Minimally Invasive Cutting of Enamel with QSP Mode Er:YAG Laser

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J Laser Dent 2014;22(1):28-35

ABSTRACT

The aim of this *in vitro* study was to investigate the ablation efficacy of an Er:YAG laser system equipped with a new Quantum Square Pulse (QSP) pulse duration modality, and to compare it with the ablation efficacy of other erbium laser pulse duration modes. A reported advantage of the QSP mode is that it significantly reduces the undesirable effects of laser beam scattering and absorption in the debris cloud consisting predominantly of dehydrated hydroxyapatite which is ejected from the ablated tooth. The experiments were conducted on randomly chosen extracted human premolar and molar teeth which were stored in a physiological saline solution immediately following extraction. Before each ablation experiment, the tooth was positioned to have its surface perpendicular to the laser beam, and to be at focal distance of the noncontact laser handpiece. Measurements were made on enamel under water/air spray conditions. Each ablation data point represented an average obtained from different cavities, each made with 10 or 20 consecutive pulses of the same laser fluence delivered to the same spot. Ablation measurements were made with QSP, SSP, and SP pulse duration modes of the Er:YAG laser, and with the H mode of the Er,Cr:YSGG laser. The measured high ablation efficacy of the QSP Er:YAG mode demonstrates that the reduction of undesirable effects of laser-debris interaction results also in the enhancement of laser ablation efficacy.

INTRODUCTION

For more than 20 years, erbium lasers, Er:YAG (2.94 µm) and Er,Cr:YSGG (2.78 µm), have been used to cut soft and hard dental tissues, including enamel, dentin, caries lesions, and bone. This is due to their strong absorption in water and hydroxyapatite, which gives them the ability to cut biological tissues with minimized thermal effects.[1-3]

The technology of dental lasers has evolved considerably in recent years.[3] Erbium-based lasers have traditionally employed a conventional Pulse Forming Network (PFN) technology to energize their flashlamps with high-energy light pulses.[4] Pulses created by single PFNs are characterized by a typical temporal bell shape with a long declining tail, and have a fixed pulse duration which is determined by the hardware component values of the PFN. Research has demonstrated, however, that providing dental practitioners with the power to adjust a laser's pulse duration is a major factor that determines the success of dental laser treatments.[5-6] With conventional instruments, such as burs or scalpels, the interaction with the patient's tissue is guided mainly through tactile pressure on the dentist's hand. A laser dentist, however, does not rely on tactile feedback but can easily optimize the speed, finesse, and depth of any treatment at the touch of a button, provided that the underlying technology can deliver the necessary power and flexibility.

Er:YAG laser technology has advanced considerably in recent years with the development of Variable Square Pulse (VSP) technology,[3-4, 7] an innovative flashlamp-pumping solution that provides nearly square-shaped laser pulses that are adjustable over a wide range of pulse durations. This enables a significantly wider range of treatment protocols as well as greater precision and control. In addition, the latest generation of VSP Er:YAG dental lasers equipped with MAX mode[8] can even exceed the drilling speeds of conventional diamond drills.[9]

Representing another technological advance in dental lasers, the recently developed Quantum Square Pulse (QSP) modality[10-15] provides even greater levels of speed, finesse, and control, especially when operating at higher pulse energies. With QSP, procedures are faster and also quieter than with traditional erbium lasers operating at the same output power, and are thus more comfortable for patients.[11-12] One of the major advantages of the QSP mode is that it significantly reduces the undesirable residual side effects of laser beam scattering and absorption in the debris cloud, which is formed immediately after the ablation of dental tissues (Figure 1a).[10] When a standard erbium laser beam is absorbed in the debris cloud, the ablation rate of dental tissue is lowered. Additionally, scattering effect caused by the cloud leads to spreading of the laser beam (Figure 1b).[10] Further, the laser-heated debris cloud is expected to contribute to the heating of the tooth as it falls back to the tooth surface.

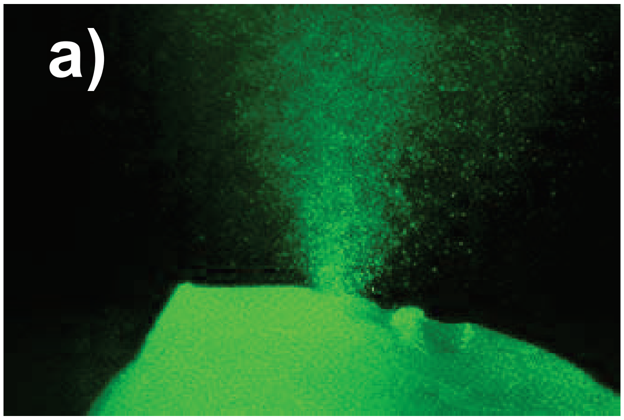

Figure 1a*: An image of the debris cloud created during erbium laser ablation*

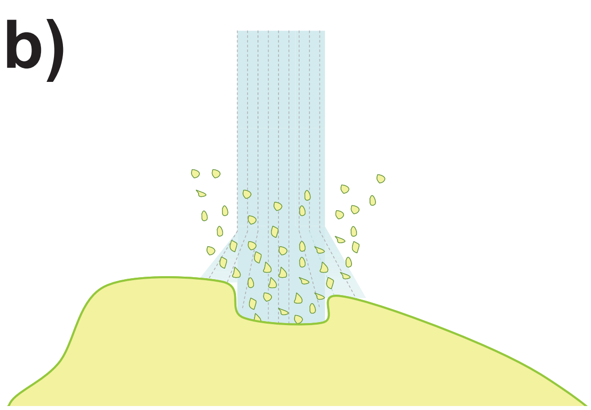

Figure 1b: *The ablation cloud absorbs and scatters the incoming laser beam. The debris cloud consists mainly of dehydrated hydroxyapatite that is ejected from the ablation site*

It is well understood that erbium laser ablation efficiency is markedly increased at short pulse durations and high laser fluencies.[7, 16-17] On the other hand, the effects of debris screening are much less pronounced at longer pulse durations and lower pulse fluencies.[16] The Er:YAG QSP mode functions by dividing a standard laser pulse of longer duration (approximately 600 µsec) into a series of five super-short pulses (pulse quanta) that follow each other at an optimally effective rate (several kHz)[10] to enable the delivery of laser energy with the efficiency of short duration pulses without sacrificing the precision provided by the long duration pulses. This is due to the fact that the duration of each of the pulse quanta (approximately 50 µsec) is shorter than the rise time of the debris cloud, while the separation between the pulse quanta of approximately 85 µsec is longer than the decay time of the debris cloud (Figure 2). Note that when the interaction between the laser beam and the ablation cloud is small, the diameter of the cut corresponds to the diameter of the laser beam, resulting in a more precise ablation. The ablation cavities are sharp and well-defined, and with minimal thermal effects at the edges of the cavities.[10]

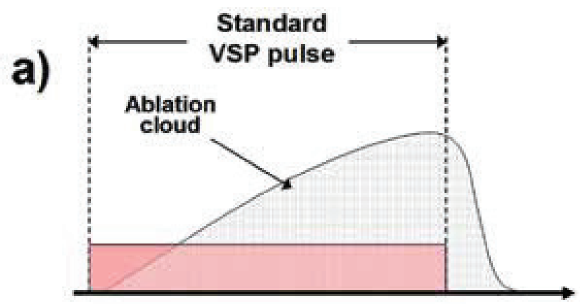

Figure 2a: *Standard VSP pulse*

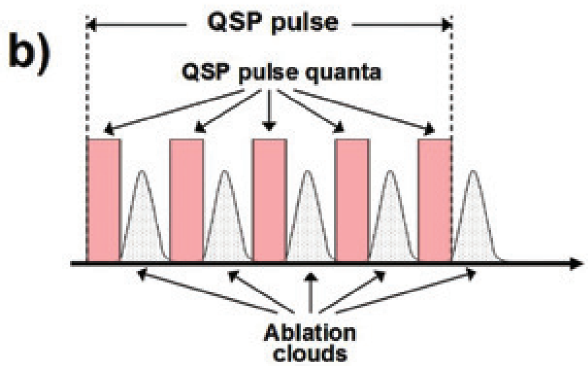

Figure 2b: *QSP pulse. A long pulse is quantized into super-short pulses (pulse quanta) distributed within the overall QSP mode pulse "duration." The QSP pulse quanta temporal sequence is optimized to avoid being absorbed and scattered by the ablation clouds*

The QSP technology makes it possible to work with higher precision at high peak powers when compared to other hard-tissue pulsing Er:YAG modes. Higher energy density and higher peak power promote cold and efficient ablation.[16] Namely, in the "cold" ablation regime,[16] the thermally affected tissue layer is confined only to the directly heated volume within the short optical penetration depth. Working with QSP modality results in craters that are deeper and have sharper edges.[10] In addition, the sound effects of the QSP pulses are softer, with lower decibels when compared to comparable power settings of other Er:YAG laser pulse modes.[11-12] The QSP mode is therefore an ideal setting of choice when fast, high-precision treatments and the avoidance of thermal side effects are advantageous or required.

With laser "conditioning" of tooth surfaces prior to composite bonding, a significant increase in the adhesion strength, especially when combined with acid etching, has been reported. The conditioning effect is optimal when the enamel and dentinal surfaces are "conditioned" by Er:YAG laser pulses of short pulse duration (50 µsec)[18] and low energy (< 90 mJ),[19] presumably because scattering and thermal effects are minimized. Surface conditioning at these low laser parameters is relatively time-consuming. However, when the QSP mode is used, the surface conditioning can be performed with up to 450 mJ of overall QSP pulse energy (5 x 90 mJ), which means that super-short, low-energy pulses can be delivered without reducing the treatment speed or compromising the bonding strength (Figure 3).[13] A recent microleakage study further demonstrated that QSP mode preparations are significantly faster and provide adequate bond strength.[15] The study concluded that the clinical benefits from the new QSP mode were easy to recognize: the margins of preparations for filling or for surface modification were clearer and sharper than with any other tested working mode.

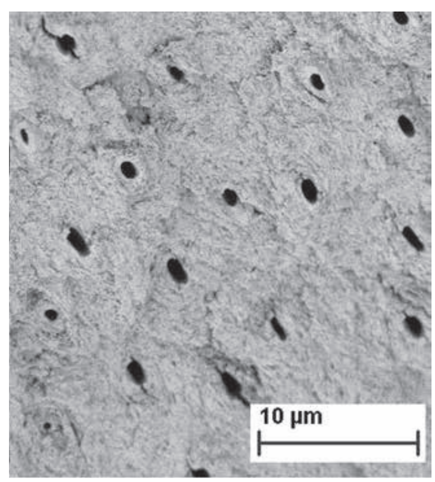

Figure 3: *Scanning electron micrograph (magnification X5000) of a dentin surface treated by the QSP Er:YAG laser irradiation (200 mJ per pulse). Note the clean and flat surface, with wide open dentinal tubules*

OBJECTIVE

The aim of this study was to determine how the reduced laser-debris interaction of the QSP modality of an Er:YAG laser affects its cutting speed. An investigation of the ablation efficacy of the QSP Er:YAG laser mode was carried out and compared to the ablation efficacy of other Er,Cr:YSGG and VSP Er:YAG laser modes. Ablation efficacy is of importance when considering the speed of the ablative treatments. Even more importantly, higher ablation efficacy indicates that more of the laser energy is being utilized for the intended ablative effect and not absorbed by interfering debris.

MATERIALS AND METHODS

An Er:YAG laser system (LightWalker® AT, Fotona, Ljubljana, Slovenia), and an Er,Cr:YSGG laser system (Waterlase iPlus, Biolase Technology, Irvine, Calif., USA) were used for this study. Both lasers were flashlamp-pumped, with the Er:YAG laser using the VSP technology, and the Er,Cr:YSGG laser being pumped with a PFN power supply. The laser systems were fitted with the appropriate noncontact handpieces (Fotona H02 handpiece, and Biolase Turbo handpiece with MX11 tip).

The lasers were operated in the following pulse duration modes and manufacturer-specified nominal pulse durations: (a) Er:YAG laser in QSP (600 µsec), SSP (50 µsec), and SP (300 µsec) pulse duration modes; (b) Er,Cr:YSGG laser in H pulse (50 µsec) duration mode. Note that the actual laser pulse durations vary with laser pulse energy, and are dependent also on the type of pump power supply and laser crystal used.[20] The SSP and H modes were chosen to represent the shortest and thus most efficacious standard pulse duration modes for the respective Er:YAG and Er,Cr:YSGG laser technologies. Similarly, the SP mode was chosen as the fastest Er:YAG laser ablation mode due its highest available average output laser power.

Water/air spray was used in all experiments. The water/air spray was provided by the laser systems, and was delivered to the tooth through the corresponding laser handpieces. The laser systems' spray settings resulted in measured water flows of 16 ml/min and 32 ml/min for Er:YAG, and 21 ml/min for Er,Cr:YSGG. Water flow rate was determined by measuring the time and water volume collected in an external container during that time.

The experiments were conducted on randomly chosen extracted human premolar and molar teeth which were stored in a physiological saline solution immediately following extraction. Before each ablation experiment, the tooth was positioned to have its surface perpendicular to the laser beam, and to be at focal distance of the laser beam.

Each ablation cavity was made in enamel with a sequence of N = 10 or 20 consecutive laser pulses of the same pulse energy delivered to the same spot. The depth (h) and the external diameter (d) of the ablated cavity following the ablation pulse sequence were measured with a focusing optical microscope. Each ablation data point represents an average obtained from at least 5 and up to 16 different cavities, each made with N consecutive pulses.

The laser pulses were delivered within each sequence at a slow repetition rate of 0.2 Hz in order to be able to control the number of delivered pulses. In the case of the Er:YAG laser system, the slow repetition rate of 0.2 Hz was achieved by controlling an internal shutter. In the case of the Er,Cr:YSGG laser, the system was left intact, and the 0.2 Hz was achieved by providing an appropriate external footswitch signal to the system. Single-pulse laser energy, E_{out} (in J), was measured with an external energy meter at the handpiece output. 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 ablated volume (in mm^3) was calculated from $V = h \pi d^2/4$, and the single pulse fluence (in J/mm^2) was calculated from $F = E_{out}/(\pi d^2/4)$. The single pulse ablation depth per laser fluence, DF (in mm^3/J), was calculated from $DF = h/(N \times F)$.

RESULTS

Initial experiments concentrated on the comparison of the ablation efficacy of the three tested VSP Er:YAG laser modes under two water spray conditions: 32 ml/min and 16 ml/min. Figure 4 shows the measured DF values for N = 10 consecutive laser pulses.

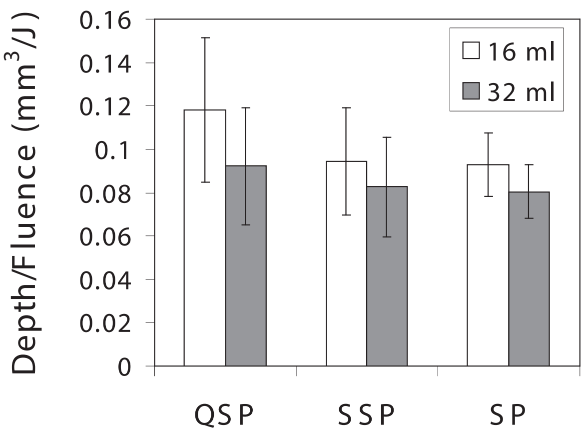

Figure 4: *Depth per laser fluence (DF) in enamel for the QSP, SSP, and SP pulse duration modes of an Er:YAG laser. The ablation cavities were made with N = 10 consecutive pulses of the same pulse laser energy of 300 mJ, and for two water spray conditions: 32 ml/min and 16 ml/min. The ANOVA's calculated significance value for the effect of water spray of* p *= 0.031 indicates that the difference between the water spray conditions is significant. The symbol* p *represents the* a posteriori *probability that the obtained result occurred by chance*

The results shown in Figure 4 demonstrate that the ablation efficacy is statistically significantly negatively affected by the increased level of water spray, in agreement with a previously published study.[17]

In the second set of experiments, the DF of the QSP laser mode was compared with that of the Er,Cr:YSGG (H) laser mode. Figure 5 shows the average DF in enamel as calculated from the measured ablation cavities made during a sequence of N = 10 and N = 20 consecutively delivered laser pulses. The water spray flow was set to 32 ml/min during tests with the VSP Er:YAG laser modes, and to 21 ml/min for the H mode.

As can be seen from Figure 5, the highest DF was obtained with the Er:YAG (QSP) mode, independent of the applied number of pulses in the sequence. Ablation with the QSP mode resulted in a statistically significant ($p < 0.05$) higher DF compared with the SP and H mode. In addition, significantly higher DF was obtained also for the SSP and SP modes as compared to the H mode.

Figure 5 also shows that ablation rate is not a linear function of the number of delivered pulses. The calculated average ablated depth per individual laser pulse fluence taken over a period of N = 10 pulses is statistically significantly larger than when taken over a period of N = 20 pulses. The initial ablation rate is therefore faster than the subsequent ablation rate. Similar nonlinear dependence of the ablation depth on the number of delivered pulses has also been reported elsewhere.[21]

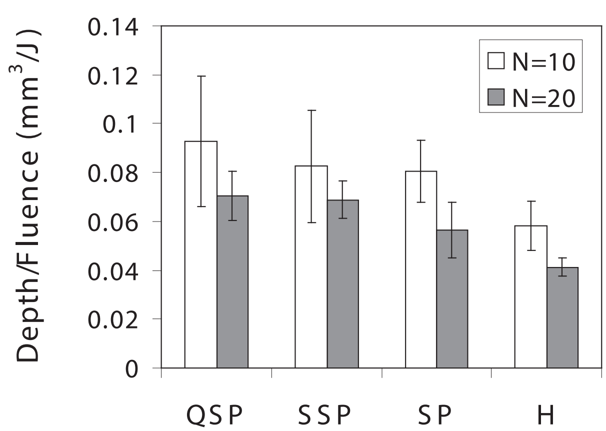

Figure 5: *Depth per laser fluence in enamel for the QSP, SSP, and SP modes of the Er:YAG laser, and for the H mode of the Er,Cr:YSGG laser. The ablation cavities were made with N = 10 and N = 20 consecutive pulses of the same pulse laser energy of 300 mJ. The ANOVA pairwise comparison of the DF values for the tested modes yields the following significance values: (QSP vs. H: p < 0.0001), (SSP vs. H: p < 0.001), (SP vs. H: p < 0.001), (QSP vs. SSP: p = 0.09), (QSP vs. SP: p = 0.02*

DISCUSSION

Our study demonstrates that the QSP mode not only improves the finesse of cutting but also improves the ablation efficacy. This characteristic of the QSP mode has two consequences of significance.

First, and more importantly, of all tested erbium laser pulse duration modes, the QSP mode is the least invasive on dental tissues. Due to its enhanced ablation efficacy, more of the laser energy is being utilized for the intended ablative effect and not absorbed by interfering debris. It should be noted that during optimal Er:YAG laser ablation conditions the water containing bulk dental tissue gets ablated in a "cold" regime,[16] where the ablation rate during each pulse is faster than the thermal diffusion rate and the layer is confined to the short (≈ 7 µm) optical penetration depth, with the layer temperature limited to below the water boiling temperature. In contrast, the debris consisting mainly of dehydrated hydroxyapatite can get heated to much higher temperatures, above 1200°C,[22] and is expected to contribute to additional heating of the tooth when the heated debris falls back to the tooth surface. Further research is needed to determine the contribution of this secondary effect to the overall ablation dynamics.

Second, for the same laser power P (in W), the ablation speed AS = P x DF (in mm^3/sec), is highest with the QSP mode. The values of the ablation speed per laser power, AS/P = DF (in mm^3/W sec = mm^3/J), for the studied laser modes are 0.082 mm^3/J, 0.076 mm^3/W, 0.069 mm^3/J, and 0.050 mm^3/J, for the QSP, SSP, SP, and H mode, correspondingly. These values were calculated from the data presented in Figure 5, averaged over the values for N = 10 and N = 20.

Note, however, that the maximum possible ablation speed (in terms of ablated volume over time) depends not only on the ablation efficacy but also on the available laser power from a particular laser device being used. This can be seen from Figure 6 which shows the dependence of the ablation speed in enamel on the laser power for different laser modes. The ablation speed of the H mode is compared to those of the QSP and SP modes which represent the two Er:YAG laser ablation extremes. The QSP mode was shown to have the highest ablation speed per laser power, and therefore exhibits in Figure 6 the steepest slope. On the other hand, the SP mode is capable of delivering the highest maximum laser power P (up to 20 W), and therefore extends in Figure 6 to the highest ablation speed value.

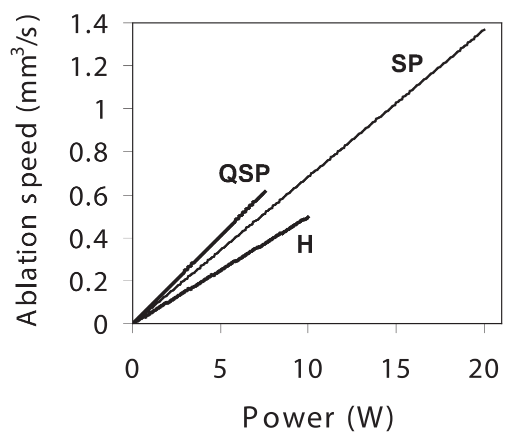

Figure 6: *Ablation speed in enamel for the QSP and SP pulse duration modes of the Er:YAG laser and for the H mode of the Er,Cr:YSGG laser. Lines extend to the maximal nominal power output at each laser mode for the laser system used in the study. The ablation speed was calculated from data presented in Figure 5, averaged over the values for N = 10 and N = 20*

The results also show that on enamel the DF is statistically significantly higher for all three tested Er:YAG laser modes (QSP, SSP, and SP), in comparison with that of the Er,Cr:YSGG (H) laser mode. It is important to note that the comparison measurements were made with a higher water spray flow rate of 32 ml/min for the Er:YAG laser modes than for the Er,Cr:YSGG (H) mode (21 ml/min), and therefore at comparably less favorable conditions for the Er:YAG laser modes.

Finally, it should be noted that the diameter of the ablated hole is not constant over the length of the hole, but gets smaller toward the bottom of the ablated cavity. For this reason, the volume as calculated from $V = h \pi d^2/4$ is larger than what would be obtained with a more exact laser triangulation measurement method,[23] and therefore the actual ablation efficacy AE (in mm^3/J), defined as the ablated volume per laser energy (in mm^3/J), is expected to be smaller than DF, equally for all tested modes.

CONCLUSION

This study demonstrates that with the new Er:YAG laser QSP mode a reduction of undesirable effects of laser-debris interaction results also in the enhancement of laser ablation efficacy. The high measured ablation efficacy of the QSP mode on enamel indicates that with the QSP mode more of the laser energy is utilized for cutting and not absorbed by interfering debris. This observation is attributed to the "quantized" characteristic of the QSP mode pulse, which reduces the interaction time between the ejected ablation debris and the laser beam.

AUTHOR BIOGRAPHIES

Dr. Matjaz Lukac obtained the MSc degree in laser physics at the University of Ljubljana in Ljubljana, Slovenia, and carried out his PhD research work in laser spectroscopy at the University of California in Berkeley, California, USA. He has been involved in the fields of lasers and laser medicine for the last 30 years, and has published more than 40 original scientific papers. Dr. Lukac is presently the CEO of a laser manufacturer, Fotona d.d., in Ljubljana, Slovenia. He is also a member and prior president of the Slovenian Academy of Engineering. Dr. Lukac may be contacted by e-mail at matjaz.lukac@fotona.com.

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Disclosures: Dr. Lukac is the CEO of a laser manufacturer Fotona, d.d. Fotona provided the Er:YAG laser system used in the experiments.

Mr. Suhovrsnik and Dr. Filipic have no financial interest in Fotona, and did not receive any financial compensation for the research that was conducted. Mr. Suhovrsnik has occasionally worked at Fotona via the student employment service.