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Abstract. Lasers have the potential for reducing the required debonding force and can prevent the mechanical damage given to the enamel surface as a result of conventional debonding procedure. However, excessive thermal effects limit the use of lasers for debonding purposes. The aim of this study was to investigate the optimal parameters of 1940-nm Tm: fiber laser for debonding ceramic brackets. Pulling force and intrapulpal temperature measurements were done during laser irradiation simultaneously. A laser beam was delivered in two different modes: scanning the fiber tip on the bracket surface with a Z shape movement or direct application of the fiber tip at one point in the center of the bracket. Results showed that debonding force could be decreased significantly compared to the control samples, in which brackets were debonded by only mechanical force. Intrapulpal temperature was kept equal or under the 5.5°C threshold value of probable thermal damage to pulp. Scanning was found to have no extra contribution to the process. It was concluded that using 1940-nm Tm: fiber laser would facilitate the debonding of ceramic brackets and can be proposed as a promising debonding tool with all the advantageous aspects of fiber lasers. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JBO.21.6.065007](https://doi.org/10.1117/1.JBO.21.6.065007)]

Keywords: laser debonding; 1940-nm Tm: fiber laser; ceramic brackets; intrapulpal temperature.

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1 Introduction

Ceramic brackets were introduced to orthodontics to meet the increasing demand for esthetic appearance. However, ceramic brackets with inert aluminum oxide composition need relatively stronger bonds than metal brackets, which have mesh gauze providing better adhesion. Strong bonding may result in irreversible enamel damage in the form of cracks and delamination that often need dental restorations. Mechanical, ultrasonic, electrothermal, and laser debonding techniques have been investigated so far.¹⁻⁴ Each method has its own limitations. One of the most popular mechanical debonding methods is the application of the blades of a debonding plier near the enamel surface. This method is quick and simple but mechanical damage on the enamel surface causes poor esthetics and increases the risk of long-term diseases of the affected tooth.^{4,5}

Use of lasers in the debonding procedure has been under investigation for decades. Laser energy can pass within the ceramic bracket and reach the adhesive material. Laser energy softens the adhesive and it results easy debonding with less mechanical force. Various lasers have been studied experimentally to find out the best laser dose and application method to reduce the debonding force needed, risk of enamel damage, and incidence of bracket fractures, and to establish a potentially less traumatic and less painful treatment (Table 1). Laser parameters {wavelength, power, mode [continuous wave (CW) or modulated], exposure time}, type of brackets (mono- or polycrystalline), type of adhesive materials, and application procedure (irradiating the bracket before or during mechanical pulling) are the parameters tested. Required debonding force, intrapulpal temperature, enamel surface inspection [adhesive remnant index (ARI) scores], and debonding time are the main components measured to test the efficiency of laser application. Less force and less debonding time with respect to the positive control

are accepted as successful. In addition, 5.5°C intrapulpal temperature increase is set to a threshold as a rule of thumb to prevent any irreversible thermal damage to the pulpal tissue.⁶

In this study, a 1940-nm Tm: fiber laser was utilized as the laser source for debonding ceramic brackets. In previous studies, 1070/1444 of Nd:YAG, 10,600 nm CO₂, Er:YAG, Tm:YAP, and diode lasers have been investigated for ceramic bracket debonding. Researches have verified that adhesive material between the enamel and the ceramic bracket base can be softened by laser energy. Lasers have their own advantages and disadvantages due to the optical properties of brackets, adhesives, and also dental tissue. A number of previous studies focused on a CO₂ laser, which emits radiation at 10.6 μm. This laser wavelength is strongly absorbed by water and hydroxyapatite, thus it can cause thermal ablation and carbonization on the enamel surface. Other infrared lasers (1064-nm Nd:YAG, 1071-nm fiber, and so on) are poorly absorbed by those layers, and can reach intrapulpal cavity resulting in temperature increase.

In this study, a 1940-nm Tm: fiber laser is investigated as a debonding aid. A similar wavelength was examined previously by Dostalova et al. In the research of Dostalova et al.¹⁵, a Tm:YAP laser (wavelength 1998 nm, power 1 W, irradiance 14 W/cm², and interacting time 60 s) with two power settings (1 to 2 W) was utilized to debond the ceramic brackets and it was found that 1998-nm Tm:YAP laser irradiation together with moderate cooling could be an efficient tool for debonding. In this study, different energy levels of similar wavelength with different application methods were tested. The wavelength of 1940-nm Tm: fiber is in between CO₂ and Nd:YAG in terms of optical properties of water and hydroxyapatite; therefore, a better adhesive softening than CO₂ laser and less intrapulpal temperature increase than Nd:YAG laser is expected. Also, fiber lasers are easier to use because of their extended lifetime and

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Table 1 Laser studies.

Researcher	Lasers	Highlights	Methods
Strobl et al. ⁷	CO ₂ (10,600 nm), Nd:YAG (1964 nm)	Reduced debonding force, thermal softening	The average torque force needed to debond the brackets and change in intrapulpal temperature was measured at different times
Tocchio et al. ⁸	KrF (248 nm), XeCl (308 nm), Nd:YAG (1064 nm)	Ablation, thermal softening, faster debonding	Only measurement of debonding times and forces was performed
Obata ⁹	CO ₂ (10,600 nm)	Different bonding agents, thermal softening and contraction, acceptable intrapulpal temperature increase	The SBS of the orthodontic brackets attached was measured. Also, the pulp cavity temperature was recorded using the same laser irradiation conditions as the shear test
Mimura et al. ¹⁰	CO ₂ (10,600 nm)	Thermal softening and contraction	The laser-aided debonding of ceramic brackets from enamel surfaces was compared between two different adhesives. So, only debonding forces were recorded during the debonding process
Rickabaugh et al. ¹¹	CO ₂ (10,600 nm)	Modified debonding pliers, linear relationship between lasing time and intrapulpal temperature change	The length of lasing time for the static force to debond the bracket was measured along with the increase in intrapulpal temperature
Ma et al. ¹²	CO ₂ (10,600 nm)	Thermal softening, linear relationship between lasing time and intrapulpal temperature change	Debonding force and intrapulpal temperature changes during ceramic orthodontic bracket removal using a carbon dioxide laser were recorded simultaneously
Abdul Kader and Ibrahim ¹³	CO ₂ (10,600 nm)	Asynchronous laser application causes higher debonding force	Debonding force and intrapulpal temperature change measurements were performed asynchronously
Hayakawa ¹⁴	Nd:YAG (1064 nm)	Different adhesive materials, intrapulpal temperature measurements	Bond strength and thermal effects of the laser on the dentin surface were assessed at the same time
Dostalova et al. ¹⁵	Tm:YAP (1980 nm), GaAlAs (808 nm), Nd:YAG (1064 nm), ytterbium fiber laser (1070 nm)	Unacceptable temperature increase, cooling methods applied	Debonding force and measurement temperature rise measurements during laser irradiation were performed simultaneously in each experiment
Kabas and Gulsoy ¹⁶	Ytterbium fiber laser (1070 nm)	CW and modulated mode laser application, synchronous lasing and debonding, acceptable temperature increase	Debonding force and temperature change measurements were performed simultaneously
Ahrari et al. ¹⁷	CO ₂ (10,600 nm)	Temperature measurements, ARI scores	Debonding force and the increase in intrapulpal temperature measurements were collected at different times
Almohaimeed and El Halim ¹⁸	Diode laser (980 nm)	SBSs and ARI scores assessments	After laser pulse had been applied, the shear bond test was performed
Macri et al. ¹⁹	CO ₂ (10,600 nm)	SBS, temperature in the bonding composite and in the pulp chamber, ARI score evaluations	The SBSs were measured after the irradiation of CO ₂ laser
Saito et al. ²⁰	CO ₂ (10,600 nm)	Bond strengths and intrapulpal temperature measurements	Bond strengths were measured after laser irradiation. Subsequently, the temperature in the pulp chamber during laser application was recorded
Nalbantgil et al. ²¹	Er:YAG (2940 nm)	Debonding force and intrapulpal temperature measurements	Debonding force measurements were recorded 45 s after the laser irradiation
Mundethu et al. ²²	Er:YAG (2940 nm)	Debonding force measurements, bracket failure and SEM analysis of the enamel-adhesive interface	Only mechanical debonding force measurements were performed during laser application

Table 2 Groups of experiment in different laser power, laser durations, and irradiation methods.

Applied laser energy (J)	Laser power (W)	Laser durations (s)	Application methods
30	3.0	10	Scanning/no scanning
25	2.5	10	Scanning/no scanning
21	3.0	7	Scanning/no scanning
No laser application	Nonlasing group	—	—

compact size. Laser output is controlled efficiently and it can be delivered via silica optical fibers.

The significance of this study was to determine the optimum parameters for 1940-nm Tm: fiber laser irradiation with the goal of establishing an effective method for debonding ceramic orthodontic brackets to prevent tooth-enamel cracks, pain, and esthetic drawbacks. Different laser energy doses were delivered to the ceramic brackets using a 1940-nm Tm: fiber laser with or without a scanning method. Also, laser energies were applied on the surface of the brackets with different laser durations. Groups of experiment in different laser power, laser durations and irradiation methods are given in Table 2. During laser irradiation, debonding force and intrapulpal temperature measurements were recorded simultaneously. After the debonding process, the enamel surfaces were examined microscopically.

2 Materials and Methods

Freshly extracted bovine mandibular incisors were selected because of their availability, higher hygiene, and their similarity to human teeth physiologically. Throughout the experiment, polycrystalline ceramic orthodontic brackets for maxillary incisors (GH.US) were selected because of their availability and

common use. The composite resin that was used to bond the polycrystalline ceramic brackets to the tooth surface was the Bis-GMA adhesive resin (3M, Unite Bonding Adhesive Set) because of its high tensile bonding strength.

2.1 Sample Preparation

Cleaned teeth were stored in isotonic solution changed three times per week. Before each experiment, 1 mm of lingual cavities was opened by a diamond bur to place thermocouple inside the pulp chamber. All teeth specimens were measured and similar ones were selected in terms of enamel thickness (2.56 ± 0.20 mm). Teeth samples were embedded in gypsum blocks. Ceramic brackets were bonded according to the recommendations of the manufacturer. The bonding interface of enamel and bracket base was axially centered and bonded parallel to the front side of the gypsum block. The bracket was positioned at the opposite side of the opened cavity on the labial surface of the tooth. Then, the bracket was pushed tightly toward the tooth in one-point contact. Each sample was stored in an incubator for 48 h to ensure the composite polymerization. All experiments and procedures were performed in accordance with ethical standards of animal experimentation approved by the Institutional Ethics Committee for the Local Use of Animals in Experiments of Bogazici University (BÜHADYEK) by researchers who have a laboratory animal study certificate.

2.2 Experimental Setup

A 1940-nm Thulium Fiber Laser System (IPG Laser, TLR-5-1940, Germany) was used in CW mode. The output power of the laser was measured by an optical power meter (Newport, Model 1918-C) at the beginning of the each experiment. Output of the Tm: fiber laser was coupled with a silica optical fiber with 400- μ m diameter (Thorlabs, FT400EMT) (Fig. 1). During laser application, the debonding force was measured with a modified universal testing machine (Ametek Lloyd Instruments, LF Plus, United Kingdom). Special gripping jaws and a testing frame were designed and implemented for placing the gypsum block properly. The testing machine was set to pull

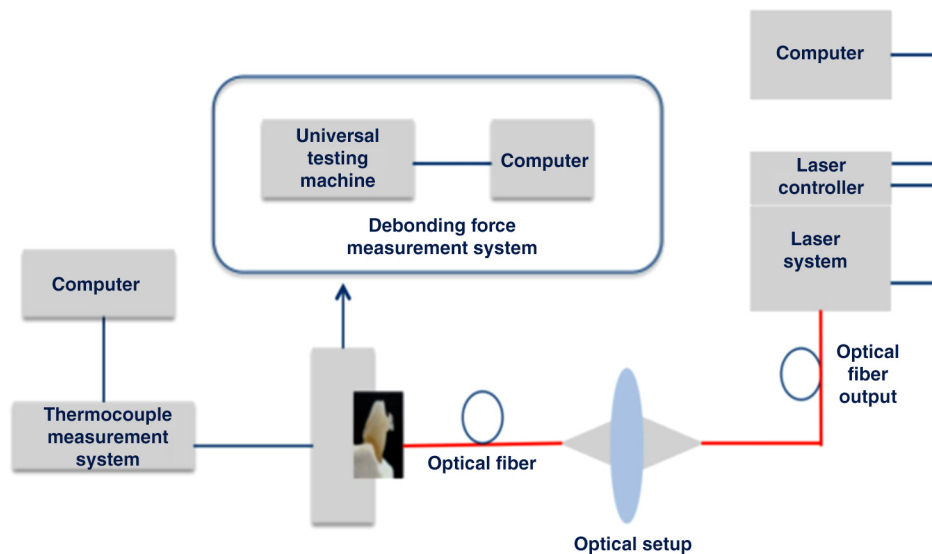


Fig. 1 Experimental setup was consisted of the 1940-nm Tm: fiber laser system, K-type thermocouple measurement system, and universal testing machine.

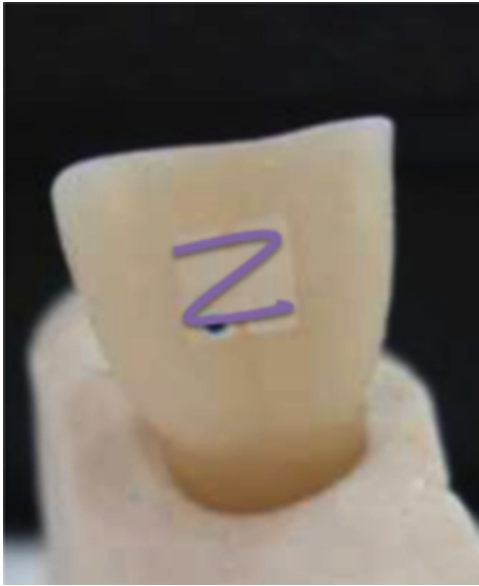


Fig. 2 The applied scanning movement on the polycrystalline ceramic bracket surface (GH.US) by the 1940-nm Tm: fiber laser application tip of 400 μm .

the bracket with a constant speed of 1 mm/min. During the debonding procedure, intrapulpal temperature changes were recorded by a *K*-type thermocouple system (OMEGA, OM-CP-0CTTEMP, United Kingdom).

2.3 Experimental Procedure

The proper output energy levels of the 1940-nm Tm: fiber laser were determined after the preliminary studies due to the intrapulpal temperature changes during the laser irradiation by this laser. Previous studies, in which a very close laser wavelength and laser power used, were also considered to determine the optimum parameters for 1940-nm Tm: fiber laser.¹⁵ Samples were grouped with respect to laser doses and application methods.

Laser irradiation was applied to the thinnest part of the bracket at one point in the center of the bracket for non-scanning groups. The fiber tip of the waveguide was located consistently as close as possible to the labial surface of the polycrystalline

ceramic brackets. For other groups, by scanning the fiber tip on the bracket surface, laser irradiation was delivered. It was a “Z” shape movement starting from the upper distal wing and ending at the opposite corner as shown in Fig. 2.

The samples of the control group were not irradiated; debonding force without any laser energy was recorded. Intrapulpal temperature was also measured.

Silicon thermal paste (BAKIR, R-1260 Silicon Gress, Turkey) was applied manually into the lingual cavity of every sample to mimic the intrapulpal conditions. The *K*-type thermocouple was located into the lingual cavity and the tip of the thermocouple was in touch with the intrapulpal wall of the tooth. The shear test, measurement of intrapulpal temperature changes, and application of laser irradiation were all done synchronously. At the moment of the debonding of the orthodontic ceramic bracket, the shear force dropped suddenly and this breaking point was the end of the procedure. Load at the breaking point was defined as the debonding force. After the replacement of the bracket, the enamel surface was examined in terms of resin remnant on the enamel surface and bracket base and a semiquantitative evaluation was done. The effect of laser application was tested in terms of breaking loads, i.e., debonding forces, and intrapulpal temperatures for all groups. ANOVA and *t*-test ($p < 0.05$) were performed to determine statistically significant differences.

3 Results

3.1 Debonding Force

A shear bond strength (SBS) test was done by a universal testing machine. Maximum value at the debonding moment of orthodontic ceramic brackets for load was named as the debonding force. Three-way ANOVA test results showed that some of the laser groups were significantly different from each other. Scanning mode and non-scanning mode groups were also compared and ANOVA results showed that both groups were different from the control group. Laser groups having the energy of 25 J or above were found to be effective in terms of debonding force. Compared to the control group, reduction in debonding force in those laser groups was almost more than 50%.

The 3-W 10-s laser groups of scanning and non-scanning modes were found significantly different ($p < 0.05$, student

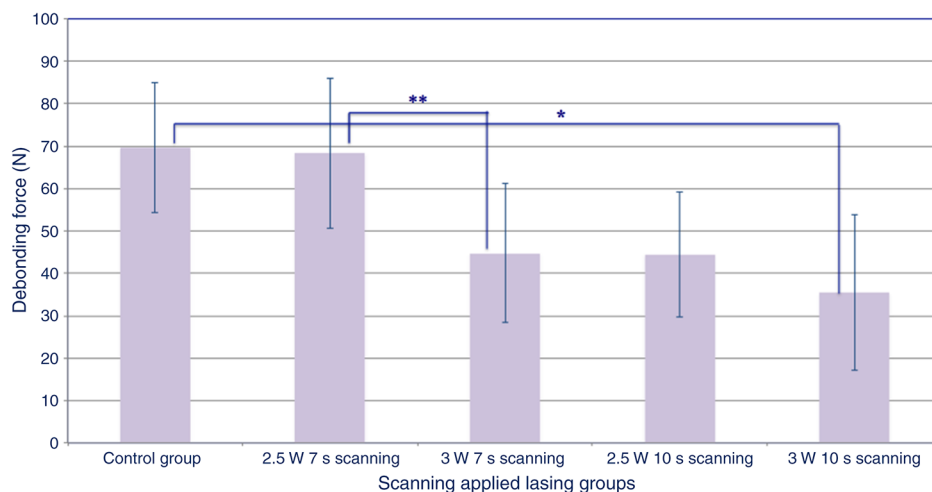


Fig. 3 Debonding force values of scanning laser groups. 3-W 10-s dose was found significantly lower than the control group (*) ($p < 0.05$). The comparisons between the laser groups indicated that 3.0-W 7-s laser group had significantly less debonding force from 2.5-W 7-s laser group (**) ($p < 0.05$).

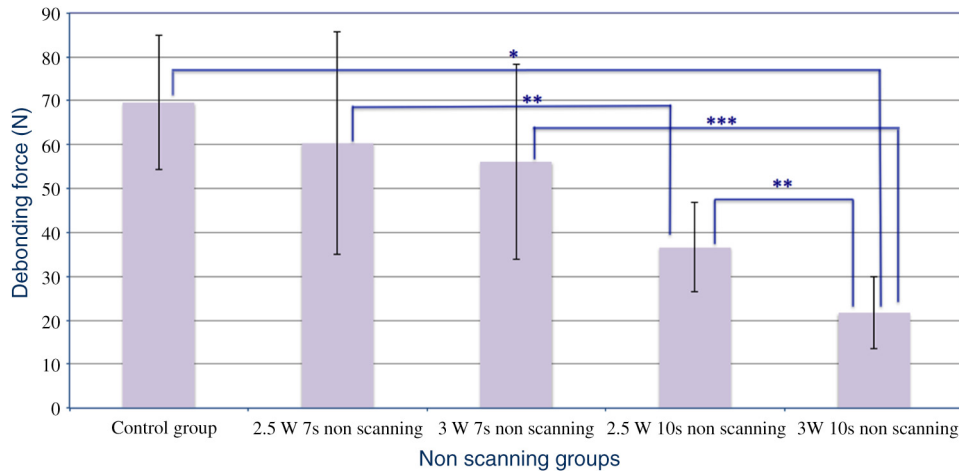


Fig. 4 Debonding force values of non-scanning laser groups. 3-W 10-s dose was found significantly lower than the control group (*) ($p < 0.05$). Among the irradiated lasing groups, 2.5-W 10-s lased group was found statistically different from both 2.5-W 7-s and 3.0-W 10-s lasing groups (**) ($p < 0.05$). The comparisons between the lasing groups indicated that 3.0-W 10-s lased group had significantly less debonding force from 3.0-W 7-s lasing group (***) ($p < 0.05$).

t-test.) from the control groups in both experiments (Figs. 3 and 4).

Scanning and non-scanning laser groups were also compared. For the same laser energy performed, the scanning irradiation method did not show any difference in terms of debonding force decrease.

3.2 Intrapulpal Temperature Changes

In the proposed study, 5.5°C is accepted as a benchmark value for all specimens to prevent pulpal damage during laser irradiation in accordance with Zach and Cohen's⁶ studies. Mean and standard deviations for intrapulpal temperature changes during laser application for each group are given in Table 3. However, because of high standard deviations, only three of the groups (2.5-W 7-s non-scanning, 3.0-W 7-s scanning, and 3.0-W 10-s non-scanning laser groups) were in the safe region, sufficiently under the 5.5°C threshold value. The significant differences were observed between 3.0-W 7-s scanning and 2.5-W 7-s scanning laser groups and 3.0-W 10-s non-scanning and 2.5-W 10-s non-scanning laser groups ($p < 0.05$, student *t*-test).

3.3 Bracket Surface Evaluation After Debonding Process

In the evaluation of the bracket bases, in more than 50% of samples with energies 25 J or more, adhesive remnants were not observed on enamel surfaces for the laser groups. Adhesive remnants were observed at the base of the brackets. In order to analyze the amount of adhesive material adhered to the enamel surfaces of the specimens after laser-assisted debonding, the surfaces before and after removal of the brackets were photographed by a digital handheld microscope (Motic EcoLine D-EL1 Digital Handheld Microscope) as shown in Fig. 5. Moreover, carbonization of the adhesive material was not observed at the enamel surface after debonding.

4 Discussion

The previous studies showed that lasers could significantly decrease the required debonding force to remove orthodontic ceramic brackets. This prevents mechanical damage given to

the enamel surface. However, thermal considerations were the bottleneck of those applications, especially intrapulpal temperature increase.

In this study, a 1940-nm Tm: fiber laser was proposed as a laser source for debonding ceramic brackets. Both debonding force and intrapulpal temperature change measurements were performed simultaneously during the laser irradiation and this provides a better understanding of the process. Most of the research studies had the lack of simultaneous measurement advantages (Table 1).

When this study was compared to the other methods in the literature, the specific value of it is that both debonding force and intrapulpal temperature change measurements were performed simultaneously during the laser irradiation. Results indicated that the debonding force could be decreased significantly compared to the control samples, in which brackets were

Table 3 Intrapulpal temperature increase. The significant difference was observed between 3.0-W 7-s scanning and 2.5-W 7-s scanning laser groups (*) ($p < 0.05$, student *t*-test). The comparisons between lasing groups showed that 3.0-W 10-s non-scanning and 2.5-W 10-s non-scanning laser groups were also statistically different (**) ($p < 0.05$, student *t*-test).

Laser power (W)	Laser durations (s)	Mean temperature increase (°C)	Irradiation methods
2.5*	7	5.02 ± 1.67	Scanning
3.0*	7	3.56 ± 0.92	
2.5	10	4.27 ± 0.89	
3	10	6.21 ± 3.45	
2.5	7	3.86 ± 1.20	No scanning
3.0	7	4.82 ± 3.10	
2.5**	10	5.57 ± 2.06	
3.0**	10	3.92 ± 0.89	

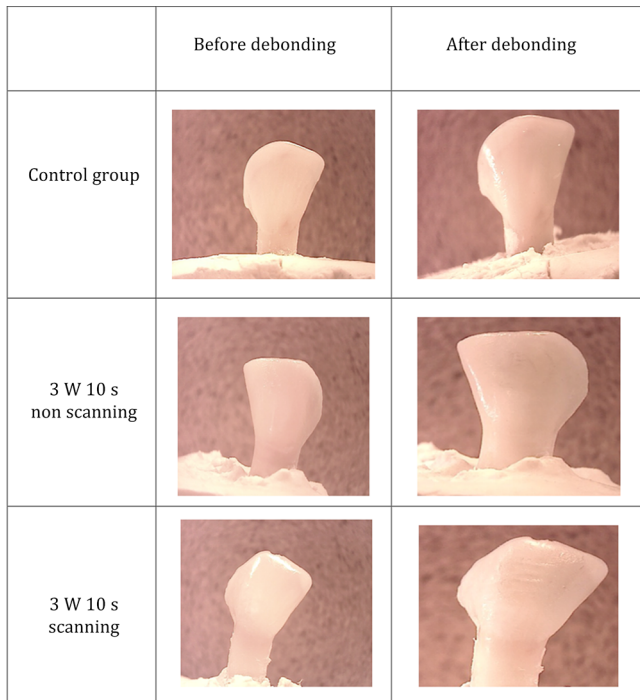


Fig. 5 Enamel surface images before and after laser debonding processes for the lasing groups having the energy of 25 J or above. Carbonization of the adhesive material did not occur at the enamel surface after debonding.

debonded by only mechanical force. Intrapulpal temperature was kept equal or under the 5.5°C threshold value for all the laser applications. The optimum laser power and exposure time were determined around 2.5 to 3 W and 7 to 10 s, respectively, by preliminary tests, which were not reported here. Samples were tested within this dose range with two different application modes: scanning the laser beam on the bracket or direct irradiation to the center. Scanning method was performed to distribute the converted thermal energy equally on the bracket base and with the aim of degrading the adhesive on the bracket base through the thermal softening.^{21,23} Results showed that increasing the power from 2.5 to 3 W for 10-s laser duration in the experiments of non-scanned lasing groups and for 7-s laser duration for scanning mode lasing groups caused a significant decrease in debonding force. However, when the laser was applied to the center of the bracket increasing the power did not provide enough decrease. But when the exposure time was increased, debonding force was reduced significantly. Increasing the exposure time by setting other parameters constant decreased the debonding force in non-scanned groups.

Intrapulpal temperature was found equal or under the 5.5°C for almost all groups. For some groups, this threshold value was exceeded slightly and for some groups it was safely under that value. Hayakawa¹⁴ reported that the temperature of the pulp wall began to increase to its maximum point immediately after irradiation by laser. Unlike the given conclusion by Hayakawa, Obata⁹ reported that the temperature rise in the pulp chamber starts 3 s after lasing. The average temperature changes of the pulp walls of the laser groups are compared with the results of previous studies of Zach and Cohen. According to their study, no pulp damage was found with an intrapulpal temperature increase of 1.8°C when laser irradiation was applied on the samples. The histological study of Zach and Cohen⁶ on monkeys

showed that the increase in intrapulpal temperature changes should be below 5.5°C. We also defined 5.5°C change as the threshold value. The intrapulpal temperature increase might be less for *in vivo* conditions. Perfusion of the pulpal tissue would cool down the heated tissue. Thus the results could be interpreted as satisfying. Changing the scanning mode and exposure time did not have any significant effect on the intrapulpal temperature change. However, a significant change was observed for changing the laser power from 2.5 to 3.0 W for different laser durations. In the study of Ma et al.,¹² a linear relationship between lasing time and an increase in intrapulpal temperature was reported. In contrast to the study of Ma et al., the results of this study did not reveal a linear relationship in the intrapulpal temperature change. For example, temperature was decreased when the laser power was increased from 2.5 to 3 W for the laser durations of 7 s with the scanning irradiation method. This might be the result of the inhomogeneities of the sample teeth; the variation of the results was found for 2.5-W group.

Moreover, one of the determinants of intrapulpal temperature increase was the lasing method. As reported by Nalbantgil et al.,²¹ laser irradiation by a scanning method could be the most effective and safest way to remove ceramic brackets without leading to a side effect of pulpal cavity.²³ Therefore, a scanning mode of application was expected to give a better result in terms of reduction of the debonding force as well as intrapulpal temperature change compared to the direct application. However, results did not support this hypothesis for the 1940-nm Tm: fiber Laser. The only significant difference was found for the debonding force in the 3-W 10-s group but the change was in the other direction, i.e., scanning did not produce reduction; direct irradiation indicated better conclusions. Perhaps as a result of the manual application of scanning, direct irradiation was easier and more reliable to apply. Thus, this result is advantageous for clinical applications; a simpler technique is more preferable.

Laser irradiation is required to soften the adhesive material in the bonding interface between enamel and adhesive agent. Any process that degrades the bonding resin makes the debonding procedure easier. All in all, from the physical and chemical point of view, the bond between the composite resin and the enamel could be broken by laser irradiation. According to the study of Tocchio et al.,⁸ laser debonding could be achieved by thermal softening, thermal ablation, and photo ablation of adhesive material. Decomposition of the adhesive material is gained by heat transmitted through the orthodontic bracket in thermal softening. Thermal softening is accepted as a responsible debonding mechanism for this study because a softened adhesive agent on the base of the ceramic bracket after the debonding process occurred. Neither thermal ablation nor photo ablation is reported during the recent study. By utilizing the results of this experiment, it can be concluded that this study agrees with the study of Tocchio et al.,⁸ Rickabaugh et al.,¹¹ and Strobl et al.⁷ According to their studies, laser irradiation during the debonding process can effectively and thermally soften the adhesive resin to cause ceramic bracket removing. Mimura et al.² and Obata⁹ stated that both thermal softening and resin contraction from orthodontic ceramic brackets could be responsible for the mechanism of debonding. In contrast, Hayakawa started debonding after lasing, not during lasing. Hayakawa mentioned that the mechanism of laser debonding was not traditional thermal softening because they observed some specimens debonded immediately after laser irradiation without mechanical effects.¹⁴

In this study, the bracket debonding was performed simultaneously with the laser irradiation and real-time intrapulpal temperature change was recorded. The results of the previous studies showed that even a 1-min latency between laser irradiation and debonding process concluded in the need of higher debonding forces compared to the control group.¹⁵ We carried out the procedure simultaneously, hence, there was no such problem. For clinical usage, it would be wise to design a probe in which the expert can both apply manual force and laser irradiation in the mean time.

Moreover, in the study of Pickett et al.,²⁴ the differences between *in vivo* and *in vitro* studies were investigated. It was reported that *in vitro* bond strength values might be higher than those obtained *in vivo*. In the present *in vitro* study, for the control samples, an average debonding force of 69.61 ± 15.26 N was needed to remove the ceramic brackets without lasing. The 30-J lasing groups produced significantly the best reduction in debonding force compared to the control group. Groups of lasing 25 J also had significantly considerable reduction in bond strength when compared to the nonlasing group. Statistical analysis indicated the significant differences to be at the 0.05% level. The results of the experiment were in agreement with the previous researches, supporting that lasers could be effective for ceramic bracket debonding by using a thermal softening debonding mechanism. Also, all types of lasers utilized for removing were effective in decreasing debonding force and simplifying ceramic bracket debonding.^{17–20}

Moreover, results of the current experiment were consistent with the study of Mimura et al. for methyl-methacrylate resin and Strobl et al. for polycrystalline ceramic brackets. Mimura mentioned that debonding force was reduced at 3-W laser output by using CO₂ laser (10,600 nm) (from an average value of 122.40 to 35.57 N). Strobl et al.,⁷ produced a 1.3-fold decrease in the total energy required for debonding by using a CO₂ laser with a power of 14.1 W for 2-s laser duration onto polycrystalline ceramic brackets. In this study, as a result of reduced laser energy and degraded adhesive material by irradiation of the 1940-nm Tm: fiber laser, a negative correlation was observed between bond strengths and laser energy levels. Debonding was performed more effectively in the 30-J groups than the other energies in two configurations: scanning and non-scanning lasing. This can be expressed by the insufficient laser energy or high rate of decrease in the energy of laser during passing through the polycrystalline brackets. Supporting the results of this study, Han et al.²⁵ had the same percentage of reduction in debonding load by applying the Nd:YAG laser at 1060 nm, pulse width with of 0.2 ms and 3 W for 3 s.

In the evaluation of the enamel surfaces and bracket bases, the examined lasing groups were selected because of the fact that they were also found statistically different compared to the control group in both scanning and non-scanning laser application modes in terms of measured debonding force ($p < 0.05$, student *t*-test.). Herein, in more than 50% of samples with energies 25 J or more, adhesive remnant was not observed on enamel surfaces for the laser groups as shown in Fig. 5. In the bases of ceramic brackets, adhesive remnant was observed. For this study, this situation was accepted as an advantage. If residual adhesive was totally observed on the enamel surface, the probability of the enamel damage would be worse because of using a bur. No carbonization of the adhesive material was observed at the enamel surface after debonding. Broken wings were rarely observed after the debonding process found in any of the

specimens. This could be the effects of the manufacturing procedure on the physical characteristics of ceramic brackets.²⁶

In conclusion, results of this study indicated that the proposed laser debonding method served for the reduction of the applied mechanical debonding force. So, it would be a significant solution to the side effects of the debonding procedure, i.e., less mechanical damages on enamel surface. The intrapulpal temperature increase was found in the acceptable range, and with air cooling, this influence can also be minimized in clinical applications. This study introduced the 1940-nm Tm: fiber laser as a debonding aid device for the first time. Further studies can be done for minimizing the heat effect and for implementing a laser-aided debonding probe.

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