Comparison of Heat Deposition of Er:YAG and Er,Cr:YSGG Lasers in Hard Dental Tissues

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ABSTRACT:

This paper describes a comparative study of residual heat deposition of Er:YAG and Er,Cr:YSGG lasers during ablation of hard dental tissues. Residual heat deposition was obtained from measured irradiated hard tissue temperature decay characteristics immediately following Erbium laser pulses. The measured residual heat was larger in enamel than in dentine for both Er:YAG and Er,Cr:YSGG sources. The amount of the unwanted residual heat that remains deposited in the tooth is for the H mode Er,Cr:YSGG by a factor of more than 2, and for the S mode Er,Cr:YSGG by a factor of more than 3 larger, compared to the deposited heat with the MSP mode Er:YAG laser. These findings, in addition to wavelength, pulse duration and pulse shape considerations made in previous studies, [4] at least partially explain the observed lower ablation efficacy of Er,Cr:YSGG lasers compared to Er:YAG lasers, and may lead to their reduced safety and comfort for patients.

Key words: Er:YAG, Er,Cr:YSGG, erbium laser, heat deposition, dental laser, hard dental tissues.

INTRODUCTION

The Er:YAG (2940 nm) and the Er,Cr:YSGG (2780 nm) are currently two of the most commonly used lasers in dentistry.[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.[2,3] The Er:YAG laser has an approximate three times higher absorption in water compared to the Er,Cr:YSGG laser.[3] Apart from the difference in laser wavelengths, the two laser sources also differ in the available pulse durations range. The Er,Cr:YSGG laser is approximately limited to pulse durations above 400μs due to the slow Er-Cr relaxation times. Er:YAG lasers can operate at pulse durations under 100μs.[4]

Optimal parameters for the ablation of hard dental tissues are determined by wavelength and pulse duration and can provide high ablation speeds and minimal residual heat deposition in the tooth. Recent studies have compared Er:YAG and Er,Cr:YSGG laser ablation rates using an optical triangulation method.[4-6] The Er:YAG laser was reported to be 60% more efficient in enamel and 30% in dentine in terms of ablation speed per average laser power (in mm^3/Ws). Differences in laser wavelength and pulse durations were attributed to this variation.

This study expands on the comparison between the two Erbium lasers to the remaining residual heat in the tooth following Erbium laser pulse ablation. The goal is to experimentally determine which conditions minimize undesirable thermal load on the tooth and thus approximate ideal "cold" optical drilling.

Numerous studies have simulated the temperature rise in tissues, or have used thermal cameras and thermocouples to measure temperature increase during laser irradiation.[7-11] However, there are only few studies of the residual heat following each ablative laser pulse.[12,13] Radiological measurements of temperatures during and immediately following the laser pulse in particular, are obscured by the high temperatures of the re-irradiated ejected tissue and plasma formation, limiting the accuracy of the method to predominantly sub-ablative regimes.[13] Fried et al. determined residual heat deposition by measuring the temperature rise ratio induced by ablative and non-ablative laser pulses on the backside of bovine block "calorimeters".[12] The measured residual heat deposition values varied between 25-70% depending on the pulse duration and wavelength of the investigated laser systems. The study also indicated that residual heat deposition was reduced as laser pulses shortened.

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This study determines residual heat from the thermal decay time of surface temperature. A thermal camera measures the temporal evolution of the tooth surface temperature following each laser pulse after the ablation plume has dispersed. This method is particularly suited for studying residual heat in ablative regimes. It can be assumed that the tissue surface temperature at the end of each pulse is always at the same approximate tissue-explosion temperature. Surface temperature decay time following each pulse depends on the final thickness of the heated tooth layer and therefore on the deposited heat during the pulse. The amount of remaining heat in the tissue after each laser pulse can thus be determined from the measured surface temperature decay time.

MATERIALS AND METHOD

The Er:YAG laser used in the study was a Fotona AT Fidelis fitted with a R02, non-contact handpiece with spotsize of 0.6 mm in focus. The Er,Cr:YSGG laser used was a Biolase Waterlase MD fitted with a 'Gold', fiber-tipped handpiece with 0.6mm spotsize. Comparisons between the two lasers were made using a range of available pulse duration settings for the two lasers; SSP (80µs), MSP (150µs) and SP (300µs) for the AT Fidelis Er:YAG, and H (500-700µs) and S (1200-1400µs) for the Waterlase MD Er,Cr:YSGG. Water sprays were not used during the measurements.

A Flir ThermaCAM P45, thermal camera, was fixed in position above the tooth surface and focused on the ablation site (Fig. 1). The Er,Cr:YSGG fiber-tip was positioned close to, but not in contact with, the tooth surface. The Er:YAG handpiece was positioned with the beam focused on the tooth surface. Thermal camera images were taken at 20ms intervals starting at approximately 2.5ms following a laser pulse. The image exposure time was approximately 5ms.

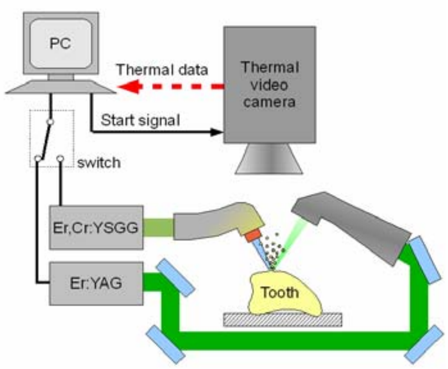

Fig. 1: Experimental set-up.

Extracted premolar and molar teeth that were stored in a 10% formalin solution immediately after extraction were randomly selected for the experiments. In each measurement, single laser pulses were delivered to different areas on the tooth to avoid cumulative tissue desiccation. Laser pulse energies (E_{pulse}) of approximately 100 mJ were used to create laser fluences above the ablation threshold while keeping the ablated depth in the order of 10 µm or lower.[4]

RESULTS

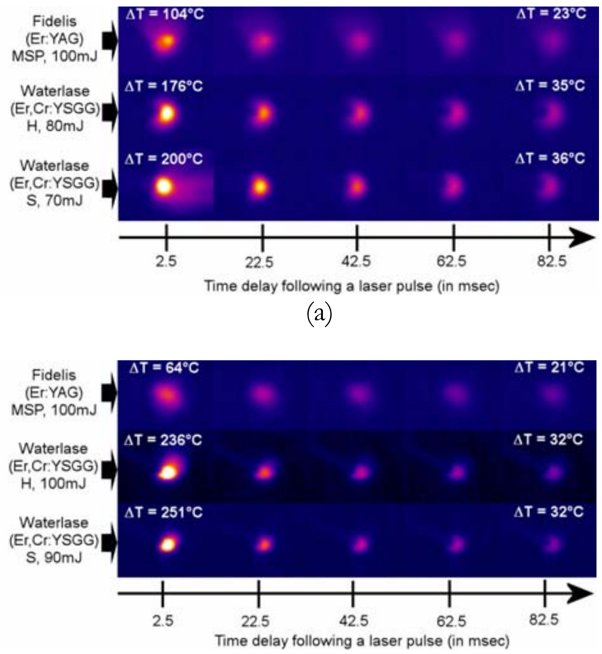

Fig. 2: Typical thermal images of the irradiated tooth surface of the enamel (a) and dentine (b) at 2.5, 22.5, 42.5, 62.5 and 82.5msec following a single laser pulse. The temperature difference, ΔT, represents the temperature increase above the initial average room temperature within a central 0.3mm illuminated spot area.

Figure 2 shows temperature decay is fastest in both dentine and enamel following MSP Er:YAG laser pulses. The difference in thermal decay times is most readily observed from the measured temperatures at 2.5 ms following a pulse, when the thermal diffusion effects are the most pronounced.

The initial temperature drop is a good indicator of the thermal decay time following a pulse, assuming that the initial surface temperature immediately after a pulse is equal to the tissue ablation temperature T_a (different for enamel and dentine) and thus independent of laser parameters.

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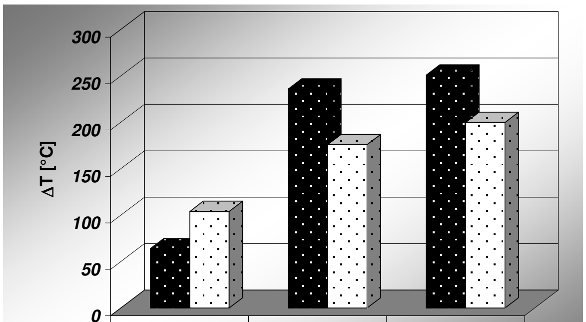
Lower measured temperatures indicate faster cooling and therefore shorter thermal decay times. Figure 3 shows the measured temperature differences, $\Delta T = T - T_0$, at 2.5 ms following a laser pulse under different experimental conditions. Here ΔT represents the temperature increase of the tooth above the initial average room temperature, T_0, measured within a central 0.3mm illuminated spot.



	Er:YAG, MSP	Er,Cr:YSGG, H	Er,Cr:YSGG, S
dentine	64	236	251
enamel	104	176	200

Fig. 3: Enamel and dentine surface temperatures 2.5 ms after a laser pulse

Figures 3 shows the measured temperatures are the lowest with the MSP Er:YAG laser pulses and therefore suggests the same for the thermal decay times. The measured temperatures are higher and thermal decay times longer in enamel than in dentine. At 100mJ pulse energies, the differences between the measured thermal decay curves of the Er:YAG SSP, MSP and SP pulse duration settings lay within the experimental error range. Measurements at higher pulse energies (not presented) revealed thermal decay to be faster for shorter Er:YAG pulse duration settings.

ANALYSIS

The pulsed Erbium laser ablation mechanism of biological tissues is still not completely understood.[14] Most researchers agree that the Erbium lasers' high ablation efficiency results from micro-explosions of overheated tissue water in which their laser energy is predominantly absorbed.[15,16]

The amount of heat that is deposited by a laser pulse on the tooth surface decreases with distance within the tissue. This is partially due to the exponential decrease of laser light intensity within tissue, as provided by

$$I = I_0 \exp(-\mu x) \quad , \qquad (1)$$

where I_0 is the incident laser intensity and μ is the optical absorption coefficient of the tissue for the particular incident laser wavelength.

Heat distribution within the tissue is also created by conductive spreading of heat, i.e. heat diffusion into the surrounding tissue. In the limit of a negligible optical absorption depth, the thermal distribution from a uniformly illuminated surface, for a duration time (t), is approximated by the Gaussian function [17,21]:

$$\Delta T = K \exp(-x^2/4Dt) \, , \qquad (2)$$

where D is the thermal diffusivity of the tissue, and K is a constant that depends on the laser and tissue parameters. The longer the pulse duration and larger the thermal tissue diffusivity, the deeper the heat will spread away from the surface.

Ablation starts when the surface tissue is heated to the ablation temperature T_a. After that, and assuming a confined boiling model of laser ablation [16], surface temperature stops increasing and remains fixed at the "boiling" temperature T_a throughout the ablation process. However, the temperature distribution away from the surface continues to change during the laser pulse as the diffusion does not stop after the ablation threshold has been reached.

In what follows, we assume that the diffusion penetration depth, $d = \sqrt{4Dt}$, is larger than the optical penetration depth, $1/\mu$, and that the thermal distribution at the end of an ablative pulse can be approximated by:

$$\Delta T = (T_a - T_0)\exp(-x^2/d_R^2) \qquad (3)$$

Here the residual depth, d_R, represents the final depth of the heated layer, exactly at the end of a laser pulse and represents a measure of the residual heat deposition. The thinner the layer, the smaller the amount of the deposited residual heat Q_{res} will be:

$$Q_{res} = A\rho c_p \int_0^\infty (T_a - T_0) \exp(-x^2/d_R^2)\, dx, \qquad (4)$$

where A is the laser spot area, ρ the tissue density, and c_p the tissue heat capacity.

Heat continues to diffuse into the tissue and surface temperature starts decreasing below T_a, after the laser pulse has ended. Here, we ignore the much slower

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convective surface cooling into the surrounding air. Assuming a thermal distribution at the end of a laser pulse to be as described in (3), the temporal surface temperature evolution, T, following a laser pulse can be calculated using a one dimensional diffusion equation [17,21]:

$$\frac{\rho c}{\lambda}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2} \qquad . \qquad (5)$$

The one dimensional diffusion equation is taken to be a good approximation since the laser spot diameter is much larger than the diffusion depth. Alternatively, the initial T_a and d_R can be determined from the measured surface temperature decay by fitting the calculated temperature decay curves to the measured results.

The parameters as shown in Table 1 were used in the diffusion model.[19]

	Enamel	Dentine
ρ [kg/m^3]	2800	1960
λ [W/mK]	0.933	0.569
c_p [/kgK]	711	1590
$D = \lambda/\rho c_p$ [m^2/s]	$4.68 \cdot 10^{-7}$	$1.83 \cdot 10^{-7}$

Table 1: Parameters used in the diffusion model.

Figures 4 and 5 show the measured temperature decay data following an Erbium pulse in dentin and enamel and the best numerical fit to the diffusion equation (5).

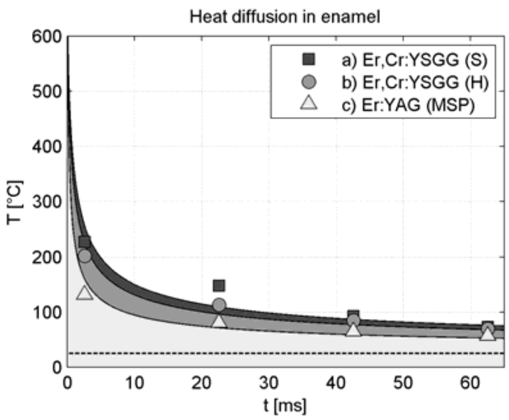

Fig. 4: Enamel surface temperature decay following an a) Er,Cr:YSGG laser S pulse; b) Er,Cr:YSGG laser H pulse; and c) Er:YAG laser MSP pulse. Lines represent a numerical fit to Eq.(5) where the best fit was obtained with diffusion constants d_R of (a) 30µm; (b) 25µm, and (c) 15µm, respectively. The horizontal dotted line represents the initial ambient temperature T_0.

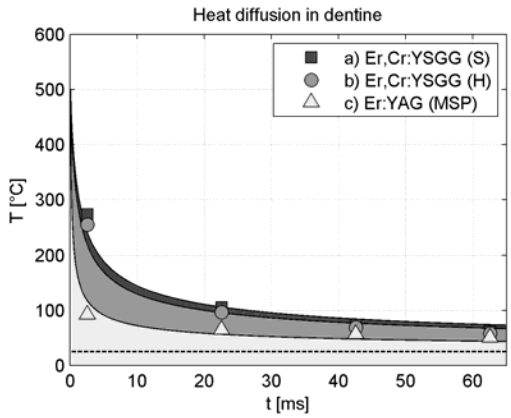

Fig. 5: *Dentine surface temperature decay following an a) Er,Cr:YSGG laser S pulse; b) Er,Cr:YSGG laser H pulse; and c) Er:YAG laser MSP pulse. Lines represent a numerical fit to Eq.(5) where the best fit was obtained with diffusion constants d_R of (a) 22µm; (b) 19µm, and (c) 7µm, respectively. The horizontal dotted line represents the initial ambient temperature T_0.*

The best fit to all measurements is obtained by taking ablative temperatures, T_a, of 600°C ± 50°C for enamel, and 500°C ± 50°C for dentine. Figure 6 presents the obtained residual depths of the deposited heat calculated from data in Figs. 4 and 5.

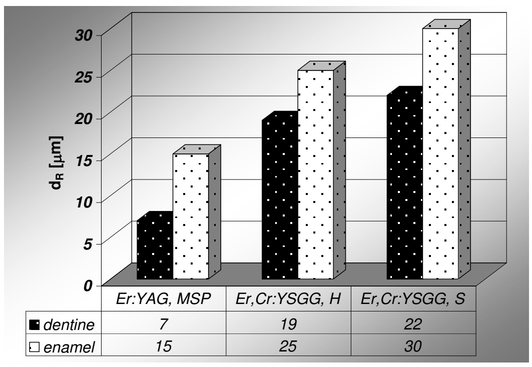

Fig. 6: Calculated residual depths d_R in dentine and enamel, obtained from the thermal decay measurements.

The corresponding values of the residual heat as obtained from (4) are shown in Fig. 7.

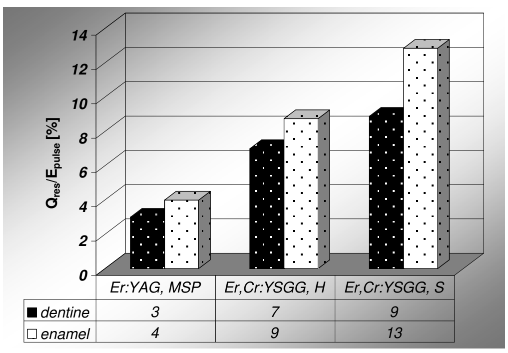

Fig. 7: Residual heat Q_{res} as a percentage of the laser pulse energy E_{pulse}.

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DISCUSSION

A water spray was not used during the measurements as the goal was to determine the residual heat deposition, and not the actual temperature decay times under clinical conditions. Water cooling of the irradiated tooth surface during the laser pulse is not substantial since the water layer is vaporized during the ablative stage and an optical "hole" is made in the layer.[18] Control measurements in which temperature decay curves were obtained following an Erbium laser pulse with a water drop deposited on the tooth, prior to laser irradiation, confirmed this. For either of the laser sources, the water layer did not affect the temperature decay values by more than 10%, which was within the temperature measurement error. As an example, Fig. 8 shows the measured temperature decay curves for the MSP Er:YAG laser pulses, with and without the water layer.

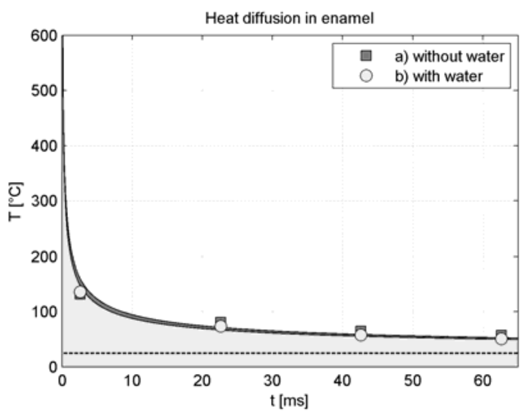

Fig. 8: Comparison of temperature decays following an Er:YAG MSP laser pulse (a) without and (b) with water layer on the enamel surface. The calculated diffusion constant d_R was estimated to be (a) 15µm and (b) 13µm, respectively. Horizontal dotted line represents the initial ambient temperature T_0.

The absorption coefficients µ for the Er:YAG laser are approximately 150mm^{-1} in enamel, and 200mm^{-1} in dentine.[15,20] The corresponding absorption coefficients for the Er,Cr:YSGG laser are approximately three times lower. The Er:YAG laser wavelength thus penetrates approximately 7µm in enamel, and 5µm in dentine (Eq.1). The Er,Cr:YSGG laser wavelength penetrates deeper; 21µm in enamel, and 15µm in dentine. Comparison shows that these optical penetration depths are smaller than the determined residual depths, d_R, under most experimental conditions and in agreement with the assumption of a diffusion-dominated temperature distribution (Eq.3). The actual temperature distribution, especially at shorter pulse durations, is undoubtedly a combination of the optical exponential and diffusive Gaussian function. However, the exact shape of the thermal distribution curve does not have a significant effect on the numerical fitting and the residual depths d_R, obtained by assuming Gaussian distribution. As shown in Fig. 6 it can be taken as a meaningful measure of the thickness of the residual thermal layer and therefore of the residual deposited heat for all considered laser parameters.

At high energies and short pulse durations (i.e. at high laser pulse powers), the ablation speed may become comparable to the rate at which heat diffuses into the tissue.[15] Towards higher laser pulse powers the thermally affected tissue layer is thus reduced by the ablation of the preheated tissue and is increasingly confined only to the directly heated volume within the optical penetration depth. This effect has been experimentally measured by Fried et al, who observed a gradual reduction in the residual heat towards higher laser fluences.[12] This also applies to our experiment, where estimated ablation depths at the fluence used were in the order of 10µm [4], possibly significantly reducing the diffusion-mediated thermal layer. The residual depths, d_R, obtained in our study thus apply only to the specific fluences used in our experiment (approximately 35 J/cm^2).

CONCLUSIONS

The amount of residual heat that remains in hard dental tissues after Erbium laser irradiation has been obtained from the measured rates of the surface temperature decay. The measurements reveal a much faster temperature decay following the Er:YAG laser compared to the Er,Cr:YSGG laser, indicating smaller depth of the remaining heated layer. This is attributed to the shorter pulse duration and smaller optical penetration depth of the Er:YAG laser. For both lasers, the measured residual heat is larger in enamel than in dentine. At pulse energies of 100 mJ, the amount of unwanted residual heat that remains deposited in the tooth is for the H mode Er,Cr:YSGG laser larger by a factor of more than two, and for the S mode Er,Cr:YSGG laser larger by a factor of more than three, compared to the deposited heat with the MSP mode Er:YAG laser. This contributes to the observed lower ablation efficacy of Er,Cr:YSGG lasers [4], and may result in their reduced safety and comfort for patients compared to Er:YAG lasers.

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