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Influence of Water Absorption Shift on Ablation Speed of Er:YAG and Er,Cr:YSGG Dental Lasers

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ABSTRACT

When comparing the wavelengths of erbium-based dental lasers, the 2.94 μm wavelength of the Er:YAG laser is at an advantage as it matches the absorption peak of water, while the absorption coefficient for the Er,Cr:YSGG laser (2.78 μm) in water is significantly lower. However, since the spectroscopy literature indicates that the absorption peak of water decreases and shifts towards shorter wavelengths for increasing temperature, it has been theorized that the ablation efficiency of the Er,Cr:YSGG should actually be higher compared to that of the Er:YAG. This hypothesis is not confirmed by our comparison study of hard dental tissue ablation speeds of the two erbium laser wavelengths. In agreement with previously published studies, the Er:YAG laser was found to be more effective for cutting enamel than Er,Cr:YSGG.

Key words: Er:YAG; Er,Cr:YSGG, laser dentistry, ablation, water absorption, dynamic optical properties, hard dental tissue.

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I. INTRODUCTION

Pulsed mid-infrared erbium lasers have been recognized as premium lasers for the ablation of human tissues with minimal thermal side-effects [1-3]. This is due to the properties of the erbium laser wavelength, which approximately coincides with the strongest absorption peak of the water molecule, thus resulting in very high absorption in virtually all biological tissues. Based on an extensive body of evidence it is now generally accepted that this highly efficient ablation process is initiated by micro explosions of overheated tissue water, followed by energetic ejection of relatively large pieces of solid tissue components (hydroxyapatite, collagen) from the interaction site [1, 4-6].

During the last twenty years, two wavelengths have been developed for clinical use on hard dental tissues. These include the Er:YAG (2.94 μm) and the Er,Cr:YSGG (2.78 μm), which by many scientific accounts have very similar properties [1-2]. These two wavelengths make up the erbium family of dental lasers. When comparing the wavelengths of the erbium lasers, the Er:YAG laser's wavelength of 2.94 μm matches the absorption peak of water at 2.94 μm, while the absorption coefficient in water for the 2.78 μm wavelength is significantly lower (See Fig. 1) [2].

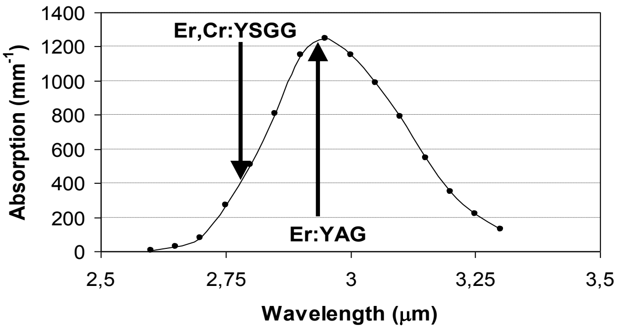

Fig. 1: The absorption curve of water in the middle infrared region. The plot shows the position of the two dental laser wavelengths used for hard-tissue ablation: Er,Cr:YSGG (2.79 micrometers), and Er:YAG (2.94 micrometers). The figure is reprinted with permission from reference [7].

The difference in the absorption coefficients leads to a difference in the penetration depths of the two erbium laser wavelengths in dental tissues. In comparison with the Er:YAG, the Er,Cr:YSGG laser wavelength penetrates approximately three times deeper into the tissue [7]. This difference is potentially important as it influences the volume of the directly illuminated tissue that needs to be rapidly heated to ablative temperatures by the laser light (direct heating) before the absorbed energy is spread out into the surrounding tissue by the process of thermal diffusion (indirect heating) [8]. Therefore, the higher the penetration depth, the larger the volume of directly heated tissue that needs to be rapidly heated up, and the longer the time required to reach the ablation temperature. For effective ablation with minimal thermal side-effects, it is important that the ablation process takes place over a short time so that very little heat is transferred to the surrounding tissue [5, 8]. Based on this consideration alone, the Er:YAG laser wavelength is at an advantage and should exhibit a larger ablation efficiency than Er,Cr:YSGG.

However, since the spectroscopy literature indicates that the absorption peak of water decreases and shifts towards shorter wavelengths for increasing temperature [9-11], it has been suggested that in the ablation process, the absorption of the Er:YAG laser should decrease and the absorption of Er,Cr:YSGG should increase, perhaps even above that of Er:YAG [12]. For this reason, it has been theorized that the ablation efficiency of the Er,Cr:YSGG should actually be higher compared to that of the Er:YAG [13]. On the other hand, some researchers have concluded that under high laser intensities the dynamic optical properties of water should lead to a higher ablation efficiency of the Er:YAG laser wavelength [14].

Experimentally, the theorized beneficial thermal effect of the water absorption shift on the ablation efficiency of the Er,Cr:YSGG wavelength has not been observed. Most of the published studies consistently show that the ablation efficiency of Er:YAG is higher compared to that of Er,Cr:YSGG [15-20].

A possible reason for why the thermal effect has not been detected in ablation experiments may be that the ablation process is very complex and depends on many parameters besides wavelength. For example, it is well known that ablation thresholds decrease towards shorter pulse durations [5, 21]. This is due to the fact that for shorter times the energy has little time to escape from the ablated volume, and so less heat is diffused into the surrounding tissue. Since most of comparison studies have been made with Er:YAG laser pulses being shorter than those of Er,Cr:YSGG [7], the effect of the absorption shift may have been over-shadowed by the stronger influence of the pulse duration.

In this paper, we report on an ablation comparison study between both erbium laser wavelengths. Two of the latest commercially available erbium laser systems were used since they both operate at approximately the same shortest laser pump pulse durations. The motivation for the study was the assumption that by reducing the influence of pulse duration, it might be possible to make a more definite conclusion on the possible influence of the water absorption shift on the ablation efficiency of erbium lasers.

II. MATERIALS AND METHODS

The Er,Cr:YSGG laser used was a WaterLase iPlus (the latest model manufactured by Biolase), and the Er:YAG system was a Fidelis Plus III (manufactured by Fotona; in terms of the output laser characteristics this system is identical to Fotona's latest model, LightWalker). Both laser systems were fitted with the appropriate contact fiber-tip handpieces (Fotona R14 with Varian 900 fiber tip, and Biolase Gold with MGG6 fiber tip). Water spray cooling with settings as recommended by the laser system manufacturers for restorative Class I preparation was used in the experiments.

Extracted premolar and molar teeth were selected and, immediately following extraction, stored in a physiological saline solution. The teeth were randomly chosen for the ablation experiments. Before each ablation experiment, the tooth was positioned with its surface perpendicular to the handpiece fiber-tip beam, and to be at a fixed distance of 0.4 mm with regard to the fiber tip, using a micro-positioning stage. The fixed distance of 0.4 mm for both laser wavelengths was chosen because previously published studies have indicated that the fiber-tip ablation efficiency depends slightly on the distance between the fiber tip and the tooth surface, and is largest at about 0.4 mm [22, 23].

Each ablation cavity was made in enamel with 10 consecutive laser pulses with a single-pulse energy of 300 mJ delivered to the same spot on the same tooth. The volume of the ablated cavity following ten pulses was then measured using the laser triangulation method [17-19]. Following the same procedure, cavities were made on three different areas on the same tooth, and repeated on three different teeth. Four cavities instead of three cavities were made on one of the three teeth. Each ablation volume data point thus represents an average obtained from 10 cavities, each made with 10 consecutive pulses (altogether 100 pulses).

The laser flash-lamp pump pulse duration mode was set to the shortest available on both of the laser systems: SSP (for Er:YAG), and H (for Er,Cr:YSGG). The output pulse energy as measured by an external energy meter was set to 300 mJ for both laser wavelengths.

III. RESULTS

The measured flash-lamp pump pulse and output laser pulse shapes for the two laser wavelengths are shown in Fig. 2.

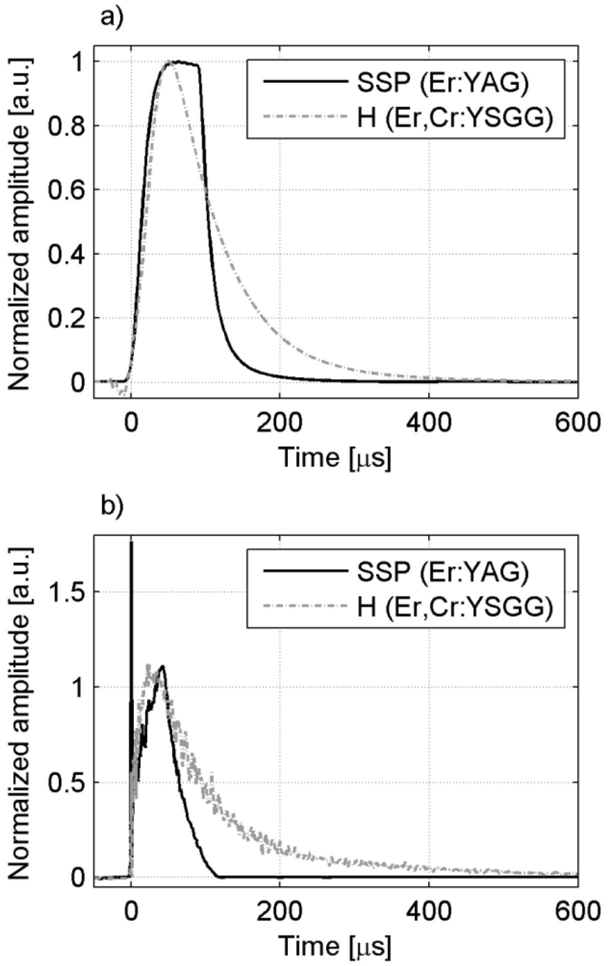

Fig. 2: Measured a) flash-lamp pump pulse and b) laser output pulse shapes for Er:YAG (Fidelis/LightWalker) and Er,Cr:YSGG (WaterLase iPlus) at the output energy of 100 mJ. The pulse shapes represent an average of 46 pulses.

The difference in the measured flash-lamp pulse shapes arises from the difference in the pump pulse technologies of the two laser systems used in the experiment. The Er,Cr:YSGG laser is based on PFN (Pulse Forming Network) pumping characterized by a bell-shaped pump-pulse profile, while the Er:YAG laser uses VSP (Variable Square Pulse) pumping with a square-shaped pump-pulse profile [24].

As seen from Fig. 2, the flash-lamp pulses and also the resulting output laser pulses are of a significantly different shape for the two erbium laser types. For this reason, a more meaningful comparison of the measured output laser pulse shapes can be made by integrating the delivered laser energy over the duration of the laser pulse. Figure 3 shows the temporal development of the cumulative output laser energy for both laser types. Since the output pulse shapes depend on the pumping level, the temporal developments are shown for different output pulse energies.

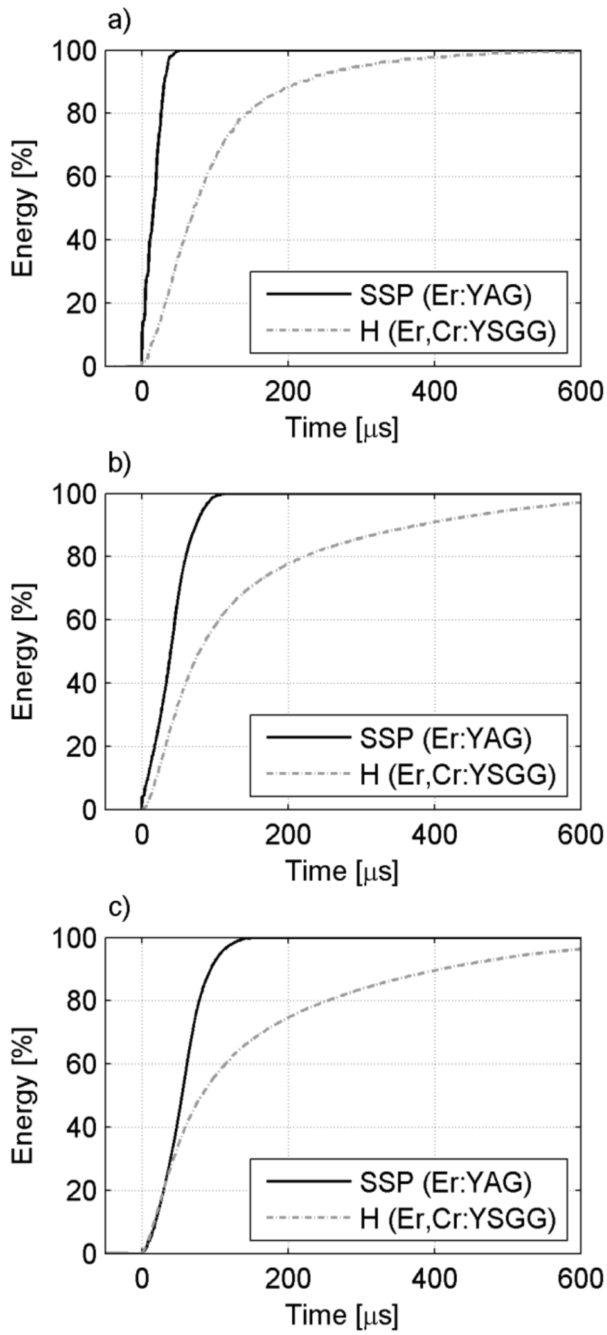

Fig. 3: Temporal development of the cumulative output laser energy for Er:YAG (SSP mode; Fidelis/LightWalker) and Er,Cr:YSGG (H mode; WaterLase iPlus). Temporal developments are shown for different total delivered (100%) output laser energies of a) 20 mJ; b) 100 mJ; and c) 300 mJ.

For clarification of Fig. 3, the pulse shape and duration of, for example, a 100 mJ laser pulse (Fig. 3b) is such that 75% of the energy is delivered to the tooth within approx. the first 50 μs of the Er:YAG pulse, and within approx. the first 150 μs of the Er,Cr:YSGG pulse. Similarly, 90% of the energy is delivered within approx. 80 μs of the Er:YAG laser pulse, and within approx. 350 μs of the Er,Cr:YSGG laser pulse.

As can be seen from Fig. 3, the Er:YAG and Er,Cr:YSGG laser pulse durations are at least, for larger output energies, comparable when considering the time during which 50% of the energy is delivered, but they differ considerably in time durations over which the remaining energy is being delivered.

Figure 4 shows the resulting measured ablation efficiency (i.e., ablated volume/laser pulse energy, in mm^3/J) obtained in human enamel for both laser wavelengths.

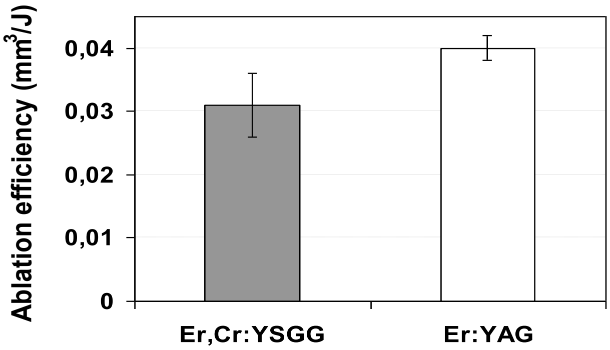

Fig. 4: Measured ablation efficiency in enamel for the Er:YAG (SSP mode; Fidelis/LightWalker) and Er,Cr:YSGG (H mode; WaterLase iPlus) laser wavelengths.

In Fig. 4, the column height represents the mean value of the sample (with $N = 10$ repeated measurements). The error bars represent the sample standard deviation.

IV. DISCUSSION

The ablation efficiency in human enamel of the Er:YAG wavelength was measured to be approximately 30% larger than that of the Er,Cr:YSGG. This observation suggests that if there is any effect of the absorption shift on the ablation efficiency it is not large enough to make the ablation efficiency of Er,Cr:YSGG lasers higher than that of Er:YAG lasers.

In a related, more extensive study (to be published), the ablation efficiency of the two erbium wavelengths was measured in enamel and cementum, and under different water cooling conditions. Observations under all tested conditions showed the ablation efficiency of the Er:YAG wavelength to be above that of the Er,Cr:YSGG laser.

There are several possible explanations as to why the water absorption shift was not found to have a significant influence on the ablation efficiency, including that the absorption shift during laser irradiation is not as pronounced as indicated by spectroscopy measurements. It is also possible, as suggested in [7] that since the shift would occur only at significantly elevated temperatures, i.e. towards the end of the heating cycle, the laser energy would have at that time already been wasted since the heat would have already had time to spread deeper into the tissue. Further, the suddenly reduced penetration depth may actually result in an increase and not a decrease of the ablation efficiency of the Er:YAG wavelength [7], similar to what was calculated and measured in [13].

It is also possible that in spite of our effort to match the pulse durations of both wavelengths, the remaining difference in the pulse durations may have still over-shadowed any effects of the absorption shift. As can be seen from Fig. 3, the delivery of the Er,Cr:YSGG laser energy was still significantly slower than that of the Er:YAG laser. At 300 mJ of laser output, and after the Er:YAG laser pulse has already ended, there still remains approximately 30% of undelivered energy within the Er,Cr:YSGG laser pulse. By defining the pulse duration as a duration during which 90% of energy has been delivered, we obtain an approximate pulse duration of 100 μs for the Er:YAG pulse, and 400 μs for the Er,Cr:YSGG pulse.

It is worth noting that ablation efficiency is most important when considering how much of the residual heat remains deposited in the tooth following a pulse [7]. A higher ablation efficiency results in lower heat deposition and thus in smaller undesirable thermal side effects in the tooth.

When considering the ablation speed (i.e., ablated volume in time, calculated from ablation speed = ablation efficiency x laser power), a lack of ablation efficiency (i.e., ablated volume per pulse energy in mm^3/J) can be to a certain degree compensated by delivering higher laser power to the tooth. Figure 5 shows a comparison of ablation speeds for some of the modes available from the two laser systems used in the experiment.

As can be seen from Fig. 5, the maximal ablation speed depends not only on the ablation efficiency (which determines the slope of the lines in Fig. 5) but also on the maximal available laser power (expressed in Fig. 5 by the length of the lines). Here, the Er:YAG's MAX mode enables considerably higher ablation speeds. Note that in Fig. 5 the maximal available laser powers were assumed to correspond to the maximal nominal laser powers as can be set by the user on a particular laser system's console.

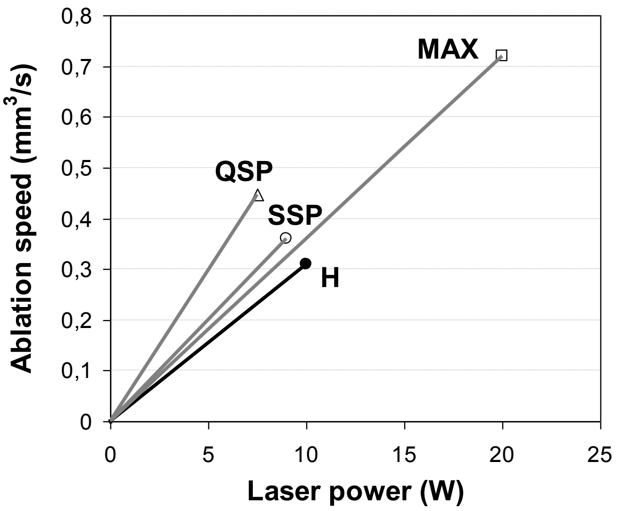

Fig. 5: Ablation speed in enamel for the QSP, SSP and MAX modes of the Er:YAG laser (Fidelis/LightWalker), and for the H mode of the Er,Cr:YSGG laser (WaterLase iPlus). The lines extend to the maximum available laser power for a particular laser mode. The data for the QSP and MAX modes is taken from refs. [25] and [17], respectively.

Note also a considerably higher ablation efficiency of the Er:YAG's QSP mode in comparison to the Er,Cr:YSGG H mode, and also to the Er:YAG SSP mode. The improved ablation efficiency of the QSP mode is due to the specific characteristic of the QSP mode that significantly reduces the undesirable effects of laser beam scattering and absorption in the debris cloud during hard tissue ablation [25-29].

V. CONCLUSIONS

Our measurements do not confirm the hypothesis that Er,Cr:YSGG lasers cut faster than Er:YAG in hard dental tissues because of the water absorption shift during laser ablation. On the contrary, in agreement with previously published studies [15-20], the Er:YAG laser was found to be more effective for cutting enamel than Er,Cr:YSGG. Therefore, if there is any effect of the absorption shift on the ablation efficiency at all, it is not large enough to improve significantly the ablation efficiency of the Er,Cr:YSSG dental lasers.

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