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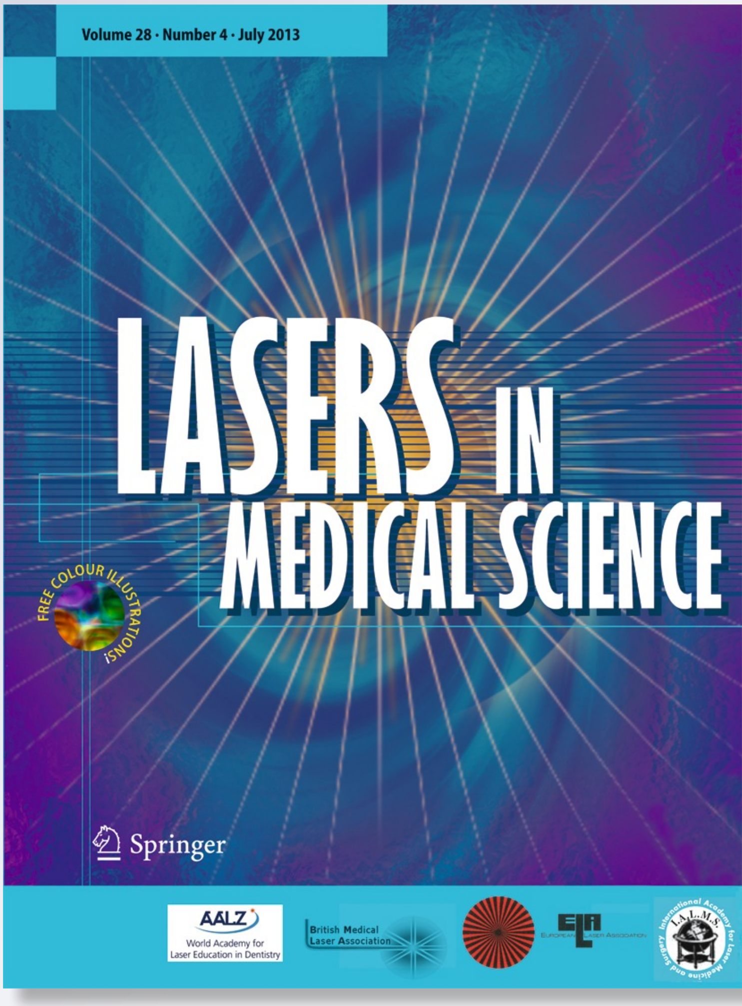

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ORIGINAL ARTICLE

CO_2 laser conditioning of porcelain surfaces for bonding metal orthodontic brackets

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Abstract Bonding to porcelain remains to be a challenge in orthodontic treatments. The objective of this study was to evaluate the effect of CO2 laser conditioning of porcelain surfaces on shear bond strength (SBS) of orthodontic brackets. Eighty feldspathic porcelain specimens were divided into four groups of 20. In each group, half of the porcelain surfaces were deglazed, while the others remained glazed. The specimens in groups 1 to 3 were treated with a fractional CO2 laser for 10 s using 10 mJ of energy, frequency of 200 Hz and powers of 10 W (group 1), 15 W (group 2) and 20 W (group 3). In group 4, a 9.6 % hydrofluoric (HF) acid gel was used for 2 min. A silane coupling agent was applied before bracket bonding, and the SBS was measured with a universal testing machine after 24 h. Deglazing caused significant increase in SBS of laser treated porcelain surfaces ($p<0.05$), but had no significant effect on SBS when HF acid was used for etching ($p=0.137$). ANOVA revealed no significant difference in SBS values of the study groups when glazed surfaces were compared ($p=0.269$). However, a significant between group difference was found among the deglazed specimens ($p<0.001$). Tukey test revealed that the bond strengths of 10 W and 15 W laser groups were significantly higher than that of the HF acid group ($p<0.05$). Laser conditioning with a fractional CO2 laser can be recommended as a suitable alternative to hydrofluoric acid for deglazed feldspathic porcelain.

Keywords CO2 · Laser · Fractional · Porcelain · Bonding · Bond strength · Ceramic · Orthodontic · Dentistry

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Introduction

Today, orthodontists are frequently encountered with adult patients who have one or more porcelain surfaces in the anterior dentition where placing bands produces an unsightly appearance. Bonding of orthodontic brackets to porcelain has long been known as a challenge, because conventional acid etching is not effective for porcelain conditioning. Application of 9.6 % hydrofluoric acid for several minutes can be regarded as a standard technique that provides sufficient bond strength for orthodontic bonding, which nevertheless includes disadvantages such as lengthy etching time and risk of soft tissue damage. Alternative modalities have been investigated for preparing porcelain surfaces before bonding orthodontic brackets including surface roughening with a diamond bur or aluminum oxide sandblasting [1–5], application of an acidulated phosphate fluoride gel (APF 4 %) [6, 7] or etching with 37 % orthophosphoric acid [1], but the resulting bond strengths were considered to be clinically insufficient [1–7]. Although the efficacy of these techniques could be enhanced by application of a silane or a bonding agent, the results were still significantly lower than that obtained from HF acid/silane or HF acid/bonding agent in several studies [1, 4, 7].

Lasers have various applications in dentistry, among which is conditioning the dental and restorative surfaces. Although Er:YAG and Nd:YAG lasers have been investigated as possible alternatives to HF acid for porcelain treatment [8–15], the CO2 laser which emits a wavelength of

10,600 nm can be considered as the most suitable for this purpose due to its high absorption rate in ceramics [1, 16, 17]. Akova et al. [1] reported that the bond strength of CO2 irradiated porcelain surfaces was significantly lower than that obtained with HF acid but clinically acceptable, and thus they considered CO2 laser irradiation as an alternative method for treatment of porcelain surfaces.

To the authors' knowledge, no study has investigated the effect of fractional CO2 laser irradiation on conditioning feldspathic porcelain. The concept of fractional photothermolysis was introduced in 2003 [18] in order to reduce the significant adverse effects of treating dermatologic conditions with ablative lasers (CO2 and Er:YAG) such as prolonged downtime, long-lasting erythema, edema, burning and scarring [19, 20]. Instead of producing layers of thermal heating, fractional photothermolysis (FP) generates multiple columns of microscopic thermal wounds called microscopic treatment zones (MTZs), while the surrounding tissues remain healthy and untreated, and thus supporting the wound healing process [19, 20]. The use of fractional CO2 laser may have several advantages in dentistry. When used for surface treatment, the exact irradiation area can be predetermined by the apparatus and the laser irradiates multiple zones in the target area with predefined space between them. Therefore, not only the need for manual movement of the handpiece is eliminated during conditioning, but also a more homogenous etching pattern can be achieved. In addition, the temperature increase in the underlying tissues should be reduced compared to that occurs with conventional CO2 laser.

When bonding to porcelain is required, the glaze is frequently removed to enhance surface roughness and thus the bond strength. Roughening the surface is associated with the risk of porcelain fracture and irreversible damage at debonding [21, 22], because the glaze that provides porcelain integrity no longer exists. Therefore, bonding to glazed porcelain has been recommended by several authors [4, 22–26] and the results were satisfactory when compared to deglazed specimens in some studies [22, 26].

The aim of this study was to investigate the efficacy of fractional CO2 laser in preparing glazed and deglazed porcelain surfaces for bonding metal orthodontic brackets, using shear bond strength (SBS) testing and scanning electron microscope (SEM) evaluation.

Methods and materials

Eighty glazed feldspathic porcelain specimens (Vita, Bad Sackingen, Germany) were prepared in the form of maxillary central incisors with handles on the base that ensured secure retention during mounting. The specimens were randomly assigned into 4 groups of 20. In each group, half of the specimens were roughened with a diamond bur to remove the glaze before conditioning (subgroups 1D to 4D), while the other half remained glazed (subgroups 1G to 4G). The porcelain specimens were mounted in polyethylene molds using self-curing acrylic resin so that the entire buccal surface of the porcelain would be aligned horizontally at the center of the mould. Before conditioning, the porcelain surfaces were cleaned with ethyl alcohol and allowed to dry in air. The surface treatment procedures in the study groups were as follows:

In group 1 (subgroups D and G) to group 3 (subgroups D and G), a fractional CO2 laser (Lutronic Inc., Princeton Junction, NJ, USA) was used for conditioning ceramic surfaces, emitting a wavelength of 10,600 nm. The laser handpiece was held manually perpendicular to the porcelain using a jig indicator to provide an approximate distance of 10 mm between the laser output and the bonding surface, and the beam irradiated a square area of 4×4 mm^2 for 10 s. The laser operated in the dynamic mode using 10 mJ of energy and frequency of 200 Hz. The power was set at 10 W for Group 1, 15 W for Group 2, and 20 W for Group 3. These parameters were drawn from a pilot study using the fractional CO2 laser at 10 mJ and 14 mJ energies with power settings of 15 W and 25 W for treatment of porcelain surfaces. This experiment indicated that the combination of 10 mJ and 15 W produced higher bond strength than those observed in other groups. Therefore, we selected 10 mJ of energy and changed the power in a narrower range.

A 9.6 % hydrofluoric acid gel (Porcelain Etch Gel, Pulpdent Corp., Watertown, MA, USA) was used for etching the porcelain in group 4 (subgroups D and G), which served as the control group. The gel was applied for 2 min, then rinsed with a copious amount of water and the surface was air-dried.

In all groups, a silane coupling agent (Silane Bond Enhancer; Pulpdent Corp.) was applied after surface preparation. Stainless steel standard edgewise maxillary central incisor brackets with 0.022-in. slot (American Orthodontics, Sheboygan, WI, USA) were used in this study. Transbond XT adhesive (3 M Unitek, Monrovia, California, USA) was applied on the base, and the bracket was bonded to the center of the porcelain specimen. The excess adhesive material was removed from the border of the bracket with a sharp explorer and the specimen was light-cured for a total time of 40 s from mesial, distal, occlusal, and gingival directions (10 s each) using a quartz tungsten halogen (QTH) curing unit (Coltolux 75; Coltene/Whaledent Inc., Cuyahoga Falls, OH, USA) at a light intensity of 1,000 mW/cm2.

The specimens were kept in water at 37 °C for 24 h after bonding, then the shear bond strength (SBS) was measured by a Zwick testing machine (model Z250, Zwick GmbH & Co, Ulm, Germany) at a crosshead speed of 1 mm/min. The shear force was applied parallel to the bonded surface of the porcelain until failure occurred. The fracture load was recorded in Newtons and divided by the bracket base area (12.1 mm^2) to give SBS in megapascals (N/mm2).

The surface morphology of porcelain after conditioning was examined in one additional glazed and one additional deglazed specimen from each study group under a scanning electron microscope (SEM, LEO 1450VP, Zeiss, Germany). Photographs were obtained from the surface treated areas at 500 X magnification.

Statistical analysis

The SBS values were analyzed with a two-way analysis of variance (ANOVA) with porcelain surface (glaze or deglazed) and conditioning method serving as discriminate variables. The statistical analysis was performed by SPSS software (Statistical Package for the Social Sciences, Version 11.5, SPSS, Chicago, Ill, USA) and the probability value was set at $p<0.05$.

Results

The average, standard deviation, minimum and maximum SBS values (MPa) for the study groups are presented in Table 1. Deglazing followed by CO2 laser treatment at 10 W produced the highest mean bond strength (11.4 MPa) while the glazed surfaces treated by CO2 laser at 20 W yielded the lowest SBS value (4.4 MPa).

The two way ANOVA revealed a significant interaction between the porcelain surface and conditioning method ($p<0.001$), making it necessary to evaluate these variables individually. Therefore, an unpaired t-test was used to determine the effect of deglazing on bond strength of orthodontic brackets in each of the study groups. The results (Table 1, Fig. 1) showed that in groups 1, 2 and 3, the deglazed surfaces had significantly higher bond strength values than those of the glazed specimens (Group 1: 11.4 versus 5.7 MPa, $p<0.001$; Group 2: 11.2 versus 5.2 MPa, $p=0.002$; Group 3: 9.0 versus 4.4 MPa, $p=0.014$). However, the difference between the deglazed and glazed porcelain surfaces was not statistically significant when HF acid was used for etching (Group 4: 6.2 versus 7.3 MPa, $p=0.137$).

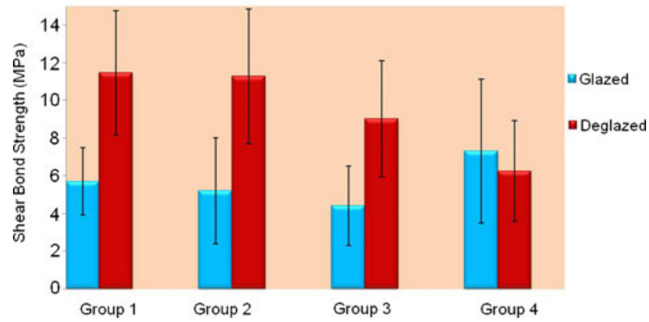

Fig. 1 Shear bond strength (MPa) of the study groups

In the glazed porcelain subgroups, the highest bond strength value was obtained with HF acid (7.3±3.8 MPa), followed by CO2 laser at power settings of 10 W (5.7±1.8 MPa), 15 W (5.2±2.8 MPa), and 20 W (4.4±2.1 MPa) (Table 1, Fig. 1). A comparison of glazed porcelain surfaces by one way ANOVA revealed no significant difference in bond strength values among the study groups ($p=0.269$).

In subgroups that were roughened before conditioning, the highest bond strengths were achieved with CO2 laser at 10 W (11.4±3.3 MPa) and 15 W (11.2±3.5 MPa), followed by CO2 laser at 20 W (9.0±3.0 MPa) and HF acid (6.2±2.6 MPa) (Table 1, Fig. 1). The ANOVA revealed a significant difference in bond strengths among the study groups ($p<0.001$). Multiple comparisons using Tukey test indicated that the bond strengths of groups 1 (CO2 laser at 10 W), 2 (CO2 laser at 15 W) and 3 (CO2 laser at 20 W) were not significantly different from each other ($p>0.05$). The Tukey test also revealed that the SBS of porcelain specimens etched by HF acid (group 4) was significantly lower than those treated with CO2

Table 1 Descriptive statistics including mean, standard deviation (SD) and range regarding shear bond strength (MPa) of the study groups and the results of unpaired t test for comparison of glazed and deglazed specimens in each group

Group	Definition	Subgroup	Mean (MPa)	SD	Range	Statistical significance
1	CO2 laser—10 W	Glazed	5.7	1.81	3.63–8.85	$p<0.001$*
		Deglazed	11.47	3.3	7.63–18.55	
2	Co2 laser—15 W	Glazed	5.2	2.8	2.96–10.83	$p=0.002$*
		Deglazed	11.28	3.58	5.40–17.27	
3	Co2 laser—20 W	Glazed	4.4	2.11	2.82–8.15	$p=0.014$*
		Deglazed	9.01	3.09	4.98–14.17	
4	9.6% HF acid	Glazed	7.31	3.81	3.98–17.18	$p=0.137$
		Deglazed	6.25	2.68	3.16–12.24	

*$p<0.05$, statistically significant difference

laser at power settings of 10 W (group 1) and 15 W (group 2) ($p<0.05$).

SEM evaluation

Figures 2 and 3 demonstrate SEM photographs of the glazed and deglazed porcelain surfaces treated by different powers of CO2 laser or 9.6 % HF acid.

Glazed porcelain specimens treated with fractional CO2 laser demonstrated relatively smooth non-retentive surfaces with shallow and dispersed craters (Fig. 2a-c) and occasional areas of carbonization (Fig. 2b,c). At the lower laser power (10 W) finer and more extensive surface irregularities were observed (Fig. 2a). The representative glazed specimen etched by HF acid revealed a uniform etching pattern with numerous microporosities and shallow erosions (Fig. 2d).

Deglazing followed by CO2 laser treatment at 10 W (Fig. 3a) and 15 W (Fig. 3b) produced uniform and superficial irregularities throughout the surface, which deemed to provide adequate mechanical retention. Laser application at 20 W caused a surface morphology similar to those observed with the lower output powers, although the surface appeared to be smoother and less retentive for composite adhesion (Fig. 3c). The surface texture of the deglazed specimen etched by HF acid was characterized by extensive and profound irregularities, producing a honeycomb shaped appearance on the porcelain surface (Fig. 3d). No cracks were observed on the porcelain after fractional CO2 laser application, either when the surface was glazed or deglazed.

Discussion

The present study reports successful results with a fractional CO2 laser for conditioning deglazed feldspathic porcelain. When glazed specimens were compared, laser-treated groups demonstrated SBS values that were lower, although statistically comparable to that obtained from HF acid. However, the SBS values of deglazed specimens treated with 10 W and 15 W CO2 laser were significantly higher when compared to that of HF acid group, a finding that can have important clinical implications. These results are in contrast with those of Akova et al. [1] who found that the SBS of deglazed porcelain surfaces treated with a superpulse CO2 laser for 20 s was significantly lower than that of the HF acid group. However, Akova et al. [1] used a conventional CO2 laser with different parameters and duration of application compared to the ones used in this study. Furthermore, the manual movement of the conventional CO2 laser's handpiece as used by Akova et al. [1] carries the risk of leaving large areas without laser energy, while other parts are being overlased. There is no need for manual scanning of the porcelain when a fractional CO2 laser is used for conditioning.

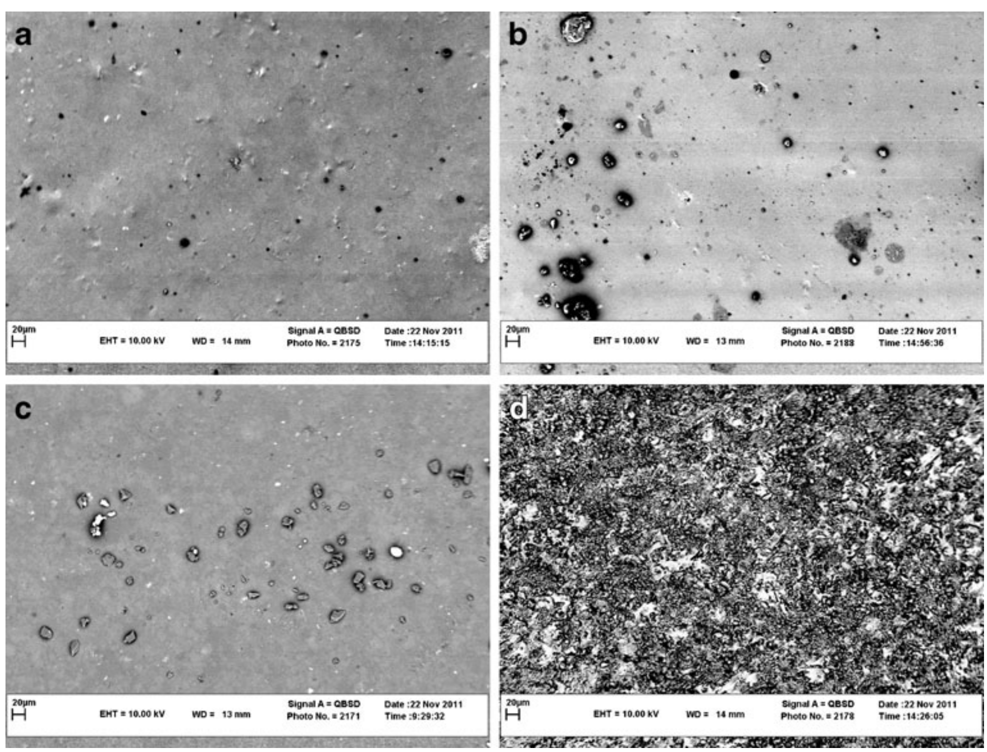

Fig. 2 Scanning electron microscope (SEM) photographs of glazed porcelain surfaces treated by fractional CO_2 laser (10 mJ, 200 Hz, 10 s) at 10 W (**a**), 15 W (**b**), and 20 W (**c**) or by 9.6 % hydrofluoric acid (**d**) under ×500 magnification

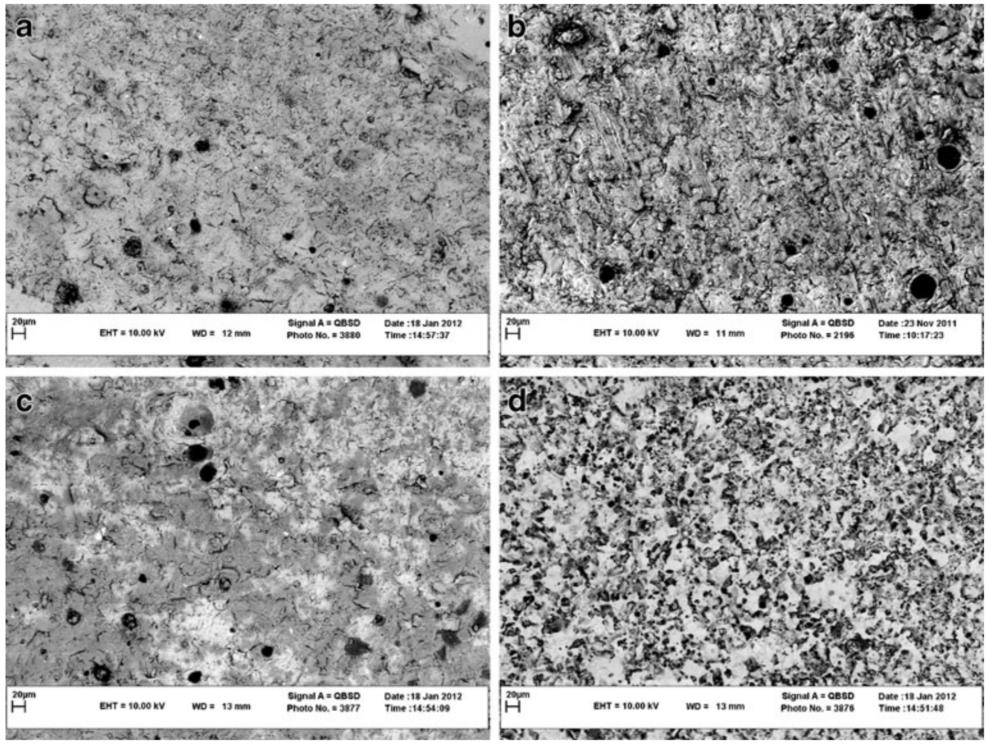

Fig. 3 Scanning electron microscope (SEM) photographs of deglazed porcelain surfaces treated by CO2 laser (10 mJ, 200 Hz, 10 s) at 10 W (**a**), 15 W (**b**), and 20 W (**c**) or by 9.6 % hydrofluoric acid (**d**) under ×500 magnification

Deglazing is usually performed before preparing the porcelain surface for bonding adhesives in order to increase porcelain surface area and in turn improving the chemical and micromechanical retention. However, deglazing includes the risk of crack propagation and the probability of porcelain fracture at debonding [21, 22]. The esthetic characteristics of the porcelain may also be irreversibly damaged with the roughening process [21, 27]. With HF acid, the glazed and deglazed porcelain surfaces presented comparable bond strength values, indicating that roughening the surface is not a prerequisite to gain significant increase in bond strength when HF acid is employed for etching. The results of this study, however, support deglazing the porcelain when a fractional CO2 laser is used for conditioning, because the SBS values of laser-treated glazed specimens were significantly lower than those achieved after deglazing. Despite the potential disadvantages of deglazing, it should be considered as a preliminary step when a fractional CO2 laser is used for porcelain surface treatment.

In the present study, there were no significant differences between SBS values of 10 W, 15 W and 20 W laser groups either in glazed or deglazed specimens, although the bond strength was lower when power was set at 20 W. Cavalcanti et al. [28] reported that the application of higher power settings with Er:YAG laser caused excessive deterioration in ceramic material. Since the side effects of CO2 laser can be reduced with lowering the output power, the minimum power setting should be preferred. Therefore, the use of fractional CO2 laser at 10 W can be recommended for ceramic treatment in order to yield favorable treatment results, while reducing the risk of heat accumulation and thermal damage to the underlying tissues.

HF acid produced significantly lower SBS value than those achieved by CO2 laser groups (10W and 15W) when used on deglazed porcelain. HF acid should also be applied for a relatively long time on the surface (about 2 min) and requires an extreme care in order to prevent soft tissue irritation. In contrast, the fractional CO2 laser can be used in a relatively short time (10 s), eliminates the need for rinsing and drying the surface and the need to use rubber dam for isolation, although the usual protection for infrared lasers should be taken such as wearing protective glasses.

There is a controversy regarding the benefits of silane application on porcelain surface, with some studies showing no significant increase in bond strength of HF treated specimens following silane application [3, 5], while most authors reported superior adhesion when silane was applied after acid etching or sandblasting [1, 4, 29–31]. Silane application is a simple treatment step that can be performed easily in the dental office. Therefore, in the present study, silane was applied in all groups to promote the bonding interface. Since surface roughening and silane application were performed in all deglazed subgroups, the significantly higher bond strengths of 10 W and 15 W laser-treated specimens indicate the efficacy of fractional CO2 laser for treatment of deglazed porcelain as compared to HF acid.

SEM images of laser-etched specimens confirmed the results of the bond strength testing to great extent. Fractional

CO2 laser treatment on glazed porcelain (Fig. 2a-c) produced a smooth surface with occasional craters, and the surface appeared to be unfavorable for resin adhesion. However, the deglazed specimens treated with CO2 laser (Fig. 3a–c) demonstrated marked irregularities with shallow erosions throughout the surface. There seemed that the glazed layer on the porcelain surface limited the efficacy of fractional CO2 laser for porcelain treatment. However, when the glaze was removed, the laser light was allowed to cause microscopic porosities through the process of thermomechanical ablation, thus increasing micromechanical retention between the resin composite and the porcelain surface. Another possible explanation for the increased adhesion may be chemical alteration of the deglazed porcelain or increasing its wettability as a result of laser irradiation, although further study is required to confirm this assumption. Similar to the observations of previous authors [3, 32], HF acid produced uniform and extensive roughness on the surface, either used on glazed (Fig. 2d) or deglazed (Fig. 3d) porcelain, and the surface appeared to be retentive for composite adhesion.

Several studies reported the observation of cracks throughout the porcelain surfaces treated with Nd:YAG [33] or CO2 [1, 33] lasers, possibly due to the high energy required by these lasers to modify the surface. These cracks can decrease porcelain resistance to fracture. However, in the present study no crack was observed after application of fractional CO2 laser even with the use of higher output power, indicating the potential safety of laser parameters for porcelain structure.

Bond strength of 6–8 MPa has been considered as the minimum requirement for orthodontic bonding [34], while 13 MPa can be regarded as the maximum permittable strength between porcelain and adhesive in order to prevent cohesive porcelain failure [35]. Keeping this in mind, the findings of the present study indicate that porcelain treatment with 9.6 % HF acid can yield bond strength values that are within the minimum range of bond strength required for clinical practice, either used on glazed or deglazed ceramic. The SBS values of glazed porcelain surfaces treated with fractional CO2 laser, although were comparable to that of HF acid group, could not be considered clinically acceptable. Deglazing followed by fractional CO2 laser irradiation provided bond strength values that were remarkably higher than that achieved by HF acid and indeed were favorable for clinical applications. The present study introduces fractional CO2 laser as a more effective and time-saving alternative to HF acid for treatment of deglazed feldspathic porcelain. This new modality eliminates the need for manual scanning of the surface. The exact area of irradiation as well as the density of the treatment zones and the amount of space between them can also be predetermined by the apparatus [36], and increase in the temperature of the underlying tissue should be lower than that occurs with conventional CO2 laser. Further studies are required to determine the efficacy of fractional CO2 laser on preparing other types of ceramics for bonding composite. The amount of heat produced by the laser in the underlying tissues and the durability of the bond after long-term water storage and thermal cycling process also needs further clarification in future studies.

Conclusions

1- Application of 9.6 % hydrofluoric acid produced bond strength values that surpassed the minimum strength required in clinical conditions, either used on glazed or deglazed porcelain.

2- Deglazing had no significant influence on bond strength of orthodontic brackets to porcelain surfaces when HF acid was used for conditioning, but it produced significant increase in bond strengths of laser-treated specimens. Therefore, deglazing should be regarded as a necessary step before employing a fractional CO2 laser for porcelain surface treatment.

3- Due to the significantly higher bond strength, porcelain treatment with a fractional CO2 laser could be recommended as a suitable alternative technique to HF acid for bonding orthodontic brackets to deglazed feldspathic porcelain.

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