Comparison of Er:YAG and Er,Cr:YSGG Dental Lasers

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Abstract: A variety of lasers has been used for hard tissue procedures in dentistry, with erbium lasers now being accepted as the golden standard for these procedures. This study describes a new, highly accurate and repeatable methodology for measuring ablation rates in hard dental tissue, comparing the performance of the two main erbium wavelengths used, Er:YAG (2940 nm) and Er,Cr:YSGG (2780 nm), and discussing the observed differences between the two types of erbium lasers.

Keywords: Er:YAG, Er,Cr:YSGG, variable square pulse technology, ablation speed, hard tissue procedures.

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Erbium lasers are now recognized as the optimal dental lasers for effective, precise and minimally invasive ablation of hard dental tissues.[1] Of all infrared lasers, they exhibit the highest absorption in water and hydroxyapatite and thus are ideally suited for the cold "optical drilling" of enamel, dentin, and composite fillings.

Early erbium and CO_2 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, and the dental lasers with their variable square pulse technology even exceed the drilling speeds of conventional burs.[2,3] Variable square pulse technology utilizes square-shaped pump pulses in order to achieve nearly square-shaped laser pulses. This technique eliminates long laser pulse decay with reduced laser intensity and therefore suboptimal ablation efficiency.

In order to properly quantify the differences in ablation speeds of the two main erbium laser wavelengths currently employed in dentistry, Er:YAG (2940 nm) and Er,Cr:YSGG (2780 nm), a new methodology for measuring ablation rates (AR) in hard dental tissue has been recently applied[4] that makes use of the optical triangulation principle.[5] Since this method does not require the laser handpiece to be in a fixed position in respect to the tooth, it allows measurements to be made under realistic conditions, identical to a manually performed laser treatment by the dental practitioner.

MATERIALS AND METHODS

The Er:YAG laser used was a Fotona Fidelis Plus III fitted with either an R02 non-contact handpiece (beam spot size in focus: 0.6 mm) or an R14 fiber-tipped contact handpiece (fiber beam diameter 0.9 mm). The Er,Cr:YSGG laser used was a Biolase Waterlase MD fitted with a fiber-tipped 'Gold' handpiece (fiber beam diameter 0.6 mm). The comparisons were made between the two lasers using a range of pulsewidth, en-

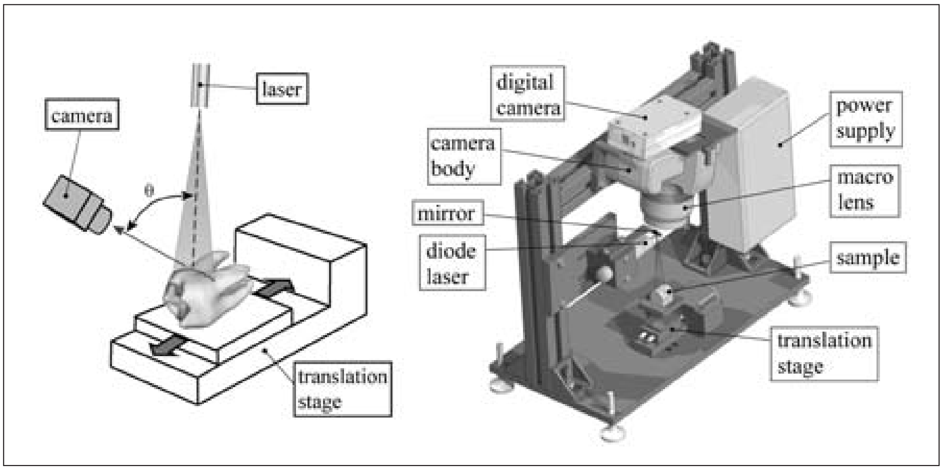

Fig 1 Schematic showing operation of profilometer, and general assembly of the equipment.

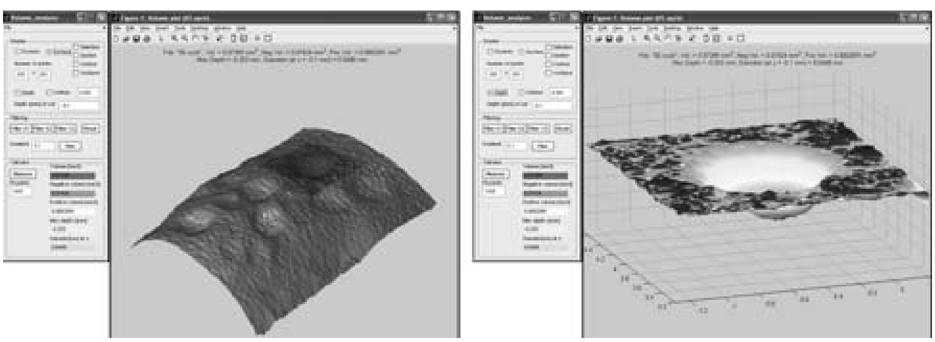

Fig 2 Screenshots of "Volume analyser" software showing various stages in volume analysis.

ergy and pulse configurations, ranging from single pulses to longer bursts of pulses. The built-in water spray cooling was used for all the experiments.

Extracted premolars and molars were selected and were stored immediately following extraction in a 10% formalin solution. 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 min and stored in a physiological saline solution. The teeth were randomly chosen for the ablation experiments. Each data point represents an average of the effects of 6x80 laser pulses from 6 different tooth samples. Since the precision of ablation efficiency measurements is very sensitive to any aging of the laser beam delivery optics, special care was taken to make measurements only with undamaged fiber tips, protective windows, and laser beam delivery systems.

Because of the very small volumes of ablated material in many of the samples, a highly-accurate methodology was required to make the appropriate measurements and calculate the ablated volumes.

To achieve this, a specialized measurement assembly was developed (Fig 1), built and tested by the Faculty of Mechanical Engineering at the University of Ljubljana, Slovenia. This makes use of a laser profilometer, running in conjunction with custom "Volume analyser" software.[4] The method is based on the optical triangulation principle. The measured surface is illuminated by a diode laser beam, formed into a light plane. The bright laser beam is visible on the illuminated surface and acquired by a camera (Fig 1). The design of the system ensures highly accurate and repeatable measurements as well as the facility for photographic recording and visual comparisons (Fig 2).

The initial measurements concentrated on the ablation rate, ie, the ablated volume per pulse energy (in mm^3/J), for a 260 mJ pulse of both lasers (260 mJ was the maximum pulse energy available from the Er,Cr:YSGG system). Pulse energies were measured at the handpiece outputs. The Er:YAG laser operated in the VSP pulse duration mode, and the Er,Cr:YSGG laser operated in the H pulse duration mode (Fig 9). All AR data represent average values for a single pulse.

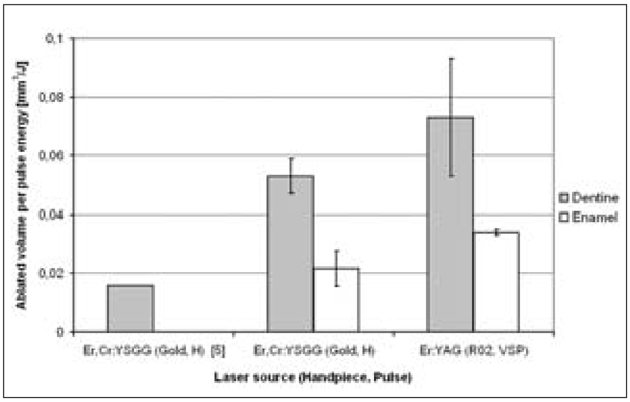

Fig 3 Plot of measured results of ablated volume per pulse energy of dentin and enamel for both laser sources at 260 mJ pulse energy.

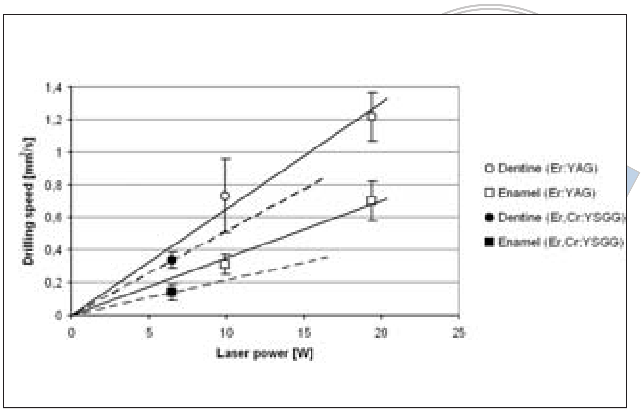

Fig 4 Plot of measured results of drilling speeds in dentin and enamel for both laser sources. Lines are linear interpolations assuming zero drilling speed at zero laser power.

RESULTS

It was found (Fig 3) that the volume of dentin per pulse energy ablated by the Er:YAG system (0.073 mm^3/J) was greater, by a factor of 1.4, than that ablated by the Er,Cr:YSGG system (0.053 mm^3/J).

For comparison, results of an earlier published study are included that show a lower rate of volume removal of 0.016 mm^3/J for the 300 mJ Er,Cr:YSGG.[6] We attribute this difference to the high sensitivity of the Er,Cr:YSGG laser ablation process to any reduction in intensity of the beam (which can be caused, for example, by an aging fiber tip) that can result in the laser moving from cold ablation to a less efficient thermal regime.

In enamel, the ablated volume per pulse energy by the Er:YAG system (0.032 mm^3/J) was greater by a factor of 1.5, compared to that achieved with the Er,Cr:YSGG system (0.021 mm^3/J).

Note that the ablation rate (in mm^3/J) increases from the initial zero value at the ablation threshold and then stabilizes at the maximum ablation rate at high laser energies. For the Er:YAG laser, the ablation rate stabilized at approximately 500 mJ, reaching 0.080 mm^3/J in dentin, and 0.035 mm^3/J in enamel.

Measurements were then made of the maximum drilling speeds available from the two laser types (Fig 4). Each laser was configured to the settings close to recommended maximum drilling efficiency. A test drilling of a fixed duration was then completed in the appropriate sample, and the ablated volume measured, resulting in an ablation rate in mm^3/s.

For the Er:YAG laser, two settings were used, one for precise ablation at 9.9 W (R14 handpiece, VSP pulse duration mode, 330 mJ at 30 Hz), and the other a special 19.4 W MAX mode designed specifically for very high speed removal of hard tissue (R02 handpiece, SP pulse duration mode, 970 mJ at 20 Hz). For the Er,Cr:YSGG laser, the maximum available output power at the handpiece fiber tip of 6.5 W (H pulse duration mode, 260 mJ at 25Hz) was used.

The measurements made showed that the Er,Cr:YSGG laser at 6.5 W removed dentin at the rate of 0.33 mm^3/s (0.051 mm^3/Ws), and enamel at a rate of 0.14 mm^3/s (0.021 mm3/Ws). The standard Er:YAG laser settings at 9.9 W resulted in removal rates of 0.72 mm^3/s (0.073 mm^3/Ws) for dentin and 0.31 mm^3/s (0.031 mm^3/Ws) for enamel. When we consider the 19.4W MAX mode of the Er:YAG laser, the results show ablation rates of 1.21 mm^3/s (0.062 mm^3/Ws) in dentin and 0.70 mm^3/s (0.036 mm^3/Ws) for enamel. Average slope efficiencies of the ablation speed as obtained from Fig 4 are, in the case of the Er:YAG laser, higher by a factor of 1.6 in enamel, and higher by a factor of 1.3 in dentin when compared with the Er,Cr:YSGG laser.

It is important to note that even at the very high ablation rates of the Er:YAG system with the MAX mode, the ablation regime remained "cold" (for the definition of ablation regimes see Majaron et al[7] and discussion on ablation regimes below) and no thermal damage to the teeth could be observed on SEM images.

From these results, it can be seen that both the Er,Cr:YSGG and the Er:YAG lasers used in these exper-

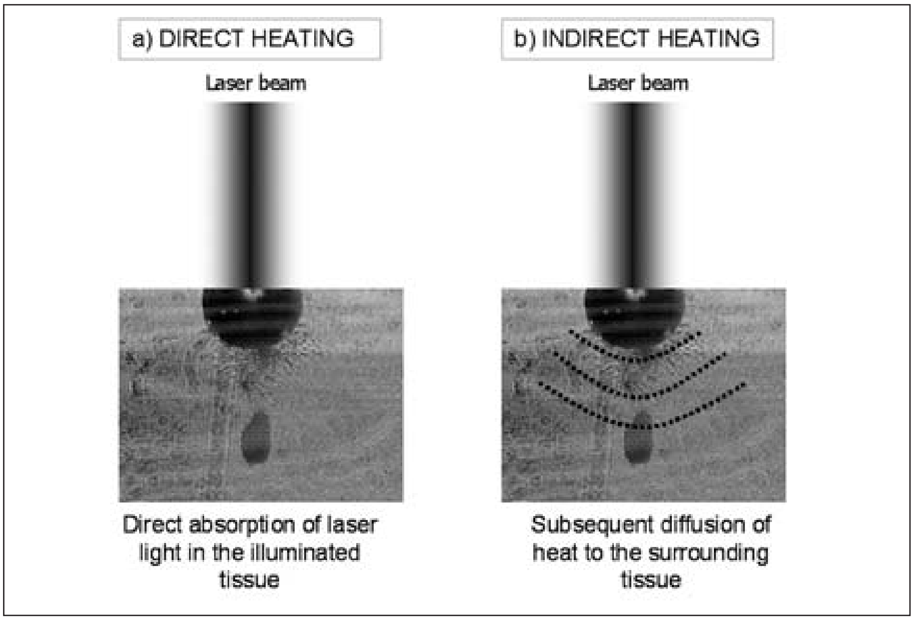

Fig 5 Two steps in tissue heating upon laser irradiation. Indirect heating must be avoided when efficient cold ablation of hard tissues is needed as the indirect heating leads to undesirable thermal effects.

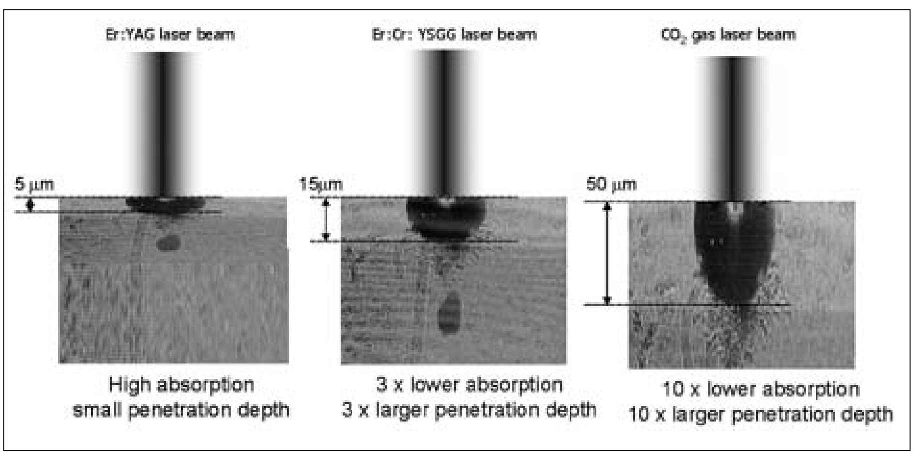

Fig 6 Depending on the laser type, different volumes of the irradiated tissue need to be directly heated. The penetration depths are for human dentin. At lower absorption coefficients, and therefore higher penetration depths, more laser pulse power is required in order to avoid secondary heating of the tissue.

iments are suitable for hard tissue ablation in dentistry. It can also be seen that, with similar settings to the Er,Cr:YSGG, the Er:YAG laser offers superior performance in terms of ablation volumes and speed, which can be of importance not only when faster treatments are desired but also when the safety of laser treatments is considered. Namely, with lower ablation efficiency of the Er,Cr:YSGG lasers, the ability to operate in a purely "cold" ablative regime with these laser systems is limited.

DISCUSSION

Wavelength considerations

Wavelength is a key factor in the suitability of any laser for hard tissue procedures in dentistry. Erbium laser wavelengths all operate in the region of the major absorption peak for water, and are thus the most suited to hard tissue ablation treatments. Closer study of the absorption peak associated with erbium lasers shows a 300% difference between the absorption coefficients μ of Er,Cr:YSGG (400 mm^{-1}) and Er:YAG (1200 mm^{-1}). Because of the different water and hydroxyapatite content levels in human dentin, the absorption coefficients

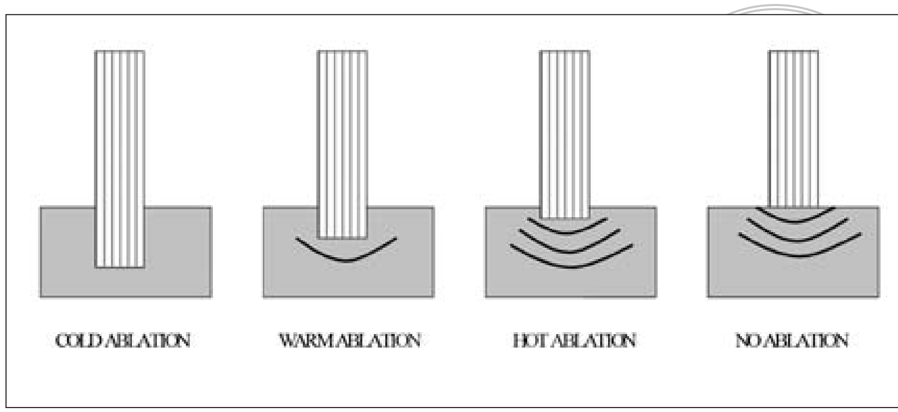

Fig 7 The effect of the laser beam on tissue in the four ablation regimes.

for the Er:YAG lasers are approximately 150 mm^{-1} in enamel, and 200 mm^{-1} in dentin. The corresponding absorption coefficients for the Er,Cr:YSGG are approximately three times lower. The Er:YAG laser wavelength thus penetrates approximately $1/\mu$ = 7 µm in the enamel, and 5 µm in the dentin. The Er,Cr:YSGG laser wavelength penetrates deeper, 21 µm in enamel, and 15 µm in dentin. This difference influences the volume of the directly irradiated tissue that needs to be rapidly heated to ablative temperatures by the laser light before the absorbed energy is spread out into the surrounding tissue by the process of thermal diffusion (Fig 5). Note, however, that hard tissue absorption may change considerably during laser irradiation. Thus, it has been suggested that the water absorption might shift at high laser energies towards shorter wavelengths. This would make the absorption difference between the Er:YAG and Er,Cr:YSGG wavelengths smaller.[8]

The higher the penetration depth, the larger the volume of directly heated tissue that needs to be rapidly heated up, and the higher the laser pulse power that is required for efficient and cold ablation (Fig 6).

Pulse duration and shape considerations

In laser ablation, we generally talk about four ablation regimes.[7] At high energies and low pulse durations (ie, 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 (Fig 7). 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 (ie, with lower laser pulse powers), the layer of tissue that has been indirectly 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.

One of the key factors that determines the regime and efficiency of laser ablation is the laser pulse duration. If the energy required is delivered to 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 8 shows the characteristic depth x_d to which the temperature of enamel is affected by indirect heating when laser fluences close to the ablation threshold are used (ie, in the hot ablation regime). The characteristic depth was calculated from $x_d = (D\ t_p)^{1/2}$ where t_p is the laser pulse duration, and the diffusion constant D for the enamel was taken to be 4.0 x 10^{-7} m^2/s.[7] The dependence of the ablation effect, defined as $1/F_{th}$, on the pulse duration is also shown. Here, F_{th} is the ablation threshold fluence, as obtained from Fig 11.

In this respect, the Er:YAG laser is at an advantage, since it offers variable pulse widths down to 50 µs, while the Er,Cr:YSGG laser is due to the long laser population inversion life time limited to a minimum pulse width of approximately 500 µs. To illustrate this limitation, Fig 9 shows measured pulse durations of the Er: YAG laser system and of the Er,Cr:YSGG laser system. Pulse durations were measured with the same photodiode at the corresponding R02 and Gold hand-

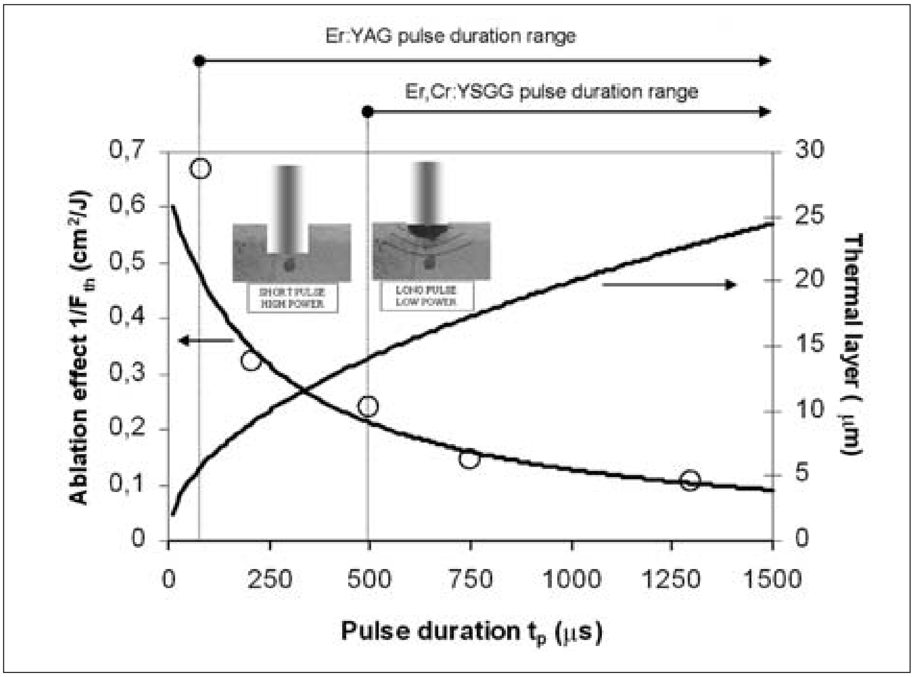

Fig 8 a) Dependence of thermal effects on laser pulse duration as represented by the characteristic depth x_d of the thermally affected layer in enamel. **b)** Dependence of ablation effect represented by $1/F_{th}$ in enamel on laser pulse duration. Circles represent experimental data from Fig 11, full line represents 1/x fit. Due to the long population inversion time of the Er,Cr:YSGG, this laser cannot be operated below approximately 500 µs.

piece outputs. Single pulse temporal evolutions without signal averaging are shown.

Note that the particular Er,Cr:YSGG laser system employs relatively short pump pulses of only 140 µs in the H mode, and 700 µs in the S mode. In spite of this, due to the long population inversion life time of the Er,Cr:YSGG laser crystal, the generated laser pulses are much longer, and are in the shortest H pulse mode on the order of 500 to 700 µs.

Based on the above wavelength and pulse duration considerations, the Er,Cr:YSGG laser is found to be suitable for soft tissue applications where some level of thermal coagulation effects are desirable, but it has limitations when used on hard tissues. On the other hand, the Er:YAG laser can be operated at widely adjustable pulse durations, from supershort pulses (SSP) that are ideal for precise ablation of hard tissues, to very long pulses (VLP) for soft tissue procedures (Fig 10).

To demonstrate this dependence, we have made rough measurements of the ablation threshold fluence F_{th} (in J/cm^2) in enamel as a function of the laser pulse duration (Fig 11).

As expected, ablation thresholds increase towards longer pulse durations. The ablation threshold was determined by keeping the laser pulse energy constant at 260 mJ and then determining the beam spot size, and therefore the laser fluence where ablation in enamel could first be observed. The beam spot size was varied by changing the distance between the handpiece fiber tip and the enamel surface, and estimated from the mark on the photographic paper.

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" pulse width and power. It can be seen from Figs 9 and 10 that the pulse profile for the particular Er:YAG laser that was used in the experiment was far more controlled, which ensured the power within the pulses to be approximately constant. This also ensured that the pulse modality did not uncontrollably shift during a pulse from "cold ablation" at the beginning of a pulse (where short Er,Cr:YSGG laser pulses had a peak), to "warm ablation" at the middle of a pulse, and to "hot ablation" or even "no ablation" towards the end of a pulse.

Another contributing factor could also be the difference in the beam spot sizes. Namely, our studies of Er:YAG laser ablation show the ablation rate to increase weakly towards higher fluences (smaller spot sizes). However, since the Er,Cr:YSGG beam spot size was slightly smaller compared to the spot sizes of the Er:YAG, this should, if anything, contribute to a higher ablation rate of the Er,Cr:YSGG, and thus cannot explain the observed lower ablation efficiency of this laser.

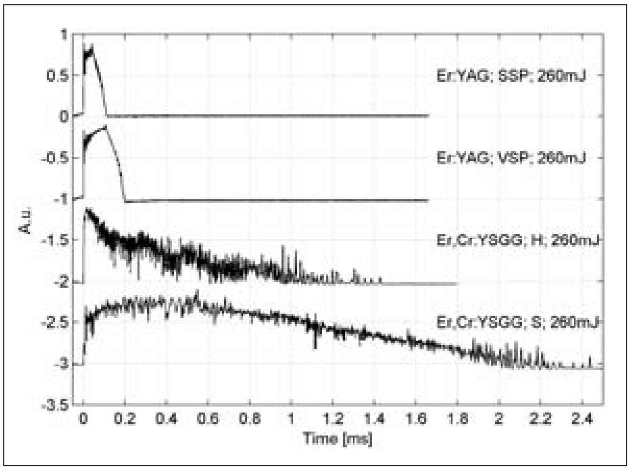

Fig 9 Comparison of pulse widths for the tested laser sources.

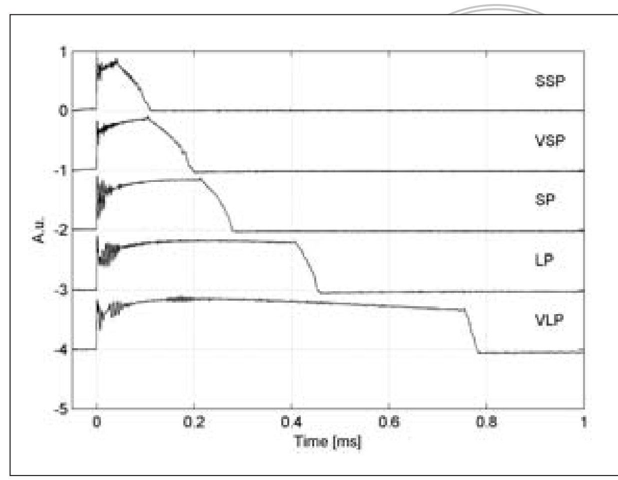

Fig 10 Measured variable pulse duration range of an Er:YAG laser.

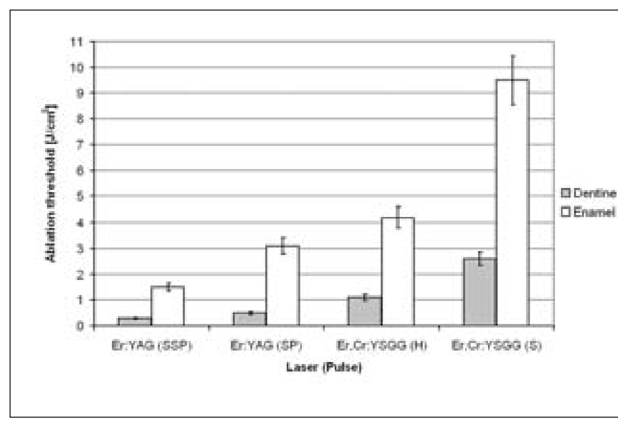

Fig 11 Dependence of the ablation threshold in enamel on the pulse duration and laser type. The ablation threshold for the shortest SSP (50 to 80 µs) Er:YAG laser pulse is lower by a factor of 3 compared to that of the H (500 to 700 µs) Er,Cr:YSGG laser pulse, and lower by a factor of 6 compared to the S (1600 to 2000 µs) Er,Cr:YSGG laser pulse.

CONCLUSIONS

A novel, highly accurate and repeatable methodology for the measurement of ablated volumes in teeth was developed. Using this methodology, a detailed comparison could be made between the two leading laser wavelengths for hard tissue procedures in dentistry, Er:YAG and Er,Cr:YSGG.

At 260 mJ output laser energy, the ablation rate (ablated volume per pulse energy) in enamel and dentin was greater by a factor of 1.5 and 1.4, respectively, with the Er:YAG laser.

In terms of the ablation speed per laser average power (in mm^3/Ws), the Er:YAG laser was found to be more efficient in enamel by a factor of 1.6, and more efficient by a factor of 1.3 in dentin. For oral laser applications where treatment speed is of essence, this translates into the maximum ablation speeds of commercially available 20 W Er:YAG lasers of 1.25 mm^3/s in dentin and 0.72 mm^3/s in enamel, and maximum ablation speeds of commercially available 8 W Er,Cr:YSGG lasers of 0.41 mm^3/s in dentin and 0.17 mm^3/s in enamel.

The observed difference in ablation rates and ablation speeds between the Er:YAG and Er,Cr:YSGG lasers may be attributed to several factors, among them the differences in wavelength, pulse duration and pulse shape. The differences in the ablation characteristics of the two erbium laser types have also been observed and studied by other authors,[9] however, further research is necessary to determine the exact role of different parameters on the ablation dynamics and efficiency of the erbium lasers.

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