©Operative Dentistry, 2014, **39-3,** 273-282

Effects of Pulsed Nd:YAG Laser on Tensile Bond Strength and Caries Resistance of Human Enamel

X Wen • L Zhang • R Liu
M Deng • Y Wang • L Liu
X Nie

Clinical Relevance

Pulsed Nd:YAG laser may contribute to the tensile bond strength of resin to enamel and increase the acid resistance of enamel surfaces. It can be a clinical alternative for pretreating enamel surfaces when direct bonding orthodontic attachments or adhesive restorations.

Xiujie Wen, MD, Department of Stomatology, Daping Hospital & Research Institute of Surgery, Third Military Medical University, Chongqing, China

Li Zhang, MD, Department of Stomatology, Daping Hospital & Research Institute of Surgery, Third Military Medical University, Chongqing, China

Rui Liu, MD, Department of Stomatology, Daping Hospital & Research Institute of Surgery, Third Military Medical University, Chongqing, China

Manjing Deng, professor, Department of Stomatology, Daping Hospital & Research Institute of Surgery, Third Military Medical University, Chongqing, China

Yu Wang, MM, Department of Stomatology, Daping Hospital & Research Institute of Surgery, Third Military Medical University, Chongqing, China

*Luchuan Liu, professor, Department of Stomatology, Daping Hospital & Research Institute of Surgery, Third Military Medical University, Chongqing, China

*Xin Nie, professor, Department of Stomatology, Daping Hospital & Research Institute of Surgery, Third Military Medical University, Chongqing, China

*Corresponding author: 10 Daping Changjiang Branch Road, Yuzhong District, Chongqing 400042, China; e-mail: Liuluchuan1957@126.com; dr.xinnie@gmail.com

DOI: 10.2341/12-416-L

SUMMARY

This study aims to evaluate the effects of pulsed Nd:YAG laser on the tensile bond strength (TBS) of resin to human enamel and caries resistance of human enamel. A total of 201 human premolars were used in this *in vitro* study. A flat enamel surface greater than 4 × 4 mm in area was prepared on each specimen using a low-speed cutting machine under a water coolant. Twenty-one specimens were divided into seven groups for morphology observations with no treatment, 35% phosphoric acid etching (30 seconds), and laser irradiation (30 seconds) of pulsed Nd:YAG laser with five different laser-parameter combinations. Another 100 specimens were used for TBS testing. They were embedded in self-cured acrylic resin and randomly divided into 10 groups. After enamel surface pretreatments according to the group design, resin was applied. The TBS values were tested using a universal testing machine. The other 80 specimens were randomly divided into eight groups for acid resistance evaluation. Scanning electron microscope (SEM) results

showed that the enamel surfaces treated with 1.5 W/20 Hz and 2.0 W/20 Hz showed more etching-like appearance than those with other laser-parameter combinations. The laser-parameter combinations of 1.5 W/15 Hz and 1.5 W/20 Hz were found to be efficient for the TBS test. The mean TBS value of 14.45 ± 1.67 MPa in the laser irradiated group was significantly higher than that in the untreated group (3.48 ± 0.35 MPa) but lower than that in the 35% phosphoric acid group (21.50 ± 3.02 MPa). The highest mean TBS value of 26.64 ± 5.22 MPa was identified in the combination group (laser irradiation and then acid etching). Acid resistance evaluation showed that the pulsed Nd:YAG laser was efficient in preventing enamel demineralization. The SEM results of the fractured enamel surfaces, resin/enamel interfaces, and demineralization depths were consistent with those of the TBS test and the acid resistance evaluation. Pulsed Nd:YAG laser as an enamel surface pretreatment method presents a potential clinical application, especially for the caries-susceptible population or individuals with recently bleached teeth.

INTRODUCTION

The field of adhesive dentistry has achieved remarkable progress over the past decades. This development is largely attributed to the major advancements in enamel surface pretreatments, which roughen the enamel surface and offer more microspace for resin monomers to penetrate and form resin tags. The microspace significantly increases the bond strength of resin to the enamel.[1,2] The acid-etching technique that usually uses 35% phosphoric acid gel is one of the most common enamel surface pretreatments for resin bonding.[3] However, the possibility of decalcification that leaves the enamel at the resin restoration margin or around orthodontic attachments more susceptible to caries attack cannot be ignored because it ultimately leads to treatment failures.[4-6] Therefore, enamel surface pretreatment needs to be improved to maintain clinically useful bond strengths while minimizing enamel loss; enamel surface pretreatment also needs to be simplified to reduce the bonding steps.[7,8]

Various lasers have recently elicited considerable interest in the field of dentistry because of their function in the detection and removal of enamel caries, diagnosis of dental caries, cavity preparation, etching of teeth for resin bonding, demineralization prevention, root canal sterilization, and so on.[9-11] Lasers have received significant attention in resin bonding, especially in terms of their roughness and demineralization prevention effect on dental hard tissues.[11,12] Laser etching eliminates the need for separate steps of water spraying and air drying, thereby reducing procedural errors and saving time.

Pulsed Nd:YAG laser emits a wavelength of 1.064 μm. It is capable of promoting the fusion and recrystallization of dental hard tissue surfaces and causing an irregular honeycomb or crater morphology, which increases surface microhardness and contributes to resin bonding.[12,13] In our previous studies, pulsed Nd:YAG laser was found to contribute significantly to root canal sterilization and to enhance the bond strength/microleakage of resin to human dentin.[14,15] However, the enamel is less pigmented than the dentin, and the Nd:YAG laser wavelength is preferentially absorbed in pigmented tissues. Therefore, the effects of pulsed Nd:YAG laser on the bond strength of human enamel may differ from its influence on human dentin.

This study aims to investigate the effects of pulsed Nd:YAG laser on the bond strength and acid resistance of human enamel to provide a potential enamel surface pretreatment for resin bonding.

METHODS AND MATERIALS

Tooth Selection and Preparation

A total of 201 human premolars that are caries-free and freshly extracted for orthodontic treatment were selected after approval from the Institutional Review Board. From the 201 human premolars, 21 teeth were used for morphology observations, 100 for tensile bond strength (TBS) testing, and 80 for acid resistance evaluation. The roots were removed and the buccal surfaces were ground using a low-speed cutting machine (MF-PERFECTA, Bürmoos, Austria) under a water coolant. A flat surface more than 4×4 mm in enamel was prepared and polished with 200-, 400-, and 600-grit silicon carbide abrasive papers.

Enamel Surface Treatments

The prepared specimens were conditioned with the treatments according to the different experiments in this study. The surface-conditioning methods used in this study are presented in Table 1.

Morphology Observations

The 21 prepared specimens were divided into seven groups (three specimens for each group). They

Table 1: *Enamel Surface Conditioning Methods Used in This Study*

Surface Conditioning Methods	Details for Each Method
Untreated	Enamel surfaces were left no treatment (as control).
Acid etching	Enamel surface were etched with 35% phosphoric acid gel for 30 s, then washed, and dried.
Laser irradiation	Enamel surface were irradiated by pulsed Nd:YAG laser (Friendly A4.0, Milan, Italy) for 30 s in a freehand scanning mode, and the laser optic fiber (320 mm) was used in the standard position, ie, perpendicular to and 1 mm from the enamel surfaces. Black ink was used to initiate and enhance absorption.

received no treatment, acid etching, or laser irradiation with five different laser-parameter combinations (Table 2). The treated specimens were cleaned with distilled water, dehydrated in a graded series of alcohol solutions (70%, 90%, and 100%) for 10 minutes at each concentration, and then sputter-coated with gold. The morphologic changes were examined using a scanning electron microscope (SEM) (Jeol JMS 5200, Tokyo, Japan).

TBS Test and Fractured Surface Examination

The 100 prepared specimens were randomly divided into 10 groups (n=10). Five groups were used to optimize laser-parameter combinations, whereas the other five were utilized to compare pulsed Nd:YAG laser with 35% phosphoric acid gel (Table 2).

The specimens were embedded in self-cured acrylic resin (Shanghai Dental Factory, Shanghai, China). The prepared buccal enamel surfaces were maintained in a face-up position and about 1 mm higher than acrylic resin to keep them unaffected. A thin paper with a 4 × 4 mm hole was fixed on the enamel surface of each specimen. The treatments were performed as shown in Table 2. A two-step etch-and-rinse adhesive system (Adper Single Bond 2, 3M/ESPE, Irvine, CA, USA) was used according to the manufacturer's instructions. The adhesive was applied with disposable microbrush tips and light-cured for 10 seconds with a halogen curing light (Elipar 2500, 3M ESPE, St Paul, MN, USA) under a light intensity of 800 mW/cm^2 after the excess solvent was evaporated with a gentle air stream for 5 seconds. A 4-mm high composite buildup that entirely covered the prepared enamel surface was made with a micro-hybrid resin composite (Filtek Z250, A2, 3M/ESPE) and light-cured for 80 seconds (20 seconds for each side). All specimens were immersed in distilled water at 37°C for 24 hours. The TBS values were tested using a universal testing machine (WDW-10, Panasonic, Osaka, Japan). Each specimen was mounted on the machine, after which tensile force was applied at a constant speed of 0.5 mm/min through the self-made clamps. The force values (N) at the failure point were recorded and converted to MPa by dividing them with the exposed enamel surface (16 mm^2).

The fractured surfaces of the specimens were examined under stereomicroscope (10×) and SEM. The fracture patterns were assessed by adhesive remnant index (ARI), which was based on the remaining resin amount on the enamel surface (ARI score: 0, no resin left; 1, little resin left; 2, resin covering less than half of the bonding surface; 3, resin covering more than half of the bonding

Table 2: *Tensile Bond Strength (TBS) Means in the Ten Groups With Different Treatments (n=10)†*

Groups	Enamel Surface Treatments	Tensile Bond Strengths, MPa
1	Laser irradiation (1.0 W/15 Hz)	5.99 ± 0.56*
2	Laser irradiation (1.0 W/20 Hz)	9.15 ± 0.51**
3	Laser irradiation (1.5 W/15 Hz)	10.43 ± 1.48**
4	Laser irradiation (1.5 W/20 Hz)	13.87 ± 1.91***
5	Laser irradiation (2.0 W/20 Hz)	5.14 ± 1.04*
A	Untreated	3.48 ± 0.35^d
B	Acid etching	21.50 ± 3.02^b
C	Laser irradiation (optimized)	14.45 ± 1.67^c
D	Laser irradiation then acid etching	26.64 ± 5.22^a
E	Acid etching then laser irradiation	12.42 ± 0.39^c

† Labeled groups showed statistical significance (p<0.05). In groups 1-5 and A-E, superscripts indicate statistically similar groups.

Table 3: Ca^{2+} Concentrations in the Eight Groups With Different Treatments (n=10)†		
Groups	**Enamel Surface Treatments**	**Ca^{2+} Concentration, ppm**
I	Laser irradiation (1.0 W/15 Hz)	116.69 ± 7.47**
II	Laser irradiation (1.0 W/20 Hz)	105.40 ± 7.82**
III	Laser irradiation (1.5 W/15 Hz)	80.57 ± 6.26*
IV	Laser irradiation (1.5 W/20 Hz)	82.32 ± 8.31*
V	Laser irradiation (2.0 W/20 Hz)	124.40 ± 8.40***
a	Untreated	247.54 ± 6.80[b]
b	Acid etching	319.84 ± 6.16[c]
c	Laser irradiation (optimized)	84.81 ± 9.57[a]

† Labeled groups showed statistical significance ($p<0.05$). In groups I-V and a-c, superscripts indicate statistically similar groups.

surface; and 4, resin covering the whole bonding surface).[16]

Acid Resistance Evaluation

The 80 prepared specimens were randomly divided into eight groups (n=10). Before undergoing the treatments listed in Table 3, the specimens were coated by an acid-resistant varnish (nail polish) with a 4-mm square window on the enamel surface left uncoated. The specimens were then subjected to an artificial demineralization solution (0.1 M lactic acid) for 48 hours, as described in a previous study.[17] The demineralization solutions were analyzed using a calcium-selective electrolyte analyzer (ISE-trol AVL 9180, AVL Scientific Corp, Roswell, GA, USA) to evaluate the concentration of calcium ion (Ca^{2+}) dissolved from the treated enamel surfaces in each group. The fully dried specimens were longitudinally sectioned and examined by SEM. An electron probe microanalyzer was used to determine the mean demineralization depths in the enamel surfaces of each group.

Statistical Analysis

The data were analyzed with SPSS 13.0 software. One-way analysis of variance (ANOVA) was used to determine whether a significant difference existed between the experimental groups on TBS, Ca^{2+} concentrations, and artificial caries depths. Pearson chi-square test was used to analyze the frequencies of the specimens in each ARI score.

RESULTS

Effect of Pulsed Nd:YAG Laser on Human Enamel Morphology

SEM images showed that the untreated enamel surfaces (Figure 1A) were coated with a smear layer that was replaced by a typical acid-etched pattern with a regular rough surface after 35% phosphoric acid gel treatment (Figure 1B). The laser irradiation caused uneven surface melting and resolidification in the enamel surface and the formation of numerous irregular honeycombs or craters (Figure 1C through G). The honeycombs or craters surrounded by abundant bubble-like cavities and numerous micropores were scattered on the enamel surface irradiated with low frequency (15 Hz) (Figure 1C,E), but became relatively equally distributed with an increase in frequency (20 Hz) (Figure 1D,F,G). The diameter of the honeycombs or craters was enlarged with a change in power from 1.0 W to 2.0 W. The enamel surfaces treated with 1.5 W/20 Hz and 2.0 W/20 Hz showed more etch-like appearance than those with other laser-parameter combinations.

Effect of Pulsed Nd:YAG Laser on Resin to Human Enamel TBS

The mean TBS values are shown in Table 2. In the five laser irradiation groups, TBS values increased and subsequently decreased with an increase in laser output energy. The mean TBS values significantly increased ($p<0.01$) when the power increased from 1.0 W to 1.5 W, and reached the highest value of 13.87 ± 1.91 MPa at 1.5 W/20 Hz. However, the values significantly decreased at a power of 2.0 W. The data indicate that the optimal laser-parameter combination for enamel pretreatment before bonding is 1.5 W/20 Hz.

Compared with the 35% phosphoric acid group whose TBS mean was 21.50 ± 3.02 MPa in this study (Table 2), the pulsed Nd:YAG laser group with optimized laser-parameter combination showed less efficient effects on TBS value, though its TBS mean (14.45 ± 1.67 MPa) was significantly higher than that of the untreated group (3.48 ± 0.35 MPa) ($p<0.01$). The combination of acid etching and laser irradiation (12.42 ± 0.39 MPa) showed no significant decrease compared with the laser group ($p>0.05$), whereas the combination of laser irradiation and

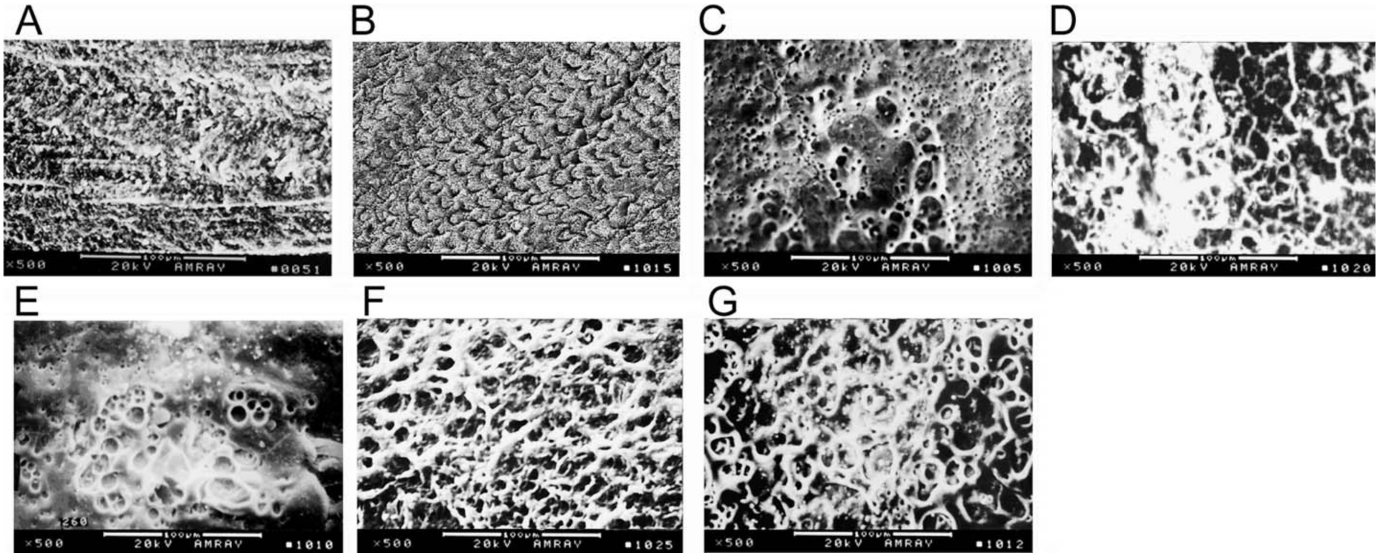

Figure 1. *SEM images of enamel surfaces with different treatments. (A): Enamel surface (untreated) coated with a smear layer. (B): Enamel surface (acid etching) showing a uniform honeycomb appearance. (C-G) Images of enamel surfaces with 1.0 W/15 Hz, 1.0 W/20 Hz, 1.5 W/15 Hz, 1.5 W/20 Hz, and 2.0 W/20 Hz laser parameters, respectively. The enamel surface irradiated with low frequency (C and E) showed scattered honeycombs or craters, whereas the enamel surface irradiated with high frequency showed an etching-like appearance (D, F, and G).*

acid etching significantly increased the TBS value. The TBS mean of the latter combined methods (26.64 ± 5.22 MPa) was significantly higher than that of the acid etching group ($p<0.01$), indicating that the irradiation of pulsed Nd:YAG laser before etching significantly contributed to the TBS of resin to human enamel.

The frequencies of the specimens in each ARI column are shown in Table 4. The ARI scores for each group are calculated as follows: 34, group D; 30, group B; 23, group C; 20, group E; and 7, group A. These scores were positively related to the TBS values. The SEM images of the fractured enamel surfaces showed that the remnant resin covered almost the whole bonding surface in most specimens of groups B and D (Figure 2B,D). By contrast, only a small amount of remnant resin was observed in group A (Figure 2A). The remnant resin covered more than half of the bonding surface in most specimens in groups B and E (Figure 2C,E). The SEM images of resin/enamel interfaces showed the thinnest gaps in groups B (Figure 3A) and D (data not shown), followed by those in groups C (Figure 3B) and E (data not shown). A clear gap was observed in group A (Figure 3C). The morphologic data enhanced understanding of the TBS results.

Table 4: *Frequencies of Specimens in Each Adhesive Remnant Index (ARI) Column for the Five Experimental Groups (n=10)*

Groups	ARI				
	0	1	2	3	4
A	6	2	1	1	0
B	0	0	3	4	3
C	0	2	4	3	1
D	0	0	1	4	5
E	0	4	3	2	1

Effect of Pulsed Nd:YAG Laser on the Acid Resistance of Human Enamel

The effects of laser-parameter settings on enamel surface demineralization were tested (Table 3). Group III showed the lowest Ca^{2+} concentration dissolved from enamel surfaces, followed by group IV. No significant difference was observed between the two groups ($p>0.05$), but they were significantly lower than those of the other three groups ($p<0.01$). The Ca^{2+} concentration in group V was significantly higher than those in all other groups ($p<0.05$). The data showed that the moderate laser-parameter combinations of 1.5 W/15 Hz and 1.5 W/20 Hz significantly contributed to enamel acid resistance.

In the comparison experiments, the pulsed Nd:YAG laser showed the lowest Ca^{2+} concentration (Table 3), whereas the 35% phosphoric acid showed the highest Ca^{2+} level dissolved from enamel surfaces, which was even significantly higher than that in the untreated group ($p<0.05$). SEM investi-

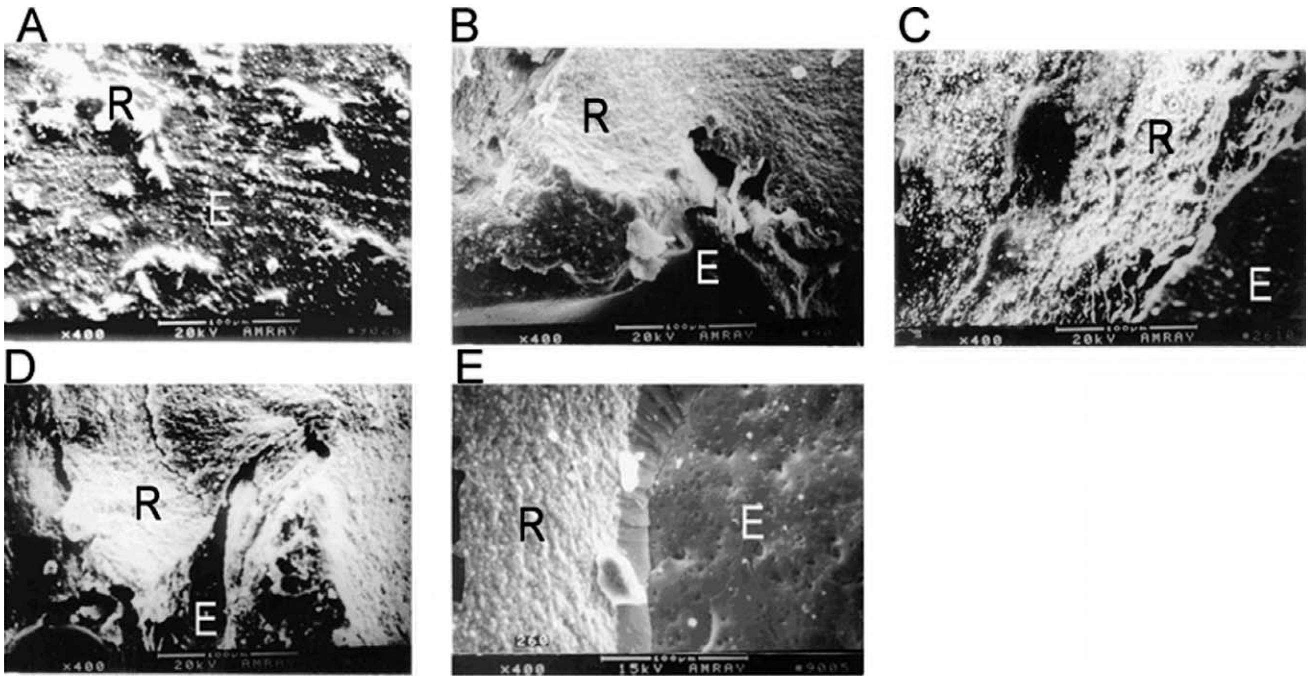

Figure 2. *SEM images of fractured enamel surfaces after TBS tests. A small amount of resin was left on the bonding surface of the untreated group (A). Remnant resin almost covered the whole bonding surface in most specimens of both acid etching (B) and laser/etching groups (D), more than half of the specimens in the laser irradiation group (C), and approximately half in the etching/laser group (E).*

gations showed that several shallow demineralization islands (Figure 4A) were found in the enamel surfaces of the laser irradiation group, whereas whole demineralization defects were found in the acid-etching (Figure 4B) and untreated groups (Figure 4C). Demineralization depth measurements (Figure 5) showed that the mean demineralization depth was only 47.78 ± 6.31 μm in the laser irradiation group, whereas it was 236.42 ± 11.88 μm in the acid etching group. This value was also significantly higher than that in the untreated group (179.06 ± 13.25 μm) ($p<0.05$). The data indicate that enamel acid resistance was significantly enhanced by the pulsed Nd:YAG laser, but adversely affected by 35% phosphoric acid.

DISCUSSION

Enamel pretreatment is critical for the application of composite resin in the direct bonding of orthodontic attachments or the esthetic restoration of anterior tooth defects.[18,19] Evidence has shown that the Nd:YAG laser can cause an irregular honeycomb or crater morphology on the enamel surface by irradiation, and thus, presents a potential use in enamel pretreatment.[13] To establish an alternative enamel

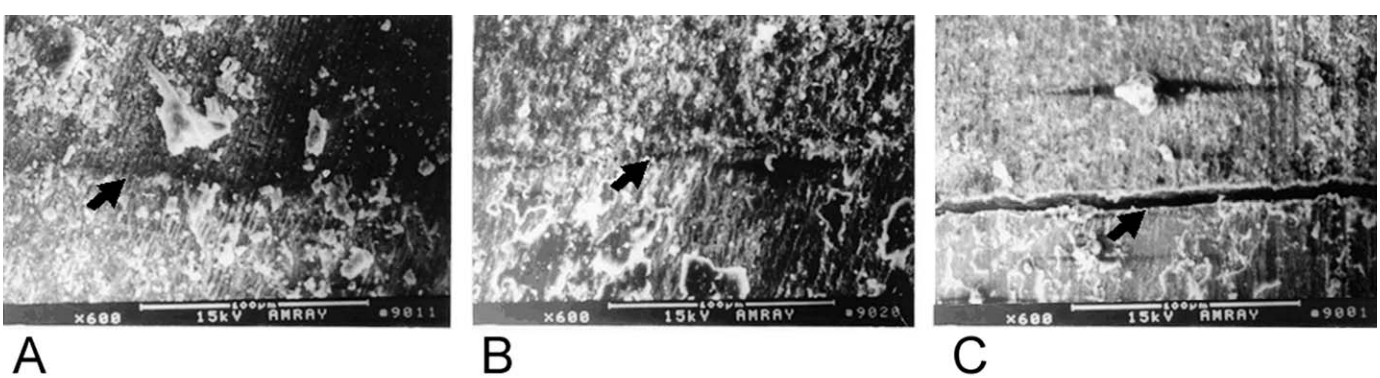

Figure 3. *SEM images of resin/enamel interfaces. The untreated group (A) showed a clear gap between the resin and enamel. A similar thin gap was observed in the acid etching (B) and laser irradiation groups (C).*

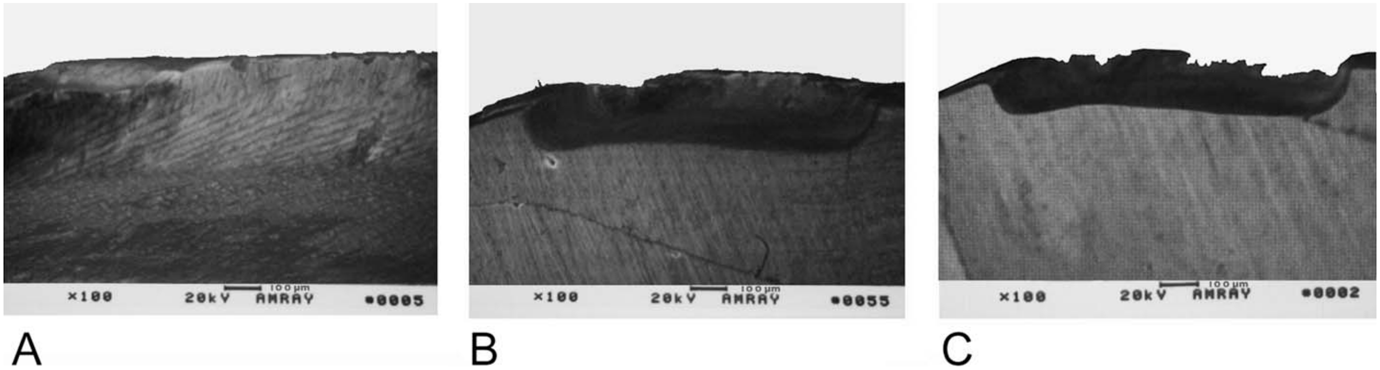

Figure 4. *SEM images of demineralized enamel interfaces. Whole demineralization defects were found in the untreated (A) and acid etching (B) groups, whereas several shallow demineralization islands were observed in the laser irradiation group (C).*

pretreatment method, we investigated the effects of pulsed Nd:YAG laser on the TBS and caries resistance of human enamel, given that acid etching increases the risk of caries.

Previous studies have indicated that lasers produce morphologic modifications on dental hard tissue by melting and solidification.[20,21] These alterations include honeycombs or craters and numerous microcavities or micropores at their periphery, which may offer microspace for the sealant or composite anchorage.[22-24] However, previous studies have shown conflicting results because of the high number of variables involved in the lasing process, such as power, pulse frequency, and duration of irradiation.[25] Laser-parameter combinations should be optimized to maximize the potential of pulsed Nd:YAG laser. We found that laser output energy level is crucial in the effects of pulsed Nd:YAG laser on enamel morphologic modifications. Low power and frequency were insufficient to alter enamel surface, and the formed honeycombs or craters were scattered. An increase in laser output energy resulted in relatively equally distributed honeycombs or craters and etching-like appearances on the enamel surfaces. This finding was consistent with the report of Bedini and others[26] that a high-energy level of Nd:YAG laser creates a retentive surface suitable for sealant or composite anchorage.

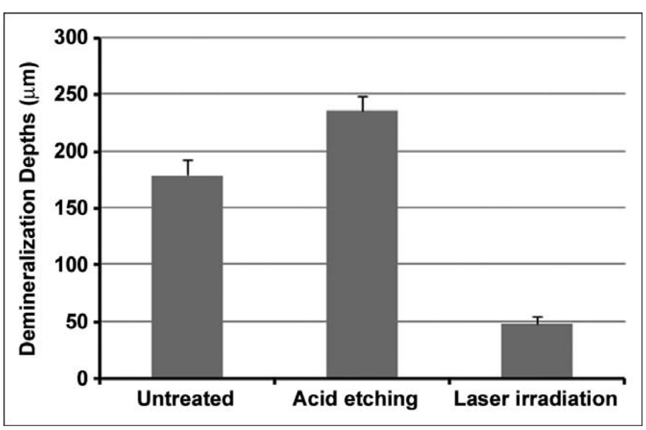

Figure 5. *Mean demineralization depths for the three experimental groups. A significant difference was observed among the groups ($p<0.05$).*

The Nd:YAG laser is less efficient in ablating the dental hard tissues compared with the Er:YAG laser, but it is superior in inducing morphologic alterations that are essential in providing microspaces for resin monomer penetration and in increasing enamel acid resistance.[27] In this study, we investigated the different output energy levels of pulsed Nd:YAG laser and found that neither low nor high laser-parameter combinations contributed to the TBS of resin to enamel. On one hand, significantly low laser-parameter combinations were proven inadequate in altering enamel surfaces and in offering sufficient microspace for resin monomers to penetrate. On the other hand, significantly high laser-parameter combinations induce excessive melting and recrystallization, as well as decrease the enamel surface free energy and microhardness that seriously damage the bond strength of resin to enamel. Moderate energy levels are more efficient in increasing the bond strength of resin to enamel. These findings were inconsistent with the study of Kwon and others[24] who reported that a higher laser power produces higher bond strength than a lower laser power. This phenomenon is possibly caused by the different laser scan speeds and irradiation times used in this study, which resulted in the different energy levels in the unit area.

Although considerable TBS values were achieved with pulsed Nd:YAG laser treatment, they remained significantly lower than that of 35% phosphoric acid treatment, as presented in previous reports.[21,28]

However, the difference in the current study is that laser irradiation, followed by etching, significantly increased the TBS of resin to enamel. We speculate that the subsequent treatment of 35% phosphoric acid further roughened the lased enamel surfaces and simultaneously eliminated the weak structures caused by the Nd:YAG laser.

Among the physical and chemical alterations of lasers on enamel surfaces, the enhancement of acid resistance has immense advantages in adhesive dentistry. A number of studies have demonstrated that lasers significantly alter the permeability, crystallinity, and acid-solubility of the enamel surface, thus promoting its resistance to demineralization.[29-31] In addition, lasers promote fluoride uptake and prolong the fluoride-releasing time in an oral environment.[32] However, the influence of laser output energy parameters on enamel acid resistance has not been fully discussed. In this study, the effect of pulsed Nd:YAG laser on Ca^{2+} concentration dissolved from human enamel surfaces was significantly affected by the laser-parameter combinations. Moderate, not low or high, laser-parameter combinations were proven efficient in preventing enamel surface demineralization. Previous studies have indicated that the thermal effect of a laser is the main factor that prevents the demineralization of enamel.[33,34] A lased enamel surface is subjected to water loss from 80°C to 120°C, to decomposition of organic substance at 350°C, to initial loss of carbonate hydroxyapatite from 400°C to 660°C, and to enamel melting at more than 800°C to 1000°C with the formation of β- and α-TCP (tri-calcium-phosphate), which is potentially soluble in an acid environment.[30,33] The foregoing are the reasons why the moderate laser-parameter combinations were tested for efficiency in the acid resistance of enamel surface in this study. Low laser-parameter combinations were insufficient to induce melting and recrystallization, which are essential factors in the acid resistance of enamel surfaces. However, high laser-parameter combinations led to the formation of acid-soluble compounds, such as β- and α-TCP, which increased the demineralization of enamel surfaces.

Unlike laser ablation, phosphoric acid etching modifies enamel surface morphology by the selective removal of interprismatic mineral structure; the organic materials are less affected.[35] This regularly rough and extensively microfissured structure is very useful in increasing the retention of resin composites for adhesion but is very vulnerable to acid attack. Acid etching does not improve the crystalline structure and block the ion diffusion channel, but it removes the acid-protecting superficial enamel layer.[36] In this study, 35% phosphoric acid significantly increased the mean Ca^{2+} concentration dissolved from enamel surfaces and the demineralization depth. Data and SEM observations suggest that the pulsed Nd:YAG laser-treated enamel subsurface presents fewer soluble compounds and may be more acid-resistant during pH cycling.

Previous studies have reported that a minimum bond strength of 5.9 MPa to 7.9 MPa could result in successful clinical bonding.[37,38] The mean TBS value of 14.45 ± 1.67 MPa in the pulsed Nd:YAG laser group in this study is adequate to meet the clinical need for dental adhesion, although this value is significantly lower than that in the 35% phosphoric acid group. Pulsed Nd:YAG laser has numerous advantages when used as an enamel surface pretreatment method. Pulsed Nd:YAG laser can eliminate the need for the separate steps of water spraying and air drying, which are essential in the acid-etching technique. In contrast to acid-etching that increased the risk of caries attack, pulsed Nd:YAG laser enhanced the acid resistance of enamel surfaces in this study. In addition, the Nd:YAG laser has been reported to be more efficient than the acid-etching technique in reinforcing the decreased bond strength of resin composite to recently bleached enamel.[39,40] Therefore, the pulsed Nd:YAG laser can be used as an alternative enamel pretreatment method, especially in the caries-susceptible population or in individuals who recently underwent 35% hydrogen peroxide bleaching of the teeth. However, the proposed method needs further investigation in our future studies.

CONCLUSIONS

The effects of pulsed Nd:YAG laser on morphologic modification, TBS, and acid resistance of human enamel were influenced by laser output energy parameters. The moderate laser parameters significantly enhanced the TBS and acid resistance of human enamel, although high-energy level laser parameters were proven efficient in altering the enamel surface. The pulsed Nd:YAG laser was less efficient in increasing the TBS of resin to enamel compared with the acid-etching technique, but the proposed method significantly contributed to the acid resistance of human enamel. The combinations of pulsed Nd:YAG laser and 35% phosphoric acid showed the highest mean TBS value in this study.

Acknowledgements

This work was supported by grants from the National Natural Science Foundation of China (Grant 31070863), the Natural Science Foundation Projects of Chongqing (Grant CSTC2010BB5161), and the Project of State Key Laboratory of Trauma, Burns, and Combined Injury (Grant SKLKF201212), China.

Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 13 March 2013)

REFERENCES

1. Alex TG (1995) Advances in adhesive technology *Current Opinion in Cosmetic Dentistry* 69-74.
2. Tay FR, & Pashley DH (2002) Dental adhesives of the future *Journal of Adhesive Dentistry* **4(2)** 91-103.
3. Buonocore MG (1955) A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces *Journal of Dental Research* **34(6)** 849-853.
4. Paschos E, Kleinschrodt T, Clementino-Luedemann T, Huth KC, Hickel R, Kunzelmann KH, & Rudzki-Janson I (2009) Effect of different bonding agents on prevention of enamel demineralization around orthodontic brackets *American Journal of Orthodontics and Dentofacial Orthopedics* **135(5)** 603-612.
5. Uysal T, Amasyali M, Ozcan S, Koyuturk AE, & Sagdic D (2011) Effect of antibacterial monomer-containing adhesive on enamel demineralization around orthodontic brackets: An in-vivo study *Journal of Orthodontics and Dentofacial Orthopedics* **139(5)** 650-656.
6. Benson PE, Higham SM, & Pender N (2003) An *in vitro* assessment using transverse microradiography of the effect on mineral loss of etching enamel for in situ studies *Orthodontics & Craniofacial Research* **6(4)** 242-249.
7. Dundar M, Gungor MA, Cal E, Darcan A, & Erdem A (2007) Evaluation of metal bond strength to dentin and enamel using different adhesives and surface treatments *General Dentistry* **55(3)** 204-209.
8. Ibrahim IM, Elkassas DW, & Yousry MM (2010) Effect of EDTA and phosphoric acid pretreatment on the bonding effectiveness of self-etch adhesives to ground enamel *European Journal of Dentistry* **4(4)** 418-428.
9. Yilmaz HG, Kurtulmus-Yilmaz S, Cengiz E, Bayindir H, & Aykac Y (2011) Clinical evaluation of Er, Cr: YSGG and GaAlAs laser therapy for treating dentine hypersensitivity: A randomized controlled clinical trial *Journal of Dentistry* **39(3)** 249-254.
10. Buchalla W, & Attin T (2007) External bleaching therapy with activation by heat, light or laser: A systematic review *Dental Materials* 2**3(5)** 586-596.
11. Lago AD, de Freitas PM, & Netto NG (2011) Evaluation of the bond strength between a composite resin and enamel submitted to bleaching treatment and etched with Er: YAG laser *Photomedicine and Laser Surgery* **29(2)** 91-95.
12. de Oliveira MT, Arrais de Paula CA, Aranha AC, Eduardo C, Miyake K, Rueggeberg FA, & Giannini M (2010) Micromorphology of resin-dentin interfaces using one-bottle etch & rinse and self-etching adhesive systems on laser-treated dentin surfaces: A confocal laser scanning microscope analysis *Lasers in Surgery and Medicine* **42(7)** 662-670.
13. Banda Vanaja NR, Reddy G, & Shashikiran ND (2011) Evaluation of primary tooth enamel surface morphology and microhardness after Nd: YAG laser irradiation and APF gel treatment—an *in vitro* study *Journal of Clinical Pediatric Dentistry* **35(4)** 377-382.
14. He H, Yu J, Song Y, Lu S, Liu H, & Liu L (2009) Thermal and morphological effects of the pulsed Nd: YAG laser on root canal surfaces *Photomedicine and Laser Surgery* **27(2)** 235-240.
15. Wen X, Liu L, Nie X, Zhang L, Deng M, & Chen Y (2010) Effect of pulse Nd: YAG laser on bond strength and microleakage of resin to human dentine *Photomedicine and Laser Surgery* **28(6)** 741-746.
16. Featherstone JDB, ten Cate JM, Shariati M, & Arends J (1983) Comparison of artificial caries like lesions by quantitative microradiography and microhardness profiles *Caries Research* **17(5)** 385-391.
17. Jepsen S, Açil Y, Peschel T, Kargas K, & Eberhard J (2008) Biochemical and morphological analysis of dentin following selective caries removal with a fluorescence-controlled Er: YAG laser *Lasers in Surgery and Medicine* **40(5)** 350-357.
18. Turner PJ (1996) Successful bonding in orthodontics: 1 *Dental Update* **23(9)** 366-370.
19. Soares CJ, Fonseca RB, Martins LR, & Giannini M (2002) Esthetic rehabilitation of anterior teeth affected by enamel hypoplasia: A case report *Journal of Esthetic and Restorative Dentistry* **14(6)** 340-348.
20. Chang KK, Staninec M, Chan KH, & Fried D (2011) Adhesion studies on dental enamel surfaces irradiated by a rapidly scanned carbon dioxide laser *Proceedings-Society of Photo-Optical Instrumentation Engineers* **1** 7884
21. Yamada MK, & Watari F (2003) Imaging and non-contact profile analysis of Nd: YAG laser-irradiated teeth by scanning electron microscopy and confocal laser scanning microscopy *Dental Materials Journal* **22(4)** 556-568.
22. Hess JA (1997) Subsurface morphologic changes of ND: YAG laser-etched enamel *Lasers in Surgery and Medicine* **21(2)** 193-197.
23. Nguyen D, Chang K, Hedayatollahnajafi S, Staninec M, Chan K, Lee R, & Fried D (2011) High-speed scanning ablation of dental hard tissues with a $\lambda = 9.3$ μm CO_2 laser: Adhesion, mechanical strength, heat accumulation, and peripheral thermal damage *Journal of Biomedical Optics* **16(7)** 071410.
24. Kwon YH, Kwon OW, Kim HI, & Kim KH (2003) Nd: YAG laser ablation of enamel for orthodontic use: Tensile bond strength and surface modification *Dental Materials Journal* **22(3)** 397-403.
25. Castellan CS, Luiz AC, Bezinelli LM, Lopes RM, Mendes FM, De P Eduardo C, & De Freitas PM (2007) *In vitro*

evaluation of enamel demineralization after Er: YAG and Nd: YAG laser irradiation on primary teeth *Photomedicine and Laser Surgery* **25(2)** 85-90.

26. Bedini R, Manzon L, Fratto G, & Pecci R (2010) Microhardness and morphological changes induced by Nd: Yag laser on dental enamel: An *in vitro* study *Annali Dell'Istituto Superiore Di Sanità* **46(2)** 168-172.
27. Yamada MK, Uo M, Ohkawa S, Akasaka T, & Watari F (2004) Three-dimensional topographic scanning electron microscope and Raman spectroscopic analyses of the irradiation effect on teeth by Nd: YAG, Er: YAG, and CO(2) lasers *Journal of Biomedical Materials Research. Part B, Applied Biomaterials* **71(1)** 7-15.
28. Goswami M, & Singh A (2011) Comparative evaluation of shear bond strength of composite resin bonded to acid etched or Nd: Yag lased enamel *Journal of the Indian Society of Pedodontics and Preventive Dentistry* **29(2)** 140-143.
29. Rechmann P, Fried D, Le CQ, Nelson G, Rapozo-Hilo M, Rechmann BM, & Featherstone JD (2011) Caries inhibition in vital teeth using 9.6-μm CO_2-laser irradiation *Journal of Biomedical Optics* **16(7)** 071405.
30. Rohanizadeh R, LeGeros RZ, Fan D, Jean A, & Daculsi G (1999) Ultrastructural properties of laser-irradiated and heat-treated dentin *Journal of Dental Research* **78(12)** 1829-1835.
31. Schmidlin PR, Dörig I, Lussi A, Roos M, & Imfeld T (2007) CO_2 laser-irradiation through topically applied fluoride increases acid resistance of demineralised human enamel *in vitro Oral Health & Preventive Dentistry* **5(3)** 201-208.
32. Zezell DM, Boari HG, Ana Eduardo PA, Cde P, & Powell GL (2009) Nd: YAG laser in caries prevention: A clinical trial *Lasers in Surgery and Medicine* **41(1)** 31-33.
33. Featherstone JDB, & Fried D (2001) Fundamental interactions of lasers with dental hard tissues *Medical Laser Application: International Journal for Laser Treatment and Research* **16(3)** 181-194.
34. Fowler BO, & Kuroda S (1986) Changes in heated and in laser-irradiated human tooth enamel and their probable effects on solubility *Calcified Tissue International* **38(4)** 197-208.
35. Kim JH, Kwon OW, Kim HI, & Kwon YH (2006) Acid resistance of erbium-doped yttrium aluminum garnet laser-treated and phosphoric acid-etched enamels *Angle Orthodontist* **76(6)** 1052-1056.
36. Martinez-Insua A, Dominguez LDS, Rivera FG, & Santana-Penin UA (2000) Differences in bonding to acid etched or Er: YAG-laser-treated enamel and dentin surfaces *Journal of Prosthetic Dentistry* **84(3)** 280-288.
37. Reynolds IR (1975) Letter: Composite filling materials as adhesives in orthodontics *British Dental Journal* **138(3)** 83.
38. Liu JK, Chuang SF, Chang CY, & Pan YJ (2004) Comparison of initial shear bond strengths of plastic and metal brackets *European Journal of Orthodontics* **26(5)** 531-534.
39. Lago AD, de Freitas PM, & Netto NG (2011) Evaluation of the bond strength between a composite resin and enamel submitted to bleaching treatment and etched with Er: YAG laser *Photomedicine and Laser Surgery* **29(2)** 91-95.
40. Rocha Gomes Torres C, Caneppele TM, Del Moral de Lazari R, Ribeiro CF, & Borges AB (2012) Effect of dental surface treatment with Nd: YAG and Er: YAG lasers on bond strength of resin composite to recently bleached enamel *Lasers in Medical Science* **27(4)** 755-760.