Journal of the Laser and Health Academy
Vol. 2007; No.6/3; www.laserandhealth.com

Dental Laser Drilling: State of the Art with the Latest Generation of Variable Square Pulse Erbium Dental Laser Systems

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Background and Objectives: The most recent technological breakthroughs incorporated in the latest generation of Variable Square Pulse (VSP) Er:YAG dental lasers involve two additional features: SSP (Super Short Pulse) mode for extremely fine and minimally invasive laser ablation; and MAX mode for maximum optical drilling speeds. The objective of this study was to make a comparison between the two new VSP Er:YAG laser modes and a mechanical handpiece, to test their efficacy in apicectomy procedures. In addition, the safety of the MAX mode was evaluated.
Study design/Materials and Methods: Laser drilling speeds on extracted human teeth was measured under different VSP laser mode conditions and compared with the previously published drilling speeds of mechanical handpieces. Electron microscope pictures of the holes made in the hard dental tissue with the Er:YAG MAX mode were also made.
Results: The SSP erbium laser mode exhibits the largest single pulse energy drilling efficiency while the treatment procedure with the MAX mode is 1.6 times faster than with a mechanical handpiece. The electron microscope pictures of the ablation holes made with the MAX mode reveal no cracks or thermal damage to the ablated hard dental tissue.
Conclusions: The latest two Er:YAG laser modes: the SSP (Super Short Pulse) mode for extremely fine and minimally invasive laser ablation; and the MAX mode for maximum optical drilling speeds, offer superior alternatives to mechanical drills, are more precise and less invasive without sacrificing safety, ease-of use or operating speeds.

INTRODUCTION

The Er:YAG (erbium) laser has been recognized as the dental laser of choice for effective, precise and minimally invasive ablation of hard dental tissues. Of all infrared lasers, the Er:YAG laser wavelength of 2.94 μm has the highest absorption in water and hydroxyapatite (see Fig. 1) and is thus optimal for cold "optical drilling" of enamel, dentin and composite fillings.

The early standard technology erbium dental lasers failed to gain wide acceptance among the dental community, as their optical drilling speeds were substantially slower than the mechanical bur. This changed with the introduction of VSP dental lasers[1] and the incorporated Fidelis VSP (Variable Square Pulse) technology[2] which provides very short, almost square-shaped erbium laser pulses of adjustable duration. Tests have shown the ablation speed of the VSP-technology based Er:YAG lasers to be comparable to those obtained by classical means.

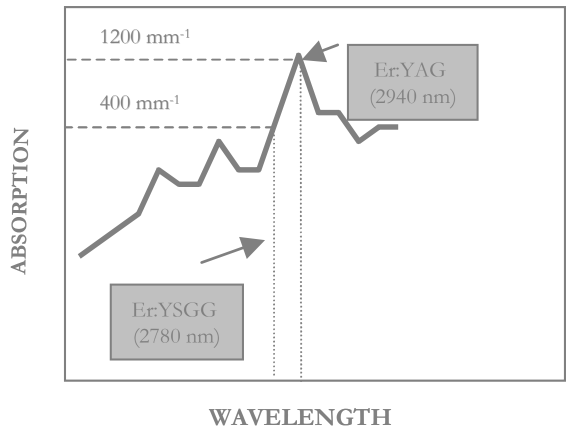

Fig.1: The Er:YAG (2.94 μm) laser has the highest absorption in water and hydroxyapatite. Another laser that emits in the 3 μm region is the Er:YSGG (2.78 μm) laser, however this laser exhibits 300% lower absorption and is thus less suitable for laser drilling.

The most recent technological breakthrough incorporated in the latest generation of VSP Er:YAG dental lasers[3] involves two features: the SSP (Super Short Pulse) mode[4] for extremely fine and minimally invasive laser ablation; and the MAX mode for maximum optical drilling speeds.

The objective of this in vitro study was to evaluate the efficacy and safety of the new VSP Er:YAG laser modes for hard dental tissue treatments compared with the efficacy of the classic dental handpiece.

MATERIALS AND METHODS

Experiments were performed with the latest generation Fidelis Plus III Er:YAG Variable Square Pulse technology dental laser (manufactured by Fotona d.d.). The following Fidelis laser pulse modes were used: VLP-1000µs, LP-500µs, SP-300µs, VSP-100µs, SSP-50µs and the MAX mode. The Fotona non-contact R02-C handpiece was used to focus the laser beam onto the extracted human tooth. The spot diameter of the beam on the tooth was 0.9 mm.

In the first set of experiments (single pulse efficacy experiment), the efficacy of single pulse laser drilling was measured under water spray conditions at a low single pulse laser energy of 100mJ and a low repetition rate of 1Hz for different laser pulse modes (durations).

In the second set of experiments (drilling speed experiment), the time required to fully cut through a 2 mm portion of the root was recorded. Measurements were made on fifteen samples of extracted mature human teeth, cut into 2 mm thick slices. Laser drilling of dentin with a water spray was performed with the laser operating in MAX mode at a high repetition rate of 20Hz. The measured time was compared to previously published results with a mechanical drill under similar conditions[5] (surgery reducing handpiece Intra 3614 N, KaVo, Biberach, Germany, with 4:1 reduction, used at 7,500 rpm with ISO size 12 fissure bur).

Electron microscope pictures of the ablated holes in hard dental tissue, obtained by the Er:YAG MAX mode, were also made.

RESULTS

Single pulse efficacy experiment

Figure 2 shows the previously published[4] dependency of the ablation efficiency on the pulse duration of the Er:YAG laser. The following Fidelis laser pulse modes were used: VLP-1000 µs, LP-500µs, SP-300µs, VSP-100µs, and the newest SSP-50µs. As Figure 2 shows, ablation efficiency increases with shorter pulse durations. The most effective mode is the new SUPER SHORT PULSE (SSP) mode where efficiency-reducing effects, the effect of heat diffusion, and the effect of debris screening are minimized. In addition, with SSP pulses the influence of light scattering in the emitted debris is minimal, and the quality and precision of the optically drilled holes is significantly improved.

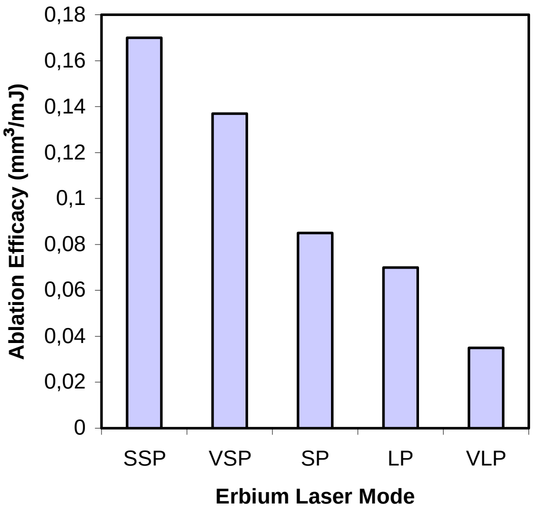

Fig.2: The ablation efficacy in dentin for different Er:YAG (2.94 µm) laser pulse duration modes, as already published in ref.4. The Er:YAG laser SSP mode has the highest single pulse ablation efficacy.

Drilling speed experiment

A comparison of the times obtained revealed a significant difference between the drilling speed of the Er:YAG laser MAX mode and the previously published drilling speed of the mechanical handpiece.

	Mechanical handpiece[5]	**Laser MAX mode**
T (s)	3.6	**2.2**
SD (standard dev.)	0.95	**0.54**

Fig.3: Comparison of timing results in dentin obtained with a mechanical handpiece[5] and the Er:YAG laser MAX mode. The MAX mode was found to be faster than the mechanical drill.

Electron microscope study

Electron microscope pictures of ablated holes in hard dental tissues with the Er:YAG laser MAX mode revealed no cracks or thermal damage.

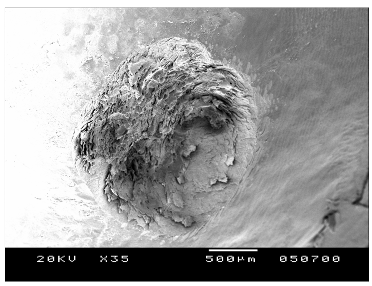

Fig.4: An example of an Er:YAG laser MAX mode ablation hole in enamel. No cracks or thermal damage were observed.

DISCUSSION

Exciting developments in the theoretical understanding of the laser ablation of biological tissues[6] have facilitated recent rapid technological advances in laser dentistry.

It is now well understood that there are four ablation regimes (see Fig. 5), defined by the relationship between the laser pulse duration and the laser pulse energy (or more correctly, laser fluence, i.e. the laser energy per surface area in J/cm^2).

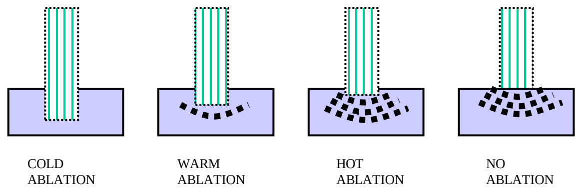

Fig.5: Schematic overview of the four ablation regimes.

At high energies and low pulse durations, the speed of ablation is faster than the diffusion of heat into the tissue with all of the energy used up for COLD ABLATION. With decreasing energies and/or longer pulse durations, the layer of tissue, that has been thermally-influenced by the time the pulse ends, becomes thicker. Thermal effects become more pronounced and, with these, ablation efficiency is considerably reduced (WARM and at even lower energies HOT ABLATION). At energies below the ablation threshold there is NO ABLATION, consequently all the energy is released in the form of heat, independent of laser pulse duration.

It is important to note that by decreasing the laser energy, with the intention of working more safely, the operator may achieve precisely the opposite, i.e. more thermal effects in the tissue. The important factor that can be used to determine the effect of the laser energy on dental tissue is the Peclet[6] or the Laser–Tissue Number (LTN). The LTN is defined by:

LTN = Laser Intensity x LTF ,

where

Laser intensity = Laser Fluence/Laser Pulse Duration,

and the LTF (Laser Tissue Factor) is a constant factor that depends on the laser wavelength and the particular dental tissue physical properties:

LTF = 0.5 x Laser Absorption Coefficient x Tissue Thermal Relaxation Time/ Specific Heat of Ablation

For laser fluences above the ablation threshold the cold ablation regime is characterized by LTN >1.

To achieve cold ablation the operator must select laser parameters where LTN >1. When a particular pulse duration t_L is selected, the ablation starts at the ablation threshold energy. The ablation efficiency then grows with increasing energy until the pulse energy exceeds the value where LTN >1. Above this value, the ablation effect is the most effective, most "cold", and increases linearly with the laser energy.

In order to perform very precise and fine treatments at low laser energies, the laser pulses must be sufficiently short in order for LTN to be greater than 1. The safest regime is the regime where pulse durations are shorter than the tissue relaxation time where no warm and hot ablation regimes exist. For enamel, the thermal relaxation time equals approximately 100 μsec.

On the other hand, when high ablation speed is desired, the best choice is to use high pulse energies at longer pulse durations, providing that LTN is kept well above 1. This is due to another effect that influences ablation dynamics - debris screening, i.e. the absorption and scattering of laser energy in the particles ejected from the ablation site. The level of debris screening depends on the density of the debris and is strongest at high LTN's. Since the density of the debris depends on the laser beam intensity, it is advantageous to achieve LTN >1 at longer pulse durations, i.e. at lower laser intensities.

The latest generation of VSP Er:YAG lasers enables the operator to select from the following modes: SSP (Super Short Pulse: 50 μsec), VSP (Very Short Pulse: 120 μsec), SP (Short Pulse: 300 μsec), LP (Long Pulse: 600 μsec), VLP (Very Long Pulse: 1000 μsec).

The SSP pulse durations are extremely short, approximately 50 μsec which is below enamel's 100 μsec tissue relaxation time. The SSP pulses are therefore best suited for precise and fine ablation at low laser energies.

For standard work, VSP and SP pulses with an LTN above 1 are recommended, while for maximum ablation speeds, MAX mode is most suitable because MAX ensures an LTN >1 by fixing the laser energy and pulse duration to the optimal high values of 1000 mJ and 300 μsec pulse duration.

For soft tissue applications, where thermal coagulation effects are desirable, LP and VLP modes are best suited.

Comparison of Er:YAG and Er,Cr:YSGG

Since the absorption coefficient of Er,Cr:YSGG is three times smaller than that of Er:YAG the range of safe parameters that can be used is considerably reduced when using Er,Cr:YSGG. The ablation threshold energy is therefore three times higher.

Secondly, the range of the Er,Cr:YSGG laser pulse durations is limited to longer pulse durations only. In this respect, the Er:YAG laser is at an advantage, since it offers variable pulsewidths down to 50µs while the Er,Cr:YSGG laser is due to the long cross-relaxation time of the Cr^{3+} ion limited to a minimum pulsewidth of approximately 500µs. To illustrate this limitation, Fig. 6 displays measured pulse durations of an Er:YAG laser system (Fidelis Plus III, Fotona), and of an Er,Cr:YSGG laser system (Waterlase MD, Biolase). Note that the Waterlase MD laser system uses relatively short pump pulses of only 140 ms in the H mode, and 700 µs in the S mode. In spite of this, due to the presence of the Cr^{3+} ion in the Er,Cr:YSGG laser crystal, the generated laser pulses are much longer, and are in the shortest H pulse mode on the order of 600 µs, and in the longer S mode on the order of 1200 µs.

PULSE MODE	PULSE DURATION
Er:YAG (Fidelis Plus III)	
SSP	80 µs
VSP	150 µs
SP	200 µs
LP	500 µs
VLP	800 µs
Cr,Er:YSGG (Waterlase MD)	
H	600 µs
S	1200 µs

***Fig.6**: Available pulse durations for the Er:YAG (Fidelis Plus III, Fotona) and Er,Cr:YSGG (Waterlase MD, Biolase) laser systems.*

One of the key factors that determines the regime and efficiency of laser ablation is the laser pulse duration. If the energy required is delivered into the target within a very short time, then the energy has little time to escape from the ablated volume, and so less heat is diffused into the surrounding tissue (see Fig. 7).

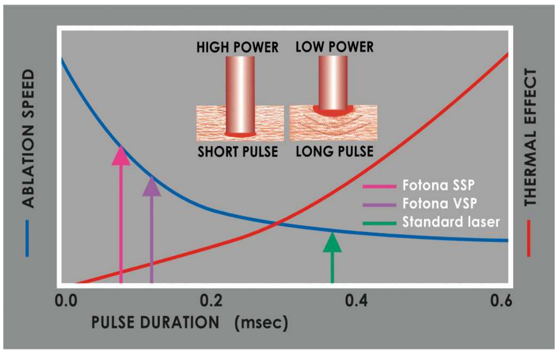

Fig.7: Keeping the pulse energy constant, the ablation efficiency increases, and the thermal effects decrease towards shorter pulse durations. Due to the long cross-relaxation time of the Cr^{3+} ion, the Er,Cr:YSGG cannot be operated bellow approximately 500 µs.

Based on the above wavelength and pulse duration considerations, the Er,Cr:YSGG laser is found to be suitable for soft tissue applications where some level of thermal coagulation effects are desirable but has limitations when used on hard tissues. On the other hand, the Er:YAG laser, especially when pumped with variable square pulse (VSP) pump technology can be operated at adjustable pulse durations, from super short pulses (SSP) that are ideal for precise ablation of hard tissues, to very long pulses (VLP) for soft tissue procedures (See Fig. 6).

CONCLUSIONS

For precise, hard-tissue laser procedures (where low pulse-energies are used), SSP mode, with a pulse duration shorter that the hard tissue relaxation time, (and LTN >1) was found to be the most suitable and safest. This is because it achieves the highest, and "coldest", single-pulse laser drilling efficiency.

When maximum laser drilling speeds are required, the MAX mode was found to be a safe and fast, hard tissue laser dentistry tool. Laser drilling with VSP MAX mode was found to be **1.6 times faster** than the published[5] drilling speeds of standard mechanical handpieces.

With two new modes, SSP and MAX, dental lasers have finally achieved their original goal: replacing mechanical drills with more precise and less-invasive optical technology without sacrificing safety, ease of use or operating speed.

REFERENCES

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