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Influence of Output Energy and Pulse Repetition Rate of the Er:YAG Laser on Dentin Ablation


Abstract

Objective: We sought to improve the efficiency of dentin ablation with the Er:YAG laser by investigating the effects of output energy and pulse repetition rate on ablation.

Background Data: The Er:YAG laser is superior to other lasers in ablating dental hard tissues. However, the factors affecting the efficiency of ablation with an Er:YAG laser remain unclear.

Methods: Fifty bovine root dentin plates were irradiated with an Er:YAG laser at an output power of 1.0 W, 1.5 W, or 2.0 W under a water spray while moving the plate at 1 mm/sec. After irradiation, the depth and volume of each ablated site were measured by laser microscopy and the ablated surfaces were examined by scanning electron microscopy.

Results: The output power showed a strong positive correlation with the depth and volume of ablation. The output energy had much more pronounced effects on the depth and volume of ablation compared to the pulse repetition rate. The shape of the ablated site varied with the output power, and no cracking or vitrification was observed under the irradiated dentin. The most effective parameters for dentin ablation were an output power of 2.0 W, with an output energy of 80 mJ/pulse at 25 pulses per second (pps) or 100 mJ/pulse at 20 pps.

Conclusion: These findings suggest that the output energy is the main factor affecting the efficiency of dentin ablation with an Er:YAG laser. We propose that the efficiency of dentin ablation can be improved by choosing an optimal combination of output energy and repetition rate.

Introduction

The Erbium:Yttrium-Aluminum-Garnet (Er:YAG) laser, a technology developed by Zharikov et al. in 1974, has a wavelength of 2.94 µm and superior water absorption efficiency. The laser reacts with hydroxyl groups in water molecules and causes explosions at the molecular level. When dentin is irradiated by the Er:YAG laser, the laser energy is absorbed by water inside the dentin tissues and vaporization of the water occurs, with a rapid increase in the water's volume that induces a small explosion that removes the hard tissue. This ablation mechanism does not damage dental pulp and the relatively low heating level almost completely eliminates the risk of thermal damage, a common problem during ablation with other lasers. Due to these advantages, the Er:YAG laser is increasingly being applied in clinical practice. Lasers produce far less sound than rotating cutting devices and do not produce sonic dissonance during cutting. Lasers also generate only minimal vibration during cutting, and there is little discomfort or unpleasant sensation for the patient. Thus the Er:YAG laser is a favorable option for treatment of adults and children who may fear a visit to the dentist.

There have been calls for improvement in the ablation efficiency of the Er:YAG laser, because the laser ablates tooth structures more slowly than conventional rotating cutting devices. The goal is to increase the output energy of Er:YAG irradiation while reducing the pulse repetition rate. However, the optimal conditions for improving ablation efficiency require reconsideration, since recent improvements in laser devices enable laser irradiation with higher pulse repetition rates. The output energy and pulse repetition rate influence the depth and volume of ablation, but only a few studies have considered the effects of these variables on ablation efficiency. Therefore, we examined the dental ablation efficiency of the Er:YAG laser by investigating the effects of varying the output energy and pulse repetition rate on the depth and volume of ablation of dentin.
Materials and Methods

Specimen preparation and irradiation conditions

Preparation of dentin plates. Fifty lower anterior bovine teeth were used as specimens in the study. Each tooth was cut at the crown cervix and then divided at the root in a lingual-buccal direction. Next, the root lateral faces were individually polished with a grinder (400 and 800 grit) and waterproof abrasive paper (800 and 1200 grit). After grinding, each specimen was cut one-third of the way into the root apex side to prepare a dentin plate in which the dentinal tubules ran in almost the same direction.

Laser device. A prototype Er:YAG laser device (J. Morita Mfg. Co., Kyoto, Japan) was used in the study. The laser produces light at a wavelength of 2.94 μm with oscillated pulse waves with a pulse duration of 250 μs at output energies ranging from 30 to 350 mJ/pulse, and with an adjustable pulse repetition rate (1, 3.3, 5, 10, 20, 25, or 30 pulses per second [pps]) (Table 1). Given the limits of the output energy (Table 1), the output energies differed for each pulse repetition rate. The Er:YAG laser was fitted with a contact tip (600 μm in diameter) for hard tissues (C600F; J. Morita Mfg. Co.).

Irradiation method and conditions. The fifty dentin plates were irradiated on a movable table (S-46 Controller; Chuo Precision Machine Co., Tokyo, Japan) to obtain homogenous irradiation. The plate was fixed to the table with the grinding face oriented horizontally to the tabletop, and the contact tip was positioned 0.05 mm from the plate surface (distance was measured using a height gauge; Futaba Co., Tokyo, Japan) to minimize diffusion of the laser energy under the water spray. The plate was moved at 1 mm/sec, which is a clinically applicable speed that allows sufficient irradiation of the dentin.

Irradiation conditions with different combinations of output energy and pulse repetition rate were used at a constant output power, as shown in Table 2. A total of ten irradiation conditions were used: four at an output power of 1.0 W (1.0 W group), four at 1.5 W (1.5 W group), and two at 2.0 W (2.0 W group). The output energy was set at <150 mJ/pulse based on the results of a preliminary experiment, in which an output energy of >150 mJ/pulse produced a crack in the dentin surface. The pulse repetition rate ranged from 10–30 pps, since a rate of at least 10 pps is required to ensure continuous ablation of the dentin, based on results of the preliminary experiment. Pulse repetition rates of 30 pps had to be excluded from the 2.0 W group to stay within the upper limit of output energy specified for the prototype device. The output energy delivered at the contact tip was measured before irradiation using a LabMaster Ultima (Coherent, Santa Clara, CA, USA) and corrected when necessary. Water was infused at a rate of 2 mL/min. Five different dentin plates were irradiated under each irradiation condition. Before irradiation, the target site on each plate was examined at 10× magnification with a stereoscopic microscope (YSTB-2E; Nikon Co., Tokyo, Japan) to confirm the absence of natural cracks.

Measurement of ablation depth and volume

After laser irradiation, the specimens were washed with an ultrasonic washer for 5 min to prevent accumulation of ablated fragments at the ablated site. Subsequently, the specimens were dried and examined under a laser microscope (VK-8500; Keyence Co., Osaka, Japan) to measure the depth and volume of ablation. Ablation depth was measured at the center of each laser-irradiated area and is reported for each plate as the mean depth of six irradiated areas, the maximum number of areas formed on one plate. Ablation volume was determined in a region with a radius of approximately 300 μm around the center of each laser-irradiated area, and the reported volume is the mean of six irradiated areas on one plate. In practice, ablation depth was measured as the distance of a virtual line from the surface of the specimen to the deepest point after creation of cross-sections of the ablated region. The measurement approach is shown in Fig. 1. The volume was measured over a diameter of 600 μm using three-dimensional images created from these results, and was defined as the ablation volume.

Statistical analysis

A Spearman rank correlation test was used to evaluate correlations between output power and ablation depth, output power, and ablation volume, and depth and volume of ablation (with \( p < 0.05 \) indicating a significant correlation). Statistical analyses were performed within the 1.0 W (four irradiation conditions), 1.5 W (four irradiation conditions), and 2.0 W (two irradiation conditions) groups to determine how the output energies and pulse repetition rates influence...
enced the depth and volume of ablation at a constant output power. These comparisons were conducted by one-dimensional analysis of variance (ANOVA) and the Scheffe method, with $p \leq 0.05$ considered to indicate significance. StatView ver. 5.0 (SAS Institute, Cary, NC, USA) was used for all analyses.

**Scanning electron microscopy**

After measurements by laser microscopy, the specimens were dried, cut in a direction vertical to the ablated surfaces, dehydrated with an alcohol series using a conventional method, freeze-dried, and examined with a scanning electron microscope (SEM) to determine the shapes of the sections and ablated surfaces. Examination was performed with Au-Pd deposition using a JSM-6340F scanning electron microscope (Japan Electron Co., Tokyo, Japan). SEM photographs were taken at magnifications of $100 \times$ to determine the shape of the ablated site and at $1000 \times$ to examine the irradiated surface.

**RESULTS**

**Depth and volume of ablation**

Ablation depths and volumes are shown in Tables 3 and 4, respectively. The depth and volume tended to increase at higher output energies and lower pulse repetition rates in each group. Table 5 shows the statistical differences in ablation volumes among irradiation conditions according to the Scheffe test. The ablation volume was significantly greater in the group irradiated at high output power and high energy density.

**Statistical analysis**

Linear regression analysis of the relationship between the depth and volume of ablation gave the equation $y = 2.9196x - 1.5506$ with a correlation coefficient of 0.93, indicating a strong positive correlation (Fig. 2). A similar analysis of the relationship between output power and ablation depth gave the equation $y = 3.2043x - 0.91$ with a correlation coefficient...
of 0.88, also indicating a strong positive correlation (Fig. 3). Analysis of the relationship between output power and ablation volume gave the equation \( y = 9.7107x - 4.705 \) with a correlation coefficient of 0.87, also indicating a strong positive correlation (Fig. 4).

**Morphologic examination of the surface and cut section by SEM**

The irradiated dentin had a rough surface with opened dentinal tubules, but without cracking, vitrification, or charring. Sections cut under different irradiation conditions could be roughly classified into three shapes: a box type (Fig. 5), a polygonal type (Fig. 6), and a bowl type (Fig. 7). The sections were mainly of the box type in the 1.0-W group, of the polygonal type in the 1.5-W group, and of the bowl type in the 2.0-W group (Table 6). No cracking or vitrification attributable to the laser radiation was observed just under the irradiated dentin in SEM images taken at 1000× magnification.

**Discussion**

More than 15 years have passed since the Er:YAG laser was introduced for cavity preparation in dentistry.\(^3,12\) Over this period, a number of problems have emerged with regard to the efficiency with which the laser cuts enamel and dentin.\(^17\) Most attempts to increase the output energy of the laser have been motivated by the need for improved ablation efficiency,\(^18–21\) but little is known about the effects of variable irradiation conditions on ablation efficiency. Therefore, we assessed the effects of output power, output energy, and pulse repetition rate on the amount and depth of ablation of dentin to identify the clinically optimal ablation conditions.

The output power was positively correlated with the depth and volume of ablation. These results are consistent with conventional studies\(^12,13\) that have reported increased ablation efficiency with an increased energy level per unit time (output power) in the irradiated dentin. We also investigated how the same output power in irradiation with variable combinations of output energy and pulse repetition rate influenced the efficiency of ablation. In the 1.0-W group, ablation depth and volume both increased as the output energy increased. This suggests that the depth and volume of ablation increase under irradiation at larger output energies delivered at lower pulse repetition rates. Only two significant differences were found in comparisons among the four irradiation conditions: between 33 mJ/pulse, 30 pps and 50 mJ/pulse, 10 pps; and between 33 mJ/pulse, 30 pps and 100 mJ/pulse, 10 pps. These findings show that the ablation...
depth and volume increase markedly when the output energy exceeds 50 mJ/pulse at an output of 1.0 W.

The ablation depth and volume in the 1.5-W group also tended to increase as the output energy increased and the pulse repetition rate decreased. However, the only significant difference in depth and volume occurred for the 150 mJ/pulse, 20 pps irradiation condition compared to the other three conditions. Thus it is unclear how the output energy and pulse repetition rate influence the depth and volume of ablation in the 1.5-W group for irradiation delivered at 50–75 mJ/pulse. At an output energy of 150 mJ/pulse, the depth and volume clearly increased and ablation was improved. Only two irradiation conditions, 80 mJ/pulse, 25 mJ and 100 mJ/pulse, 20 pps, were examined in the 2.0-W group, and the ablation depth and volume both differed significantly between these conditions. At higher output power, a slight increase in output energy led to conspicuous changes in the depth and volume, and ablation of dentin occurred more easily with increased output energy.

Collectively, these findings confirm that the output power is important for improving ablation efficiency, and that the ablation efficiency is influenced by the combination of parameters selected for the output power (i.e., the combination of the output energy and pulse repetition rate).15,16

The ablated sites were divided into box, polygonal, and bowl types. In the box type, there was little cutting and the cutting depth was shallow. The polygonal type had an increased cutting depth compared to the box type, and the cutting depth and amount of cutting were largest in the bowl type. Changes in output power resulted in a change in the ablated shape from a box type to either a polygonal type or a bowl type, and at a fixed output power the ablated shape was influenced by the output energy, but not by the pulse repetition rate. Even at a high pulse repetition rate of 20 or 30 pps, the ablation efficiency did not improve if the output energy remained below a certain level. In contrast, at a low pulse rate, output energies of all levels had a major influence on the ablated shape. Thus the output energy had the main influence on ablation of hard tissue under our experimental conditions.

When the Er:YAG laser is used for cavity preparation, a high efficiency of dentin ablation, reduced pulp damage, and reduced damage to dentin are required for achieving strong adhesion in composite restoration. Keller et al.3,8,12 recommended that Er:YAG laser irradiation for cavity preparation should be performed at a high output energy and a low frequency (pulse repetition rate) to obtain high ablation efficiency without pulp damage, and also commented that high-frequency laser irradiation may cause pulp damage due to accumulation of heat produced by the laser;19–21 therefore, conditions of 150–300 mJ/pulse with a frequency of 1–2 Hz for dentin and 200–400 mJ/pulse with a frequency of 2–4 Hz for enamel were proposed for use of an Er:YAG laser in...

FIG. 4. **Relationship between output power and ablation volume.**

![Graph showing the relationship between output power and ablation volume.](image)

\[ y = 9.7107x - 4.705 \]

\[ R^2 = 0.7787 \]

**FIG. 5.** Morphologic presentation of a cut section by SEM, showing a typical box type ablation at 33 mJ/pulse and 30 pps in the 1.0-W group. The box type was only observed in the 1.0-W group. The dentin was ablated along the dentinal tubules. There was no cracking or charring just under the irradiated dentin.

![Morphologic presentation of a cut section by SEM showing a typical box type ablation.](image)

**FIG. 6.** Morphologic presentation of a cut section by SEM, showing a typical polygonal type ablation at 60 mJ/pulse and 25 pps in the 1.5-W group. The polygonal type was observed in the 1.0-W and 1.5-W groups. The dentin was sharply ablated along the dentinal tubules. There was no cracking or charring just under the irradiated dentin.

![Morphologic presentation of a cut section by SEM showing a typical polygonal type ablation.](image)
dentin ablation in clinical practice. Many other studies have supported these conclusions in reporting use of the Er:YAG laser for cavity preparation. However, for use of the Er:YAG laser in the contact mode, an output energy of 100–150 mJ/pulse at a pulse repetition rate of 10 pps for dentin ablation and 200–300 mJ/pulse at 10 pps for enamel ablation have been proposed. Jayawardena et al. suggested that the pulses nature of laser energy may be transmitted through the dentinal tubules in the form of photomechanical shocks that disturb the network of blood vessels in the outermost area of the pulp; therefore, a high output energy may cause more pulp damage compared to a low output energy.

Délmé et al. commented that to obtain a more retentive surface without cohesive microfractures, it is advisable to apply an output energy of less than 200 mJ for dentin and enamel when using the Er:YAG laser since a higher output energy produces vitrification of the dentin surface. A rough surface may contribute to adhesion of resin to dentin, but the presence of fragments and microfractures has adverse effects on the adhesion of resin by decreasing the bonding quality. Hence, there are many opinions on the appropriate conditions of Er:YAG laser irradiation for dentin or enamel ablation, including differences regarding the type of Er:YAG laser and various laser parameters: the amount of energy per pulse, the pulse repetition rate, the pulse duration, distance from the laser to the experimental surface, the time of irradiation (exposure of the surface to the laser), and use of a contact or non-contact mode.

In this study, we used the Er:YAG laser in the contact mode (a contact tip 0.6 mm in diameter) with a water spray at a rate of 2 mL/min and different combinations of output energy and pulse repetition rate. The laser-irradiated dentin plate was moved at a speed of 1 mm/sec. Output powers of 2.0 W (100 mJ/pulse, 20 pps and 80 mJ/pulse, 25 pps) and 1.5 W (150 mJ/pulse, 10 pps) yielded high-efficiency dentin ablation under our experimental conditions. Cutting efficiency was particularly improved in the 2-W group by increasing the pulse repetition rate at a low output energy, resulting in little damage to the dental pulp through the impact of irradiation on the dentinal tubules, compared to irradiation at high output energy. Moreover, these conditions produced a rough dentine surface with opened dentinal tubules without cracks or vitrification. The damage to the dentin or pulp caused by accumulation of heat produced by raising the pulse repetition rate may be prevented by supplying an appropriate volume of water during laser irradiation. Therefore, irradiation using a low output energy and a high repetition rate may give better adhesion of resin to irradiated dentin compared with irradiation at high output energy.

Finally, we note that similar cutting depths of dentin at the same output energies and pulse repetition rates (100 mJ/pulse at 10 pps and 150 mJ/pulse at 10 pps) were obtained in our study and in that of Délmé et al. even though the irradiation method (contact or non-contact mode, irradiation spot size, and scanning speed during irradiation) differed between the two studies. Therefore, it seems likely that the power density or energy density was similar in these studies, although these data were not given in Délmé et al. Based on our results, we emphasize the importance of choosing the correct irradiation parameters in using an Er:YAG laser for cavity preparation.

**Conclusion**

In this study we used a prototype Er:YAG laser to investigate the effects of irradiation conditions such as output energy and pulse repetition rate on the depth and volume of ablation. Our findings support the following conclusions: (1) the output power showed a strong positive correlation with the depth and volume of ablation; (2) the output energy had much stronger effects on the depth and volume of ablation compared to the repetition rate; (3) the shape of the ablated site varied with the output power, and no cracking or vitrification attributable to the laser radiation was observed just

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<th>2.0 W</th>
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<td>Irradiation condition (mJ/pulse, pps)</td>
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<td>40, 25</td>
<td>50, 20</td>
</tr>
<tr>
<td>Box</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Polygonal</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Bowl</td>
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**FIG. 7.** Morphologic presentation of a cut section by SEM, showing a typical bowl type ablation at 100 mJ/pulse and 20 pps in the 2.0-W group. The bowl type was observed in the 1.5-W and 2.0-W groups. The dentin was deeply ablated along the dentinal tubules. No cracking, charring, or vitrification was observed just under the irradiated dentin.
under the irradiated dentin; and (4) among the various irradiation conditions investigated in this study, the optimal condition for ablation of dentin is an output of 2.0 W, with an output energy of 80 mJ/pulse at a pulse repetition rate of 25 pps or 100 mJ/pulse at 20 pps.

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References


Address reprint requests to:
Dr. Akihiro Igarashi
Department of Operative Dentistry
Tokyo Dental College
1-2-2, Masago, Mihama-ku
Chiba, 261-8502, Japan

E-mail: igarasia@tdc.ac.jp