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Modification of Enamel Surface Morphology and Strength Using Nd:YAG Laser with Proper and Safe Parameters

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Abstract

Objective The aim of this study was to determine the effect of a Nd:YAG laser on enamel surface morphology and hardness using different energies and pulses.

Materials and Methods Twenty freshly extracted mature teeth were collected and sectioned. An Nd:YAG laser operating at 1,064 nm wavelength and providing up to 9 nanosecond laser pulses (1 J), with a laser spot diameter of 0.8 mm and irradiated surface area of $3 \times 3\ mm^2$, was applied to carbon black-coated teeth. The samples were randomly divided into two main groups; each group comprised 20 samples, according to the treatment parameters. The first group was further divided into subgroups A, B1, C1, and D1 using the different energies of 0, 350, 450, and 550 mJ, respectively, with 1 pulse for B1, C1, and D1. The second group was subdivided into A, B2, C2, and D2 and treated with 200 mJ, 3, 4, and 6 pulses for subgroups B2, C2 and D2, respectively. Subgroup A was the same sample for both groups as control with 0 pulses and 0 energy. Morphological features and microhardness were evaluated after laser exposure.

Statistical Analysis Analysis of variance (Kruskal–Wallis test) was used to compare all subgroups, followed by the Scheefy significant difference post hoc test to determine the highest significance of the subgroups. Alpha < 0.05 was set as significant.

Results The changes in the surface morphology of the enamel included increased crystal sizes, cracks, fissures, and voids with increasing energies and pulses. In group 1, the microhardness was 405.6, 562.7, 612, and 637 for energies of 0, 350, 450, and 550 mJ, respectively. In group 2, the microhardness was 405.6, 673, 866, and 1,050 for 0, 3, 4, and 6 pulses, respectively.

Conclusion The Nd:YAG laser is efficient for increasing the microhardness of the enamel surface with minimum morphological damage by applying low energy with more pulses.

Keywords
- enamel
- morphology
- pulses
- energy
- Nd:YAG

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Introduction

Currently, laser therapies are widely used in medicine and dentistry as they allow for blood vessel welding that minimizes bleeding and enhances the clear operative field with excellent visualization during a surgical operation.[1] Dental lasers can be used to reduce pain without requiring anesthesia,[2] cause less edema, and allow for rapid healing and sterilization of the tissue in comparison with scalpels used in surgery.[2] There are several types of lasers with specific features, such as wavelengths and spot sizes, which are important for specific applications.[3,4] Currently, dental lasers can be used in diagnosis, composite curing, and photodisinfections.[5] In addition, different types of lasers with a specific wavelength can be used to control bleeding in vascular lesions, biopsies, tumor excisions, second-stage implant recovery, temporomandibular joint surgeries, surgical treatment of lichen planus, gingival melanin pigmentation, oral dysplasia, mucocele, Ranula, epulis fissuratum, gingivoplasty, gingivectomy, frenectomy, pulp amputation, the removal of smear layers in root canal disinfection and the activation of tooth bleaching solutions.[6–10] An Nd:YAG laser is recommended in pediatric dentistry to seal pits and fissures, increasing the acid resistance of primary enamel and preventing tooth decay.[11–13]

A unique property of lasers is their monochromaticity, which affects a specific type of tissue or compound without interfering with the others.[14,15] The interaction between tissues and laser energy is mainly determined by the laser wavelength and the properties of the target tissue. However, laser parameters, energy density, power density, pulse repetition rate, pulse duration, and the mode of energy transfer to the tissue are selected by the operator according to the clinical case that is being treated.[16]

Each tissue has its special absorption property depending on its consistency and chromophore; melanin, hemoglobin, protein, and water are the main chromophores present in the mammalian tissue. Water is mainly absorbed by infrared light, while hemoglobin and melanin are absorbed by visible and ultraviolet light, respectively. Therefore, a wavelength that is highly absorbed by a specific region chromophore must be selected.[14] The mechanisms of interaction between lasers and biological tissues are mainly photochemical, photoacoustic, and photothermic mechanisms. In the oral cavity, the soft tissue effect is based on the transformation of light energy into thermal energy, which in turn heats the target tissue to produce the desired effect.[17] It was reported that most medical lasers act by heating the target tissue, and the effects of high-temperature laser application on soft tissue are sterilization, coagulation and hemostasis, incision and excision, ablation, and vaporization.[18] In the hard tissue of teeth (enamel and dentin) and bone, the main effects are ablation and melting as well as the absorption of energy by hydroxyapatite in addition to water.[14,17]

Temperature elevation in the interaction site leads to water evaporation, rapid volumetric expansion, and hard tissue disintegration caused by the production of microexplosions. Irreversible damage to the vital pulp can occur if the temperature increase is more than 5.5°C; as a result, care must be taken when using lasers in tooth substances. Therefore, preserving the odontoblast nuclei and the intracellular tissue composition after laser ablation is an important factor for the viability of cells.[18] There are high variations in the energy, pulse frequency, and irradiation duration chosen in the literature.[19] In this work, we studied the effect of an Nd:YAG laser on the enamel surface morphology and hardness with different energies and pulses to choose the best and safest parameters for its modification.

Materials and Methods

Study Design

A randomized controlled study was conducted in Technology University laboratories between May 2020 and January 2021.

Sample Preparation

Twenty freshly extracted mature, molar and premolar teeth with no active caries and periodontal disease were stored in 10% formalin. The teeth were placed in plastic molds with their buccal surfaces facing outward. Epoxy resin was slightly warmed to solidify rapidly, mixed with a small amount of epoxy hardener, and poured on the teeth until the epoxy became solid. The molds were lifted. The teeth were sectioned either longitudinally or transversely using a low-speed diamond wheel saw (Model SYJ-150, MTI Corporation) under water cooling. The samples were polished under water spray cooling using a grinding machine (grinder polisher MPD 200 Dual Speed Polisher, Laree Technology Co. Ltd., China) at rotating speeds between 150 and 300 r/min and Amery silicon carbide papers no. 1200 to 3000. At the final polishing stage, a cloth and 0.05 polishing alumina were utilized in a metallurgical polisher (DP-U4; Struers, Denmark) at a low speed, with a light load on the samples. The samples were cleaned ultrasonically (Laboratory Tech, Daihan Labtech Co., Ltd., model LUC-410, Korea) in distilled water for 5 minutes and stored in distilled water at room temperature.

Lasing Procedures

A Q-switched Nd:YAG laser supplied by HUAFEL (Single pulse mode, China), operating at 1064 nm wavelength and providing up to 9 nanosecond laser pulses (1 J), was employed to irradiate the tooth enamel surfaces. A positive lens of 10 cm focal length was used to obtain the required laser energy fluence on the enamel surface, with a laser spot diameter of 0.8 mm, which was checked by making a burn mark on carbon paper and viewed by an optical microscope. Irradiated surface areas of $3 \times 3\,mm^2$ were performed on carbon black-coated tooth surfaces to enhance laser absorption. Alternatively, each sample was placed in a beaker containing black ink–water solution at a level slightly higher than the sample surface. Thirty-five samples were randomly divided into two main groups; each group comprised 20 samples, according to the treatment parameters, with 5 for each subgroup (Subgroup A was the same sample for both groups as control with 0 pulses and 0 energy). The first group was

labeled with different laser energy level treatments. This group was subdivided into four subgroups A, B1, C1, and D1 using different energies of 0, 350, 450, and 550 mJ, respectively, with 1 pulse for B1, C1, and D1. The second group was subdivided into four subgroups A, B2, C2, and D2, which were treated with 200 mJ energy and different numbers of pulses; 3, 4, and 6 pulses were used for subgroups B2, C2, and D2, respectively. The subgroup (A) in each main group was the control group (untreated samples).

Evaluations

Observations of Morphological Changes

Two samples from each group were gold-coated for scanning electron microscope analysis using a scanning electron microscope (SEM) (Tescan, vega3, Czech) to observe structural changes in the enamel surfaces after each treatment in comparison with the non-treated one.

Vickers Microhardness Tests

A digital Micro Vickers hardness tester (TH 715, 2008, China) equipped with a high-resolution optical microscope was used to evaluate the surface modifications by a laser under 500 g loads and 15-second indentation conditions.

Statistical Analysis

SPSS version 25 software was used for data analysis, in which nonparametric analysis of variance (ANOVA) (Kruskal–Wallis test) was used to compare all subgroups followed by the Scheefy significant difference post hoc test to determine the highest significance of subgroups. Alpha < 0.05 was set as significant.

Results

Scanning Electron Microscopy Results

Morphology

After exposure to the Nd:YAG laser, remarkable changes in the enamel surface were observed by SEM and these changes increased with increasing energy or pulses.

Group 1

Subgroup A: SEM image of subgroup A, 0 mJ and 0 pulse (control) showed normal smooth enamel with well-defined circumferentially arranged enamel rods filled with interrod material on the surface and depressions.

Subgroup B1: SEM image of subgroup B1 (350 mJ, one pulse). The enamel features were seen clearly with minimum alteration in the morphology despite the presence of a few cavitations and fissures.

Subgroup C1: SEM image of subgroup C1 (450 mJ, one pulse). Alterations in enamel morphology, melting enamel with the presence of enamel granules, holes, and fissures were observed.

Subgroup D1: SEM image of subgroup D1 (550 mJ, one pulse) showed a complete change in features. A glass-like appearance with melted smooth enamel surfaces was observed. Large cracks and fissures were seen.

Group 2

Subgroup B2: SEM image of subgroup B2, 200 mJ and 3 pulses. The sample appeared uniform, the enamel surface was smooth and homogenous with well-coalesced enamel rods; there were a few cavities and cracks.

Subgroup C2: SEM image of subgroup 200 mJ and 4 pulses showed melted enamel with large granules and fine fissures

Subgroup D2: The SEM image of subgroup D2 (200 mJ and 6 pulses) appeared rough and nonuniform with the fusion of granules; there was an appearance of cracks and cavities with small smooth areas (►**Figs. 1** and **2**).

Vickers Microhardness

►**Figs. 3–5** show the increase in microhardness with increasing energy and pulses. The increase in the hardness was higher with the increase in pulses than with the increase in energy.

Statistical Analysis

Generally, there were highly significant differences between all subgroups ($p < 0.001$) (►**Table 1**). There was a significant difference between group A and DI, B2, C2, and D2, with $p = 0.023$, 0.003, < 0.001, and < 0.001, respectively. However, there were no significant differences between group A and groups B1 and C1, $p = 0.264$ and 0.058, respectively, in group B1. Interestingly, there was no significant difference between D1 and B2, $p = 0.988$, although high energy was used in D1 (550 mJ) and lower energy was used in B2 (200 mJ).

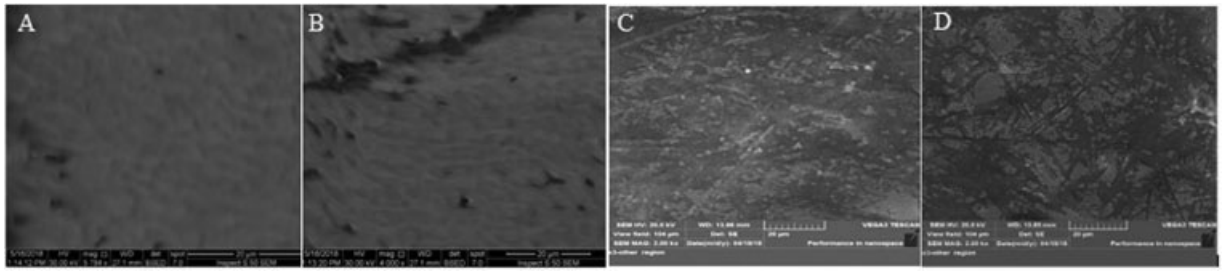

Fig. 1 Scanning electron microscopy of 0 and 1 pulses with different energies: (A) SEM image of subgroup A, 0 mJ and 0 pulse (control), magnification, 5.784 k×. (B) SEM image of subgroup B1, 350 mJ, one pulse, magnification, 4.00 k×. (C) SEM image of subgroup C1, 450 mJ, one pulse, magnification, 2.00 k×. (D) SEM image of subgroup D1, 550 mJ, one pulse, magnification 2.00 k×.

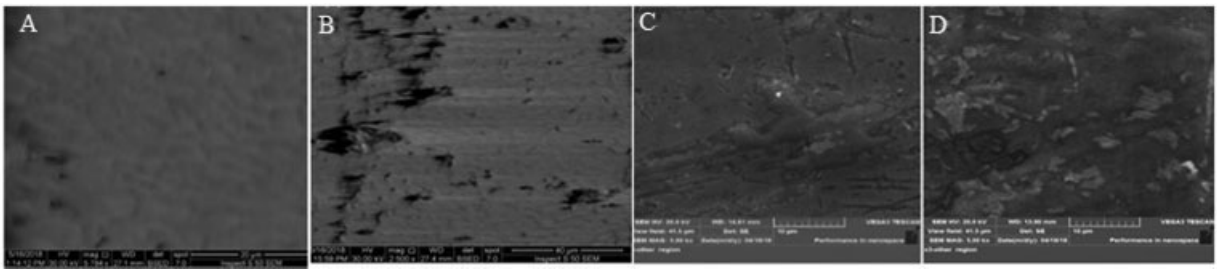

Fig. 2 Scanning electron microscopy image of constant energy with different pulses: (**A**) SEM image of subgroup A, 0 mJ and 0 pulses (control), magnification, 5.784 k ×. (**B**) SEM image of subgroup B2, 200 mJ and 3 pulses, magnification 2.500 k ×. (**C**) SEM image of subgroup 200 mJ and 4 pulses, magnification, 5.00 k ×. (**D**) SEM image of subgroup D2, 200 mJ and 6 pulses, magnification 5.00 k ×.

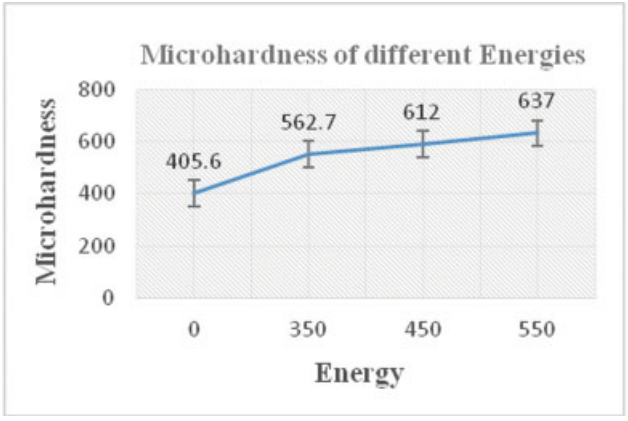

Fig. 3 Microhardness of different energies.

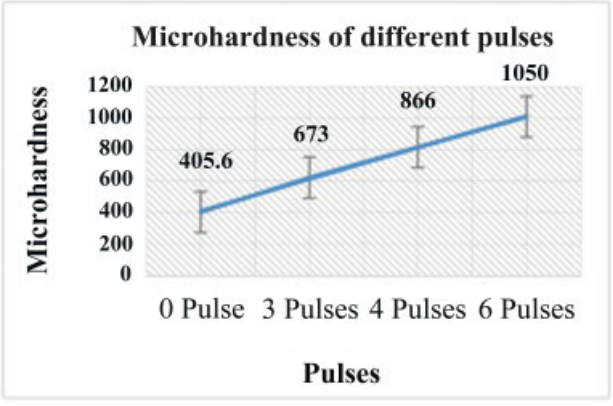

Fig. 4 Microhardness of different pulses.

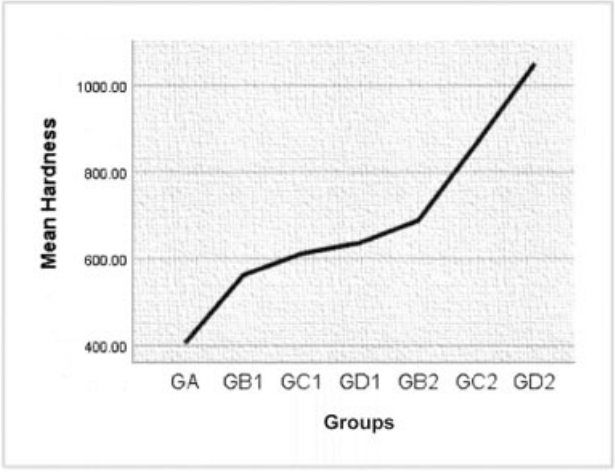

Fig. 5 Microhardness of all subgroups.

Table 1 Statistical analysis results

Test Statistics[a,b]	
	Hardness
Kruskal–Wallis H	30.583
D_f	6.000
Asymp. Sig.	0.000

[a]Kruskal–Wallis test.
[b]Grouping variable.

Discussion

The use of laser beams in the treatment of dental hard tissues has recently gained acceptance, and a precise irradiation parameter must be selected for clinical application to avoid morphological damage in the form of surface carbonization or cracking that destroys the structure and esthetics. Safe energy densities must be chosen to protect the pulp and periodontal tissue vitality, and short pulses must be used to prevent thermal damage to the irradiated surface.[20–23] One study reported that the chosen area could be targeted and that the surrounding tissue was relatively unaffected.[14] In the current study, we limit the energy to 550 mJ according to our previous study, in which we found that energy higher than 600 mJ damaged the enamel surface with cracks.[24]

Morphologic Features

In the current study, different changes were observed in the morphology of all subgroups in comparison with the control after using different energies and pulses. Al-Jedani et al characterized the normal enamel surface by the presence of enamel rods and depressions with dentinal tubules extending from the pulp outward through the dentin to the external enamel surface.[25] Several authors agree with our finding; they reported that the exposure of enamel to a laser beam altered its morphology. SEM results showed

different morphologic features, cracks, and holes in the irradiated surface depending on the intensity of the radiation and number of pulses when more changes were seen.[25,26] These alterations in the surface appear as a result of melting, followed by enamel recrystallization during cooling, and the authors observed that the alterations occurred only in the enamel surface layers as the section taken perpendicular to it and that no changes occurred in the enamel crystals on the internal side of the tooth.[26]

Altering the composition and morphology of enamel requires strong absorption of light, and more absorption of radiation by the target tissue decreases the depth of light penetration.[24,27] In this study, an Nd:YAG laser was used, which was weakly absorbed by enamel; therefore, the tooth surface was coated with carbon black, which acts as a photoabsorber, to increase the absorption of the laser and decrease the thermal damage to the adjacent tissues. One study used waterproof India ink, which is commonly applied onto enamel surfaces before Nd:YAG laser irradiation, to serve as a photoabsorber.[25,28] The use of a photoabsorber is recommended before Nd:YAG laser application; otherwise, incomplete absorption of the light by the enamel surface leads to reflection scattering or transmission to the dentin and pulp, which compromise its vitality.[28,29]

The predominant mechanism of the nanosecond laser pulse as described by Lee is that when the intensity is less than 108 W/cm^2, an increase in the temperature of the solid surface, thermal vaporization, and phase transition occurs from solid to liquid, vapor, and plasma, respectively.[27,30] Columns separated by voids are the result of enamel melting and then solidification, and the strongest morphological changes occur when a higher energy density or a higher number of pulses are used.[25] Fissures appear on the enamel surface due to sudden and rapid changes in temperature, and they cannot be distributed due to the tight structure of the enamel that lacks porosities, which damages the enamel.[31]

It was reported that the increase in temperature on dental tissues, generated by irradiation, is responsible for the change in the morphology and structure of the irradiated surface, and temperature changes are extremely high at the irradiated spot, even for a short exposure time.[32,33]

Several authors stated that the effect of high temperature produced by Nd:YAG irradiation is the formation of tricalcium phosphate (TCP) $Ca_3(PO_4)_2$ on enamel[34] and changes in the organic matrix, chemical, crystallographic aspects, and morphology.[26,35,36]

A study concluded that the structure and chemical composition of dental enamel are changed when the temperature increases. These alterations include a decrease in carbonate, loss of water, pyrophosphate formation by condensation of acid phosphate ions, thermal recrystallization, and increases in the crystal size and TCP formation.[35] Hydroxyapatite becomes less soluble when the amount of carbonate decreases because carbonate causes defects in the crystal such that it does not fit into the lattice, generating more acid-soluble apatite unstable phases. Pyrophosphate inhibits hydroxyapatite crystal dissolution, while tri- and tetracalcium phosphates are more susceptible to acid dissolution than hydroxyapatite. Additionally, organic matrix decomposition increases tooth enamel resistance to acid, closes the pores of the enamel, and prevents the penetration of acid ions.[36,37]

Microhardness

This study observed a significant increase in microhardness in all groups with increasing energy and pulses. This result is in agreement with that reported by Florin et al, who observed an increase in enamel microhardness after laser irradiation.[38] We believe that we used energy within a safe range that did not lower the microhardness of our samples, as our results showed minimum alteration in the morphology of the enamel in the 350 mJ and 3 pulse subgroups. Morphological changes increase with increasing energy and pulse. These increased morphological changes were associated with an increase in microhardness, and none of the subgroups showed a decrease in microhardness with an increase in morphology alteration.

However, several authors found that the increase in radiation intensity decreases the solubility in lactic acid associated with a reduction in enamel hardness, which may be due to column-shaped crack and void formation.[19,39,40] One study observed that microhardness decreased in irradiated specimens,[26] while another study reported no alteration in microhardness after laser irradiation.[41] They concluded that the difference between the authors' results was due to different parameter settings, wavelengths, methodologies, and the use of primary or permanent teeth.[41]

Conclusion

The Nd:YAG laser is efficient for modifying the enamel surface by increasing its microhardness with minimal morphological changes. We found that increasing pulses rather than increasing energy is beneficial. A specific parameter must be selected to reach the treatment goal by concentrating on the target area without damaging the nearby structures; therefore, we recommend an in vivo study to confirm the safety of this parameter setting in living tissue.

Conflict of Interest
None declared.

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