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REVIEW
Comparison of Er:YAG and Er,Cr:YSGG lasers used in dentistry

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ABSTRACT

Erbium-doped solid-state laser systems have become an established tool in dentistry. The two most commonly used Erbium lasers in dentistry are Er:YAG and Er,Cr:YSGG, with a subtle but important difference in their respective laser wavelengths. There is also an important difference in the type of technology they utilize to energize the flashlamps. The conventional PFN (Pulse Forming Network) pulses are bell shaped and are, in most cases, of fixed duration, while VSP (Variable Square Pulse) pulses are nearly square-shaped and of variable pulse duration.

When used on hard dental tissues, the Erbium laser energy heats up the water within the hard tissue and causes that water to be turned into steam. This causes a mini-explosion to occur and the hard tissue is "ablated" (removed). Ideally, the remaining dental tissue beneath should not be affected by the Erbium laser ablation, thereby allowing precise control and minimal damage to the surrounding tissue. On the other hand, there are times, particularly when treating soft tissue, when the coagulation of the remaining tissue is exactly what is needed. In this paper we analyze and compare Er:YAG and Er,Cr:YSGG dental lasers and their pulse forming technologies from the viewpoint of which laser allows the highest possible control of tissue ablation and of the effects on the underlying tissue that remains.

Key words: Er:YAG, Er,Cr:YSGG, dental laser, hard tissue, ablation efficacy, heat deposition.

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I. INTRODUCTION

Currently two erbium laser wavelengths are commonly used in dentistry; the Er:YAG (2940 nm) laser and the Er,Cr:YSGG (2790 nm) laser [1]. They exhibit the highest absorption of all infrared lasers in water and hydroxyapatite, and are thus ideally suited for 'optical drilling' in enamel, dentin and composite fillings (Fig.1) [2,3].

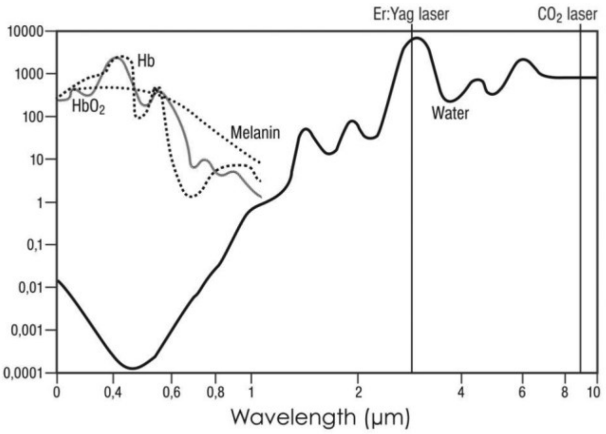

Fig. 1: Solid crystal Erbium lasers have the highest absorption in water and consequently in hard and soft dental tissues

The Er:YAG and Er,Cr:YSGG dental lasers are very similar in their basic design and characteristics. Both laser types use solid state crystals, YAG or YSGG, doped with erbium ions (Er3+) as their active materials. Also, both lasers are pumped by a pulsed broad band flashlamp (See Fig. 1). A typical simplified laser configuration is shown in Fig. 2.

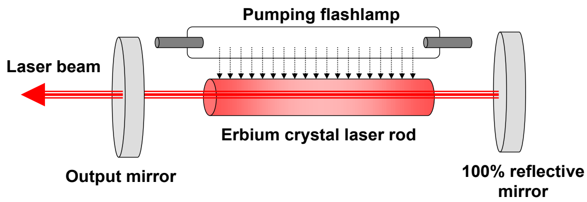

Fig. 2: A typical simplified Erbium laser configuration.

While both laser types, Er:YAG and Er,Cr:YSGG have been proven to be effective and safe modern tools for the removal of tooth decay and cavity preparation (in addition to many other hard tissue and soft tissue surgical procedures) there are subtle differences between the two type of lasers, such as in the laser wavelength and in the range of available pulse durations. In the dental laser market there are many misconceptions and misunderstandings of the influence of these subtle differences on the use of Erbium lasers in dentistry. The optimal laser should provide high ablation speed and minimize residual heat deposition in the tooth. In this paper, we address some of the misconceptions and analyze how these differences influence the optical ablation speeds and the amount of the heat deposition within the tooth during and after the treatment.

II. MATERIALS AND METHOD

The analysis and comparison of the Er:YAG and Er,Cr:YSGG lasers used in dentistry was made based on published research results from the past two decades. Because of the important role that the pulse generation method may play with respect to how Erbium lasers are used in clinical settings, we compared Erbium lasers not only from the viewpoint of the active material but also from the viewpoint of the type of employed pulse generating technology.

All commercially available Erbium dental lasers are optically pumped with pulsed flashlamps [32]. There is, however, an important difference among Erbium lasers regarding the type of technology that is utilized to energize the flashlamps. The major difference between the conventional, so called PFN (Pulse Forming Network) pumping [32], and VSP (Variable Square Pulse) pumping is in the shape of the flashlamp's current pulses [2]. PFN pulses are bell shaped and are, in most cases, of a fixed duration, while VSP pulses are almost square-shaped, and of variable pulse duration. A significant difference between the two types of pulses is that for VSP pulses, the average power and the peak power is nearly the same, which cannot be said for PFN-generated pulses. This means that the effect of VSP generated pulses on the dental tissue may be significantly different from that of the PFN generated pulses.

The only commercially available Er,Cr:YSGG dental laser (manufactured by Biolase) and most of the Er:YAG dental lasers utilize PFN generated pulses. There is at least one Er:YAG dental laser, however, (see www.fotona.com) that utilizes VSP technology.

a) Conventional PFN Pumping

Most Erbium lasers use a standard PFN (Pulse Forming Network) technology to generate high energy light pulses. This conventional method of energizing a flashlamp consists of discharging a pulse forming network (PFN) through the flashlamp [32]. A pulse forming network is comprised of capacitors (C) to store electrical energy and inductance (L) to limit the discharge current into the flashlamp load (R).

The flashlamp light emission is proportional to the power of the discharge current. A typical PFN pulse shape is shown in Fig. 3.

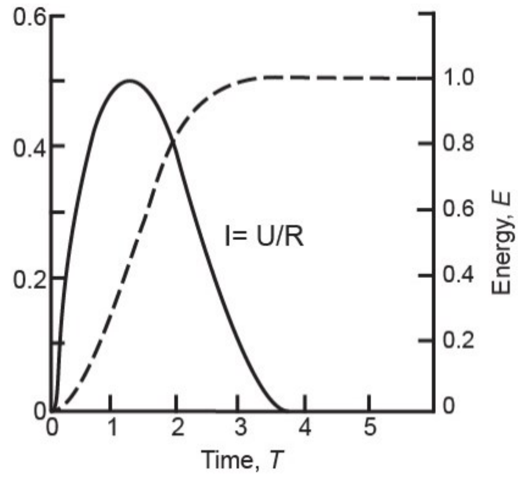

Fig. 3: Normalized discharge current and energy of a critically damped non-linear flashlamp discharge circuit [32]. The PFN pulse is bell shaped and asymmetrical, with the full width half-max range of the pulse always closer to the beginning than to the end of the pulse.

PFN pulses have a typical temporal shape with a slow rise time and a long declining tail; the pulse power is not constant during the pulse and the exact pulse duration is not defined.

The sum of the rise and fall times of a PFN pulse defines the total duration of the PFN power pulse, which can be changed only by changing the component values in the PFN. A good measure of the PFN pulse duration is the pulse length T_p measured at the 10% points of the maximum value, and is approximately equal to $T_p = 3(LC)^{1/2}$ [32].

The rise time T_r required for the power to rise from zero to its maximum value is also fully defined by the PFN components, and is approximately equal to $T_r = 0.4\ T_p$ [32]. The PFN pulse is therefore not symmetrical, with the full width half-max range of the pulse always closer to the beginning than to the end of the pulse.

b) VSP Pumping

A more advanced and practical means for pulse pumping of Erbium lasers is Variable Square Pulse (VSP) pumping [34]. The basic approach is that of using a switching transistor to control the current in a flashlamp from a constant voltage power supply [35]. This solution provides nearly square power pulses, the duration of which can be conveniently controlled over a wide range of pulse durations. With this method, the pulse duration T_p is for all practical reasons not directly related to the rise and fall times, and is defined by the externally controlled on and off time of the switching transistor. The next important development, and its further refinements, occurred when the use of an Insulated Gate Bipolar Transistor (IGBT) was proposed to control the current pulse from a large storage capacitor through a flashlamp (see Fig. 3a) [36,37]. This enabled small and efficient laser systems with variable square pulse (VSP) pumping of flashlamps. The typical temporal development of the flashlamp voltage and current during a VSP pulse is shown in Fig. 4.

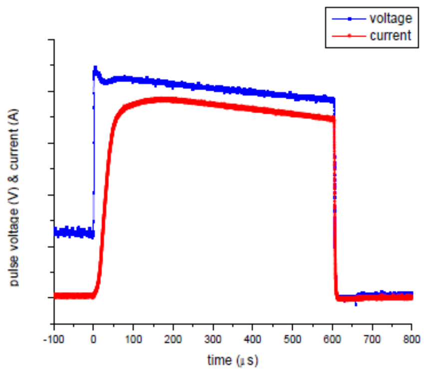

Fig. 4: Temporal development of the flashlamp voltage and current during a VSP flashlamp pulse of duration 600 µsec. Note that the current pulse duration is not defined by the rise and fall times but with the on and off time of the switching transistor. The VSP pulse is almost "square shaped", with the full width half max range of the pulse slightly closer to the end of the pulse. The Figure is based on data from references 44.

One of the first reports on the use of square-shaped pumping for Er:YAG lasers is in ref. 38. In this work, the dependence of the input pump energy Eth on the square-shaped pump pulse power was studied experimentally and analytically. In another early study, the influence of square-pulse pumping on Er(50%):YAG laser efficiency was analyzed by numerically solving laser rate equations [39]. The numerical simulations showed that for square-shaped, VSP pumping, the pump energy threshold Eth increased with pump pulse length T_p.

III. RESULTS

a) Wavelength Considerations

Wavelength is a key factor in the suitability of any laser for hard-tissue procedures in dentistry. The Er:YAG and Er,Cr:YSGG laser wavelengths both operate in the region of the major absorption peak for water, and are thus the most suited to hard-tissue ablation treatments. For example, CO_2 and Ho:YAG lasers show significantly lower absorption in water and are thus less suited for treatments in this field (See Fig 1).

Closer study of the absorption peak associated with Erbium lasers shows a 300% difference between the absorption coefficients of Er,Cr:YSGG (400 mm^{-1}) and Er:YAG (1200 mm^{-1}) (see Fig. 5).

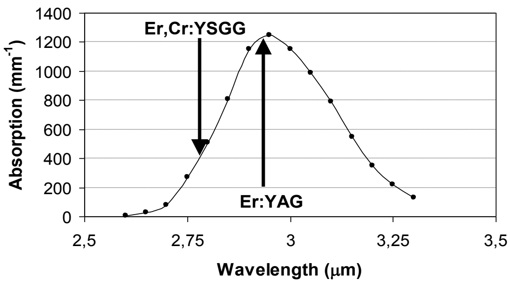

Fig. 5: The absorption curve of water in the middle infrared region. The plot shows the position of the two dental laser wavelengths used for hard-tissue ablation: Er,Cr:YSGG (2.79 micrometers), and Er:YAG (2.94 micrometers). The Figure is based on data from references 4 and 5.

Because of the different water content levels in human dentine and enamel, the absorption coefficients for the Er:YAG lasers are approximately 150 mm^{-1} in enamel, and 200 mm^{-1} in dentine. The corresponding absorption coefficients for the Er,Cr:YSGG are approximately three times lower.

The Er:YAG laser wavelength thus penetrates approximately 7 micrometers in enamel, and 5 micrometers in dentine. The Er,Cr:YSGG laser wavelength penetrates deeper, 21 micrometers in enamel, and 15 micrometers in dentine (see Fig. 6).

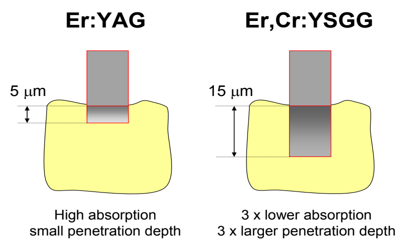

Fig. 6: Because of the higher absorption, the Er:YAG laser has a smaller penetration depth, and therefore requires less energy and less time to ablate the tissue. The shown penetration depths are for dentine.

The Erbium lasers' high ablation efficiency results from micro-explosions of overheated tissue water in which their laser energy is predominantly absorbed [15,16]. Although the OH absorption band of the mineral content (hydroxyapatite) in enamel more strongly absorbs the Er,Cr:YSGG energy, it is the stronger water absorption of the Er:YAG laser energy that plays the dominant role in dental laser ablation [27,42].

The difference in penetration depth due to the difference in water absorption 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; see Fig. 7).

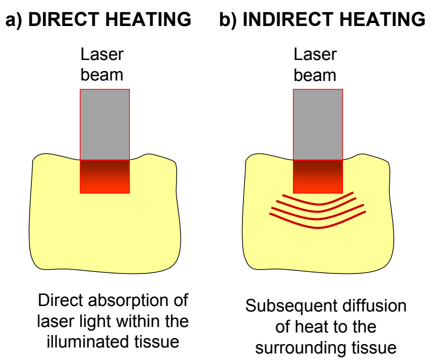

Fig.7: Two steps in tissue heating upon laser irradiation. Indirect heating must be avoided when efficient cold ablation of hard tissues is needed, as the indirect heating leads to undesirable thermal effects.

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.

Figure 8 shows a schematic presentation of the ablation dynamics for the two Erbium laser wavelengths.

Upon irradiation of the tissue (at t=0), the Er,Cr:YSGG light penetrates 3 times deeper into the tissue than the Er:YAG laser. This means that the Er,Cr:YSGG shall take three times longer time in order to deliver three times more energy required to heat up the three-times-thicker illuminated layer up to the ablation temperature. During this time, the Er:YAG heated tissue will have already reached ablation temperatures three times (at t = 1, t = 3 and t = 5), progressing each time deeper into the tissue. Each time the Er:YAG laser evaporates the tissue, the heated tissue particles are expelled from the treatment site, leaving the thermally-affected tissue layer confined only to the directly heated volume within the

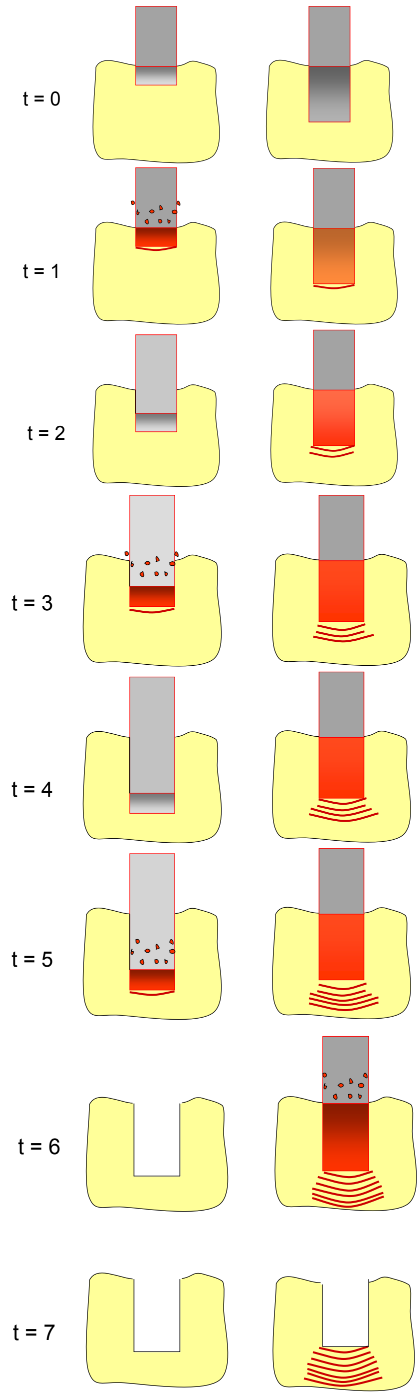

Fig. 8: A schematic presentation of the ablation dynamics for the two Erbium laser wavelengths. The irradiation starts at t =0. Since the Er,Cr:YSGG laser wavelength penetrates 3 times deeper into the tissue it requires 3 times longer time to heat up the irradiated volume to the evaporation temperature. During this time, the Er:YAG heated tissue will have already reached ablation temperatures three times (at t = 1, t = 3 and t = 5), progressing each time deeper into the tissue. For Er,Cr:YSGG, the ablation starts at a later time, at t = 6. Note that since some of the energy has been lost due to heat diffusion, the final Er,Cr:YSGG ablated depth is slightly smaller compared to that of the Er:YAG. Also, the remaining tissue below is more strongly heated.

shallow optical penetration depth. On the other hand, with the Er,Cr:YSGG laser, the heat has three times more time to spread deeper into the tissue, and the layer of tissue that has indirectly been heated becomes thicker. Thermal effects to the tooth become more pronounced and because a portion of the laser energy gets wasted as a result of the undesirable heating of the surrounding tissue, the ablation efficiency is reduced.

In agreement with the above, published studies of the efficiency of ablation (measured in terms of decreases in volume and mass of tooth structure for identical energy parameters) show the Er:YAG laser to be more efficient compared to the Er,Cr:YSGG laser [6,7,8,9,10,27]. In addition, under the same conditions, the irradiation with Er,Cr:YSGG results more readily in a brownish coloration (charring) (Fig. 9) [19], which can be attributed to the higher heat deposition within the tooth (See Fig. 8, t=7). The higher heat deposition can be partially attributed also to the higher absorption of the Er,Cr:YSGG wavelength in the mineral hydroxyapatite. It has been observed that bellow the ablation threshold, the Er:YSGG-irradiated enamel surface exhibits 30% higher surface temperatures, in spite of the ablation threshold of Er:YSGG being markedly higher in comparison to Er:YAG [43].

a) Er:YAG **b) Er:YSGG**

Fig. 9: Pictures of cavities in dentin, made with Er:YAG and Er,Cr:YSGG lasers following three consecutive laser pulses of the same laser pulse fluence of 80 J/cm2 [19]. In order to eliminate any influence of the difference in pulse duration, the Er:YAG pulse duration (Fotona dental laser, VSP mode) was adjusted to match that of the Er,Cr:YSGG (Waterlase PFN S mode). In this experiment, no water spray was used.

Detailed histological analyses of ablated tissue after irradiation with an Er:YAG laser have described well-defined cuts with very small zones of thermal necrosis [28]. In comparison, the thermal necrosis zones caused by Er:YSGG laser systems were approximately twice as large [28]. Therefore, among the major clinical advantages of using the Er:YAG laser is its ability to ablate both hard and soft tissues with minimal thermal damage [29].

It should be noted that if water spray had been used in the experiment, the charring shown in Fig. 9 for the Er,Cr:YSGG would be considerably reduced. Nevertheless, the experiment clearly demonstrates that under the same conditions, there is a much higher heat deposition with the Er,Cr:YSGG dental laser.

b) Possible Absorption Shift during Water Excitation?

Motivated by spectroscopy literature indicating that the absorption peak of water drops and shifts towards shorter wavelengths for increasing temperature [11-13], some researchers have 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 the Er:YAG [14]. For this reason, it has been proposed that the ablation efficiency of the Er,Cr:YSGG should actually be higher compared to that of the Er:YAG. However, numerous measurements and studies have not confirmed this. All studies have consistently shown that the ablation efficiency of Er:YAG is higher compared to that of Er,Cr:YSGG [6,7,8,9,10,27]. As an example, Fig. 10 shows one of the most recently published results [8].

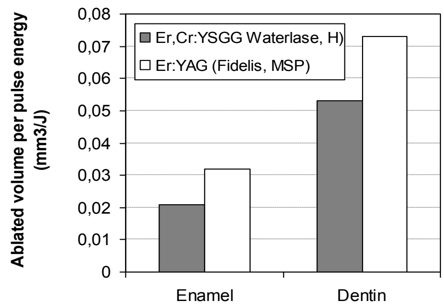

Fig. 10: Plot of measured results of ablated volume per pulse energy of dentine and enamel for both laser sources at 260 mJ pulse energy. The figure is based on data from ref. 8.

The measured ablation results suggest that either there is no spectroscopic shift under the conditions of hard dental-tissue ablation, or that there is no difference that can be detected in a real clinical application or setting. One reason why the theoretically postulated effects of the spectroscopic shift have not been confirmed by the actual ablation measurements may be that the spectroscopic shift has been detected under completely different laser intensity conditions compared to those that are used in laser dentistry. Namely, the shift was observed under laboratory conditions using extremely short nanosecond pulses, with laser intensities on the order of 100-1000 times higher compared to those used in dentistry [13]. Even more importantly, the assumed absorption shift occurs only at very high temperatures (374°C) [11]. This means that the shift, if it occurs, would occur towards the end of the heating cycle (in terms of Fig. 6, at t = 6) when the tissue temperature has been raised up to evaporation temperatures. However, at such a late stage in the heating cycle, the energy would have been wasted and the heat would have already spread deep into the tissue. In addition, the suddenly reduced penetration depth leads to the reduced thickness of ablated tissue, leaving an even thicker layer of heated tissue behind.

c) Pulse Duration Considerations

In laser ablation we generally talk about four ablation regimes [16]. 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. 11). 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.

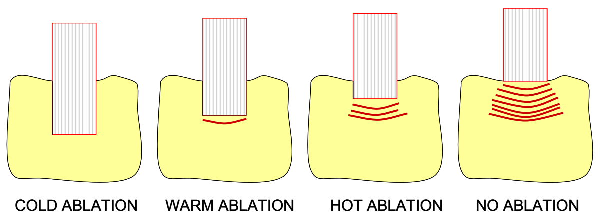

Fig. 11: The effect of the laser beam on tissue in the four ablation regimes.

One of the key factors that determines the regime and efficiency of laser ablation is thus also 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. As an example, Fig. 12 shows the relationship between laser pulse duration and the ablation efficiency (as well as the thermal layer for which the temperature of enamel is affected by indirect heating).

In this respect, the VSP Er:YAG laser is at an advantage, since the shape and the duration of the Er:YAG laser output pulse follow very closely the shape and the duration of the flashlamp pumping pulse (see Fig. 11a). On the other hand, because of the different lasing properties, the output laser pulse of the Er,Cr:YSGG laser exhibits a long decay tail, resulting in laser pulses being much longer than the flashlamp pumping pulse (Fig. 13b). This means that there is a lower limit to the Er,Cr:YSGG pulse duration. Regardless of how short the flashlamp pumping pulses may be, the Er,Cr:YSGG laser pulses will always be at least several hundred microseconds long.

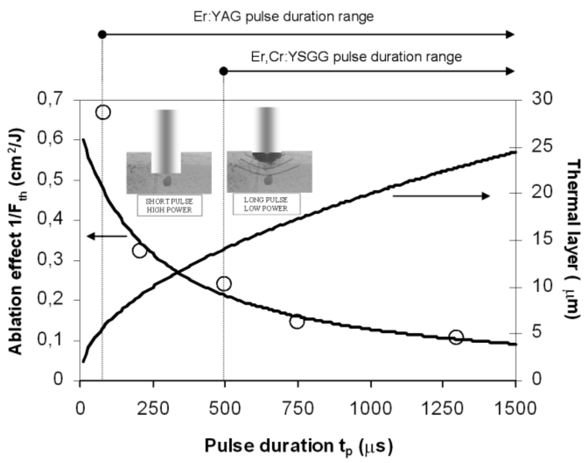

Fig. 12: a) Dependence of thermal effects on laser pulse duration as represented by the thickness of the thermally affected layer in enamel. b) Dependence of ablation effect, represented by the inverse of the ablation threshold fluence in enamel on laser pulse duration. Circles represent experimental data from Fig. 13, the full line represents 1/x fit. Due to the long population inversion time of Er,Cr:YSGG, this laser cannot be operated bellow approximately 500 μs.

It should be noted here that the above results and conclusions apply to the conditions when the Er,Cr:YSGG laser operates significantly above the lasing threshold. At very low output laser pulse energies, i.e. when the laser operates close to the lasing threshold, both types of Erbium lasers emit laser spikes much shorter than the flashlamp pulse duration. However, when short pulse durations are mandatory, this limits the usability of Er,Cr:YSGG lasers only to applications which require very low laser powers.

Measurements of the ablation threshold have demonstrated the dependence of ablation efficiency on laser pulse duration (See Fig. 14) [8].

As expected, ablation thresholds increase towards longer pulse durations. Similarly, the heat deposition has been observed to decrease at high energies and short pulse durations (i.e. at high laser pulse powers), where the ablation speed becomes comparable to the rate at which heat diffuses into the tissue [18,20]. This effect has been experimentally measured by Fried et al, who observed a gradual reduction in the residual heat towards higher laser fluences [18,20]. In a comparative study of residual heat deposition of Er:YAG and Er,Cr:YSGG lasers during ablation of hard dental tissues, the amount of the unwanted residual heat that remained deposited in the tooth was for the H mode Er,Cr:YSGG measured to be by a factor of more than 2, and for the S mode Er,Cr:YSGG by a factor of more than 3 times larger than the deposited heat measured with the MSP mode Er:YAG laser (See Fig. 15) [18].

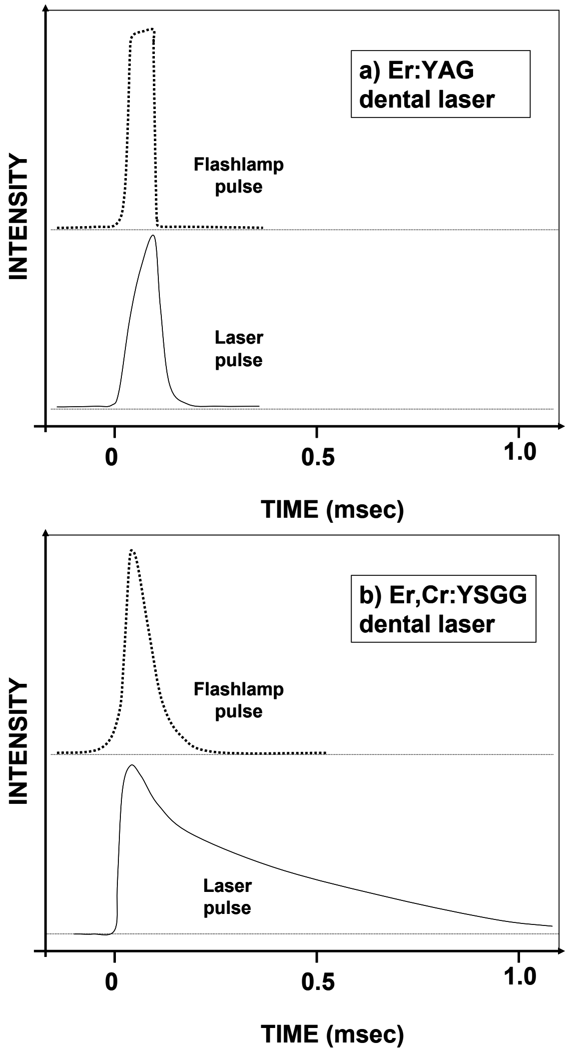

Fig. 13: Schematic representation of the temporal evolutions of the flashlamp pump optical emission (dotted line), and the output laser radiation (full line) for the Er:YAG laser (a) and Er,Cr:YSGG laser (b). The figure is based on data from ref. 17 for Er:YAG (Fotona dental laser), and from ref. 18 for Er,Cr:YSGG (Biolase Waterlase). Note the difference between the VSP nearly square-shaped pulse generation in Er:YAG and the PFN bell-shaped pulse generation in Er,Cr:YSGG.

Similarly, Fig. 16 represents the temperature increase of the tooth above the initial temperature, at the time of 2.5 msec following a laser pulse [18]. As expected, the measured temperatures are higher for the Er,Cr:YSGG laser.

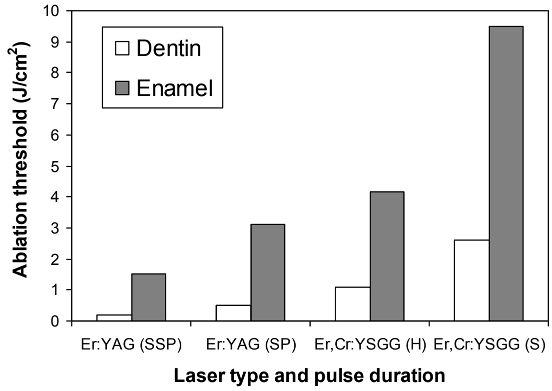

Fig. 14: Dependence of the ablation threshold in enamel and dentin on the pulse duration and laser type. The ablation threshold for the shortest SSP (50 μs) Er:YAG (Fotona dental laser) laser pulse is by a factor of 3 lower compared to that of the H (500-700 μs) Er,Cr:YSGG laser pulse, and by a factor of 6 lower compared to the S (1600-2000 μs) Er,Cr:YSGG laser pulse (Biolase Waterlase). Figure is based on data from ref. 8.

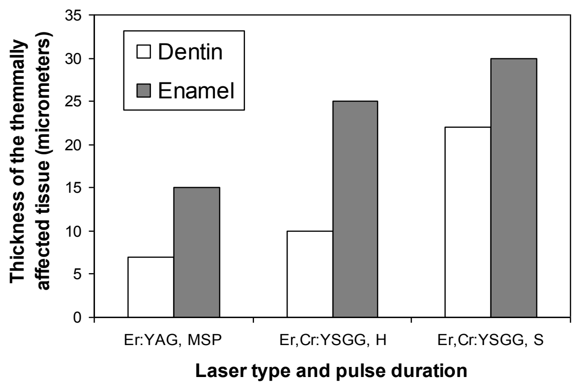

Fig. 15: Measured depths of thermally affected layers in dentin and enamel for Er:YAG (Fotona dental laser, MSP) and Er,Cr:YSGG (Biolase Waterlase, H and S). Figure is based on data from ref. 18.

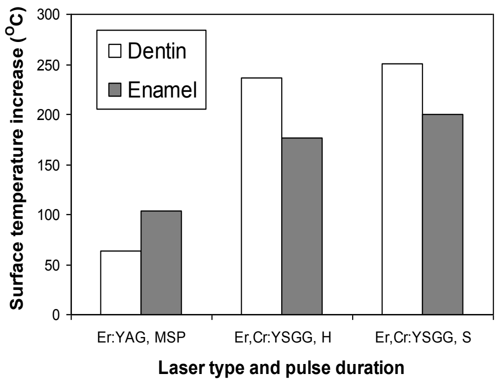

Fig. 16: Enamel and dentine surface temperatures 2.5 ms following a laser pulse for Er:YAG (Fotona dental laser) and Er,Cr:YSGG (Biolase Waterlase). Figure is based on data from ref. 18.

d) Pulse Generation Technology Considerations

In order to explain the observed differences between the two laser types, pulse shape should also be considered, as this has a strong influence on the 'true' pulsewidth and instantaneous power.

The commercially available Er,Cr:YSGG lasers utilize PFN pulse generating technology and are based on a concept which requires optical pulses to have a high initial peak, with the full-width half-max range of the pulse closer to the beginning than to the end of the pulse [40].

Er:YAG lasers that utilize VSP technology are based on a completely different concept which requires the laser output to be as constant (flat and symmetrical) as technically possible throughout the duration of the pulse, and not to have an initial peak within the pulse as with the PFN approach. The VSP concept is based on the understanding that the ablation regime defining whether the ablation process is cold or hot depends on the instantaneous laser power. If the instantaneous power varies considerably throughout the pulse then the ablation process is not under control. When a PFN pulsing is used, there is an initial peak (where at high laser energies cold ablation is reached), followed by a very long tail where cold ablation switches to warm and then hot ablation and finally to very hot zero ablation. An additional advantage of VSP technology is that it allows the user to easily adjust the pulsewidth and laser power. The versatility and the instantaneous power control of the VSP technology can be seen in Fig. 17 which shows different pulse durations and corresponding pulse shapes.

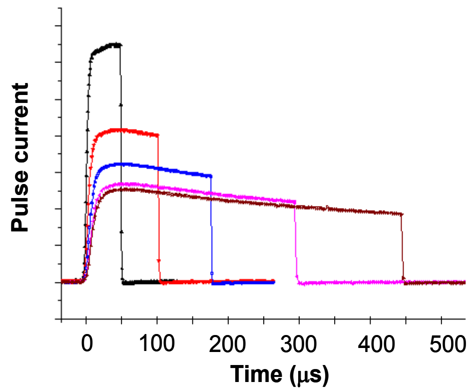

Fig. 17: VSP pulse shapes for different pulse durations (Fotona dental laser). Note that the rise and fall times are approximately the same for all pulse durations. Also, the pulse durations are in no relation with the rise and fall times. Data is from ref. 44.

As a comparison, Fig. 18 shows temporal shapes of the two types of pumping for the same optical output energy.

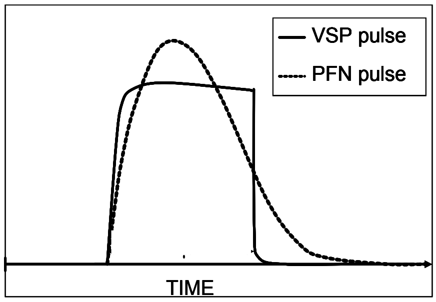

Fig. 18: Temporal shape of the VSP (full line) and PFN (dotted line) current pump pulse. Data is from ref. 44.

It is important to note that as shown in Fig. 13, the Er,Cr:YSGG lasers exhibit even longer output laser pulse tails that extends much further than the PFN pulses. The measured results for the Er,Cr:YSGG laser system (Waterlase) at nominal flashlamp pulse durations of 150 µs (H mode), and 700 µs (S mode) are shown in Fig. 19 [18].

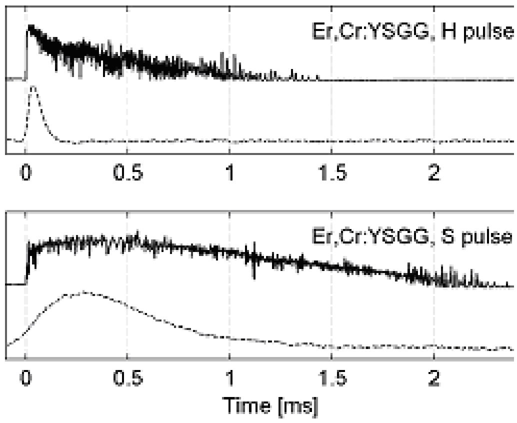

Fig. 19: Measured temporal evolutions of the output laser radiation (full line), and flashlamp pump optical emission (dotted line) for an Er,Cr:YSGG laser system (Waterlase MD, H and S pulse mode). Data is from ref. 18.

The generated Er,Cr:YSGG laser pulses are considerably longer than the flashlamp pulses, and are in the shortest H pulse mode on the order of 500 – 700µs, and for the longer S mode on the order of 1200 – 1400 µs. While the VSP Er:YAG laser offers variable pulsewidths down to 50 µs, the Er,Cr:YSGG laser is limited to a minimum pulsewidth of approximately 500 µs due to its long lasing tail.

Compared to PFN pulses, the effect of VSP pulses on the dental tissues is far more predictable, which ultimately leads to superior treatment outcomes, with less discomfort and fewer side effects.

e) Ablation Cloud Considerations

When an ablative laser light pulse is directed onto tissue, an ablation of the tissue starts that leads to the emission of ablated particles above the tissue surface, forming a debris cloud [19]. The debris cloud does not develop instantaneously. Figure 20 shows the captured images of the debris cloud development at different times from the onset of an Erbium laser pulse. As can be seen from Fig. 20, the cloud formation time is in the 50-150 µsec range.

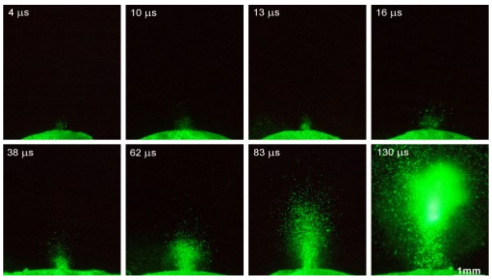

Fig. 20: Cloud images at different delays from the onset of an Erbium laser pulse. Cloud formation time is approx. 50-150 µsec. Figure is reprinted with permission from ref. 41.

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. 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 (See Fig. 21).

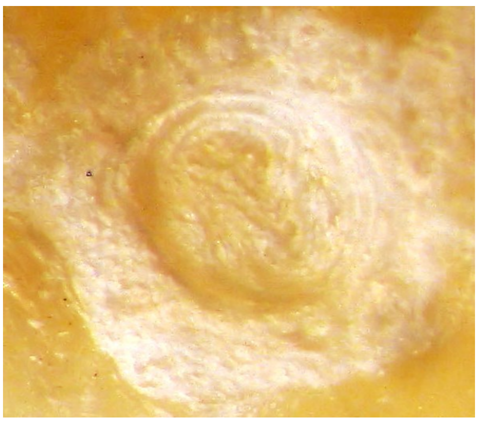

Fig. 21: The shape of ablated crater in dentin for long Erbium laser pulses. During long pulse durations the ablation cloud has sufficient time to develop and scatter the incoming laser beam. Figure is reprinted with permission from ref. 41.

One of the advantages of VSP technology is that it allows the system to form a controlled train of micro pulses within a larger overall pulse, thereby optimizing the efficacy and safety of treatments by making each pulse with a particular pulsewidth completely predictable from a clinical outcome point of view. Recently, the range of treatment parameters of VSP Er:YAG lasers has been extended with the latest QSP (Quantum Square Pulse) mode [41]. 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. 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 Erbium 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 (Fig. 22).

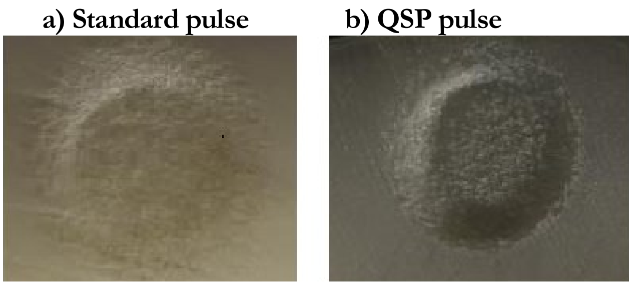

Fig. 22: Comparison of the quality of laser-ablated cavities in dentin with a high energy Erbium pulse and with a QSP Er:YAG pulse of the same pulse energy. Note the difference in the ablated depth and the sharpness of the cavity edges. Figure reprinted with permission from ref. 41.

f) Power and Drilling Speed Considerations

The first generation of erbium laser systems failed to gain wide acceptance as their ablation or "drilling" speeds were slower compared to, for example, the mechanical bur. This has changed with the latest VSP Er:YAG lasers, which provide ablation speeds comparable to those obtained by classical dental tools [2,3].

The parameters that determine the optical drilling speed are the single pulse energy and the repetition rate at which the single pulse energy can be repeatedly delivered to the treatment spot. The maximum optical drilling speed is thus determined by the available Erbium laser power P (W) = Energy (in J) x Repetition Rate (in Hz). Considering commercially available Erbium dental lasers, the Er:YAG laser parameters exceed those of the Er,Cr:YSGG. For example, the latest VSP technology Fotona Fidelis and LightWalker dental lasers are capable of operating at laser powers up to

20 W, while the commercially available Er,Cr:YSGG dental lasers (Biolase Waterlase and iPlus) are limited to powers up to 8-10 W. Lower powers of commercially available Er,Cr:YSGG lasers are possibly due to the inferior thermal characteristics of YSGG crystals [24] and lower transmission capacity fiber delivery systems currently employed by these lasers.

Figure 23 shows a comparison of the measured ablation speeds of VSP Er:YAG and Er,Cr:YSGG lasers [8].

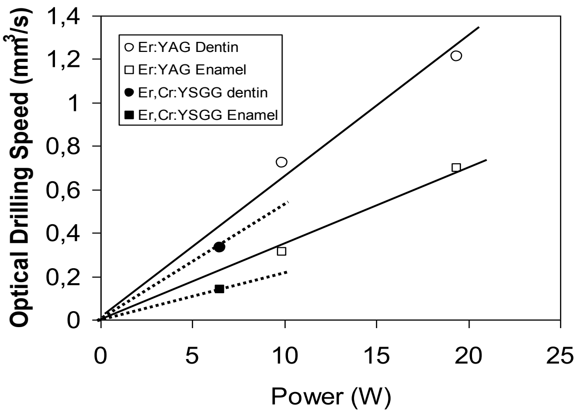

Fig. 23: Plot of measured results of drilling speeds in dentine and enamel for VSP Er:YAG (Fotona dental laser, MSP mode) and Er,Cr:YSGG (Biolase Waterlase, H mode). Figure is based on data from ref. 8.

There are two observations that can be made based on Fig. 23. First, there is a basic difference in the slopes (representing the ratio between the ablation speed and laser power) of the ablation lines. In terms of the ablation speed per average laser power (in mm^3/Ws), the VSP Er:YAG laser was found to be by a factor of 1.6 more efficient in enamel, and by a factor of 1.3 more efficient in dentine. As explained in previous sections, this difference can be attributed to a higher absorption and shorter pulse duration of the VSP Er:YAG laser.

Second, for a dental practitioner this translates into the maximum ablation speeds of commercially available 20 W VSP Er:YAG lasers (Fidelis and LightWalker) of 1.25 mm^3/s in dentine and 0.72 mm^3/s in enamel, compared to the maximum ablation speeds of commercially available 8 W Er,Cr:YSGG lasers of 0.41 mm^3/s in dentine and 0.17 mm^3/s in enamel [8]. In terms of what is available to a dental practitioner, the VSP Er:YAG laser is currently up to 3-4 times faster than the Er,Cr:YSGG laser. It is important to note that treatments even at highest Erbium laser powers have been shown to be safe for fast cavity preparations [22].

g) Water Spray Considerations

It is now well accepted that the mechanism of action for laser ablation in hard tissue is basically the same for all Erbium lasers: the rapid subsurface expansion of the interstitially trapped water within the mineral substrate causes a massive volume expansion, and this expansion causes the surrounding material to be exploded away [25].

In one of the earlier published papers [21] a systematic study was reported on the Erbium laser ablation rates in enamel and dentin, with and without water spray. The results clearly demonstrated that the presence of the water spray did not decrease nor increase the ablation efficiency of the Erbium laser. The conclusion of the study was that the presence of water spray was not essential for hard dental tissue ablation. However, as is the case with mechanical drilling, the use of water spray is strictly required as it prevents temperature build-up and tissue desiccation during the drilling process.

It has been suggested that a more aggressive ablative mechanism, designated as a “hydrokinetic effect”, occurs when atomized water droplets, introduced between the erbium laser and the surface of the tooth, are accelerated in the laser's field and impact the tooth's surface [40]. Several studies have been made to determine if the proposed hydrokinetic effect exists and to establish its contribution to the dental hard-tissue ablation process [1,5,21,23,25,26].

In one of the studies [23], two commercially available dental laser systems (Er,Cr:YSGG from Biolase, and Er:YAG from Premier) were employed in the hard tissue ablation studies. One system employed a water irrigation system in which the water was applied directly to the tooth, forming a thin film of water on the tooth's surface. The other system employed pressurized air and water to create an atomized mist of water droplets between the laser handpiece and the tooth. The ablative properties of the two lasers were studied upon hard inorganic materials, which were void of any water content, as well as dental enamel, which contained interstitial water within its crystalline structure. In each case the erbium laser beam was moved across the surface of the target material at a constant velocity. When exposing material void of any water content, no ablation of the surfaces was observed with either laser system. In contrast, when the irrigated dental enamel was exposed to the laser radiation, a linear groove was formed in the enamel surface. The volume of ablated dental tissue associated with each irrigation method was measured and plotted as a function of the energy within the laser pulse. Both dental laser systems exhibited similar enamel ablation rates and comparable ablated surface characteristics. The results of the study determined that, although the manner in which the water irrigation was introduced differed, the mechanism by which the enamel was removed appeared basically the same for both dental laser systems, namely rapid subsurface expansion of the interstitially trapped water. It was the conclusion of the study that if the proposed hydrokinetic effect exists, it is not effective on hard materials that are void of water, and it does not contribute in any significant degree in the ablation of dental enamel.

In conclusion, the published scientific literature cannot give any credence to the "hydrokinetic effect" as being a viable means of how laser ablation works [1,5,21,23,25,26]. The ability of erbium lasers to ablate hard dental tissue is due primarily to the laser-initiated subsurface expansion of the interstitial water trapped within the tissue.

It has also been suggested that a lower absorption in water by the Er,Cr:YSGG results in a better penetration of the laser light through the water spray above the tooth and through the surface water film on the surface of the tooth. This hypothesis is not correct, and in fact just the opposite applies. The argument is basically the same as in the case of tissue ablation (See Fig. 7). Due to the three-times-lower absorption, the Er,Cr:YSGG laser requires three times more energy and three times more time to create a vapor bubble tunnel within the water spray droplet or superficial water film. Due to the heat diffusion during this time, a portion of the laser energy is wasted, and the efficacy of bubble formation is reduced.

Note also that the diameter of water spray droplets and the thickness of the superficial water layer are in the range of 10 to 1000 micrometers [30]. With a diameter of 0.5 mm, an Er:YAG laser beam that gets partially absorbed within the penetration depth of 1 micrometer of water will create a vapor bubble with a diameter much larger than 1000 micrometers. This means that the Er:YAG laser radiation will "instantaneously" (and with very little energy expended) create a "vapor tunnel" through even the largest of spray droplets and the thickest of water layers (see Fig. 24). Due to this "tunneling" effect [32] the absorption of the Er:YAG (and Er,Cr:YSGG) laser radiation in water spray has negligible effect on the efficacy of hard tissue ablation [21].

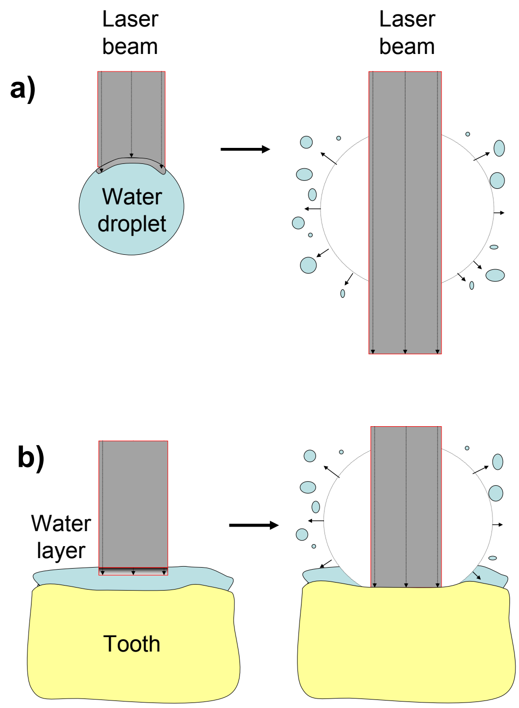

Fig. 24: An Er:YAG laser beam that gets partially absorbed within the penetration depth of 1 micrometer of water will create a vapor bubble with a diameter much larger than 1000 micrometers. The laser radiation will thus "instantaneously" (and with very little energy lost) create a "vapor tunnel" through even the largest of spray droplets (a) and the thickest of water layers (b).

IV. DISCUSSION

As presented above, the Erbium laser pulse duration and wavelength absorption depth determine how much heat remains deposited within the tissue following the treatment. Based on these 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 is more versatile. The VSP Er:YAG laser can be operated at adjustable pulse duration, from super short pulses (SSP) that are ideal for precise ablation of hard tissue, to very long pulses (VLP) for more coagulative soft tissue procedures. To demonstrate the adjustability of the thermal effect with the VSP Er:YAG laser, Fig. 25 shows the measured dependence of the dental tissue surface temperature following a laser pulse as a function of the VSP Er:YAG pulse duration.

As can be seen from Fig. 25, the VSP pump technology allows the user to adjust the thermal effect during dental treatments by simply adjusting the duration of the VSP Er:YAG laser.

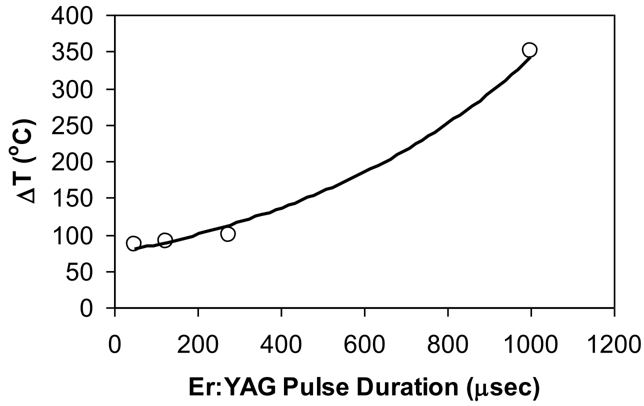

Fig. 25: Enamel surface temperatures 2.5 ms following a laser pulse for different VSP Er:YAG pulse durations (Fotona dental laser, pulse durations SSP, MSP, SP and VLP). Figure is based on data from ref. 43.

V. CONCLUSIONS

For precise dental tissue procedures, Erbium lasers offer the safest and most efficient solutions. Of the available Erbium laser technologies, Er:YAG and Er,Cr:YSGG, the Er:YAG has the optimum absorption characteristics, with cold ablation possible even when using minimally invasive low pulse energies. In addition, the latest generation Er:YAG lasers with the Variable Square Pulse (VSP) technology allow precise control of the nature of the treatment by allowing the user to adjust the VSP laser pulsewidth to the desired effect. The VSP Er:YAG laser can thus be operated from super short pulses (SSP) that are ideal for precise ablation of hard tissue, to very long pulses (VLP) for coagulative soft tissue procedures. The Erbium lasers have achieved their original goal: to supplement and improve upon the limitations of the classical mechanical tools in the dentist's office.

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