens were polished sequentially using 600-, 800-, and 1200-grit silicon carbide abrasive papers under continuous water irrigation. Subsequently, all specimens were kept in distilled water at room temperature for 24 hours. Prior to further procedures, the specimens were ultrasonically cleaned in distilled water for 10 minutes using an ultrasonic cleaner (CD-4820, Codyson, Shenzhen, China). Following ultrasonic cleaning, all specimens were handled using clean stainless-steel tweezers (Aesculap, Tuttlingen, Germany) to minimize surface contamination prior to surface treatment procedures.

Surface Treatments

The slow- and rapid-sintered specimens were further randomized into five surface-treatment subgroups, producing 10 experimental groups overall (n = 8 per group). To minimize operator-dependent variability, all conditioning procedures were carried out by the same investigator. No additional surface conditioning was performed for the control specimens.

Laser treatment was performed using an erbium-doped yttrium aluminum garnet (Er:YAG) device (LightWalker; Fotona, Ljubljana, Slovenia) operating at 2940 nm with water/air spray settings of 4/4. Both non-contact and slight-contact irradiation modes were used (Figure 2).

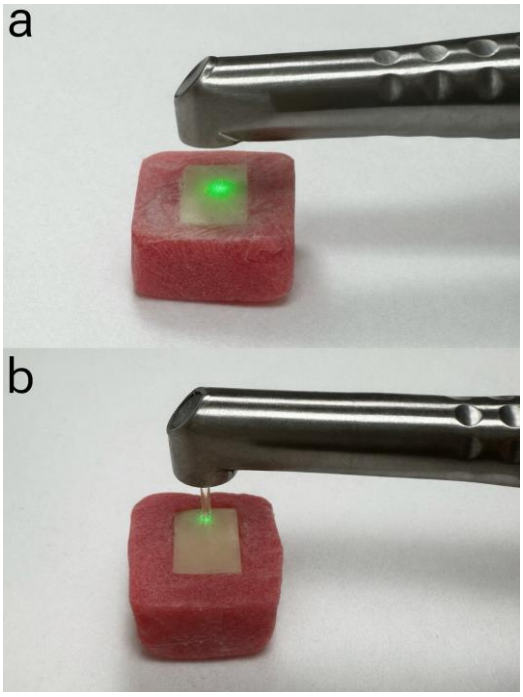


Figure 2. Er:YAG laser irradiation modes applied to zirconia surfaces. (a) Non-contact mode, (b) Slight-contact mode.

In the 3 W non-contact subgroup, irradiation was delivered at 200 mJ, 15 Hz, and 3.0 W. Using a non-contact handpiece (H02; Fotona, Ljubljana, Slovenia), the beam was applied from approximately 5-8 mm away under water cooling in super short pulse mode (SSP, 50 μs). Continuous sweeping axial movements were maintained for 20 seconds, followed by 20 seconds of air drying.

For the 5 W non-contact condition, the parameters were 335 mJ, 15 Hz, and 5 W. The same non-contact handpiece, water/air settings, irradiation time, and motion pattern were used. The manufacturer-reported spot size of the H02 handpiece was 0.9 mm, corresponding to calculated energy densities of approximately 31.4 J/cm² at 200 mJ and 52.7 J/cm² at 335 mJ.

In the 3 W slight-contact subgroup, the Er:YAG laser was set to 200 mJ, 15 Hz, and 3 W. Irradiation was applied under water cooling with a sapphire-tipped handpiece (H14; Fotona, Ljubljana, Slovenia; tip diameter 1.3 mm, length 6.5 mm) in SSP mode (50 μs). The sapphire tip was maintained in gentle passive contact with the zirconia surface without additional pressure, while standardized axial sweeping movements were performed for 20 seconds by the same operator to minimize variability in contact pressure, followed by 20 seconds of air drying.

MMDJ
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Table 1. Mean microshear bond strength (μSBS) values of zirconia-resin specimens according to sintering protocol and surface treatment procedure (MPa)

	Control	Er:YAG laser slight-contact 3 W	Er:YAG laser slight-contact 5 W	Er:YAG laser non-contact 3 W	Er:YAG laser non-contact 5 W
Type of Sintering	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**
Slow	103.54 ± 5.3^{Aa}	125.28 ± 7.4^{Ab}	149.12 ± 11.4^{Ac}	85.42 ± 4.5^{Ad}	118.42 ± 9.5^{Ab}
Rapid	109.5 ± 5^{Ba}	132.6 ± 11.4^{Bb}	156.2 ± 10.5^{Bc}	98 ± 6.1^{Ba}	129.62 ± 9.3^{Bb}

* SD: standard deviation. Statistically significant differences were indicated by uppercase letters in columns and lowercase letters in rows ($p < 0.05$)

For the 5 W slight-contact subgroup, irradiation was carried out at 335 mJ, 15 Hz, and 5 W using the same sapphire-tipped handpiece and the same application protocol. The calculated energy densities for the H14 tip were approximately 15.1 J/cm² at 200 mJ and 25.3 J/cm² at 335 mJ. Laser irradiation was applied to the entire standardized zirconia bonding surface before placement of the Tygon tubes and bonding procedures.

The study groups were as follows:
Group 1: Slow sintering control
Group 2: Slow sintering + 3 W laser + non-contact
Group 3: Slow sintering + 5 W laser + non-contact
Group 4: Slow sintering + 3 W laser + slight-contact
Group 5: Slow sintering + 5 W laser + slight-contact
Group 6: Rapid sintering control
Group 7: Rapid sintering + 3 W laser + non-contact
Group 8: Rapid sintering + 5 W laser + non-contact
Group 9: Rapid sintering + 3 W laser + slight-contact
Group 10: Rapid sintering + 5 W laser + slight-contact

After surface conditioning, a universal adhesive containing 10-MDP (Prime&Bond Universal Adhesive, Dentsply Sirona, Konstanz, Germany) was applied to the zirconia surfaces with a brush for 20 seconds. The adhesive was then gently air-dried for 5 seconds to evaporate the solvent and light-cured for 10 seconds using an LED curing device (Elipar, 3M ESPE, St. Paul, MN, USA) with an irradiance of 1200 mW/cm², in accordance with the manufacturer's instructions. Tygon tubes with an internal diameter of 0.8 mm and a height of 1 mm were subsequently positioned on the treated surfaces. A flowable composite resin in A2 shade (Neo Spectra ST Flow, Dentsply Sirona, Konstanz, Germany) was placed into the tubes and light-cured for 10 seconds. During curing, the light tip was positioned as close as possible to the composite surface to maximize irradiance.

Microshear Bond Strength (μSBS) Analysis

For μSBS testing, the specimens were secured in a universal testing machine (Instron Corp., Norwood, MA, USA). A 0.4-mm-thick blade was aligned precisely at the zirconia-resin interface, and load was applied at a crosshead speed of 1.0 mm/min until debonding occurred. The recorded failure load (N) was converted into MPa by dividing it by the bonding area (mm²). The bonding area was calculated using the formula $A = \pi r^2$. Based on the internal diameter of the Tygon tubes (0.8 mm), the bonding area was approximately 0.502 mm².

Statistical analysis

Data analysis was performed with SPSS software (version 25; IBM Corp., Chicago, IL, USA). Distribution normality was checked with the Shapiro-Wilk test and found to be acceptable. Two-way ANOVA was used to assess the effects of sintering protocol and laser treatment on bond strength, and Bonferroni post hoc comparisons were applied. Statistical significance was set at $\alpha = 0.05$.

RESULTS

Table 1 summarizes the mean μSBS values and standard deviations for all groups. Among the tested conditions, the highest bond strength was observed in the rapid-sintered specimens treated with 5 W slight-contact Er:YAG laser irradiation (156.2 ± 10.5 MPa), whereas the lowest value was found in the slow-sintered specimens exposed to 3 W non-contact irradiation (85.42 ± 4.5 MPa).

Table 2. Two-way analysis of variance (ANOVA) results evaluating the effects of sintering protocol and surface treatment procedure on microshear bond strength (μSBS)

Tests of Between-Subjects Effects						
Source of Variation	**SS**	**df**	**MS**	**F**	**p value**	**η^2**
Sintering Type	1563.266	1	1563.266	21.728	$< 0.001^*$	0.237
Surface Treatment	34241.647	4	8560.412	118.98	$< 0.001^*$	0.872
Sintering Type × Surface Treatment	134.942	4	33.736	0.469	0.758	0.026
Error	5036.363	70	71.948			
Corrected Total	40976.219	79				

* df: degrees of freedom, MS: mean square, SS: sum of squares, η^2: partial eta squared

MMDJ
MEANDROS MEDICAL AND DENTAL JOURNAL
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Two-way ANOVA showed that both sintering protocol ($p < 0.001$) and surface treatment procedure ($p < 0.001$) had significant effects on zirconia bond strength (Table 2). Overall, rapid sintering produced significantly greater bond strength values than slow sintering ($p < 0.001$) (Table 1).

For both sintering protocols, 5 W slight-contact irradiation yielded the highest μSBS values and was significantly higher than all other surface treatment groups ($p < 0.05$). No significant difference was found between the 3 W slight-contact and 5 W non-contact groups ($p > 0.05$) (Table 1).

When surface treatment procedures were evaluated irrespective of sintering protocol, the highest overall μSBS values were observed in the 5 W slight-contact group, whereas the lowest values were recorded in the 3 W non-contact group (Table 3).

Table 3. Total mean microshear bond strength (μSBS) values according to surface treatment (MPa)

Surface treatment	Mean ± SD
Control	106.52 ± 5.89
Slight-contact 3 W	128.94 ± 10.06
Slight-contact 5 W	152.66 ± 11.22
Non-contact 3 W	91.74 ± 8.36
Non-contact 5 W	124.02 ± 10.83

* SD: standard deviation

DISCUSSION

This study examined how sintering schedule (rapid or slow) and Er:YAG laser delivery mode (non-contact or slight-contact) influence the adhesive behavior of monolithic 5Y-TZP zirconia. The statistical findings showed that both independent variables significantly affected μSBS values, whereas their interaction was not significant. Therefore, the null hypothesis was rejected because both factors contributed to variation in zirconia-resin bond strength.

The effect of surface treatment was especially strong, as reflected by the high partial eta squared value for this factor ($\eta^2 = 0.872$), indicating that laser-related parameters explained most of the observed variability in bonding. By comparison, sintering protocol showed a more moderate effect size ($\eta^2 = 0.237$). This suggests that although microstructural differences created during manufacturing are relevant, surface conditioning plays the leading role in determining adhesive performance (14). Previous reviews have similarly emphasized that zirconia bonding depends greatly on the selected surface treatment, adhesive chemistry, and surface morphology (4, 8, 14).

The absence of a significant interaction between sintering protocol and surface treatment suggests that the influence of laser conditioning on μSBS remained relatively consistent across both thermal schedules. Although rapid sintering generally increased bond strength, the relative performance pattern of the surface-treatment procedures remained similar under slow and rapid sintering conditions. This finding may indicate that surface conditioning contributed to zirconia-resin bonding in a relatively stable manner despite sintering-related microstructural variations (4,8,15). Previous studies have shown that zirconia bonding is strongly influenced by surface treatment together with adhesive chemistry and surface morphology, whereas sintering protocols may alter zirconia microstructure and phase composition to varying extents (11,16). Therefore, the absence of interaction should not be interpreted as evidence that laser treatment overrides sintering-related effects. Rather, under the present experimental conditions, surface treatment appeared to represent the more influential determinant of immediate bonding performance, consistent with the larger effect size observed for this factor ($\eta^2 = 0.872$) compared with sintering protocol ($\eta^2 = 0.237$).

Rapid sintering produced significantly higher μSBS values than slow sintering across all surface-treatment conditions. Previous studies suggest that accelerated thermal cycles may influence zirconia densification behavior, grain characteristics, and phase composition, although the reported effects remain inconsistent depending on zirconia composition and sintering parameters (12,13,16). Therefore, the improved bond strength observed in the rapid sintering groups in the present study should be interpreted cautiously. One possible explanation is that sintering-related material differences may have influenced zirconia-resin bonding by altering zirconia microstructure, surface characteristics, or the effectiveness of adhesive and surface-conditioning procedures (12,13,15,17,18). However, because no direct microstructural or surface-characterization analyses were performed in the present study, any interpretation regarding the underlying mechanism remains hypothetical.

The literature does not provide a completely uniform picture regarding the mechanical implications of rapid sintering. Some studies report preserved or even improved properties, whereas others describe changes in grain-boundary features or phase composition after

MMDJ
MEANDROS MEDICAL AND DENTAL JOURNAL
September 2026 27(3):447-455
Meandros Medical and Dental Journal
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accelerated thermal cycles (13,19-21). This issue may be particularly important for 5Y-TZP, in which the cubic phase content is higher and the contribution of transformation toughening is already reduced compared with conventional zirconia (2,3,22). For that reason, although rapid sintering improved immediate bond strength in the present study, its long-term structural consequences deserve further investigation.

The laser parameters used in the present study were selected according to previously reported Er:YAG laser irradiation settings applied to zirconia (20,23). The lower-energy condition (200 mJ, 15 Hz, 3 W) was comparable to parameters previously used in zirconia bonding studies (20), whereas the higher-energy condition (335 mJ, 15 Hz, 5 W) corresponded to settings used for evaluating zirconia response to Er:YAG laser irradiation (23). Although the objectives of these studies differed, both investigated the response of zirconia to Er:YAG laser exposure and support the conclusion that the selected parameters fall within previously studied irradiation ranges. Differences in energy delivery may influence the extent of surface modification and consequently bonding behavior; however, because no direct surface characterization was performed in the present study, mechanistic interpretation should remain cautious.

With respect to irradiation mode, the 5 W slight-contact subgroup showed the highest μSBS values under both sintering schedules, whereas the 3 W non-contact subgroup demonstrated the lowest performance. These results suggest that the manner in which laser energy reaches the zirconia surface may influence bonding performance. In non-contact mode, some energy may be lost before reaching the target surface, which could limit the degree of microtopographic modification (24). In contrast, slight-contact positioning may deliver energy in a more concentrated and localized fashion, which may have contributed to greater surface irregularities and improved micromechanical interlocking (6,24).

When surface-treatment procedures were evaluated irrespective of sintering protocol (Table 3), slight-contact Er:YAG laser irradiation, particularly at 5 W, produced the highest overall μSBS values, whereas non-contact 3 W irradiation demonstrated the lowest performance. This finding may have practical relevance, as clinicians may not always have access to detailed information regarding the specific sintering workflows used during laboratory fabrication. Given that surface treatment exhibited the largest effect size in the present study ($\eta^2 = 0.872$), evaluating the overall performance of conditioning methods may provide a more clinically applicable perspective. Within the limitations of this in vitro study, 5 W slight-contact Er:YAG laser irradiation showed the most favorable bonding performance among the tested surface-treatment procedures. This may be attributed to more localized energy delivery, facilitating effective microtopographic modification and improved micromechanical interlocking (6,15,17,24). Nevertheless, these observations should be interpreted cautiously, since long-term durability and possible microstructural effects were not assessed.

At the same time, laser treatment of zirconia requires careful control. When energy input is excessive, microcracks, localized melting, or unfavorable tetragonal-to-monoclinic transformation may occur (25). Although 5Y-TZP contains more cubic phase and exhibits lower transformation toughening than 3Y-TZP, it is also less prone to stress-induced phase transformation (11). The findings of the present study suggest that the selected irradiation parameters may have promoted more favorable bonding performance without obvious adverse effects on immediate μSBS values. The relatively low μSBS values observed in the 3 W non-contact groups may indicate that insufficient energy delivery was less effective in creating surface conditions favorable for adhesion, although the underlying mechanism remains unclear. The relatively high μSBS values observed in the present study should be interpreted with caution when compared with previous zirconia bonding reports. Variations in bonding area, specimen geometry, loading configuration, and testing setup may substantially influence stress distribution and the calculated bond strength values obtained from microshear testing. In particular, the relatively small bonding area used in the present study may have reduced defect probability and altered stress concentration patterns, potentially contributing to higher measured values. Therefore, comparisons across studies should consider methodological differences rather than absolute bond strength values alone. From a clinical perspective, although there is no universally accepted minimum bond-strength threshold for zirconia, higher μSBS values are generally considered more favorable for resistance to debonding under functional stresses (4,15). Nevertheless, immediate laboratory μSBS outcomes should not be interpreted as a direct indicator of long-term clinical success, as hydrolytic degradation, thermomechanical fatigue, and chemical aging may compromise the durability of the resin-zirconia interface over time (19,25).

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Overall, the present findings support the view that laser-assisted zirconia conditioning is influenced by factors such as sintering history and irradiation parameters. Although 5 W slight-contact Er:YAG laser irradiation showed the most favorable bonding performance across the conditions tested in the present study, the response of zirconia may vary according to material composition, as reported in previous studies (17,23,24). Therefore, while this specific irradiation approach may represent a promising option for improving zirconia-resin bonding, adhesive strategies should always be selected with consideration of the specific zirconia material and manufacturing workflows involved.

This study has several limitations. It was conducted entirely in vitro and did not include aging procedures, such as thermocycling, prolonged water storage, or mechanical fatigue simulation, which may limit the interpretation of long-term zirconia-resin bond durability and clinical relevance. In addition, no phase-transformation analysis or surface-characterization method was performed, which prevents direct correlation between bonding outcomes and specific microstructural changes. Future studies should incorporate aging procedures, surface analyses, and zirconia materials with different yttria contents to clarify the long-term clinical reliability of these treatment approaches.

CONCLUSION

Within the limitations of this in vitro study, both sintering schedule and Er:YAG laser application mode significantly influenced the bond strength of monolithic 5Y-TZP zirconia. The larger effect size observed for surface treatment indicates that controlled surface conditioning is particularly important for improving zirconia-resin bonding. Slight-contact Er:YAG laser irradiation at suitable power settings may represent a useful alternative for enhancing bonding performance, particularly under rapid sintering conditions. However, the durability of this interface under aging conditions remains uncertain, and further studies including long-term aging and surface-characterization methods are needed before definite clinical conclusions can be drawn.

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Artificial intelligence tools were used only for language editing and grammatical improvement of the manuscript. No AI tools were used in the generation of scientific content, data analysis, or interpretation of the study findings.

Authorship contributions
Concept and design: MH, HSB; Supervision: MH; Funding: MH, HSB; Materials: MH; Data collection and/or processing: MH; Analysis and/or interpretation: MH, HSB; Literature review: MH; Writing-original draft preparation: MH; Critical revision of the article: MH, HSB; All authors reviewed the results and approved the final version of the manuscript.

Data availability statement
The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of competing interest
The authors declare no competing interests.

Ethics
Ethical approval was not required for this study because no human participants or animals were involved.

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