The ablation threshold of Er;Cr:YSGG laser radiation in bone tissue

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ABSTRACT

In laser cut clinical applications, the use of energy densities lower than the ablation threshold causes increase of temperature of the irradiated tissue, which might result in an irreversible thermal damage. Hence, knowing the ablation threshold is crucial for insuring the safety of these procedures. The aim of this study was to determine the ablation threshold of the Er,Cr:YSGG laser in bone tissue. Bone pieces from jaws of New Zealand rabbits were cut as blocks of 5 mm × 8 mm and polished with sandpaper. The Er,Cr:YSGG laser used in this study had wavelength of 2780 nm, 20 Hz of frequency, and the irradiation condition was chosen so as to simulate the irradiation during a surgical procedure. The laser irradiation was performed with 12 different values of laser energy densities, between 3 J/cm^2 and 42 J/cm^2, during 3 seconds, resulting in the overlap of 60 pulses. This process was repeated in each sample, for all laser energy densities. After irradiation, the samples were analyzed by scanning electron microscope (SEM), and it was measured the crater diameter for each energy density. By fitting a curve that related the ablation threshold with the energy density and the corresponding diameter of ablation crater, it was possible to determine the ablation threshold. The results showed that the ablation threshold of the Er,Cr:YSGG in bone tissue was 1.95±0.42 J/cm^2.

Keywords: ablation threshold, laser, Er,Cr:YSGG, bone

1. INTRODUCTION

Laser ablation is the process of material removal by laser irradiation. The energy density required for the removal depends on the associated ablation process, the irradiated material and the characteristics of the laser used (mainly wavelength, emission frequency and pulse width).

The infrared emitting lasers such as the Er: YAG (2.94 μm) and Er, Cr: YSGG (2,78 μm) have great potential for usage in the ablation of mineralized tissues, since they are strongly absorbed by the main components of these tissues[1]. Accordingly, the stripping and cutting of the material occurs by thermal ablation process in which the energy deposited by the laser is absorbed by the water present in the material, increasing its temperature. Water heats and increases the pressure inside the tissue, generating a microburst leading to material removal, resulting in an ablation crater[2].

There is no consensus in the literature as to the exact definition of the ablation threshold materials. Kang et al. 2007 state that the ablation threshold corresponds to laser energy density with some 50% probability of removing the material[3]. Lin et al. 2010 and Apel et al. 2002 believe that this probability should be of 80% in order to match the ablation threshold[4,5]. Girard et al. 2007 consider in their experiment that the ablation threshold is the lowest energy density at which it is able to verify changes on the surface by Scanning Electron Microscopy (SEM)[6].

The various ablation threshold settings, as well as the different ways to find it, mean that there is a significant difference between the ablation thresholds reported in the literature for the same material when using the same laser, as it can be seen in Table 1.

In this study, we determine the bone tissue ablation threshold for the Er, Cr: YSGG laser, to assist in the selection of energy density used in surgical procedures.

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Table 1- Values of ablation threshold reported on literature from bone, enamel and dentine.[3–7]

Material	Wavelength (nm)	Frequency (Hz)	Pulse length (µs)	Presence of refrigeration	Ablation threshold (J/cm^2)
Human enamel[3]	2790	5 - 50	100 - 150	yes	2.1
Human enamel desiccated[3]	2790	5 - 50	100 - 150	no	1.2
Human dentine[4]	2790	20	100	yes	2.69 – 3.66
Human enamel[5]	2790	5	200 - 250	no	10 - 14
Human dentine[4]	2940	1	140 - 5000	yes	2.97 – 3.56
Human enamel[5]	2940	5	200 - 250	no	9.0 – 10.0
Human dentine[7]	1064	100	1,0 – 2,0	no	200
Human enamel[7]	1064	100	1,0 – 2,0	no	300
Big cortical bone[6]	775	1000	$200x10^{-9}$	no	0.69 +/- 0.08
Big cortical bone[6]	387	1000	$200x10^{-9}$	no	0.19 +/- 0.05

2. METHODOLOGY

This study was approved by the Animal Ethics Committee of IPEN (6/CEPA-IPEN/SP).

Samples preparation

The determination of bone ablation for filing the Er, Cr: YSGG was performed in ex-vivo bone tissue using the mandible bone of nine adult New Zealand rabbits. By using a high-speed diamond tip, bone blocks of approximately 15 x 8 mm have been removed from each side of the jaws. These blocks were subsequently divided into two or three blocks of approximately 5 x 8 mm and polished with sandpaper. Until irradiation, the samples were kept in a refrigerated and moist environment.

Laser Er,Cr:YSGG

We used the Er,Cr:YSGG laser (Waterlase, Biolaser - USA), with a wavelength of 2.78 µm. It is effective in causing ablation of mineralized biological tissues because its wavelength is strongly absorbed by water and hydroxyapatite causing a minimum amount of heat to be transmitted to the underlying tissues. The knowledge of this laser effects in biological tissues is of great importance for its application[8].

The beam delivery system is carried out by a flexible and highly sensitive optical fiber system and a hand piece that allows several options sapphire tips in the beam output. The system also features a water jet and air to cool the samples during irradiation when desired.

Samples irradiation

The samples were placed on a high precision motor shifter (ESP300, Newport Corporation, Invine, CA, USA) in order to standardize the location of each irradiation, and the laser was positioned approximately 1 mm from the sample surface. The output tip used in the experiment was the G4, with a diameter of 600 µm, according to manufacturer's specifications. It was chosen because both its diameter and length allow good accuracy during bone cutting. Water and air used for cooling were adjusted at 80%, following the recommendations given by the manufacturer for hard tissue procedures. Irradiation at each energy density was performed at the same location in the sample for 3 seconds and with an overlap of 60 pulses. As previously mentioned, the irradiation condition was chosen to simulate the irradiation during surgery.

Fifteen samples were used and, for each of them, 12 irradiations were performed with different energy densities, as illustrated in Figure 1. The values of used energy densities are shown in Table 2. We tried even the minimum energy allowed by the laser equipment until 12 different energies were obtained, varying the energy in the least variation made possible by the equipment.

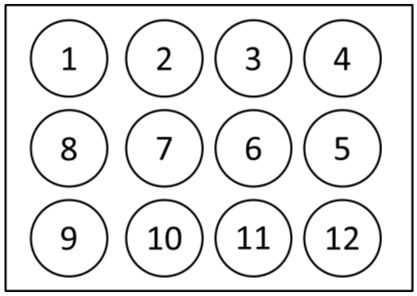

Figure 1 - Illustration showing how the laser irradiation was performed on each sample.

Table 2 – The laser energy density used in determining the ablation threshold bone

Group	**Energy Density (J/cm^2)**
1	2.9
2	6.6
3	9.7
4	14.3
5	17.7
6	20.7
7	24.5
8	28.0
9	29.4
10	33.4
11	37.8
12	42.3

After irradiation, the samples were analyzed by SEM with an increase of 40X and 100X, and it was checked the diameter of the formed crater for each energy density.

Threshold of ablation

In determining the ablation threshold of the Er, Cr: YSGG laser, it was used the Baudach method. This method assumes that the laser features a beam with a Gaussian energy distribution, i.e. the beam energy falls exponentially towards the center of the edge, a condition met by the Er, Cr: YSGG laser. In this case, the size of the craters is related to the energy density used for irradiation[9,10].

In order to determine the ablation threshold using the Baudach method, the diameter of each ablation crater was measured and we calculated the mean and uncertainty of the diameter of the crater for each energy density. We plotted a graph of the crater diameter and the energy density, by adjusting the following function:

$$D^2 = r_{ef}^2 . \ln(E) + r_{ef}^2 . \ln(2) - r_{ef}^2 . \ln(\pi . r_{ef}^2 . F_{th}) \quad (1)$$

where D is the diameter of the ablation crater, E is the energy used, Ref is the effective radius of the laser beam and FTH is the threshold ablation[9]. Thus, by making use of this adjustment, it is possible to find the laser effective radius, apart from determining the ablation threshold.

3. RESULTS

A SEM image with a 40X increase in an irradiated sample is shown in Figure 2, as the value of the energy density corresponding to each crater is also indicated in Fig. It can be seen that the crater is better defined the greater the energy density is used. One can also notice that greater energy density leads to higher diameter of the resulting craters and that from the second energy density used on, the sample was perforated with larger craters sizes for higher power densities.

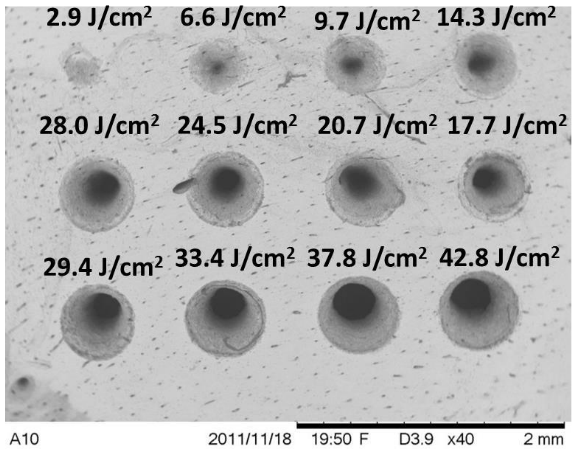

Figure 2 – SEM image of one irradiated sample showing the ablation crater for the 12 energy density used.

The mean values of the diameters of the craters for each energy density used are shown in Table 3 along with their uncertainties. The obtained values confirm the increase in diameter of the ablation craters as there is an increase in the used energy density, actually an expected trend for this type of laser. The ablation in Group 1 (energy density of 2.9 J/cm^2) was small by the irradiation conditions used, and it was not possible to observe a regular ablation crater. Thus this group was removed from the analysis.

Table 3 – The laser energy density used in determining the ablation threshold bone

Group	Average Diameter (μm)	Standard error (μm)
2	425	38
3	480	44
4	543	34
5	589	11
6	598	14
7	613	19
8	624	22
9	630	23
10	643	22
10	651	21
12	665	20

We built the Napierian logarithm graph of energy (ln (E)) by the square of crater diameter (D2), and performed the adjustment of Expression 1, as shown in Figure 3. The values found for the ablation threshold and the effective radius of the laser are presented in Table 4

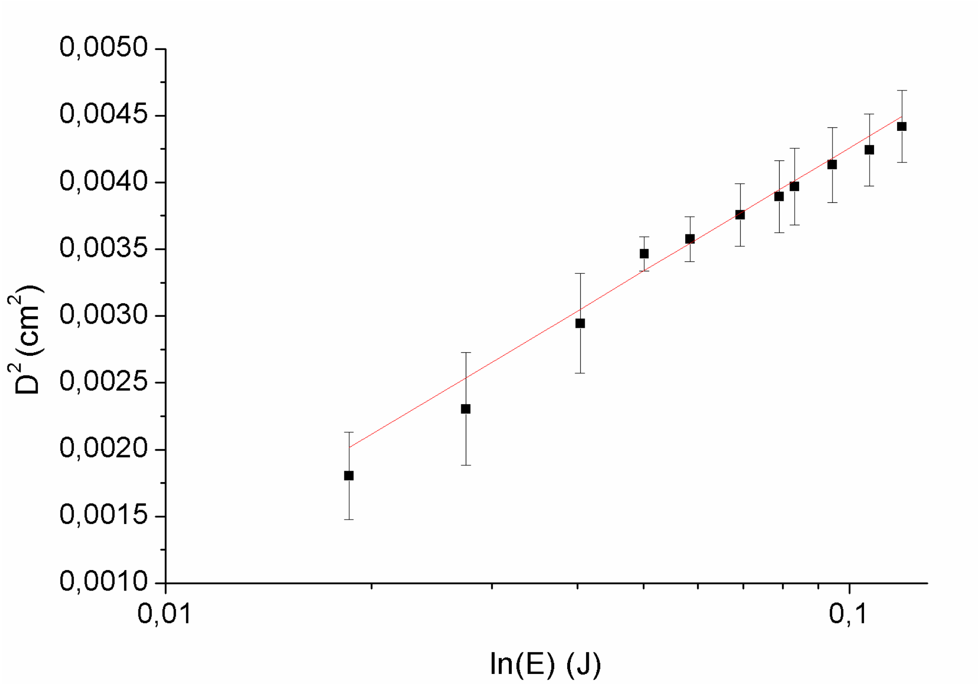

Figure 3- Plot of equation (1) on the dates showed on Table 2 (laser energy) and Table 3 (crater diameter).

Table 4 – Values of the ablation threshold and effective radius of the beam:

Threshold Ablation (J/cm^2)	1.95±0.42
Effective radius of the laser beam (cm)	0.364±0.022

The value of the effective radius of the laser beam obtained by Baudach method is compatible with the value provided by the manufacturer within three standard errors. However, considering the beam divergence and the fact that irradiation was 1 mm away from the laser output, it can be said that the comparison with the nominal radius of the beam supplied by the manufacturer is not adequate. Thus, the expected value of the effective radius must be greater than supplied by the manufacturer, as previously noted and the expected value for the effective radius

The obtained value of the ablation threshold is also in agreement with the expected value, as, considering the uncertainty, there is a 95.4% probability of ablation occurrence in the sample when using a power density value of 1.11 - 2.79 J/cm^2. By comparing this interval with the ablation threshold values shown in Table 1 for a similar wavelength laser, it appears that this value is somewhat lower than needed for ablating dentin, which is an expected result due to the similarities in their compositions and the larger amount of organic material in the bone tissue.

The results show the importance and influence that the chosen method has on the ablation threshold value and justifies the differences between ablation threshold values obtained for materials and laser reported in the literature.

4. CONCLUSION

The ablation threshold of laser Er,Cr:YSGG for bone tissue was 1,95±0.42 J/cm^2, and the effective radius of the Er,Cr:YSGG laser when the G4 tip was used and the sample was located 1 mm of the laser output was 0.364±0.022 cm. These results can be used as references values for the applications of this laser in dental surgery or in applications that require the bone cut.

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