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Quantum Square Pulse Mode Ablation Measurements with a Digitally Controlled Er:YAG Dental Laser Handpiece

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ABSTRACT

Recently, the range of treatment parameters of Variable Square Pulse (VSP) Er:YAG lasers has been significantly extended. With the latest Quantum Square Pulse (QSP) technology, minimally invasive treatments that require extremely high finesse are now possible. In addition, a new digitally controlled dental laser handpiece has been developed to help guide the laser light swiftly and accurately across the surface of treated tissues, thus allowing the practitioner to perform treatments involving otherwise unattainable patterns.

In this study, a digitally controlled dental laser handpiece was utilized to measure the ablation efficacy of the Er:YAG laser's QSP mode. The QSP mode was found to have a considerably higher ablation efficacy (by a factor of 1.4) when compared to the standard "single" (non-quantized) Er:YAG laser pulses.

Key words: Er:YAG; variable square pulse technology; quantum square pulse; QSP mode; digitally controlled handpiece, laser dentistry, ablation, hard dental tissue.

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I. INTRODUCTION

The great potential of lasers for use in dentistry was recognized almost immediately after their invention. However, the technological challenges were such that it has taken several decades before dental lasers have fulfilled, and recently even surpassed, the early expectations of the dental community [1].

The development of Erbium (Er:YAG) solid-state crystal lasers represented one of the first breakthroughs [2]. Of all infrared lasers, the Er:YAG laser wavelength of 2940 nm has the highest absorption in water, which is the major constituent of the human body and is thus especially optimal for optically treating hard dental tissues [9].

Another major breakthrough was achieved with the introduction of Variable Square Pulse (VSP) pumping of Erbium and Neodymium lasers [3-9]. This solution provides nearly square-shaped power pulses, the duration of which can be conveniently controlled over a wide range of pulse durations. By being able to adjust the VSP laser pulse duration, a dentist has complete control over whether the treatment is "cold" – as is optimal when ablating hard tissues, or coagulatively "hot" for treating soft tissues [9]. This treatment dimension is not available with classical dental tools. In addition, with the advanced VSP technology, the speed of cavity preparations with lasers became comparable and even higher than with standard diamond drills [8].

The most recent technological advances incorporated in the latest generation of VSP Erbium dental lasers include two additional features: the QSP (Quantum Square Pulse) mode for extremely fine, yet fast minimally invasive laser ablation [10-14]; and the digitally controlled dental laser handpiece technology [15, 26].

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. This enables the QSP mode to deliver super-short, low-energy pulses with the efficiency of long-duration, higher energy laser pulses, without sacrificing the efficiency 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 are now faster and more precise, even when compared to the shortest SSP pulses (Super Short Pulse, SSP) available with VSP technology.

By helping the dentist in guiding the laser "drill" or "scalpel" swiftly and accurately across the surface of the treated tissues, the new digitally controlled dental laser handpiece allows the practitioner to perform treatments involving otherwise unattainable patterns. This new technology finally enables practitioners to fully utilize the most important feature of laser light, its weightlessness, which creates the potential to revolutionize dental fields such as implantology, conservative dentistry and apicoectomy.

In this study, the X-Runner™ advanced handpiece technology was utilized to measure the ablation efficacy of the QSP mode, and to compare the QSP mode ablation characteristics with those of the SSP and MAX modes [23], which had been, until recently, the fastest available VSP technology pulse modes.

II. MATERIALS AND METHODS

The Er:YAG laser used was a LightWalker AT (manufactured by Fotona) fitted with a non-contact X-Runner (model SX02) digitally controlled Er:YAG laser handpiece (See Figs. 1 and 2).

Fig. 1: LightWalker® AT dental laser system equipped with the X-Runner™ Er:YAG handpiece, as used in the study.

Fig. 2: Digitally controlled Er:YAG laser handpiece (X-Runner™) used in the study.

The X-Runner handpiece is capable of guiding the focused Er:YAG laser beam over the treated surface to form circular, rectangular or hexagonal shaped cavities of adjustable dimensions up to 6 mm (See Figs. 3 and 4).

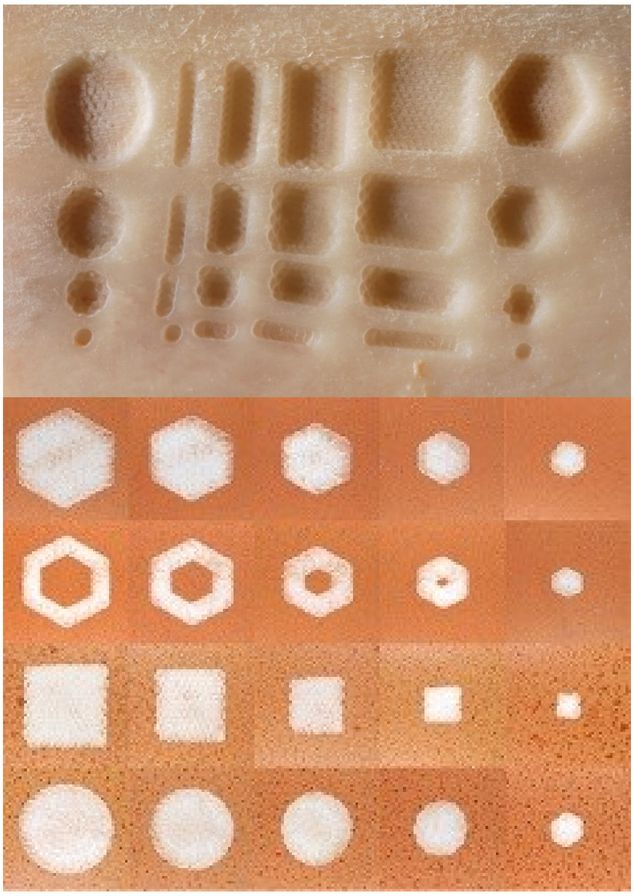

Fig. 3: Examples of cavity shapes as made with the digitally controlled X-Runner™ Er:YAG handpiece, a) in bone; and b) in egg shell.

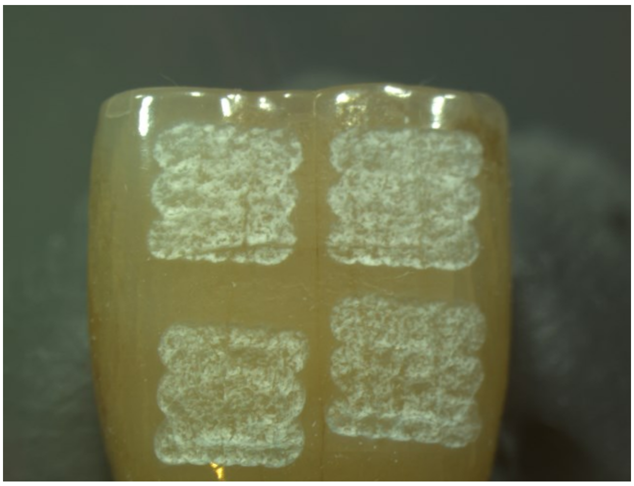

Fig. 4: Typical cavities in dental enamel as made with the X-Runner™ digitally controlled handpiece. The X-Runner was set to a square 3 mm x 3 mm pattern. Five scans with the QSP pulse mode energy of 150 mJ were made.

Measurements were made with three LightWalker pulse duration modes, SSP mode (Super Short Pulse) [4], MAX mode [25], and the new QSP mode (Quantum Square Pulse) [14]. The built-in water spray cooling was used for all the experiments.

Extracted premolar and molar teeth were selected, and immediately following extraction were stored in a 10% formalin solution. The teeth were thoroughly cleaned of all residual debris using brushes and curettes. Prior to the procedure, all teeth were sterilized in an autoclave at 121 °C and 2.1 atm for 30 minutes and stored in a physiological saline solution. The teeth were randomly chosen for the ablation experiments.

For the ablation efficacy measurements, rectangular cavities of a nominal square shape of 2 mm x 2 mm were made in enamel with the digitally controlled handpiece (X-Runner). Ten consecutive Er:YAG laser beam scans were made over the same area. A focusing microscope method [17] was used to measure the ablation depths of the X-Runner-made cavities. Relatively large transverse dimensions of the square-shaped cavities made it possible to measure the cavity depth at several transverse locations within the cavity. The depth of each cavity was thus measured at 5 transverse locations within the cavity. Since four cavities were made for each parameter setting, each ablation data point represents an average depth of four cavities, each measured at five transverse locations. In one set of measurements, laser pulse energy was set to a relatively low value of 250 mJ, resulting in cavities shallower than the enamel thickness. In the second set of experiments, the laser pulse energy was set to higher energies (750 mJ for QSP and 1000 mJ for MAX), resulting in cavities extending through the enamel and into the dentin.

III. RESULTS

Figure 5 shows typical cavities as made with the X-Runner, set to a square, 2 mm x 2 mm scan pattern.

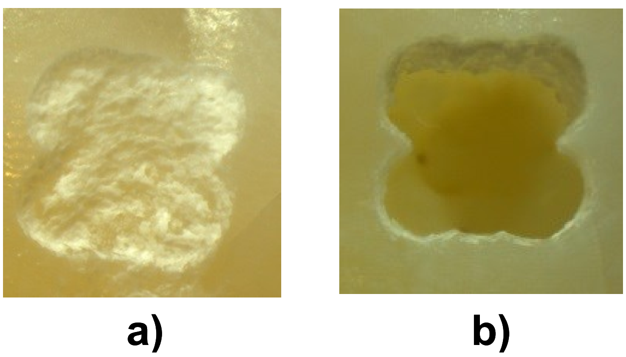

Fig. 5: Typical nominal 2 mm x 2 mm cavities in dental hard tissue as obtained at: a) low laser pulse energies (cavity within enamel only); and b) high laser pulse energies (cavity extending through the enamel into the dentin).

The ablated volume of the square-shaped cavities was obtained by multiplying the measured average cavity depth by the measured cavity's transverse cross section area. The total laser energy delivered to each cavity represented the energy of a single laser pulse, multiplied by the number of pulses within each scan (or laser beam passage over the treated surface) and the number of consecutive scans that were delivered to the cavity.

Figure 6 shows the obtained ablation efficacy (in mm^3/J) in enamel for the QSP and SSP modes.

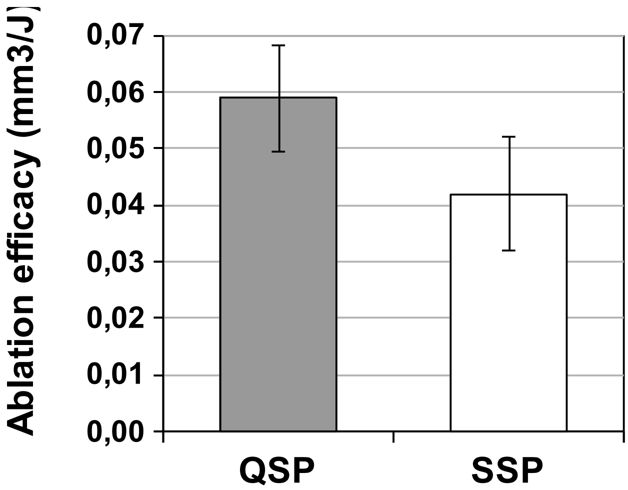

Fig. 6: Measured ablation efficacy for the QSP and SSP modes in enamel.

Measurements were made also with the QSP and MAX modes at higher laser pulse energies where cavities of approximately 1.5 mm were obtained with both modes. The obtained ablation efficacy for deep cavities is shown in Fig. 7.

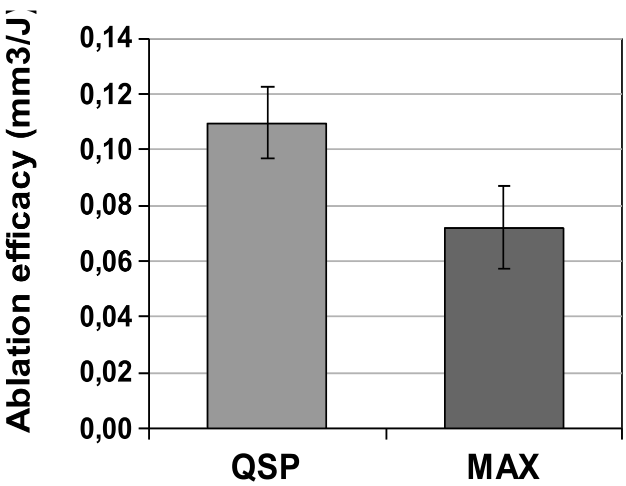

Fig. 7: Measured ablation efficacy for the QSP and MAX modes for deep cavities of approximately 1.5 mm. The observed ablation efficacy of the QSP mode is larger by a factor of 1.5 compared to the efficacy of the MAX mode.

IV. DISCUSSION

Our ablation measurements revealed that the ablation efficacy in human enamel of the QSP mode is by a factor of 1.4 times larger compared to the efficacy of the SSP mode.

Similarly, for deeper cavities, the ablation efficacy of the QSP mode was observed to be by a factor of 1.5 times larger compared to the efficacy of the MAX mode. It is to be noted that the ablation efficacy as obtained at larger laser energies represents a combination of the ablation efficacies in enamel and dentin. It is for this reason that the observed ablation efficacy was higher in comparison with the ablation efficacy in enamel, where due to the lower water content, the ablation was slower.

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 [14, 18-22]. 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 second pulse quantum does not encounter any cloud remains from the previous pulse quantum (Fig. 8).

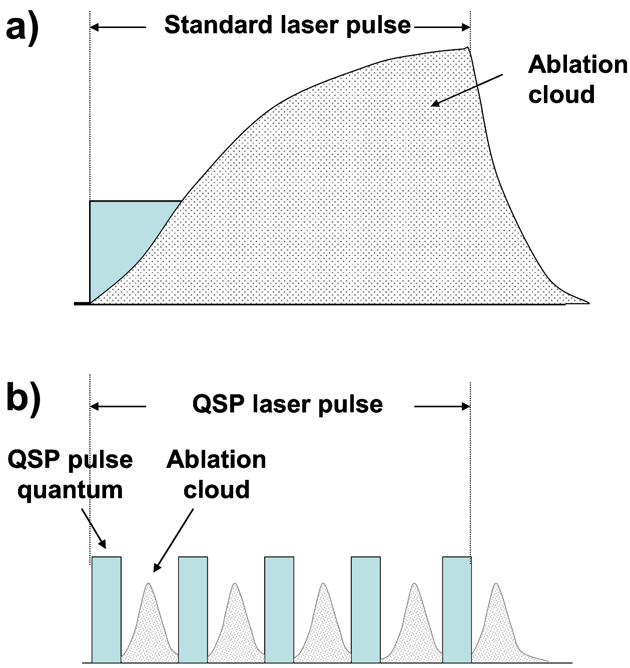

Fig. 8: a) Standard laser pulse; b) QSP pulse: a long laser pulse is quantized into short pulslets (pulse quanta) distributed within the overall QSP mode pulse "duration". The QSP pulse quanta temporal sequence is resonantly optimized to avoid being absorbed and scattered by the ablation clouds.

The clinical benefits of the new QSP mode are also easily recognizable. The margins of preparations for fillings or for surface modification are clearer and sharper [12, 14]. QSP-treated surfaces also appear to have the high quality required for high bond strength, in addition to being free of a smear layer [11].

It is important to note that even though the QSP mode has the highest ablation volume per laser pulse energy compared to all studied Er:YAG laser modes, this does not necessarily make it the fastest laser drilling mode. Namely, the ablation speed, V = ablated volume/time (in mm^3/sec), of the optical drilling depends not only on the laser mode's ablation efficacy but also on the maximum laser power that a laser device can deliver at this mode. Since the highest laser power output available with the LightWalker's MAX mode of 20 W is considerably higher in comparison to the 7.5 W power limit of the QSP mode, the fastest optical drilling can still be achieved with the MAX mode. Of course, due to the higher pulse ablation efficacy of the QSP mode, the laser power utilization U, defined as the ratio between the ablation speed (V) and laser power (P), $U = V/P$, is highest with the QSP mode.

V. CONCLUSIONS

A digitally controlled Er:YAG dental laser handpiece was utilized to measure the ablation efficacy of the Quantum Square Pulse (QSP) Er:YAG laser mode in comparison with other Er:YAG laser modes.

The ablation efficacy in human enamel of the QSP mode was observed to be considerably higher (by a factor of 1.4) in comparison to the "single" (non-quantized) Super Short Pulse (SSP) laser mode. This observation is attributed to 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.

Acknowledgment

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