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A Novel Quantum Square Pulse (QSP) Mode Erbium Dental Laser

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ABSTRACT

Recently, a novel quantum square pulse (QSP) modality has been added to the range of treatment parameters of variable square pulse (VSP) Er:YAG dental lasers. In this paper, physical mechanisms enabling the QSP technology are reported. One of the major advantages of the QSP mode is that it significantly reduces undesirable effects of laser beam scattering in the debris cloud during hard tissue ablation. The cavities made with the QSP mode are sharp and well defined, and with minimal thermal effects at the edges of the cavities.

Key words: Er:YAG; variable square pulse technology; quantum square pulse; QSP mode; MAX mode; ablation speed; cavity preparations; scattering; plume dynamics.

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I. INTRODUCTION

In the field of dentistry, Er:YAG lasers are revolutionizing the concept of patient care [1,2]. As opposed to classical tools, such as burrs or scalpels, lasers offer a much wider range of treatment protocols and precision of control. With the classical tools the effect on the patient's tissue is controlled mainly through the tactile pressure of the dentist's hand. On the other hand, a laser dentist can, at a touch of a button, adjust and optimize the speed, finesse and thermal depth of any treatment.

The development of dental lasers has been exceptionally rapid in the past ten years [3,4]. Early erbium lasers failed to gain wide acceptance by the dental community because their optical drilling speeds were slower in comparison to the mechanical bur. This has changed in the past years, with much faster ablation speeds now possible; dental lasers with variable square pulse technology (VSP), [4, 5] and it's MAX mode even exceed the drilling speeds of conventional burs [5-13].

Recently, the range of treatment parameters of VSP Er:YAG lasers has been significantly extended. With the latest proprietary quantum square pulse (QSP) technology [14], minimally invasive treatments that require extremely high finesse have now been made possible. With high finesse it is meant that the tissue is treated with high spatial precision and with small or moderate pulse energy and short duration laser pulses at high repetition rates.

Extremely high finesse of laser treatment is required, for example, when making final hard tissue surface modifications before applying composite fillings. High finesse is also desirable when making fine cuts with controlled bleeding into the soft tissue.

Similarly to achieving high ablation speeds, obtaining high treatment finesse has represented a significant technological challenge. This is due to the fact that short pulses of low energy have suboptimal efficiency and are extremely difficult to generate at sufficiently high repetition rates.

In the QSP mode, a longer laser pulse is divided, i.e. quantized, into several short pulses (pulse quanta) that follow each other at an optimally fast rate. This enables the QSP mode to deliver short, high finesse pulses with the efficiency of long duration laser pulses without sacrificing the precision that is provided by short duration pulses.

One of the major advantages 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. The cavities made with the QSP mode are sharp and well defined, and with minimal thermal effects at the edges of the cavities.

In this study, we report on a study of the physical mechanisms and potential clinical benefits of the latest quantum square pulse (QSP) Er:YAG dental laser modality.

II. MATERIALS AND METHODS

a) Measurements of QSP pulse mode characteristics

The Er:YAG solid-state lasers are operated in pulsed operation. The pulsed operation is needed in order for the heat to be generated at the treatment location only for a very short time period and within a locally limited area.

In laser ablation we generally talk about four ablation regimes [4, 7, 15]. At high energies and low pulse durations (i.e. at high laser pulse powers), the ablation speed is higher than the rate at which heat diffuses into the tissue. All laser energy is thus used up in COLD ABLATION (see Fig. 1). Here, what is meant by "cold" ablation is that the thermally affected tissue layer is confined only to the directly heated volume within the optical penetration depth. With decreasing energies and/or longer pulse durations (i.e. with lower laser pulse powers), the layer of tissue that has indirectly been heated becomes thicker. Thermal effects become more pronounced and, with these, ablation efficiency is considerably reduced (WARM ABLATION and, at even lower energies, HOT ABLATION). At energies below the ablation threshold there is NO ABLATION and all the energy is released in the form of heat, irrespective of the laser pulse duration.

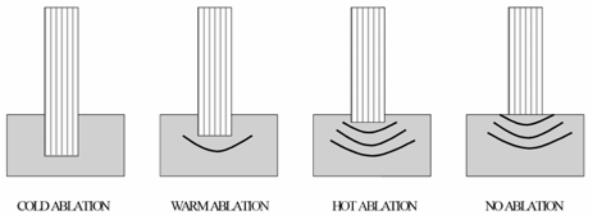

Fig. 1: The effect of the laser beam on tissue in the four ablation regimes.

For the effective and safe treatment of hard tissues, laser parameters must be chosen in such a manner that the ablation is in the cold regime and the thermal influence on the adjacent tissue is minimal. The cold ablation regime is achieved at high pulse powers, which means that sufficiently high pulse energies and/or sufficiently short pulse durations must be used.

Therefore, when low energy pulses are to be used for high finesse treatments, the pulse duration must be reduced accordingly in order to keep the laser pulse power at a sufficiently high level for cold ablation.

In general, Er:YAG lasers are very inefficient when operating in the low pulse energy regime. This is due to the fact that a laser rod generates a laser beam only above a certain energy threshold, which must be overcome through pumping by means of a flashlamp. At very short pulses of low energy, a significant portion of the pumping energy is required for overcoming this energy threshold before a usable quantity of laser energy is even made available. Therefore, short pulses of low energy have poor efficiency and are extremely difficult to generate at sufficiently high repetition rates.

In this study, we used an Er:YAG dental laser (LightWalker AT, manufactured by Fotona d.d., see Fig. 2) that operates in a QSP (Quantum Square Pulse) mode that improves the efficiency of Er:YAG lasers in a high-finesse treatment regime. The laser system was fitted with a tip-less (non-contact) H14 handpiece (beam spot size in focus: 0.6 mm).

Fig. 2: LightWalker AT dental laser system with the QSP modality that was used in the study.

The novel quantum square pulse (QSP) technology improves the efficiency of short Er:YAG pulses in the following way. A standard laser pulse of a longer duration is divided (i.e. quantized) into several, short duration individual "pulslets" (quanta) that are separated by sufficiently short temporal pulslet spacing (see Fig. 3). For the same overall pulse energy, the pulse power of individual quanta is thus higher compared to the pulse power of the original long pulse.

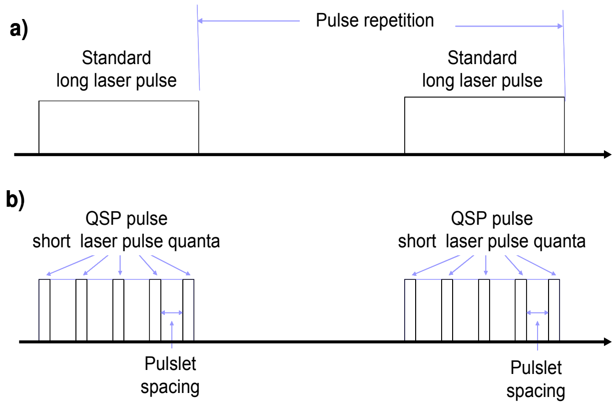

Fig. 3: a) Standard laser pulse; b) QSP pulse: a long laser pulse is quantized into several pulslets (pulse quanta).

The sufficiently short temporal pulslet spacing is required because there is some inversion population of the laser energy status remaining after the end of the laser pulse. When a laser material is supplied with energy by pumping, the individual erbium ions are successively moved into a higher laser-enabling energy state. A significant share of the atoms remains at this higher energy state for a short period of time after termination of the pumping process and even after termination of the laser emission. This period of time is limited by the inversion population remaining time (the time within which, in the absence of pumping, the remaining inversion population of the laser energy status is reduced to 10% of the initial value). In cases where the pumping for the second pulslet starts early enough, the threshold is reduced as the laser has already been pre-pumped from the previous pump pulse. From this viewpoint, the temporal pulslet spacing should be shorter than the inversion population remaining time. The shortening of the pulslet spacing utilizes this effect, in that after termination of a very short individual pulslet and after completion of the very short temporal pulslet spacing within the inversion population remaining time, there is still residual energy in the laser material that is available for the subsequent individual pulslet. This significantly enhances the efficiency of QSP laser pulses as compared to standard short laser pulses.

In our first experiment, we studied the influence of temporal separation between pulselets (pulse quanta) on the efficiency of QSP laser pulses by measuring the Er:YAG output energy as a function of the laser pulslet temporal separation for five laser pulslets with an individual pulslet duration of 50 μsec.

b) Measurements of Er:YAG laser ablation plume dynamics

When an ablative laser light pulse is directed onto the tissue an ablation of the tissue starts that leads to the emission of ablated particles above the tissue surface, forming a debris cloud [18-22]. The debris cloud does not develop instantaneously. Particles begin to be emitted after some delay following the onset of a laser pulse, after which they spread at a certain particle cloud speed and within a certain spatial angle above the ablated tissue surface. So in the beginning the emitted particles are close to the surface, and after longer periods of time the particles are well above the surface. The debris cloud interferes with the laser beam, resulting in laser light scattering. The undesired scattered portion of the laser beam is present to a significant extent only at the later time steps of the single laser pulse.

In order to avoid the effects of scattering, the pulse duration should be shorter than the time required for the ablation cloud to develop. At the same time, when using the QSP laser pulse technology, the pulslet spacing should be longer than the debris cloud decay time. This ensures that the second pulslet does not encounter any cloud remains from the previous pulslet.

In the second experiment, we applied laser flash photography to measure the temporal evolution of the ablation cloud (Fig. 4) [22].

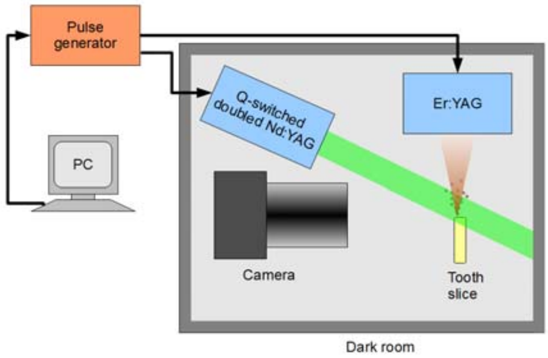

Fig. 4: Experimental set-up for measuring Er:YAG laser ablation plume dynamics.

A Canon EOS 300D camera with 100 mm F2.8 macro lens was placed in front of an extracted human tooth. The extracted teeth were sliced into 2 mm thick slices along their longer axis. Their surface was properly cleaned in order to avoid any undesired side effects during the ablation process. The camera's focus was at the tooth surface. The camera's optical axis was perpendicular to the optical axis of the ablative Er:YAG laser beam. The camera exposure time was set to continuous mode. To achieve good lighting conditions of the ablation process, the tooth surface was illuminated by a Q-switched frequency doubled Nd:YAG laser (QX Max, manufactured by Fotona d.d.) pulse of 10 ns duration. Both lasers, the ablative Er:YAG laser and the illuminating frequency doubled Nd:YAG, were controlled by a PC and a pulse generator. In order to avoid overexposure the experiments were carried out in a dark room.

III. RESULTS

a) Ablation plume dynamics

Figure 5 shows the captured images of the debris cloud development at different times from the onset of an Er:YAG laser pulse. As can be seen from Fig. 5 the cloud formation time is in the 50-150 µsec range.

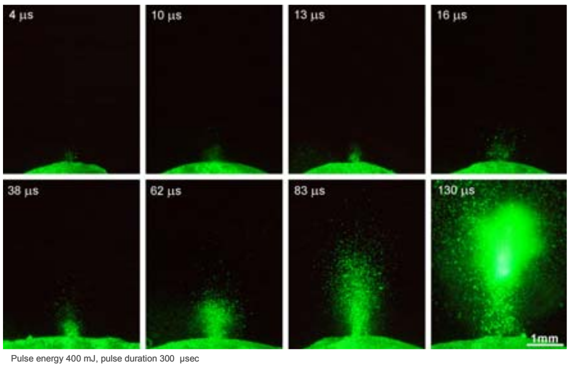

Fig. 5: Cloud images at different delays from the onset of an Er:YAG laser pulse. Cloud formation time is approx. 50-150 µsec.

Figure 6 depicts the temporal evolution of the speed at which the debris cloud spreads vertically away from the tooth surface. The cloud speed starts above 100 m/s and settles at approximately 45 m/s.

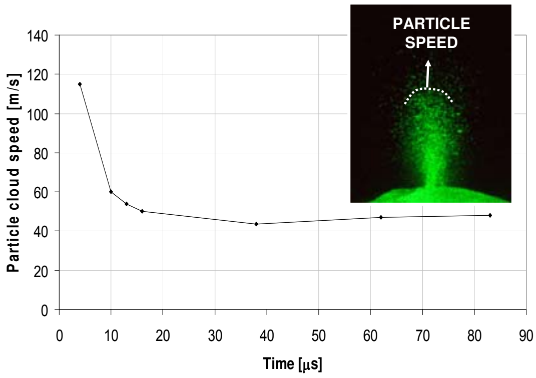

Fig. 6: The temporal dependence of the particle cloud speed following the onset of an Er:YAG laser pulse.

Fig. 7 shows a schematic illustration of the debris cloud generation during the course of a single laser pulse at four different points of time, namely at the beginning of the single laser pulse at 0 µsec, followed by subsequent time steps of 50 µsec, 100 µsec and 500 µsec. Mie scattering in the ejected debris particles that are large compared to the laser wavelength is assumed. In this type of scattering the light gets scattered predominantly in the forward direction [26].

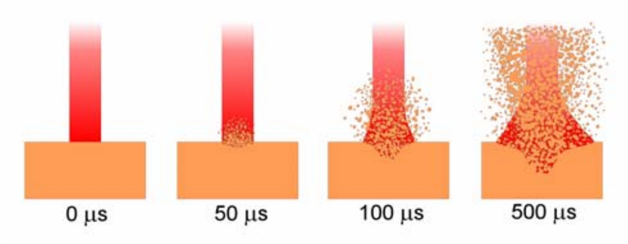

Fig. 7: Graphical representation of the beam scattering in the ablation debris cloud.

It is important to note that the scattering of light in the debris cloud represents a problem only when the cloud is high enough above the surface so that it can redirect a considerable portion of the laser beam energy away from the original laser beam position. Since typical beam sizes are within 0.3 and 2 mm of diameter, scattering becomes a serious problem when the cloud reaches a height of approximately 2 mm or higher. This happens within approximately 50 - 100 microseconds of the laser pulse onset [3]. Therefore, with laser pulse durations of approximately 50 microseconds or shorter, the effect of scattering is small and becomes more pronounced only at very high pulse powers where the instantaneous density of debris becomes high.

The influence of beam scattering on the precision of hard tissue ablation can be seen in Fig. 8, which shows laser ablated craters in enamel and dentin at two Er:YAG pulse durations. As a result of scattering, the ablated cavities do not have well defined edges. This effect is more pronounced at higher pulse energies and longer pulse durations.

The latest Er:YAG dental lasers are able to operate with pulse durations as short as 50 µsec [3, 23]. Compared to longer pulse duration modes, these "super short pulses" (SSP) are thus less susceptible to scattering. However, scattering affects also 50 µsec pulses when they contain high energy. At high pulse energies, i.e high instantaneous pulse powers, the dynamics and the density of the ablation cloud are high. This leads not only to stronger scattering but also to considerable absorption of the incoming beam. Figure 9 shows the difference in the ablated craters in dentin with the 50 µsec (SSP) pulse at a moderate energy (100 mJ) and at high energy (450 mJ).

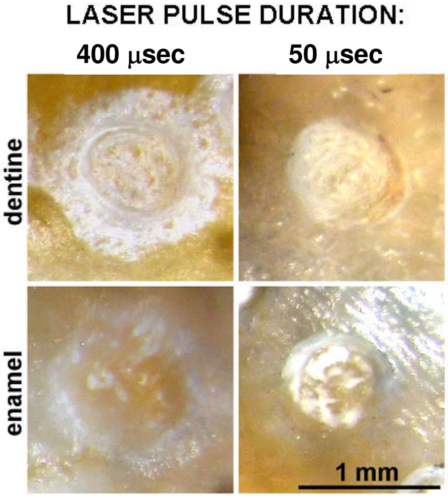

Fig. 8: The shape of ablated craters in dentin and enamel for the same Er:YAG pulse energy of 200 mJ at two pulse durations. During long pulse durations the ablation cloud has sufficient time to develop and scatter the incoming laser beam. During short pulses the ablation cloud does not have time to develop and the scattering is smaller.

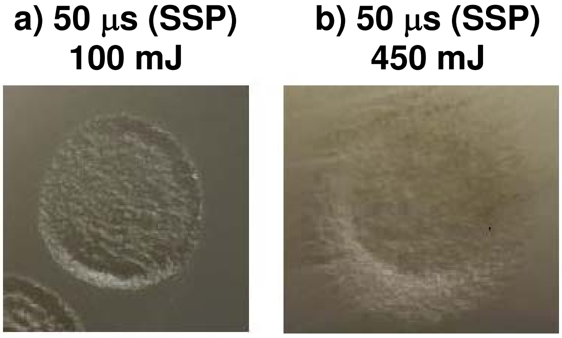

Fig. 9: The shape of ablated craters in dentin for 50 μsec (SSP) Er:YAG laser pulses for two pulse energies. At high pulse energies, scattering becomes strong and the cavities are less defined.

The laser system used in our experiments delivered the laser beam with a multi-mode approximately top-hat profile. The pronounced lateral ablation at higher pulse energy in Fig. 9b was therefore not a result of a long tail of a Gaussian profile that exceeded ablation threshold at laser pulse energies [24, 25]. Note also that when the laser beam was directed on a material where no ablation occurred (such as a photo sensitive paper or a metal) the resulting laser marks on the material were sharp independently of the laser pulse energy.

As can be concluded from Figs. 8 and 9, the preferred Er:YAG laser pulses, from the viewpoint of scattering, are pulses of short duration and low-to-moderate pulse energy.

b) QSP mode

Figure 10 shows the measured dependence of the overall QSP laser pulse energy on the temporal separation between the pulslets (pulse quanta). The QSP pulse consisted of five pulselets of 50 μsec pulse duration. As expected, the lasing efficiency, and consequently the QSP laser output energy, increases significantly towards shorter pulslet separations.

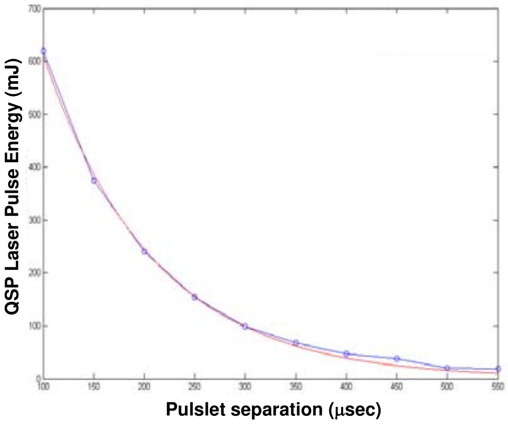

Fig. 10: Measured dependence of the QSP Er:YAG laser pulse energy on the temporal separation of laser pulslets (pulse quanta) within a QSP pulse.

Based on Fig. 10, the temporal pulslet separation should be as short as possible in order for the lasing efficiency to be high. However, from the viewpoint of debris screening the temporal separation between the pulslets should be as long as possible, or at least longer than the time the debris cloud needs to settle down. This way there would be no debris cloud remaining from the previous pulslet.

Figure 11 shows the crater images obtained with a standard 600 μsec Er:YAG laser pulse and with a train of five 50 μsec long laser pulslets with the same overall pulse energy.

With the QSP mode a compromise is found, whereby the temporal pulse spacing between pulslets is longer than the cloud decay time and shorter than the inversion population remaining time. This ensures an enhancement of lasing efficiency without significantly compromising the quality of laser ablation. Figure 12 shows the difference in the effect on dentin of a high laser energy 50 μs (SSP) pulse and a QSP pulse of equal pulse energy (450 mJ).

When the QSP modality is used the craters are deeper and have much sharper edges. As can be seen from Fig. 12, the QSP pulses are less affected by the scattering in the debris cloud and consequently ablate not only more precisely but also more effectively.

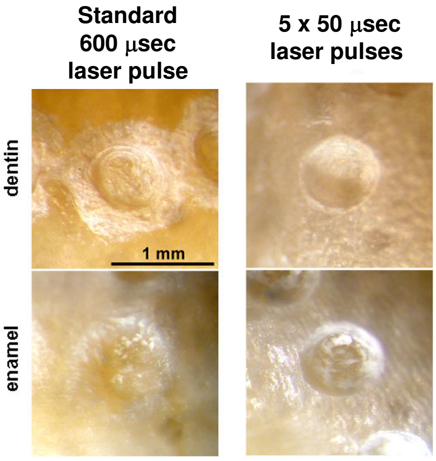

Fig. 11: Comparison of the quality of laser ablated cavities with a standard 600 µsec laser pulse and with a train of five laser pulslets with the same total pulse energy of 200 mJ.

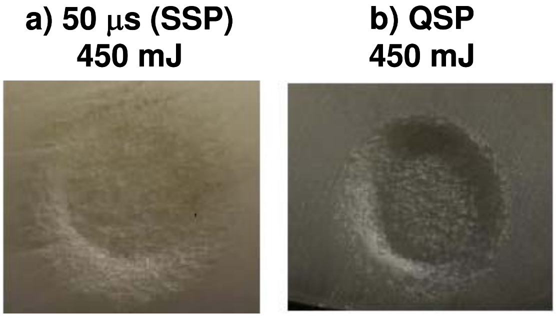

Fig. 12: Comparison of the quality of laser ablated cavities in dentin with a high energy SSP pulse and with a QSP pulse of the same pulse energy. Note the difference in the ablated depth and the sharpness of the cavity edges.

IV. DISCUSSION AND CONCLUSIONS

Quantum square pulse (QSP) mode provides laser dentists with an additional high finesse treatment modality. With six pulslets per QSP mode the average repetition rate of Er:YAG dental lasers can be easily increased to 120 Hz and above. The parameters of the QSP mode were found to represent an optimal solution for reducing the undesirable effects of debris screening without significantly affecting the available range of laser power. Compared to standard Er:YAG laser pulse modes, the cavities made with the QSP mode are sharper and more well-defined, which minimizes any undesirable thermal effects at the edges of the cavities.

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