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Effects of Diode and Nd:YAG Laser Irradiation on Friction Forces Between Two Types of Ceramic Brackets and Rhodium-Coated Archwires

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Abstract

Introduction: Ceramic brackets have gained increasing popularity among dental clinicians and orthodontic patients but friction is a major concern when using them. This study sought to assess the effects of diode and Nd:YAG (neodymium-doped yttrium aluminum garnet) laser irradiation on friction forces between two types of ceramic brackets and rhodium-coated esthetic archwires.

Methods: Thirty polycrystalline and 30 poly-sapphire brackets were divided into 6 groups (n=10) as follows: (I) control polycrystalline brackets (no laser irradiation), (II) polycrystalline brackets subjected to diode laser irradiation, (III) polycrystalline brackets subjected to Nd:YAG laser irradiation, (IV) control poly-sapphire brackets (no laser irradiation), (V) poly-sapphire brackets subjected to diode laser irradiation, and (VI) poly-sapphire brackets subjected to Nd:YAG laser irradiation. The bracket slots were laser-irradiated on a custom-made table. Sixty 5-cm pieces of rhodium-coated archwires were used for the friction test in a universal testing machine at a speed of 10 mm/min. Ten brackets from the six groups underwent scanning electron microscopy (SEM), X-ray diffraction (XRD) and energy-dispersive X-ray spectroscopy (EDX).

Results: The frictional resistance value of polycrystalline brackets was significantly higher than that of poly-sapphire brackets, irrespective of laser type ($P<0.05$). Irradiation of diode and Nd:YAG lasers, compared with the control group, had no significant effect on friction, irrespective of bracket type ($P>0.05$).

Conclusion: It appears that diode and Nd:YAG laser irradiation cannot significantly decrease the friction. Future studies are warranted on different laser types with variable exposure.

Keywords: Orthodontic Friction, Laser Therapy, Esthetics, Orthodontic Bracket, Ceramics

Introduction

Adults demanding orthodontic treatment without the metallic appearance of orthodontic brackets and wires currently comprise a large portion of orthodontic patients. Thus, orthodontists are obliged to meet the esthetic demands of their patients. Lingual orthodontics, clear aligners, ceramic brackets, and tooth-colored orthodontic archwires are the most recent modalities suggested to meet the esthetic demands of orthodontic patients.[1] Among the available modalities, ceramic brackets have gained more popularity due to their greater similarity to the conventional orthodontic systems and lower need for modification of treatment mechanics while being esthetically acceptable and easily available.[2]

However, aside from some drawbacks of ceramic brackets such as enamel wear, fragility, and difficult bonding, their high friction coefficient and its adverse effect on the treatment course are a major concern for dental clinicians. The friction of ceramic brackets is so high that can cause up to 60% of force loss.[3] Several studies have evaluated the efficacy of different combinations of archwires and brackets, and have reviewed their properties such as surface roughness and friction, their effect on the duration of treatment, and their cost-effectiveness.[4,5]

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For instance, Cacciafesta et al[6] reported that ceramic brackets with metal slots had significantly lower friction than ceramic brackets without metal slots. However, their friction was still higher than that of metal brackets. They concluded that ceramic brackets with metal slots are excellent alternatives to meet both the esthetic and mechanical requirements.

Surface modification has been commonly used in studies on friction or bond strength to reach the desired outcome.[7] For instance, zinc oxide nanoparticle coating has been suggested to decrease the friction between ceramic brackets and orthodontic wires.[8] The application of lubricants is another suggested strategy to decrease the frictional forces.[9] Laser treatment is another emerging, fast-growing modality in dental sciences. Laser irradiation results in energy concentration close to the surface of opaque targets and leads to physicochemical reactions on the surface, which would morphologically alter the ceramic surface. Melting, reorientation of crystals, micro-explosions, and formation of bubble-shaped blisters are among the surface modifications caused by laser irradiation, which may vary depending on the target tissue, laser energy, duration of laser irradiation, and laser wavelength.[10]

Evidence shows that irradiation of high-power CO_2 and excimer lasers for the purpose of glazing results in the smoothness of the surface, without modifying the inherent properties of alumina ceramics (ceramic bracket material).[11] Also, atomic force microscopic observations have shown that the Nd:YAG (neodymium-doped yttrium aluminum garnet) laser provides a smoother ceramic surface compared with acid-etching and air abrasion. The same findings have been reported for the Er:YAG laser, and it has been emphasized that laser irradiation creates significantly lower irregularity than other surface modifications.[12,13]

A systematic review on the effect of laser irradiation on ceramic surface properties discussed that the absorption of Nd:YAG laser by the ceramic structure depends on the water content, surface roughness, and pigmentation of ceramic. Following absorption, laser energy is converted to heat and leads to ceramic surface melting, its re-solidification, volumetric changes, and subsequent morphological modifications in the ceramic surface.[14] Unlike the Er:YAG laser, the diode laser cannot pass through the ceramic and is absorbed by the surface.[15]

Considering all the above, the purpose of this study was to assess the effects of Nd:YAG and diode laser irradiation, as two commonly used lasers in dentistry, on the friction forces between two types of ceramic brackets and rhodium-coated esthetic archwires.

Materials and Methods

Sample Preparation

A total of 35 edgewise polycrystalline alumina ceramic brackets with 0.022 × 0.028-inch slots and 35 edgewise poly-sapphire alumina ceramic brackets with 0.022 × 0.028-inch slots were used in this study. Three brackets of each type were used for scanning electron microscopy (SEM). Also, two brackets of each type underwent X-ray diffraction (XRD) and energy-dispersive X-ray spectroscopy (EDS) for more detailed assessment of ceramic structure and the remaining were used for the friction test.

A total of 30 prefabricated 0.019 × 0.025-inch rectangular rhodium-coated stainless steel archwires were also used. The 5-cm end segments of archwires at both ends were used for the friction test. Table 1 lists the items used in this study.

This experimental study had six groups as follows:

- Group I: Ten polycrystalline brackets without laser irradiation (control group 1)
- Group II: Ten polycrystalline brackets subjected to diode laser irradiation
- Group III: Ten polycrystalline brackets subjected to Nd:YAG laser irradiation
- Group IV: Ten poly-sapphire brackets without laser irradiation (control group 2)
- Group V: Ten poly-sapphire brackets subjected to diode laser irradiation
- Group VI: Ten poly-sapphire brackets subjected to Nd:YAG laser irradiation

The archwires and bracket slots were first cleaned with gauze dipped in ethanol to eliminate any residual oil remaining from the manufacturing process. The brackets then underwent laser irradiation. Table 2 presents the characteristics of diode and Nd:YAG lasers used in this study. The tip diameter was 320 µm for both laser handpieces.

The brackets in groups II, III, V and VI were

Table 1. Items Used in This Study

Items	Number	Manufacturing Company	Characteristics
Polycrystalline brackets	35	Ceramic Dental Brackets, CDB corporation, Wilmington, North Carolina, USA.	Straight-wire edgewise, ceramic bracket 7D-1 series.
Poly-sapphire brackets	35	Ceramic dental brackets, CDB corporation, Wilmington, North Carolina, USA.	Straight-wire edgewise, ceramic bracket 9S-1 series
0.019 x 0.025-inch esthetic archwires	30	Sentalloy, GC Orthodontics, Japan.	Rhodium coated stainless steel archwires
Elastic O-ring	60	Dentaurum intraoral elastics, Dentarum GmbH & Co. KG, Ispringen, Germany.	Elastomer (polymer)

Table 2. Characteristics of Diode and Nd:YAG Lasers Used in This Study

Type of Laser Diode	Diode 980 nm	Nd:YAG 1064 nm
Model	Simpler, Doctor Smile, Italy	LightWalker, Fotona, Slovenia
Emission mode	CW	Pulsed
Time on/time off	CW	650 µs
Delivery system	Fiber optic	Fiber optic
Energy distribution	Gaussian	Gaussian
Peak power	1 W	230.76 W
Average power	1 W	1.5 W
Spot diameter at the focus	320 µm	320 µm
Focus-to-tissue	Yes	Yes
Spot area at the tissue	320 µ	320 µ
Average power density at the tissue	1244 W/cm^2	1866 W/cm^2
Water irrigation	No	No
Air and aspirating airflow	No	No

individually fixed at the center of a mobile custom-made table (Figure 1) with sticky wax. The laser handpiece was fixed to the designed vertical clamp while its tip had a distance of 1 mm from the slot (Figure 2). After ensuring the correct positioning of the bracket and laser handpiece, the table started to move and the operator commenced laser irradiation. The bracket slot was subjected to laser irradiation while moving for a total duration of 15 seconds. During the procedure, another operator carefully monitored the path of movement of the bracket to ensure that it did not deviate from the laser irradiation path.

Friction Test

After laser irradiation, the samples underwent the friction test in a universal testing machine (Z50; ZwickRoell, Ulm, Germany). A fixture, custom designed for this purpose, was used to hold the wire along the direction of load application to the bracket. In this design, a pure load was applied to the bracket along the direction of the wire. The instrument used to pull the bracket had a rigid structure (Figure 3). The applied load caused sliding of the bracket attached to the elastomeric O-ring along the wire. The load cell was calibrated between 0-5 N, and the brackets were dragged over the wire at a speed of 10 mm/min in a 5-mm path.[16] Static friction was measured as the maximum load required to initiate the bracket movement along the wire. The frictional resistance value was calculated by dividing the measured static force by the cross-sectional area of the bracket using the following equation[17]:

$$\frac{frictional\ force}{12.83}$$

Scanning Electron Microscopy/Energy-Dispersive X-Ray SEM/EDS

SEM/EDS (VEGA, TESCAN, Czech republic/Rontec, Germany) with 15 kV accelerated voltage was performed to assess the morphology and composition of ceramics used in the bracket structure. In order to decrease the charge, the samples were gold-coated with a thin layer of gold.

X-Ray Diffraction

XRD (X'Pert PRO MPD, PANalytical, the Netherlands) with a copper target was performed at 40 kV, 40 mA, 0.02 step size, and 5-120˚2θ to identify the crystalline phases in the composition of brackets. The crystalline phases of ceramic brackets were identified and quantified according to the method described by Krimm and Tobolsky.[18] In this method, the percentage of crystallinity (I_c) is calculated by the surface ratio of crystal (A_c) in the diffractogram of the ceramic sample to the total surface (A_t=amorphous + crystalline) in the diffractogram using the equation below:

$I_C = (A_c/A_t) \times 100\%$

Statistical Analysis

Two-way ANOVA was applied to compare the friction and assess the effect of bracket type and laser type on friction with the wire. All statistical analyses were carried out using SPSS version 22 (SPSS Inc., IL, USA) at a 0.05

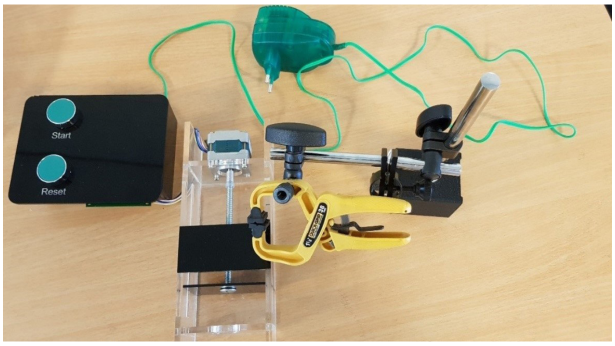

Figure 1. Custom-designed table for movement of bracket during laser irradiation

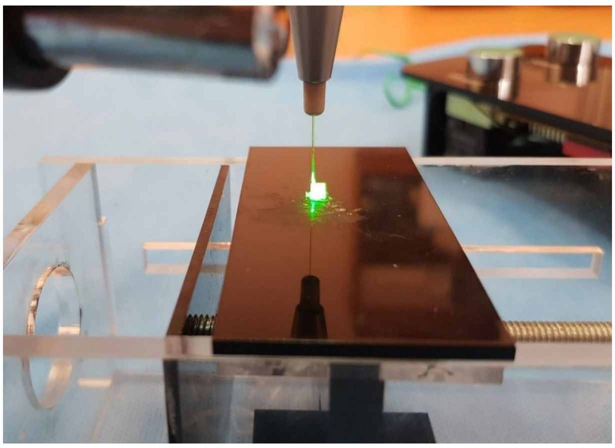

Figure 2. Laser irradiation of bracket slot

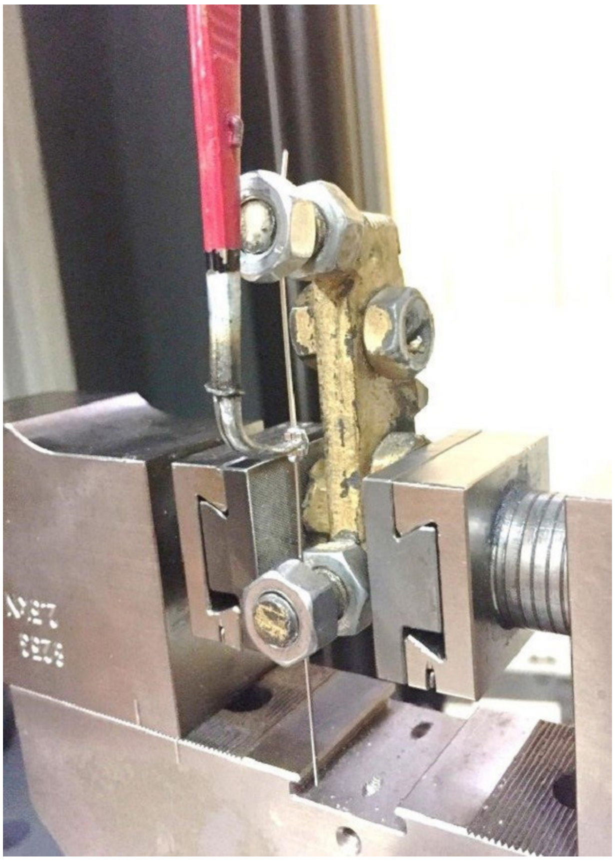

Figure 3. Fixing the wire and bracket to the designed fixture

level of significance.

Results

Friction Test

Table 3 presents the mean frictional resistance value during the bracket movement along the archwire in the six groups.

Evaluation of the effect of bracket type and laser type on the frictional resistance value revealed that the interaction effect of bracket type and laser type on the frictional resistance value was not significant ($P = 0.406$). Comparison of the mean frictional resistance value of the two bracket types revealed that polycrystalline brackets in all three groups of control, diode laser, and Nd:YAG laser had significantly higher frictional resistance value than poly-sapphire brackets ($P < 0.001$).

Comparison of the mean frictional resistance value between the two laser types revealed no significant difference in the same bracket groups of diode laser, Nd:YAG laser and control, which indicates that laser type had no role in increasing or decreasing the friction of ceramic brackets with the wire ($P = 0.427$).

SEM/EDS Findings

The polycrystalline brackets had rougher surfaces than the poly-sapphire brackets and showed irregularly arranged grains on their surface. Also, some particles were noted on their surface that had caused surface irregularities.

The poly-sapphire brackets had distinct, regular grains with clear grain boundaries, creating a uniform surface. Also, the grain size in these brackets was larger than that in polycrystalline brackets, and the grain boundaries were clearer. Laser irradiation of polycrystalline brackets did not cause significant surface modification except for slight rounding of the borders of some grains (mainly by the diode laser). Nonetheless, the diode laser had a more prominent effect on poly-sapphire brackets, and some melting points were observed. Nd:YAG laser irradiation did not have a significant effect on poly-sapphire brackets (Figures 4 and 5).

Table 3. Mean frictional resistance value (N/mm^2) during the bracket movement along the archwire in the six groups (n=10)

Bracket Type	Laser Type	Minimum	Maximum	Mean	Standard Deviation
Polycrystalline	Control	0.13	0.27	0.1850	0.04515
	Diode	0.16	0.33	0.2027	0.04734
	Nd:YAG	0.14	0.28	0.1927	0.04671
Poly-sapphire	Control	0.09	0.19	0.1292	0.03223
	Diode	0.10	0.15	0.1249	0.01817
	Nd:YAG	0.07	0.14	0.1060	0.01940

X-Ray Diffraction Test Results

According to the XRD test results, Al_2O_3 was the main crystalline phase in the composition of both brackets, and the intensity of the peaks of this phase was higher in the conventional polycrystalline ceramic. The percentage of crystallinity was found to be 42.20% in the polycrystalline and 26.13% in the poly-sapphire brackets (Figure 6).

Discussion

Although a combination of ceramic brackets and esthetic archwires can achieve patient and orthodontist satisfaction by creating an exceptional, almost invisible appearance, high friction forces can have adverse consequences such as the application of loads exceeding the biological tolerance threshold of the teeth and loss of posterior anchorage in contemporary orthodontic systems with mainly sliding mechanics.[19] Thus, it is clinically important to assess the friction of different types of ceramic brackets to come up with strategies to decrease it. Aside from the factors such as the method of ligation, the contact angle of bracket and wire, and orthodontic treatment phase, the bracket-wire contact area is another important parameter involved in friction. Some strategies have been proposed to modify the contact area of bracket and wire and subsequently decrease friction. For instance, Tanne et al[20] discussed that friction can be minimized by changing the manufacturing process of ceramic brackets and creating a smoother surface. Thus, in this study, the ceramic bracket slots were irradiated with diode and Nd:YAG lasers to modify their

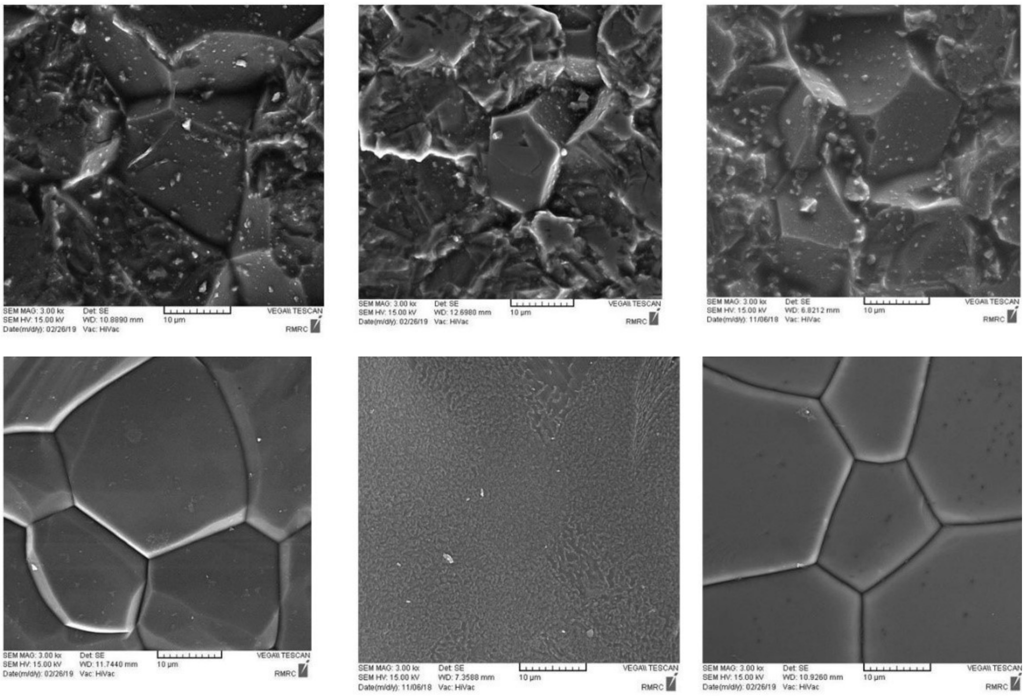

Figure 4. SEM micrographs of (a) polycrystalline bracket without laser irradiation, (b) polycrystalline bracket subjected to diode laser irradiation, (c) polycrystalline bracket subjected to Nd:YAG laser irradiation, (d) poly-sapphire bracket without laser irradiation, (e) poly-sapphire bracket subjected to diode laser irradiation, (f) poly-sapphire bracket subjected to Nd:YAG laser irradiation

surface in contact with the wire and assess the effect of laser irradiation on friction.

Two types of ceramic brackets were tested in this study, including a conventional polycrystalline type with an opaque appearance and a poly-sapphire type with a translucent appearance. The difference in the appearance of the two types of ceramic brackets can be explained based on SEM micrographs. The SEM micrographs of the conventional polycrystalline brackets indicated an irregular structure and variable grain sizes without distinct boundaries, which seem to play a major role in the refraction of light and consequently the opaque appearance of the brackets. However, the SEM micrographs of the poly-sapphire brackets indicated more regular orientation of crystals with distinct boundaries and relatively uniform sizes. Such different structures and crystallinity phases were also noted in XRD analysis such that the polycrystalline brackets showed a higher crystalline phase with more intense Al_2O_3 peaks and a lower glass phase (amorphous). These findings supported the results of EDX analysis. The aluminum content was found to be higher than other elements, and the ceramic composition of the two bracket types was the same. Despite similar composition, different crystalline structures and the percentage of crystallization may explain the differences between the two ceramic brackets. The crystalline phase leads to greater light scattering and opacity.[21] The difference in the crystalline structure of the two brackets not only affects their appearance, but also influences the results of the friction test. In the control group of the conventional polycrystalline brackets (n=10), the mean frictional resistance value was measured by the universal testing machine to be 0.18 N/mm^2; this value was 0.12 N/mm^2 in the control group of the poly-sapphire brackets, which indicated significantly higher friction of brackets with an irregular crystalline structure. Such a significant difference was noted not only in the control group, but also in all laser-irradiated groups between the two bracket types. Arash et al[22] showed that the friction of polycrystalline brackets was significantly higher than that of monocrystalline brackets. Assessment of the effect of the diode laser on the friction of brackets with wire revealed that diode laser irradiation of polycrystalline and poly-sapphire brackets could not significantly change their friction compared with the control groups ($P > 0.05$). The mean frictional resistance value of polycrystalline brackets was 0.20 N/mm^2 while this value was 0.12 N/mm^2 for poly-sapphire brackets. This finding indicates that the diode laser with the adopted settings in this study could not cause significant surface modification although it caused morphological changes in the poly-sapphire brackets. These findings confirmed the results of Stubinger et al, to some extent, regarding the effect of irradiation of different laser types on zirconia implants. They concluded that the diode laser, unlike the Nd:YAG and CO_2 lasers, could not alter the ceramic surface morphology. Unlike the Er:YAG laser, the diode laser did not pass through the ceramic and was absorbed by the ceramic surface.[15] Assessment

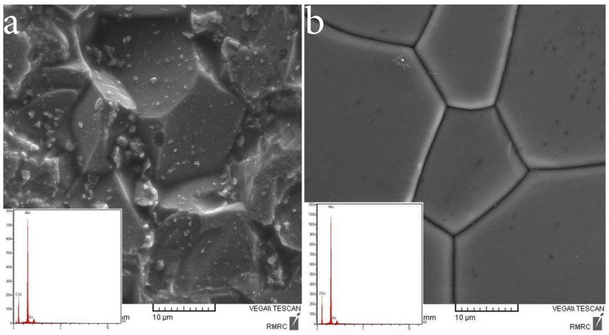

Figure 5. Results of EDS analysis for (a) polycrystalline bracket and (b) poly-sapphire bracket

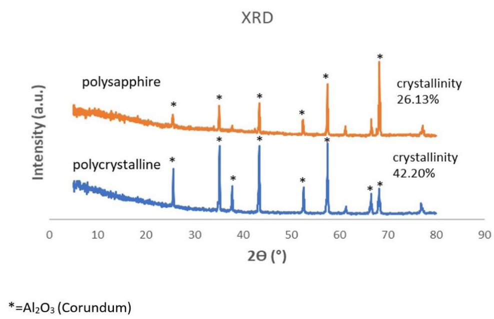

Figure 6. XRD analysis for phase identification of the two bracket types

of SEM micrographs following diode laser irradiation revealed that the irregular surface of polycrystalline brackets did not change significantly; the most prominent modification was rounding of the corners of the grains, and the surface irregularity was similar to that of the control group. The SEM micrographs of the poly-sapphire brackets after diode laser irradiation revealed evidence of melting and destruction of grain boundaries although these alterations did not contribute to a significant change. Such modifications indicate energy absorption by poly-sapphire brackets and have been the focus of some previous investigations. Feldon et al[23] reported that the diode laser greatly passes through the structure of translucent monocrystalline brackets while most of the laser energy is absorbed by the bracket following an increase in the percentage of crystals and further opacity of the bracket; however, they did not provide photographs of laser-irradiated brackets. Ivanov[24] measured the pulpal temperature following diode laser irradiation of monocrystalline and polycrystalline brackets. They noticed lower pulpal temperature in the polycrystalline group while the use of monocrystalline brackets resulted in higher pulpal temperature since they allowed greater passage of laser energy. The authors declared that the polycrystalline bracket structure probably allows greater energy absorption; however, they did not provide images of the brackets.

It should be noted that friction has a direct correlation with the compression load of surfaces over each other, the nature of surfaces, chemical reactions, use of lubricants, and so on. As stated by Kusy and Whitley,[25] the required load for shearing of microscopic points of attachments between the two surfaces as well as the resistance created by surface irregularities are among the determinants of the friction value. In other words, the friction coefficient is more influenced by the yield strength and shear strength of attachment points rather than the surface roughness. Therefore, a material with high surface roughness does not necessarily have a high friction coefficient.[25] They also evaluated the composition of different wires and brackets and observed that the friction coefficient of polycrystalline ceramic brackets and steel and beta-titanium wires was significantly higher than the combination of bracket and steel wires, while the nickel titanium wires had the highest surface roughness (they performed laser specular reflectance measurements for the assessment of roughness).[26]

Nd:YAG laser irradiation could not cause a significant change in friction compared with the control group ($P > 0.05$), neither in the polycrystalline nor in the poly-sapphire brackets (0.10 N/mm^2 for the poly-sapphire and 0.19 N/mm^2 for the polycrystalline brackets). The effect of the Nd:YAG laser on bracket morphology was much lower than that of the diode laser according to SEM micrographs. Nonetheless, Harimkar and Dahotre[27] evaluated the effect of Nd:YAG laser irradiation on the surface properties of alumina ceramics and reported that according to the XRD and SEM analyses, the resultant surface properties and thermal alterations dictate the changes in the size and shape of the grains and the ceramic phases and consequently affect the surface-related behaviors such as friction. They showed that higher laser energy results in the melting of a higher percentage of aluminum oxide crystals although laser parameters in their study were different from ours. Lee et al[28] discussed that dynamic melting of the ceramic surface and its re-solidification decreased the surface porosity and roughness and resulted in the formation of a mainly amorphous, glassy superficial layer. Similar to our methodology, they employed SEM/EDS for bracket surface analysis.[27,28] It should be noted that the mean friction of brackets did not significantly change following irradiation of the two laser types, which indicates no superiority of any laser type over the other.

In a study highly similar to our study, Rabiee et al[29] evaluated the effect of CO_2 laser irradiation on the friction between steel wire and polycrystalline bracket. The type of laser and use of different CO_2 laser powers in their study were different from our methodology. They found that increasing the CO_2 laser power significantly affected the friction, and lower friction was noted in groups subjected to laser irradiation with energy level >70 J/cm^2. They also added that atomic force microscopic images revealed more homogenous formation of laser blisters in higher laser powers, while lower powers of laser yielded a more irregular surface. Quantitative assessment of surface roughness in their study revealed lower ceramic surface roughness following the use of higher laser powers; nonetheless, the lowest surface roughness was reported in the control group (no laser irradiation). They only evaluated one type of bracket. In explaining the mechanism of friction reduction by the formation of laser blisters, they discussed that laser blisters increase the homogeneity and uniformity of the porous surface and consequently decrease the contact area of bracket and wire. Thus, sliding of wire over these blisters would result in a smaller contact area and subsequently lower friction. The uniformity of laser blisters increased by an increase in laser power.

Arash et al[30] evaluated the effect of Er:YAG laser irradiation of polycrystalline brackets and stated that at a 0° angle between the wire and bracket (as in our study), increasing the laser power from 100 to 300 mJ/s significantly decreased the friction; however, at a 10° angle between the wire and bracket, the change in friction was no longer significant. This finding highlights the fundamental role of binding in the generation of resistance against sliding of the teeth. Irrespective of laser type in their study, which was different from the lasers used in our study, their findings highlighted the significance of using different laser powers. They attributed the reduction in friction to the melting of superficial grains and rounding of their corners. The same observations were reported by Abdallah et al[11] following high-power CO_2 laser irradiation of In-Ceram ceramic surfaces, such that laser-irradiated ceramics showed smoother surfaces. However, in our observations of SEM micrographs, the grains did not experience a significant change in size after laser irradiation.

Future studies are required to use different laser types with different powers, durations and wavelengths to obtain more reliable results. Also, the clinical setting must be simulated as much as possible. The use of artificial saliva and taking into account the role of masticatory forces and bacterial plaque can greatly enhance the generalizability of in vitro results to the clinical setting.

Moreover, optical profilometry and atomic force microscopy can be employed in future studies to quantitatively assess the surface modification of slots. Furthermore, the use of different laser settings can further shed light on the results. Last but not least, the conventional steel wires can be used as the control group for the purpose of comparison in future studies on the effect of coating of esthetic wires on friction.

Conclusion

Irradiation of the diode laser, compared with the Nd:YAG laser, with the suggested settings (in terms of power and duration) caused significant surface modification in poly-sapphire slots. This effect was attenuated by an increase in the percentage of surface crystallinity (polycrystalline brackets). No significant difference was noted in the mean frictional resistance value of the test and control groups of the two bracket types with rhodium-coated esthetic wires. On the other hand, polycrystalline brackets in the test and control groups showed higher friction than poly-sapphire brackets, irrespective of laser irradiation.

Authors' contributions

HG contributed to the design of the study and execution of the procedure, AG designed the study and revised the final manuscript, SH assisted in laboratory setting and preparation of the article, NC contributed to the determination of lasers settings and collection of the data, and MAK collected the data, analyzed the results, and wrote the article.

Ethical Considerations

This study was approved by the ethics committee of Tehran University of Medical Sciences. Ethics code: IR.TUMS.DENTISTRY.REC.1397.109.

Conflict of Interests

The authors declare that they have no conflict of interest.

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