Comparative Measurement of the Ablation Efficacy of a Quantum Square Pulse Er:YAG Dental Laser

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ABSTRACT

Erbium dental lasers differ not only in their wavelength (Er:YAG at 2.94 µm and Er,Cr:YSGG at 2.73 µm) but also in their range of available pulse duration modes. Recently, a new Er:YAG laser pulse duration mode, the Quantum Square Pulse (QSP) mode, was introduced. An important advantage of the QSP mode is that it significantly reduces the undesirable effects of laser beam scattering and absorption in the debris cloud during hard-tissue ablation. In this comparative ablation study, the ablation efficacy and speed of the QSP mode in enamel was compared with those of the highest power modes available in Er:YAG and Er,Cr:YSGG dental lasers. In terms of the ablated volume per laser energy, the QSP mode Er:YAG laser was found to be about 1.3 times more efficacious than the SP mode Er:YAG laser, and 1.8 times more efficacious than the H mode Er,Cr:YSGG laser. Due to the enhanced ablation efficacy of the QSP mode, a larger percentage of the Er:YAG laser is utilized for ablation, and not for undesirable heating of the treated tissue. Consequently, doctors using QSP mode, in contrast to other tested erbium laser pulse duration modes, are expected to benefit from significantly faster ablation and greater precision.

Key words: Er:YAG; Er,Cr:YSGG, laser dentistry, ablation, QSP, quantum square pulse.

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I. INTRODUCTION

There are currently two erbium laser technologies, Er:YAG (2.94 µm) and Er,Cr:YSGG (2.79 µm), that are being clinically used to treat hard dental tissues [1-3]. While there are many similarities between the two erbium laser technologies, there are also differences, among them the difference in laser wavelength as well as in the lasers’ pulse-duration modes. These differences may potentially lead to a difference in the ablation properties of these two erbium laser technologies [4-6].

The ablation process with erbium lasers is very complex and depends on many parameters besides wavelength. Among the factors that can significantly affect the ablation process are the scattering and absorption of the erbium laser light in the ablation debris cloud. The most recent technological advances incorporated in the latest generation of Er:YAG dental lasers include the QSP (Quantum Square Pulse) mode, which was developed with a goal to significantly reduce the undesirable effects of the debris cloud [7-11].

In the QSP mode technology, a standard laser pulse is divided (quantized) into several super-short pulses (pulse quanta) that follow each other at an optimally fast rate [7]. This enables the QSP mode to deliver super-short, low-energy pulses with the efficacy of long-duration, higher energy laser pulses, without sacrificing the efficacy and precision that is provided by super-short duration pulses. Another important advantage of the QSP mode is that it significantly reduces the undesirable effects of laser beam scattering and absorption in the debris cloud during hard-tissue ablation. As a result, treatments with QSP mode have been found to be faster and more precise, even when compared to the shortest SSP pulses (Super Short Pulse, SSP) available with Er:YAG laser technology [9, 11].

In this study, measurements of the ablation speed and efficacy in enamel of the Er:YAG and Er,Cr:YSGG dental lasers were carried out at their corresponding maximum available pulse energies and powers, and compared with those achievable with the latest Er:YAG QSP laser mode.

II. MATERIALS AND METHODS

The Er,Cr:YSGG laser used was a WaterLase iPlus (manufactured by Biolase) and the Er:YAG system was a LightWalker AT (manufactured by Fotona). Both laser systems were fitted with appropriate non-contact handpieces (Fotona H02 handpiece and Biolase MX11 Turbo handpiece) enabling the highest output laser powers in both of the devices.

The lasers were operated in the following three modes: a) Er,Cr:YSGG in H pulse duration mode;
b) Er:YAG laser in MAX pulse duration mode; and
c) Er:YAG laser in QSP pulse duration mode.

For QSP and H modes, the water spray was set respectively to 5 water / 9 air and 70% water / 90% air, which resulted in the same measured water flow for both modes of 19 ml/min. For the higher power MAX mode, the water spray was set to 9 water / 9 air, resulting in 44 ml/min of measured water flow.

Extracted premolar and molar teeth were cut with a diamond saw into 2-3 mm thick slices and stored in a physiological saline solution. Ten teeth slices were randomly chosen for the ablation experiments. Before each ablation experiment, the cut side surface of the tooth slice was positioned vertically to be parallel to the vertically oriented incoming laser beam. The horizontally oriented un-cut top enamel surface was fixed at a focal distance from the corresponding laser handpiece. The positioning of the laser beam and tooth slice is shown in Fig. 1.

Two experimental set-ups were used:
a) “Hole” set-up where the laser beam was positioned on the top surface in such a manner that a hole was drilled into the tooth slice along its side surface axis.

b) “Groove” set-up where the laser beam was positioned to intersect with the edge of the top surface in such a manner that the top surface was irradiated by only one half of the beam. As a result, externally visible open grooves were ablated along the side surface of the tooth slice.

Each data point for any of the modes represents an average of ten ablation cavities (holes or grooves).

The laser parameters were set on the console to be at or close to the particular device’s maximum. The actual laser pulse energies, $E_{\text{pulse}}$, were measured at the output of the handpieces with an external energy meter. The average laser power, $P_{\text{ave}}$, was calculated from $P_{\text{ave}} = f \times E_{\text{pulse}}$, where $f$ was the pulse repetition rate. Special care was taken to ensure that for both laser types the ablation measurement pulse sequence was emitted after the laser output had already stabilized. The total laser energy $E_{\text{tot}}$ delivered to a single cavity was represented by $E_{\text{tot}} = P_{\text{ave}} \times \text{Time}$, where Time was the duration of the exposure of the tooth to the laser irradiation.

The laser parameters used for the “hole” and “groove” ablation experiments are listed in Tables 1 and 2, respectively.

Table 1: Laser parameters used in the “hole” ablation measurements:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Laser Type</th>
<th>Er,Cr:YSGG (H)</th>
<th>Er:YAG (MAX)</th>
<th>Er:YAG (QSP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOLE</td>
<td>$E_{\text{pulse}}$</td>
<td>420 mJ</td>
<td>840 mJ</td>
<td>510 mJ</td>
</tr>
<tr>
<td></td>
<td>$f$</td>
<td>20 Hz</td>
<td>20 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{ave}}$</td>
<td>8.4 W</td>
<td>16.8 W</td>
<td>5.1 W</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>1 s</td>
<td>1 s</td>
<td>1.5 s</td>
</tr>
</tbody>
</table>

Table 2: Laser parameters used in the “groove” ablation measurements:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Laser Type</th>
<th>Er,Cr:YSGG (H)</th>
<th>Er:YAG (MAX)</th>
<th>Er:YAG (QSP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROOVE</td>
<td>$E_{\text{pulse}}$</td>
<td>460 mJ</td>
<td>840 mJ</td>
<td>510 mJ</td>
</tr>
<tr>
<td></td>
<td>$f$</td>
<td>15 Hz</td>
<td>20 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{ave}}$</td>
<td>6.9 W</td>
<td>16.8 W</td>
<td>5.1 W</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>1 s</td>
<td>1 s</td>
<td>1.5 s</td>
</tr>
</tbody>
</table>

The depth ($h$) of the ablated hole, and the diameter ($d$) of the hole as measured at the top surface were obtained using a focusing optical microscope. The ablated volume, $V$ of the holes was then calculated using:

$$V_{\text{hole}} = h \pi \times \frac{d^2}{4} \quad (1)$$

Similarly, the volume $V$ of the ablated groove, $V_{\text{groove}}$, was calculated from the length $h$ of the groove, and from the groove’s diameter, $d$ as measured at the top surface of the tooth slice:
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\[ V_{\text{groove}} = \frac{\pi d^2}{8} \]  

The ablation speed, \( AS \) (in mm\(^3\)/s), was calculated from \( AS = \frac{V}{\text{Time}} \), and the ablation efficacy, \( AE \) (in mm\(^3\)/J), was calculated from \( AE = \frac{V}{E_{\text{total}}} \).

### III. RESULTS

#### a) Hole ablation conditions

The results of the “hole” ablation measurements are depicted in Table 3. The maximum ablation speed (\( AS \)) for each mode is also shown. The maximum ablation speed was obtained by multiplying the measured ablation efficacy (\( AE \)) with the maximum nominal laser power available in the laser devices used in the experiment (10 W for H mode, 20 W for MAX mode and 7.5 W for QSP mode).

**Table 3: Ablation measurement results under “hole” experimental conditions.**

<table>
<thead>
<tr>
<th>HOLE</th>
<th>AS (mm(^3)/s)</th>
<th>AE (mm(^3)/J)</th>
<th>Maximum AS (mm(^3)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er:Cr:YSGG H (8.4 W, 1 s)</td>
<td>0.27 ± 0.05</td>
<td>0.033 ± 0.006</td>
<td>0.33</td>
</tr>
<tr>
<td>Er:YAG MAX (16.8 W, 1 s)</td>
<td>0.84 ± 0.15</td>
<td>0.050 ± 0.009</td>
<td>1.00</td>
</tr>
<tr>
<td>Er:YAG QSP (5.1 W, 1.5 s)</td>
<td>0.31 ± 0.02</td>
<td>0.060 ± 0.005</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Figure 2 shows the measured ablation speeds (in mm\(^3\)/s) for the “hole” experimental conditions, and the resulting ablation efficacies as obtained from the “hole” measurements are shown in Fig. 3.

Fig. 2: Measured ablation speed for the Er:YAG (MAX), Er:YAG (QSP) and Er:Cr:YSGG (H) modes under “hole” experimental conditions. Each data point represents an average of ten ablation holes. The lines extend to the maximal nominal power output at each laser mode. The error bars represent the sample standard deviation.

#### b) Groove ablation conditions

Results of the “groove” ablation measurements are depicted in Table 4.

**Table 4: Ablation measurement results under “groove” experimental conditions.**

<table>
<thead>
<tr>
<th>GROOVE</th>
<th>AS (mm(^3)/s)</th>
<th>AE (mm(^3)/J)</th>
<th>Maximum AS (mm(^3)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er:Cr:YSGG H (6.9 W, 1 s)</td>
<td>0.27 ± 0.02</td>
<td>0.039 ± 0.004</td>
<td>0.39</td>
</tr>
<tr>
<td>Er:YAG MAX (16.8 W, 1 s)</td>
<td>0.79 ± 0.19</td>
<td>0.047 ± 0.011</td>
<td>0.94</td>
</tr>
<tr>
<td>Er:YAG QSP (5.1 W, 1.5 s)</td>
<td>0.34 ± 0.06</td>
<td>0.066 ± 0.012</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Figure 4 shows the obtained ablation speeds (in mm\(^3\)/s) under “groove” experimental conditions.

Fig. 4: Measured ablation speed for the Er:YAG (MAX), Er:YAG (QSP) and Er:Cr:YSGG (H) modes under “groove” experimental conditions. Each data point represents an average of ten ablation grooves. The lines extend to the maximal nominal power output at each laser mode. The error bars represent the sample standard deviation.
Fig. 5: Measured ablation efficacy for the Er:YAG (MAX), Er:YAG (QSP) and Er,Cr:YSGG (H) modes under “groove” experimental conditions. Each data point represents an average of ten ablation grooves. The error bars represent the sample standard deviation.

Fig. 6: Ablation efficacy (AE) for three erbium laser modes, as obtained under “300 mJ” conditions (white bars). For comparison, the ablation efficacies, as obtained under “high power” conditions (with averaged data from Tables 3 and 4), are also shown (grey bars).

We have also carried out a set of “hole” measurements at a low repetition rate of 0.2 Hz and at the same laser pulse energy of 300 mJ for all three Erbium modes. The enamel was exposed to N = 20 consecutive pulses. The obtained ablation efficacies at the “300 mJ” energy are shown in Fig. 6, together with the ablation efficacies obtained with the “high power” laser parameters, averaged over the “hole” and “groove” conditions (Tables 3 and 4). Note that the MAX mode consists of high-pulse-energy SP mode Er:YAG laser pulses.

IV. DISCUSSION

The relatively large depth of ablation cavities prevented the use of the standard triangulation method for measuring ablation volumes [6, 12, 13]. Instead, an optical microscope technique was used, and the ablation volumes were calculated assuming cylindrically shaped cavities. Since the diameter of an ablated hole is not constant over the length of the hole, but gets smaller towards the bottom of the ablated cavity, the obtained volumes and ablation efficacies are therefore larger than what would be obtained with a more exact laser triangulation measurement method. However, since this error is expected to be systematic for the measurement method employed in this study, we believe that this effect does not considerably affect the comparison ratios of the ablation speeds and efficacies of the studied laser modes.

For some of the measurements, the ablation cavity extended to a certain extent through the enamel layer into the softer and more readily removable dentin. This resulted in slightly higher measured ablation efficacies than what would be observed when ablating only enamel. However, since special effort was made to create ablation cavities of similar length, regardless of the mode used, this fact should not affect considerably the comparison of the ablation efficiencies and speeds among the studied laser modes.

It is interesting to note that under the “groove” experimental conditions, the measured ablation speed and ablation efficacy are higher for both laser wavelengths as compared to those obtained under the “hole” conditions. This observation can be at least partially explained by the fact that under the “groove” conditions the water from the water spray does not collect at the bottom of the groove as is the case under the “hole” conditions. It is well known that any water pooling at the bottom of the ablated cavity significantly reduces the ablation efficacy.

Our measurements show that for high single-pulse fluences and ablation depths, the Er:YAG (QSP) mode is about 1.8 times more efficacious than the Er,Cr:YSGG (H) mode, and about 1.3 times more efficacious than the Er:YAG (SP, MAX) modes. And the Er:YAG (SP) mode is about 1.3 times more efficacious that the Er,Cr:YSGG (H) mode.

This agrees well with previous laser triangulation comparison studies which revealed the Er:YAG (SSP) mode to be about 1.3 times [5] or 1.2 times [14] more efficacious than the Er,Cr:YSGG (H) mode. Similarly, in another study with a digitally controlled laser handpiece, the Er:YAG (QSP) mode was found to be about 1.5 times more efficacious than the Er:YAG (SP, MAX) modes [11].

The improved ablation efficacy of the QSP mode can be attributed to the specific characteristics of the QSP mode that significantly reduce the undesirable effects of laser beam scattering and absorption in the debris cloud during hard-tissue ablation [7]. In order to avoid the effects of scattering, the individual QSP pulse quantum is designed to be shorter than the time required for the ablation cloud to develop. At the same time, the temporal spacing between consecutive
pulse quanta is longer than the debris cloud decay time. This ensures that the following pulse quantum does not encounter any cloud remains from the previous pulse quantum [11].

The higher ablation efficacy of the QSP mode in comparison to the other tested modes means that for the same laser power, the ablation speed (in terms of the removed volume of dental tissue per second) is also higher with the QSP mode.

Note, however, that the maximum possible ablation speed depends not only on the ablation efficacy, but also on the maximum possible laser power from a particular laser device being used. A comparison of the ratios of the maximum possible ablation speeds of the laser devices used in this study, averaged over “holes” and “groove” high power experimental conditions, shows the MAX mode Er:YAG laser, at its maximum power of 20 W, to be 2 times faster than the QSP Er:YAG mode at 7.5 W, and 2.6 times faster than the H mode Er,Cr:YSGG laser at 10 W.

V. CONCLUSIONS

The measurements demonstrate that the new Er:YAG QSP mode improves upon the ablation efficacy of the current Erbium lasers. The improved ablation efficacy of the QSP mode is attributed to the “quantized” characteristic of the QSP mode pulse, which significantly reduces the undesirable effects of laser beam scattering and absorption in the debris cloud during hard-tissue ablation. This indicates that for the same laser power, the ablation speed is highest with the QSP mode. In addition, with QSP more of the laser energy is used up for the intended ablative effect, and less for undesirable heating of the surrounding tissues. Consequently, doctors using QSP mode, in comparison to other erbium laser pulse duration modes, are expected to benefit from significantly faster ablation and greater precision.

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