Comparison of the Emission Characteristics of Three Erbium Laser Systems – A Physical Case Report

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Abstract: The physical characteristics of pulsed radiation delivered by three different commercially available Erbium laser systems were investigated. To collect real field data and avoid the evaluation of “laboratory values” provided by many manufacturers, each of the systems chosen has been in practical use for at least 6 months. The results are compared to the physical requirements for cavity preparation with the least collateral damage.

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Erbium lasers have become a well-established tool for dental hard tissue treatment during the last ten years. Thus, the comparison of the individual laser systems provided by several manufacturers is of great interest. Many studies and case reports on this topic have been published before. It is noteworthy that many of them dealing with the same therapy concept claim one system to be the best out of several on the market although this contradicts other publications. In some cases, this inconsistency leaves room for very speculative explanations of certain effects and system capabilities. The main reason seems to be that the individual laser units cannot be compared solely based on front panel parameter settings, without considering that additional laser parameters which are highly responsible for the quality of laser-tissue interactions cannot specifically be set on the instruments.\textsuperscript{1,2}

Based on the work of Vogel and Venugopalan,\textsuperscript{1} we investigated the Er-based laser systems of three leading manufacturers, comparing the measured parameter values to each other and, if existing, the theoretical optimum.

MATERIALS AND METHODS

To collect real field data, one Er,Cr:YSGG (laser 1) and two Er:YAG laser systems (lasers 2 and 3) installed at the Department of Conservative Dentistry, Dental School, University of Vienna were investigated. Each had been in use for at least 6 months. Each system was produced by a different manufacturer and belonged to its current model series. System maintenance during use was performed according to the manufacturers’ requirements.

The parameters investigated were pulse energy, pulse repetition rate, average power, pulse width, temporal pulse shape, and beam profile at the outcoupling end of the handpiece.

Emitted pulse energy, pulse repetition rate, and av-
verage power were measured using a power meter with a pyroelectric head (Ophir Laser Star with head Ophir PE50DIF/Er, Jerusalem, Israel). Pulse width and pulse shape were measured with an infrared-B sensor and an oscilloscope (Velleman PC 500i, Gevere, Belgium). The pulse shapes were recorded at a sampling rate of 50 MHz to average the spiking of the laser pulses. The emitted spatial beam profile was recorded with thermal paper (Pelikan telefax paper PNr. 404303.

RESULTS

Pulse Energy and Average Power

For each laser unit emitting pulsed radiation a rather significant fluctuation of the emitted pulse energy is evident. This is mainly caused by the pumping mechanism: as all the investigated solid state systems were pumped by flash lamps having no constant emission intensity due to discharge fluctuations of the Xenon lamp, the laser pulse energy is not exactly predictable by lamp voltage and lamp current adjusted by internal controls. Thus, the average of about 100 pulses was always calculated for further use. In addition, the pulse repetition rate (PRR) fluctuated about 3% to 5% in those systems where it was adjustable.

The outcoupled average power also differed from the values set at the control panels: in one case it was 54.14% less than displayed (laser 3), in the second one 18.7% less (laser 2), and the third revealed a discrepancy of 5% to 20%, rising with increasing pulse energy (laser 1). The losses also depended on the kind of sapphire tip used with the handpieces. The tip of laser 3 is simply plugged into the handpiece without proper fixation, thus allowing it to tilt easily upon any surface contact. Consequently, the outcoupled energy changed in relation to the actual position and angle of the incoming surface with respect to the irradiating laser beam. It must be mentioned that the tip-holder device in this case was so inadequate that the tip fell out of the handpiece several times during measurement, presenting a high risk of being swallowed by a patient during treatment.

Pulse Width and Pulse Shape

Pulse width and pulse shape were measured by an IR-B detector and an oscilloscope. The results were compared to the work of Vogel and Venugopalan,1 and evaluated according to their theoretical requirements.

Usually, pulse duration is determined by the FWHM method (full width at half maximum): the duration of the pulse is measured at its half-maximum power. Within the time regimen of free running laser systems – pulse durations of about 80 to 300 µs – heat transfer to the surrounding material plays an important role. As this process strongly depends on the pulse shape and thus also on the width of the pulse base, we additionally measured the pulse at a level of 1/e², ie, 13.5% of the pulse maximum.

Additionally, the rise time τlead of the pulse is of significant influence for heat transport. Thus, we also measured the time elapsed from the beginning of the pulse to its first maximum. Again, two values were recorded: the first one starting with the 1/e² value of the maximum power and the second one from the baseline of the signal. Figures 1 through 3 show the pulse shapes of the three laser systems recorded at a pulse energy of 200 mJ.

Tables 1 and 2 show the pulse width and the rise time of the pulses at different power settings. As the different systems do not provide the same pulse repetition rates and only allow different pulse energies in the lower ranges, a direct comparison can be made only by using the same pulse energy at a higher setting.

The pulse width within each power regimen was very stable for all systems, yet sometimes exhibiting significant differences between the single settings. The only laser not having a higher FWHM pulse width at higher pulse energies was laser 1; on the contrary, the pulse width was even reduced by 20.0%. The rise time τlead in this case also shortened slightly by about 8.5%.

Laser 2 had the highest pulse broadening with a plus of 74.2% from 0.4 to 4 W. The rise time increased by 17.7%.

For laser 3, the pulse width was raised by 53.5%. This unit had the largest rise time increase of 40.7%.

Compared to each other, laser 1 had the shortest pulses of an average of 91 µs, followed by laser 3 with 182.67 µs and laser 2 with 275 µs.

Looking at the temporal pulse shape in Figs 1 to 3, laser 1 shows a fast rise to the maximum followed immediately by a fast, exponential drop of the curve. At higher pulse energies, a slight leveling of this drop was observed, yielding a higher energy content in the trailing edge of the pulse (Fig 1).

For laser 2, the pulse rises relatively slowly up to the maximum. Afterwards, a very slow decrease follows lasting for about half of the pulse width before evolving to an exponential drop again. Generally, this laser unit showed irregular ripples in the pulse shape, perhaps caused by slightly misaligned resonator mirrors (Fig 2).
Fig 1  Pulse shape, laser 1, Ep = 200 mJ.

Fig 2  Pulse shape, laser 2, Ep = 200 mJ.

Fig 3  Pulse shape, laser 3, Ep = 200 mJ.
Laser 3 has a leading pulse edge similar to laser 2, but falls exponentially after the maximum without further delay (Fig 3).

Spatial Beam Profile and Emission Characteristics of Several Delivery Systems

Depending on the delivery system, ie, transmission system to the handpiece, as well as the outcoupling system of the handpiece, different intensity distributions (transversal electrical modes, TEMs) in the laser beam can be generated. Usually, after transmission through a fiber, the TEM has a quasi-Gaussian shape which is preserved by focusing through a lens or coupling through a cylindrical sapphire tip (Fig 5). If an articulated arm is used, even modes of higher orders, ie, with maxima around the central peak, or just a ring-shaped intensity distribution can be achieved (Fig 6). Even if noncylindri-

cally shaped sapphire tips are used, the quasi-Gaussian beam profile can be redistributed to higher order modes.

To visualize the TEM modes of the investigated delivery systems, we irradiated thermal paper (Pelikan telefax paper) with low energy densities. As all delivery systems were fiber based, they had a quasi-Gaussian shape at the distal end of the handpiece coupling. When focused into a cylindrical sapphire tip, this energy distribution was maintained (Fig 9). If a conical tip was used, at a distance of several centimeters a sharply confined internal peak was visible with a surrounding lunar-shaped region. Of course, this lunar region is located closer to the center in the vicinity of the outcoupling plane of the tip; however, the characteristics of its distribution do not change even there.

The difference in the intensity distribution of the conical and the cylindrical tip can be explained by the angle of the lateral surface with respect to the optical

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<th>Pulse width FWHM [µs]</th>
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<td>Power setting</td>
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<td>0.25 W</td>
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<td>Pulse broadening at rising power [%]</td>
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<th>Rise time from base [µs]</th>
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<td>Rise time change with rising power [%]</td>
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axis: If a part of this surface is not parallel to the axis as for the cone, the angle of incidence of a part of the in-coupled light can fall below the angle of acceptance, yielding a refraction out of the tip instead of total internal reflection, creating a ring-shaped maximum around the center. As the tip axis may not exactly coincide with the beam axis due to fabrication tolerances, at one side of the tip more light will be coupled out creating the lunar-shaped corona depicted in Fig 10.
DISCUSSION

As a result of our investigation, it can be stated that a direct comparison of different laser systems available on the market must be performed very carefully.

In practice, it is very common to investigate two or more laser units of different make just comparing different “front panel settings” without considering any other influencing factors, such as pulse shape or intensity distribution. This may even explain contradictory results from several studies on the same topic.

Comparing just the characteristics of the three laser systems investigated in this study with respect to each other and to principal findings on laser-tissue interactions, significant differences in performance between the single systems as well as deviations from the required ideal values can be found.

For example, one of the lasers with adjustable pulse repetition rate has no setting for the value where one of its strongest competitors has fixed this rate. Another laser allows no pulse energy settings below 100 mJ, whereas both of the other systems allow much lower settings for more gentle tissue treatment. However, its energy settings range up to values in excess of 6 W average power, a level provided by neither of the other systems. This shows that even a direct comparison of the same adjustable parameters is not always
possible, and comparative studies should be read very carefully before applying their results.

Hence, to evaluate the measured data in a consistent way, we only compared single pulses of the same energy, representing the smallest ablative quantity in the ablation process thereby determining the actual ablation efficiency of a laser system. Furthermore, we compared the parameters of the single pulses to the values requested in the literature. As there are sometimes differences in the published data or only a very small portion of a larger problem is treated, we refer to recent study by Vogel and Venugopalan, which gives a very broad review of the literature published up to this time.

Pulse Duration

From the literature, an ideally required pulse duration shorter than 0.5 µs for ablation of hard tissue without thermal collateral influence can be deduced, representing the time after which the path length of heat diffusion is equal to the penetration depth of Er:YAG radiation into dental hard tissue. As all systems investigated are operated in the free running mode, ie, the pulse duration is determined by the length of the pumping pulse without any additional pulse-shortening methods (such Q-switching), this value cannot be attained by any of them.

At constant pulse energy, laser 1 with a pulse duration of about 90 µs is expected to have the highest ablation efficiency and the lowest thermal impact on the residual tissue. It is followed by laser 3 with 200 µs and laser 2 with 250 µs. The extention of pulse duration by more than 100% yields a significant reduction of the peak power, as depicted in Fig 12: laser 3 reaches 77% of the peak power of laser 1 and laser 2 just 53%.

Pulse Shape

The faster the pulse rises, the faster the energy is deposited in the irradiated volume and the better it stays confined. After reaching the maximum, the pulse should decay very rapidly again to avoid further heating of the tissue after ablation.

Laser 1 has the steepest leading edge. After the pulse has reached the maximum, it drops quasi-exponentially. As it can be seen in Figs 4 and 12, this decay is not as steep as that of the other pulses. This indicates
that a significant amount of energy is delivered to the tissue after ablation.

Laser 2 has a rise time to its maximum that is 4.3 times faster than that of laser 1. This means that the energy can penetrate very deep into the tissue before ablation, causing a high temperature increase. The decay after the maximum shows a very flat slope for about 150 µs before it drops again, following a nearly exponential curve. The flat middle part indicates a deep penetration of the energy into the tissue. How much energy is delivered into these deeper regions after ablation depends on the ablation threshold of the tissue and the irradiating conditions of the incoming laser beam.

The rise time of laser 3 is 5 times longer than that for laser 1. After reaching the maximum, the pulse falls exponentially. Laser 3 has the shortest decay time of the three investigated systems.

Considering these findings under the aspect of ablation and thermal impact, laser 2 can be expected to have the lowest pulse ablation efficiency caused by the large pulse width, the slow rise time, and the long decay time, yielding a low pulse peak power. It can be estimated that this laser has the greatest thermal impact on the surrounding tissue. Used on soft tissue, this offers an advantage in terms of hemostasis. However, in hard tissue applications, sufficient cooling must be assured to prevent thermal damage.

Laser 3 has a smaller pulse width and a better rise and decay quality than laser 2 in terms of collateral energy deposition. A disadvantage of this system is that the pulse energy cannot be scaled down to energies similar to those of the other two lasers. The higher pulse energies may give the user the subjective impression of a high ablation rate, although the objective pulse ablation efficiency at constant energy might not be the optimum compared to other systems due to the long pulse duration. Like for laser 2, the user can be tempted in this case to use higher pulse energies than necessary for hard tissue preparation, thus easily causing damage to the residual tissue.

Out of the three investigated systems, laser 1 has the relatively best results in terms of pulse width and pulse shape for efficient hard tissue ablation, although the trailing edge of the pulse contains the relatively highest energy, thus introducing more energy than appropriate to the remaining tissue. The main advantage is the short pulse duration together with the short rise time, yielding very high pulse peak powers and a well-confined energy distribution in the tissue, according to Vogel and Venugopalan.¹

CONCLUSION

The results of our measurements show that it is not possible just to compare different laser systems based on similar “front panel” parameter settings. Pulse formation, pulse width, beam profile, and outcoupling conditions have to be taken into account to evaluate the impacts of laser radiation on tissue. Especially for studies on the effects of laser treatment on the pulp, these parameters have to be thoroughly considered, as they may yield completely different results even for the same pulse energy and average power when applied via different products.

Thus, we suggest using single pulses as a solid base for comparable investigations, as the single laser pulse represents the smallest ablative quantity in the process of material removal. In addition, the outcoupling situation with respect to beam diameter, beam profile, and beam divergence must be taken into account for publication of results suitable as a base for further studies.

Of the investigated lasers, lasers 2 and 3 can be expected to have the highest thermal impact at the same pulse energy and average power applied. Measurements leading to the determination of quantitative ratios will be the aim of following studies.

REFERENCES


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