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ABSTRACT

The aim of the present study is to investigate the effect of laser pulse duration on ablation efficiency of hard bones. The bones were ablated using a microsecond pulsed Er-YAG laser. The laser wavelength was 2.94 μm and the repetition rate was 10 Hz. Three samples of porcine femur were used and several areas were ablated with a fixed pulse energy of 280 mJ and different pulse durations. The ablation procedure was applied during five seconds for all the experiments, therefore, the same amount of energy (14 J) was deposited in each trial. The ablation efficiency was determined by measuring the ablated volume per second for each experiment.

Keywords: pulse duration, ablation efficiency, Er-YAG laser, pulse energy, bone ablation.

1. INTRODUCTION

In conventional hard tissue surgeries, unwanted injuries can occur as well as collateral damage to soft tissue in the surroundings. Those side effects are due to heat and vibrations during the surgical procedure.[1] To avoid these side effects that mainly arise from direct-contact interaction between the tools and the tissue, cutting tissue with laser light (so-called laser ablation) can be a solution. Laser ablation allows contact-free ablation of bone which offers several advantages since the control system can be developed to be very accurate and monitored (robotic guidance): small cuts and flexible shapes can be achieved. Laser technology for medicine has been mostly used in soft tissue applications such as dermatology,[2] ophthalmology,[3] otolaryngology[4] and dentistry.[5]

Several investigations have been also devoted to the study of laser ablation in bone. Up to now, there is no laser which can perform hard-tissue ablation at high speed and high volume ablation rate as the mechanical tools can do in osteotomy: for instance, in spine surgery and craniotomy.[6] Thus, laser surgery for hard tissue remains a challenge in surgery. The only exception is dentistry, where lasers have made their way to the surgeons since the necessary cuts are not deep and thus cutting speed is not an issue.

The initial investigations on laser hard-tissue ablation took place in 1965,[7–9] performed on dental structures after the invention of the Ruby laser (1960). Those studies have been extended together with the implementation of laser ablation in dentistry.[5,10–14] Currently, the erbium-doped yttrium aluminium garnet (Er:YAG) pulsed laser has achieved the most successful results in dental surgery.[15–17] The Er:YAG laser used for dental applications works typically in the microseconds regime and has a wavelength of 2.94 μm. This wavelength coincides with the absorption coefficient peak of water and hydroxyapatite, the main component of bone.

There are studies which already show that the ablation efficiency of lasers is proportional to the pulse energy.[18] In this work, we performed studies on bone ablation and analyzed the ablation efficiency while changing the pulse duration of the laser but keeping the pulse energy constant. The ablation efficiency is defined as the ablated volume per time unit.

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Third International Conference on Applications of Optics and Photonics, edited by Manuel F. M. Costa,
Proc. of SPIE Vol. 10453, 104531S · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2272253

2. MATERIALS AND METHODS

2.1 Laser system and ablation method

A high power Er:YAG dental laser system (Syneron litetouch LI-FG0001A) of 2.94 μm wavelength was used to perform ablation in ex vivo porcine bones. Pulse durations between 244 μs and 388 μs were used with an emission of an approximately Gaussian shape. A fixed pulse energy of 280 mJ, a repetition rate of 10 Hz, and therefore, an average power of 2.8 W was used. The ablation time per trial was 5 seconds, which provides a total deposited energy of 14 J per trial. The experiments were performed in free space (Fig. 1) with the help of a set of lenses: $f_1 = -20$ mm and $f_2 = 80$ mm form a telescope system for expanding the beam, and $f_3 = 80$ mm for focusing the beam on the bone surface. A variable aperture was used to keep the pulse energy constant for all the experiments. The aperture was used carefully in such a way that no diffraction effects were present during the experiments. A sapphire window was used in front of the optical system for its protection from the scattered particles due to the laser ablation process.

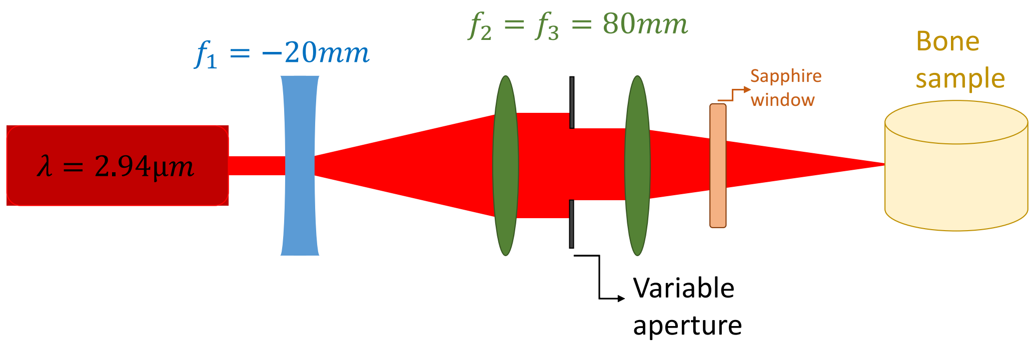

Figure 1. Sketch of the setup used to ablate bone with the Er:YAG laser.

The ablation process in bone performed by the Er:YAG laser is due to the absorption coefficient peak of water and hydroxyapatite (the main component of bone). When the hydrated bone is exposed to microseconds or nanoseconds Er:YAG laser pulses, there are effects of vaporization and cavitation. These effects lead to tissue removal, called photo-thermal ablation[19]

Three pig femur samples were stored at -18°C and were thawed approximately 4 hours prior to ablation at 4°C. Six different holes were created corresponding to six different pulse durations of the laser and the same experiment was performed for three samples. Additionally, a simple cooling system was used by continuous water irrigation using a spray rate of 114 mL/min.[20]

2.2 Computed tomography analysis

A micro-computed tomography analysis was performed to measure the ablated volume on the samples. A SkyScan1275 scanner with a source type Hamamatsu L11871 and a resolution of 18 μm in each direction was used. The angle step used for this measurement was 0.25°, obtaining 1441 projections for each bone sample and 3 frames average. The scanner used a copper (Cu) beam hardening filter to avoid low energy electrons that would produce artifacts in the images. The three-dimensional reconstruction of the samples was performed after the scanning (see Fig. 2).

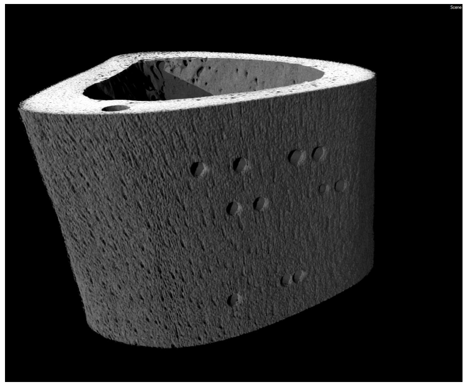

Figure 2. Reconstructed ablated bone after computed tomography (CT). The holes shown in the image correspond to the ablated areas.

3. RESULTS

First of all, the pulse energy of the Er:YAG laser was measured as a function of the pulse duration at FWHM (Fig. 3) from 244 μs to 388 μs. The pulse duration and repetition rate of the laser were measured by means of a PbSe sensor (PDA20 from thorlabs) and an oscilloscope (Fluke 190-504). An infrared neutral density filter (NDIR20A, thorlabs) together with a bandpass filter (FB3000-500, thorlabs) for filtering the flash pump were used.

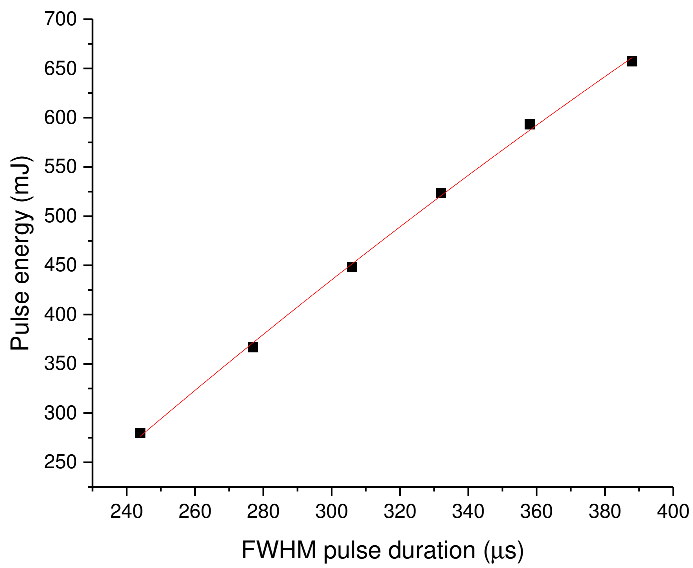

Figure 3. Pulse energy measurement.

The tendency shown in Fig. 3 was fitted with a second degree polynomial function, obtaining a coefficient of correlation of $r^2 = 0.99897$ for the measured pulse energies.

For the measurement of the ablated volume, tomography scans were taken and the bone sample was reconstructed in 3D. Afterwards, the volume was determined with the help of the SkyScan software, the graph in Fig. 4 shows the ablated volume for 5 seconds exposure time and for each pulse duration. The average ablated volume was $0.82\,\text{mm}^3$ with an standard deviation of $\sigma = 0.098\,\text{mm}^3$. As observed, the change in pulse duration does not have a considerable effect on the ablated volume. Moreover, the deviation of the measurements is very small, therefore the ablated volume is approximately the same for all the experiments.

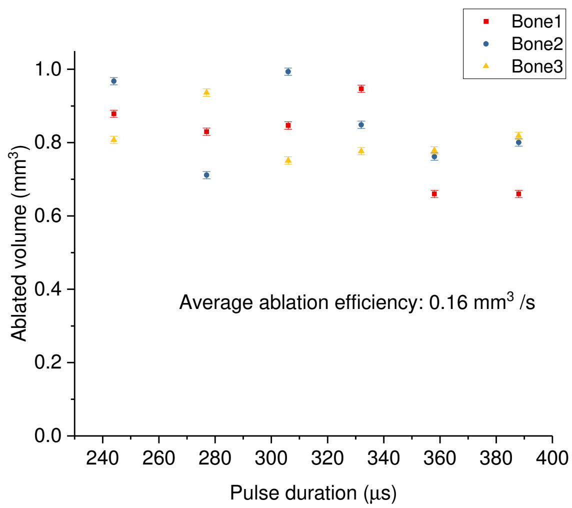

Figure 4. Ablated volume for each pulse duration for the three samples. The average ablated volume is $0.82\,\text{mm}^3$ in five seconds.

The ablated volumes have conical shapes and for visualization purposes, we chose the height at which the ablated area is more pronounced, and those slices are shown in Fig. 5 for each sample and for each pulse duration used during the ablation processes. Each sample has more ablated regions than the evaluated ones, this is because some of them were not taken into account due to errors during the experiments.

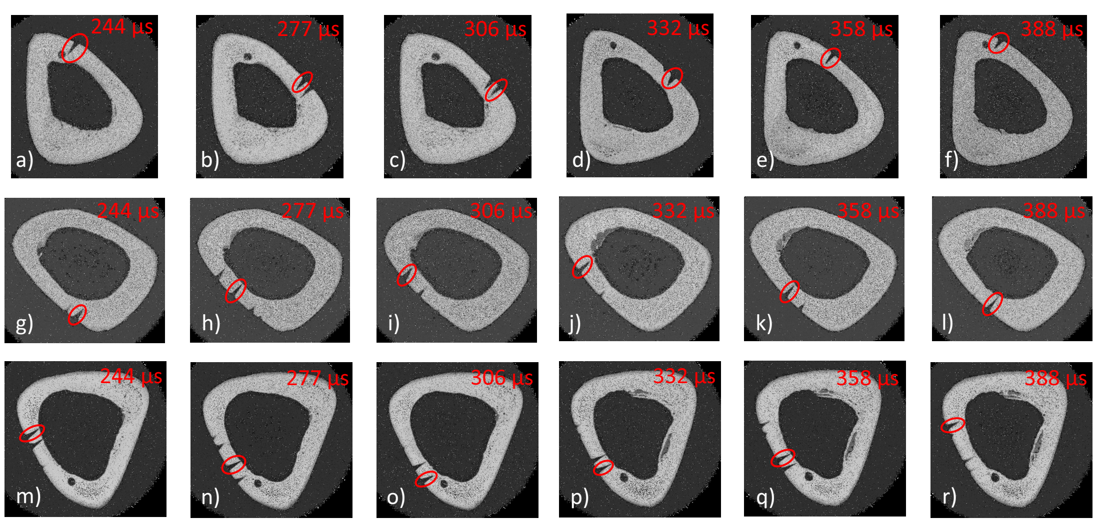

Figure 5. Images of the slices at which the ablated region is bigger. Panels a-f: sample 1. Panels g-l: sample 2. Panels m-r: sample 3. Each sample was ablated in six different regions (holes) for the pulse durations: $244\,\mu$m, $277\,\mu$m, $306\,\mu$m, $332\,\mu$m, $358\,\mu$m and $388\,\mu$m.

4. CONCLUSION

During the performance of the experiments, we confirmed that the higher the energy of the laser, the greater the ablated volume. This result is not shown here because it is out of the scope of this paper and also because there is already literature reporting that.[18, 20] Instead, the effect of pulse duration in the ablation efficiency was shown in this paper for a pulse duration region from 244 μs to 388 μs, which corresponds to a change of 370 mJ in the pulse energy of the laser. This change in energy would lead to considerable changes in the ablation efficiency (as already shown in previous studies) if no aperture were used for keeping the energy constant (in our experiments, an energy of 280 mJ was kept constant for all pulse durations by means of a variable aperture). This shows that the pulse energy of the laser and not the pulse duration is responsible for the ablation efficiency in this pulse duration region. The average ablated volume was 0.16 mm^3 with a small deviation of the data $\sigma = 0.098\,mm^3$. Further experiments should be performed with improving the cooling system for the tissue during the surgery, because the better the cooling system, the better the ablation performance of the laser. Carbonization should be also studied by scanning electron microscopy and by histological tests to monitor the state of the bones after the ablation process.

ACKNOWLEDGMENTS

The authors gratefully acknowledge funding of the Werner Siemens Foundation through the MIRACLE project and Mr. Marek Zelechowski for his collaboration and support on running the laser.

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