Evaluation of Er:YAG Laser Interaction With Dentin and Enamel Hard Tissues

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Abstract

Background: Pulsed Er:YAG lasers is an effective instrument to drill hard dental tissues. This article evaluates the effect of Er:YAG (2.94 µm) laser on both dentin and enamel hard tissues.

Objectives: The current study aimed to evaluate the exact depth of ablation and effective ablation area on dental hard tissues, in different conditions and various factors of Er:YAG laser.

Patients and Methods: In this research, a total of 20 human molar teeth were irradiated by Er:YAG (2.94 µm) laser, after mounting process and sterilization. Half of them were used as enamel samples and the rest, after removing the enamel tissue from their crowns, were used as dentin samples. The crowns of the samples were regarded as cube with all their lateral sides and were exposed by one special setting of the laser. Laser Irradiation was done in two different frequencies and all the procedure was accompanied by water cooling. The number of 100 pulses was selected as a fixed factor; therefore, 11 holes for all enamel and dentin samples were obtained. The hole images were taken by combining optical and computer methods, and then by processing them in MATLAB software, the depth of ablation and effective ablation area were calculated.

Results: After evaluating the exact amounts of ablation depth and effective ablation area and analyzing the data, it was found that increasing energy yields in increasing the depth of ablation, which was the case for both enamel and dentine tissues. It was also found that variations in effective ablation area were insignificant for both tissues. Ablation depth and effective ablation area were more tangible in dentin rather than enamel tissues. Finally, using this laser did not result in blunt and clear borders for the created holes.

Conclusions: Application of the Er:YAG laser for hard tissue removal and cavity preparation, compared to conventional methods, is considered as a more comfortable technique because there isn’t any contact between laser beam and teeth. Secondly there is no vibration. However, this procedure is not recommended without water cooling.

Keywords: Er:YAG Laser, Ablation Depth, Dentin, Enamel, Cavity Preparation

1. Background

It was not until 1989 that Er:YAG lasers were noticed and used for the first time in an investigation to stripe and remove dentin and enamel tissues and also to eliminate dental caries on the extracted human teeth. Since then, several studies are performed to determine the parameters and find safe and optimum conditions for their widely applications on both soft and hard dental tissues (1). Following their approval for dental operations in 1992, these lasers are increasingly used in dental practices and are a quite comfortable and painless device for the patients under treatment of dental caries (2).

From the very beginning of laser invention, this technology has had very important practical usages. Especially, it is one of the most attractive options in dental fields. This technology reduces time and is a more comfortable treatment for the patients. One of the main goals of restorative dentistry is to develop new methods for dental carries removals and preparing cavities which is important in conservative treatment and are acceptable and preferred by patients (3). Erbium family lasers, with two well-known wavelengths (2.94 µm and 2.78 µm), have high absorptions in water and hydroxyapatite which makes these lasers suitable for removal of carious enamel and dentin without any damage to the surrounding tissues. First, these lasers vaporize the water and other hydrated components in the tissues. During this process, internal pressure increases continuously to the point that destructive explosions of minerals occur within the tissues. As a result, the hydrokinetic forces, which are capable of stripping and removing hard tissues, are formed. The mechanism is reputed as hydrokinetic (3).
According to Niemz, lasers with pulse duration lying in the range of $10^{-6} - 10^{-3}$ second provide considerable heat via thermal interaction during ablation of the hard tissues (4). Commercial Erbium lasers are now available with pulse duration of microsecond, shorter than the thermal relaxation time of dental hard tissues ($< 1$ ms), which lead to heat dissipation during ablation and avoid the excessive transmission of heat to the pulp chamber (5). Application of most hard tissue lasers for cavity preparation and removing decays is based on photo thermal mechanism by which the hard tissue can be removed (6). However, some lasers can remove hard dental tissues through photothermal effect because of their specific physical characteristics. Using this method, laser pulses of nanosecond duration, which can transmit high energy density, lead to high accumulation of energy in a very short time leading to the breakdown of edge molecular bonds. This results in removing the exposed tissues. High intensity laser beam can directly break molecular bonds.

Radiation of Er:YAG laser has an absorption peak in hydroxyapatite and water with a minimum penetration depth in enamel and dentine tissues, $(5 \mu m - 7 \mu m)$, which results in concentration of energy only in a superficial layer $(4 \mu m - 5 \mu m)$ of the radiated tissues. The large share of this energy is spent on ablation and only a minimum part remains for the controlled heating of tissues (7-10). Therefore, interaction of this laser with hard dental structures can result in an efficient ablation of enamel and dentin with minimal changes on adjacent tissues and without any adverse effects on dental pulp. By suitable water cooling, the maximum temperature in the pulp chamber does not exceed $3\degree C - 4\degree C$. Therefore, dental manipulations by this laser can be described as a safe and secure procedure (7, 10).

One of the main factors that cause pain and discomfort during caries treatment is contact between dentine surface and turbine, used for caries removing, leading to vibration inside the tissue. It is found that the vibration speed caused by high-speed dental drills is 100 times greater than that of laser beam and according to Takamori et al. this high frequency range has a spectrum near the peak sensitivity of hearing and can cause pain and discomfort in the patients as a potential factor; on the contrary, applying the non-contact method in cavity preparation by Er:YAG laser does not result in any tangible vibrations in tissues (11).

Since the late 1980s, an excessive number of researches are conducted on this type of lasers and many of the published articles are focused on cavity preparation, measuring the temperature increase in the tissues, microscopic analysis and cooling effects (12). Removing the tissues depends on the specifications of the laser and also the characteristics of the target region. The wavelength of laser and its transmission, the pulse duration, energy of each pulse, the energy density and also spot size are the most physical laser parameters (13). Understanding the optical properties of tissue such as scattering and absorption coefficient are important to achieve better results and reduce heat or mechanical stress on hard tissues (14).

2. Objectives

The current study aimed to evaluate the effects of $2.94 \mu m$ wavelength of Er:YAG laser on both enamel and dentine hard tissues. The study aimed to calculate and provide numerical values of the ablation depth and effective ablation area of the holes created on both enamel and dentin tissues under different conditions and with different parameters of the laser.

3. Patients and Methods

In this research, conducted in the laser research center of dentistry at Tehran University of Medical Sciences, 20 human molar teeth were irradiated by Er:YAG $(2.94 \mu m)$ laser after mounting and sterilization process. The sterilization process consisted of cleaning the teeth by brush at the first step to completely remove the bacterial plaques and calculus deposits from their surfaces. Then the samples were disinfected by 1% aqueous solution of chloramine-T and 2% thymol in two sequential stages. Since the crowns were needed for irradiation and the roots for mount processing, it was necessary to have samples free from defects and fractures both in crown and root sections.

The samples were divided into two groups. Half of them (10) were used as enamel samples and the rest (10) were used as dentin samples after removing the enamel tissue from their crowns. Removing enamel tissues for dentin samples was done by conventional dental drills. The crown of each sample was regarded as a cube and each lateral side of the cube was exposed to one special setting of the laser. This resulted in one or two holes on each lateral sides of the cube.

To cut the samples, if necessary, it was recommended to place them on the base of regular geometric shape which also helped to increase the accuracy of the operation and eliminate any possible movements of the samples during the irradiation. Thus, the teeth were mounted in acrylic crystal from their roots to easily expose the crowns to laser radiation. To protect them from dryness and minimize their vulnerability, samples were kept in water during the procedure.

The Er:YAG laser used in the current study had a $2.94 \mu m$ wavelength, pulse duration of $230 \mu s$ and a spot size
of 0.5 mm². The laser included a controllable beam transmitter with a handpiece equipped with a water-cooling system to water spray the target while the beam was radiated. It was done by non-contact method in a close distance of handpiece with target and various powers and energies of the pulsed laser were applied.

The procedure was done in two different frequencies of 10 Hz and 15 Hz. Power and energy were defined as variables. Thus, five different steps of power (0.5, 1, 1.5, 2, and 2.5W) and energy (50, 100, 150, 200, and 250 mJ) were considered in the frequency of 10 Hz and the duration of irradiation was six seconds. Six different steps of power (0.75, 1.5, 2.25, 3, 3.75, and 4.5W) and energy (50, 100, 150, 200, 250, and 300 mJ) were also considered in the frequency of 15 Hz and duration of 4 seconds. Considering the different conditions of laser in the mentioned frequencies it was natural to use different irradiation time. With this procedure, 11 holes for enamel and the same number for dentin samples were obtained (two sides of a sample were irradiated and the total number of 11 holes were produced). Images were taken of the holes by combining optical and computer methods. By processing these images in MATLAB software, the precise depth of ablation and effective ablation area for each hole were calculated.

4. Results

After completing the irradiation process on tooth samples, it was necessary to record and analyze the obtained information. First of all, the images of holes were taken by combining optical and software recording methods. A microscope and a camera (Samsung SDC-313B) were combined and then connected to a computer (Figure 1). Upon reaching the best resolution, image capture software (Ulead Video Studio) was used to provide images of the samples. The resulting images are shown in Figures 2 - 5.

Following recording the images of holes, two and three-dimensional graphs for each hole were drawn using an image processing program, written in MATLAB, to measure the depth and effective area of ablation versus light intensity. The three-dimensional graphs were used to represent the true shape of each hole and evaluate the ablation depth of the holes. These graphs were also capable of changing into the two-dimensional graphs which could be effective to evaluate the effective ablation area. Some of these two and three-dimensional graphs, provided by the mentioned method, are illustrated in the Figures 6 - 9.

The above graphs represent the number of pixels in (two) all dimensions. The number of pixels per micrometer depends on the magnification of both camera and microscope and also the model of the camera used. Therefore, considering the fact that the standard size of each pixel is 264 µm, in order to convert the graphical pixels into magnification (power) related pixels and then converting them into micrometers following the formula is used. The conversion factor of 1/67.92 was estimated by referring to the brochures of some similar cameras used and also by considering the microscope magnification power.

Equation 1.

\[
\text{Size(µm)} = \frac{\text{The Number of Pixels} \times 264}{67/92}
\]

As colors of different light intensities in the graphs were different, the deepest point and the ablation borders for each three dimensional graphs were specified according to the difference in their colors. On the other hand the ablation depth for each hole was calculated by converting the number of pixels to micrometer. Determination of the effective ablation areas was completed through the same method using the two-dimensional graphs. It means that the number of pixels for the removed holes was turned to micrometer and then the required values were calculated. Therefore, the ablated areas were considered as regular circular shapes. The data obtained from analyzing the graphs and also from the numerical values are represented in the Tables 1 and 2.

Since the cross section of the laser beam was 0.005 cm², fluency values for each energy step were as of Table 3.

After calculating the ablation depth and the effective ablation area, some diagrams were drown to evaluate and compare the behaviors of enamel and dentin when irradiated by Er:YAG laser beam. Some diagrams of the mentioned tissues with extra explanations are provided here.

Figure 10 is drown to compare the variations of ablation depth at the frequency of 10 Hz for both enamel
and dentin tissues. In both tissues, the ablation depth increased as energy did. In the energy levels of 50, 100, and 150 mJ, the ablation depth for dentin were more than those of the enamel, which was expected; since there is more water in the dentin tissue, it causes more absorption and hence deeper ablation. But what was surprising was the outrun of the ablation depth for enamel in energy level of 200 and 250 mJ. Since the depth values for dentin are more
Table 1. The Values of Ablation Depth for Different Energy Levels and Frequencies

<table>
<thead>
<tr>
<th>Energy, mJ</th>
<th>The Frequency of 10 Hz</th>
<th>The Frequency of 15 Hz</th>
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<tbody>
<tr>
<td></td>
<td>Enamel</td>
<td>Dentin</td>
</tr>
<tr>
<td>50</td>
<td>127.879</td>
<td>138.763</td>
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<tr>
<td>100</td>
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<td>150</td>
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<td>200</td>
<td>191.236</td>
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<td>273.879</td>
<td>249.540</td>
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<td>300</td>
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Table 2. The Values of Effective Ablation Area for Different Energy Levels and Frequencies

<table>
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<th>Energy, mJ</th>
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<th>The Frequency of 15 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Enamel</td>
<td>Dentin</td>
</tr>
<tr>
<td>50</td>
<td>0.00354955</td>
<td>0.00359070</td>
</tr>
<tr>
<td>100</td>
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<td>0.00359070</td>
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Table 3. The Values of Fluency for Different Energy Levels and Frequencies

<table>
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<th>Frequency of 15 Hz</th>
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than those of the enamel in all the experiments and that it was the only unusual case, it is likely that the operator’s hands shake or possible movements can be a good justification for these incompatibilities. Possible movements or handshakes can lead to reduction in the effect of laser beam on the target. Also, since the gamut of 0.5 - 2 mm is thought to be the most efficacious distance between tissue surface and Er:YAG laser, it is argued that handshakes lead to increasing this proper distance and thereby limiting its efficacy.

Variations of the effective ablation area for both enamel and dentin tissues at the frequency of 10 Hz can be observed in Figure 11. The diagram clearly indicates that both tissues showed the same behavior and the trend of variations is increasing. But the increases of the ablation area were negligible for the energy levels of 50, 100, and 150 mJ in both tissues the effective ablation area was a constant value for the mentioned pulse energies. On the other hand, the values of effective ablation area for dentin were slightly more than those of enamel; however, as mentioned earlier, it can be attributed to the higher level of water and hence more absorption in dentine rather than enamel tissue, although this difference was insignificant.

The variations of ablation depth in terms of energy variations at the frequency of 15 Hz are shown in Figure 12. At the frequency of 10 Hz (Figure 10), ablation depth increased as energy did and the values of ablation depth for dentin tissue was more than those of enamel, a completely logical result.

Figure 13 shows the variations of effective ablation area versus increase of energy at the fixed frequency of 15 Hz. As it was the case for the effective area at 10 Hz (Figure 11); a very slight uptrend behavior can be observed in the effective ablation area. However, in some energy levels it can be assumed that the ablation area is almost the same. Again, the values of effective ablation area are a bit bigger in dentin than that of enamel due to the presence of more
water molecules and hence greater absorption in dentine tissue; although the values in both tissues are very close.

Finally, to have a closer look at the holes’ surfaces and the kind of ablations created, some photographs were taken by scanning electron microscope (SEM) from some selected holes. These pictures are shown in Figures 14 and 15. Delving these photographs deeply reveals that the ablation threshold and the hole borders are not clear and sharp. It is also evident that using Er:YAG laser causes hard tissues to remove in layers without any micro cracks in the ablated area and the hole borders, which is of valuable importance in restorative dentistry.

5. Discussion

Today Er:YAG lasers are the most suitable cavity preparation devices. Although the first research report on the Er:YAG laser was in 1988, it was only much later that the equipment was approved by the U.S. food and drug administration (FDA) for cavity preparation and hard tissue management. Since the 2.94 µm wavelength of the Er:YAG laser has absorption peaks in both enamel and dentin, the Er:YAG laser has the ability, through a process called ablation, to remove particles in micro explosions and vaporize them (12). With the high absorption of erbium family lasers (with two different wavelengths of 2.94 and 2.78 µm)
in water and hydroxyapatite, removal of carious enamel and dentin without damaging the surrounding tissues are in hand (3). These are valuable achievements considering other lasers such as CO\textsubscript{2} and Nd:YAG lasers, since using these lasers for surface conditioning and thermal side effects (e.g., melting, carbonization, fissures, and cracks occurred in the surrounding tissue) are unavoidable (3).

It was found that using Er:YAG laser for dental hard tissue is a safe method without damaging the surrounding areas (3). Using Er:YAG laser for surface modification showed irregular surface with no crack and smear layer. The laser initially vaporizes water and other hydrated organic components of the tissue. During this process, the internal pressure increases in the tissue until the explosive destruction of inorganic substances occurs, it subsequently forms hydrokinetic forces that can quickly ablate the dental hard tissues. This mechanism of ablation is called hydrokinetic system (3).

A research by Feritas et al. revealed the effectiveness of Er:YAG for dental purposes. SEM of cavity prepared with different parameters of Er:YAG laser indicated the efficacy of Er:YAG laser for ablation of hard tissue and creation of surface irregularities without smear layer (15). Several studies showed that temperature rise during Er:YAG laser irrad-
Ablation with different powers does not exceed 3°C which is below the threshold safe temperature (5°C) reported previously (3, 15).

Using an air/water spray during laser ablation process is of great importance to keep the intrapulpal temperature within the safe and authorized region. A research by Geraldo-Martins et al. also verified the importance of cooling the irradiated samples (12). They found that without cooling, the higher variation of intrapulpal temperature occurs in 6 Hz of 250 mJ, and the smallest value is for 350 mJ in repetition rate of 2 Hz. Carbonization of the tissue irradiated without cooling, was apparent in macroscopic observations as dark lesions. On the contrary, in samples irradiated in conjunction with water cooling, the highest variation of intrapulpal temperature was in 300 mJ of 6 Hz, and the smallest value occurred when 2 Hz of 250 mJ was applied. The samples irradiated with cooling did not show macroscopic signs of carbonization (12). Geraldo-Martins et al. also revealed in their study that pulpal temperature increases as repetition rates, fluency and exposure times do. This increase may be up to the levels that can cause detrimental pulp effects. They observed that for short exposition times, the intrapulpal temperatures do not reach critical levels. Their findings, along with the poor thermal conductivity of dentin, suggest that use of high repetition rates and fluencies with short exposition time can reduce the risks of pulp damage. However repetition rates must be restricted to an acceptable limit (12).

The current study findings revealed the efficacy of Er:YAG lasers for medical purposes in dental hard tissue.
Using this laser leads to satisfactory results. The current study results indicated larger amount of ablation for dentine tissue. As discussed earlier, it is expected that since dentine has more quantities of water, hence it has greater absorption in Er:YAG wavelength. Also, it was noticed that ablation depth shows more regular uptrend behavior as energy increased. As most related researches offer, it is better to perform laser irradiation with some kinds of air or water cooling. It is recommended to avoid some damages such as cracks or carbonization of the tissue.

5.1. Conclusion

As a general conclusion, in accordance with the previous similar studies, it can be said that Er:YAG lasers can be used as a safe method to prepare cavities, ablation and removing the hard tissues at a low range of energy. However, higher energy pulses can cause some thermal damages such as micro cracks, melting, and tissue carbonization. Therefore, using a correct set of laser parameters with water spray, to avoid side effects, is necessary in clinical applications.

Footnote

Authors’ Contribution: Abbas Majdabadi, designing the study as a M.Sc. dissertation, providing valuable share in completing the research. He was the advisor of Mahshid Yaghmaeian Mahabadi; Mahshid Yaghmaeian Mahabadi, gathering data and analyzing all information gathered in experimental procedure; Reza Fekrazad, the co-advisor of Mahshid Yaghmaeian Mahabadi, contributing valuable aids in structural knowledge of human teeth and preparation process of the teeth before laser treatment; Mohammad Abazari, writing the manuscript, editing and revising the article. He was responsible for the accuracy of concepts.

References


