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Ultrashort Pulse Laser Osteotomy

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Abstract—Laser treatment of bone tissue has already been the subject of many studies to find substitutes for mechanical instruments that are nowadays used in implantology and orthopaedics. Mainly lasers with pulse durations in the μs region have been tested leaving surface features that are not always satisfactory. Therefore, in the present study laser osteotomy has been performed with a 330 fs Yb:glass laser, $\lambda = 1040$ nm, at a pulse repetition rate of 1 kHz. For bovine spongiosa, compacta, and cartilage, the ablation thresholds as well as the ablation rates for various pulse energies have been determined. Additionally, quadratic areas have been ablated in bone tissue. The remaining morphology has been analyzed via scanning electron microscopy. Laser ablation has also been performed with an Er, Cr:YSGG laser, $\lambda = 2780$ nm, PRR = 20 Hz, $\tau \sim 50$ μs. The results of USPL and Erbium laser ablation are compared.

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INTRODUCTION

The first questions one has to ask before going deeper into this subject are: what is laser osteotomy and why is laser osteotomy that interesting? The incipient question can be answered briefly. Laser osteotomy is the treatment of bone tissue using laser systems instead of mechanical tools. The answer to the second questions requires more detailed information. In orthopedics and implantology, mechanical tools such as saws, drills, and diamond discs are commonly used for bone tissue treatment. Nevertheless, their use is accompanied by several disadvantages:

(1) When operating with mechanical tools, friction arises that may cause high temperatures. As a consequence of excessive temperatures, the vital bone cells may be destroyed and the regeneration process of bone tissue is extended or even inhibited. Absolute temperatures of >43°C applied for seconds to minutes already yield irreversible damage such as membrane damage with edema or denaturations of enzymes. Temperatures of >60°C applied for less then a second can lead to necrosis [1].

(2) In the case of a drill, a smear layer is produced and saws can generate rough surfaces.

(3) Furthermore, the size and shape of traditional mechanical tools often make them unsuitable for geometrically complicated incisions and for minimal invasive treatment.

Therefore, different laser systems in the μs (10^{-6} s) and sub-μs pulse regime, among them Erbium lasers, have already been tested by other research groups [1–12] in the hope of overcoming the above drawbacks. Although some authors consider Erbium lasers as useful tools in surgery [2, 3], the results are often not very satisfying and sometimes even controversial. The drawbacks considered include, e.g., melting, carbonization, and unfavorable cavity shapes. They are mainly due to the long pulse durations of these laser systems and the underlying ablation mechanism which is water-mediated. When the laser beam is focused onto the tissue surface, the energy contained in the pulses is mainly absorbed by water embedded in the tissue as the absorption peak of water coincides with the Erbium laser wavelengths (~3 μm). The water is heated up and expands. Microcracks are induced and microexplosions take place which expel tissue particles. This ablation mechanism is quite rough compared to the plasma-induced ablation associated with ultrashort pulse lasers (USPL). When the USPL beam is focused, high power densities in the TW/cm^2 region are generated at the tissue surface. Through multiphoton absorption, free electrons are created. Subsequent impact ionization supports plasma formation. Due to the hydrodynamic laws, the plasma is ejected. The remaining cavity is very smooth compared to the rough surfaces common after Erbium treatment.

Therefore, in the present study an USPL system has been tested and evaluated for bone treatment. A 330 fs Yb:glass laser in combination with an *x*–*y* scanner has been employed. Ablation thresholds and ablation rates have been determined for bovine compacta, spongiosa, and cartilage. Additionally, the morphology of the remaining cavities has been inspected. The results obtained have been compared to Erbium laser ablation of bone tissue. Therefore, a commercially available Er, Cr:YSGG laser already applied for dental treatments has been employed. Nevertheless, the study has been conducted with the expectation of superior performance by the USPL system compared to Erbium systems. This anticipation can be confirmed.

MATERIALS AND METHODS

The ultrashort pulse laser system involved in this study was the IC-1040 fs Yb:glass AMP produced by High Q Laser Production GmbH, Austria. Its specifications are a center wavelength of 1040 nm and pulse duration of 330 fs. It has been operated at a 1 kHz pulse repetition rate, thereby yielding the maximum average pulse energy of 130 μJ. Because it is designed for technical applications, the USPL has been used with open beam propagation. The beam diameter at the exit of the system is 1.7 mm. After passing a λ/2-plate to attenuate and regulate the pulse energy, the laser beam was directed through a convex lens of 100 mm focal length. The knife-edge method was applied to measure the resulting $1/e^2$ diameter of the focal spot, which was determined to be 72.4 μm.

For ablation threshold and ablation rate determination, the samples mounted on a motorized *x*–*y*–*z* translation stage were positioned in the focal plane. During ablation, the samples were moved at a speed of 1 mm/s, which implies that an average of 72.4 pulses overlapped during movement. By using this method, grooves of 4 mm in length were generated for decreasing pulse energy values from 130 to 10 μJ in steps of 10 or 5 μJ, respectively.

The prepared samples were analyzed via digital light microscopy. Through the micrographs, the diameters and depths of the prepared lines were determined.

These diameters and depths have just been obtained in the middle part of the lines which is not affected by distorting acceleration and deceleration effects caused by the translation stage. The measured diameters were used to calculate the ablation threshold, while the etch depths are the basis for ablation rate determination.

The Erbium laser, an Er, Cr:YSGG system (Biolase Waterlase), is already used in dentistry for cavity preparations. It has a wavelength of 2780 nm, maximum pulse energy of 300 mJ, and fixed pulse repetition rate of 20 Hz. Its pulse duration is 53 μs. The laser beam is led through a fiber delivery system before it is coupled out by a conical sapphire tip which is mounted on a handpiece. Erbium laser treatment has always been accompanied by an air–water spray.

Besides ablation threshold and ablation rate measurements, the morphology of bone material after laser treatment was examined. In the case of the Yb:glass laser with a focal spot diameter in the μm region, scanning of the laser beam was necessary to treat larger areas. Therefore, an *x*–*y* scanner (SCANcube 7 from Scanlab AG, Germany) was used. Erbium laser ablation was performed without this scanner. The remaining cavities were analyzed by means of environmental scanning electron microscopy (FEI/PhilipsXL30 ESEM, The Netherlands).

Fresh bovine compacta, spongiosa, and cartilage served as bone samples. The samples were cut into cubes of 1 cm side–length for better handling. Compacta was additionally ground with carbide paper to smoothen the surface. Grinding of spongiosa and cartilage would have destroyed the natural morphology of the tissue. All biological samples were stored in saline solution and kept refrigerated until the ablation.

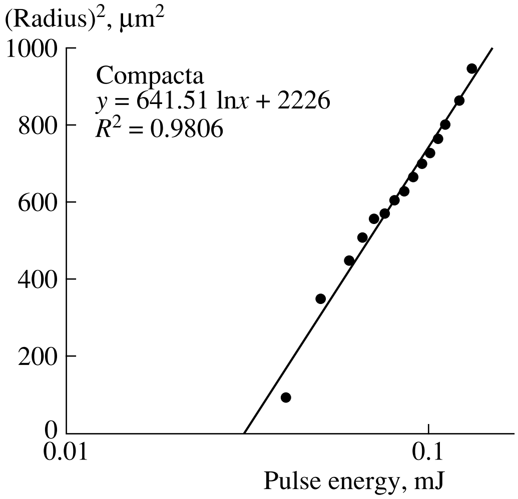

Fig. 1. Determination of the ablation threshold for the 330 fs Yb:glass laser ablation of compacta according to Eq. (2).

RESULTS AND DISCUSSION

Ablation Thresholds

The starting point for determining the threshold fluence of the 330 fs Yb:glass laser for compacta, spongiosa, and cartilage ablation is the following well-known equation of the Gaussian beam profile:

$$\Phi(r) = \Phi_0 e^{-\frac{2r^2}{\omega^2}}, \tag{1}$$

where $\Phi(r)$ is the fluence at the radial distance r, Φ_0 is the maximum fluence, and ω is the radius of the beam waist. Rearranging Eq. (1) yields

$$r^2 = \frac{\omega^2}{2}\ln\left(\frac{\Phi_0}{\Phi_{\text{th}}}\right), \tag{2}$$

where r represents the radius of the ablation site at the ablation threshold Φ_{th}. According to this equation, the squared radii of the ablated grooves were drawn versus the applied pulse energies in a semilogarithmic plot. Regression tools applying the least-square fit and extrapolation allowed for the calculation of the ablation threshold. The graph in Fig. 1 shows this procedure for compact bone tissue.

For all three different types of bone materials, the ablation threshold for the USPL system was determined. The results are listed in the table.

The ablation thresholds were determined for just the USPL system. The dental Erbium laser could only be operated in a limited set of parameters. Ablation thresh-

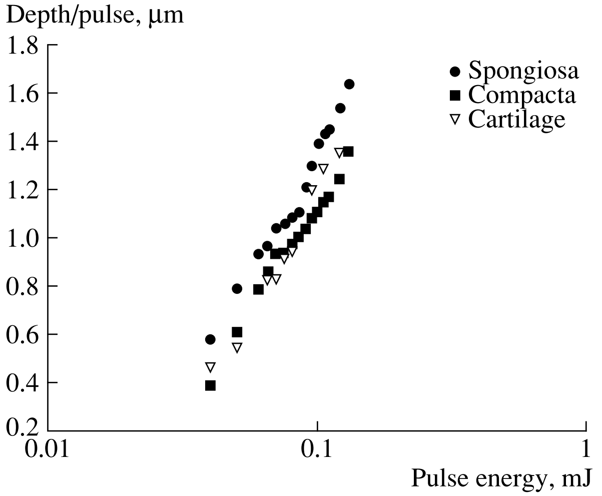

Fig. 2. Etch depth per pulse vs. rising pulse energy obtained in spongiosa, compacta, and cartilage with the Yb:glass USP laser.

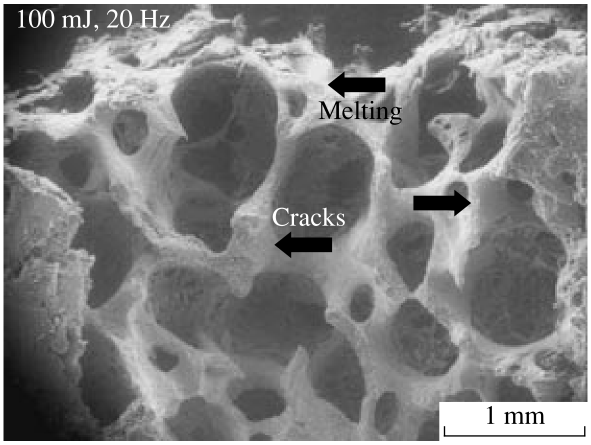

Fig. 3. View of the cavity walls of Erbium laser ablated spongiosa. Although the trabecular structure is preserved, some cracks and melting appear.

old determination for this system would have been too inaccurate. Therefore, values from the literature shall give an overview of Erbium ablation thresholds of bone tissue. The group working with Jovanvovic [9] reports on an ablation threshold of less than 5 J/cm^2 for bovine compact bone. They used an Er:YSGG laser with a temporal pulse duration of 500 μs at FWHM and a focal spot diameter of 480 μm. Walsh et al. [10] found a threshold energy density of 2.1–3.4 J/cm^2 for pig parietal bone. An Er:YAG laser ($\lambda = 2.94$ μm) operated in normal spiking mode with a macropulse duration of 200 μs and a 1.1 mm round spot at the tissue surface was used in their study.

Fried and Fried [11] determined the thresholds of an Er:YAG laser in adult bovine skulls. The laser was operated in free-running mode with a pulse duration of 300 μs and in Q-switched mode yielding a pulse duration of 0.5 μs. They determined threshold fluences of ~10 and <2 J/cm^2, respectively.

Although different types of bone tissue are considered, one can clearly see that the ablation thresholds of Erbium lasers are well above the USPL values determined in our study. This is due to the longer pulse durations associated with Erbium systems and the different ablation mechanisms—water mediated versus plasma induced—corresponding to Erbium and USPL ablation, respectively.

Ablation Rates

The ablation rates defined as the etch depth per laser pulse were determined by measuring the depths of the grooves generated during the line scans of the USPL. As mentioned above, line scans were performed with a velocity of 1 mm/s. An overlap of ~97% has, therefore, been considered in our calculations. Referring to Ivanenko et al. [12], this was done using the following equations:

$$n = PRR\omega/v, \tag{3}$$

$$N_{\mathrm{eq}} = N_{\mathrm{pass}}n, \tag{4}$$

$$\delta D = D/N_{\mathrm{eq}}, \tag{5}$$

where n is the geometrical pulse overlap factor on the tissue, PRR marks the pulse repetition rate, ω is the beam waist at $1/e^2$ level, v is the velocity of the line scan, N_{eq} is the equivalent pulse number, N_{pass} is the number of passes of the scans, D represents the depth of the ablated grooves, and δD is the ablation depth per laser pulse to be determined.

In Fig. 2, the obtained ablation rate values for all three types of bone tissue are drawn versus rising pulse energies in a semilogarithmic plot.

The etch depth per pulse of spongiosa is largest for all of the applied energies. This is due to the bridge-like trabecular structure of the tissue with its intertrabecular space, i.e., holes surrounded by trabeculae which are filled with blood vessels (see Fig. 3). Including this intertrabecular space, it is clear that the overall volume removed by the laser pulse is larger than for other bone tissue types with their compact structure. For pulse energies below ~80 μJ, ablation rates for compacta and cartilage are comparable. Above that energy, cartilage is more ablated than compacta. This behavior seems logical because of the structure and hardness of compacta and cartilage.

Besides this, the data points for each bone sample captured in Fig. 2 follow a line in this semilogarithmic plot. That implies that the theoretical law

$$D = \frac{1}{\alpha_{\mathrm{eff}}}\ln\left(\frac{\Phi_0}{\Phi_{\mathrm{th}}}\right), \tag{6}$$

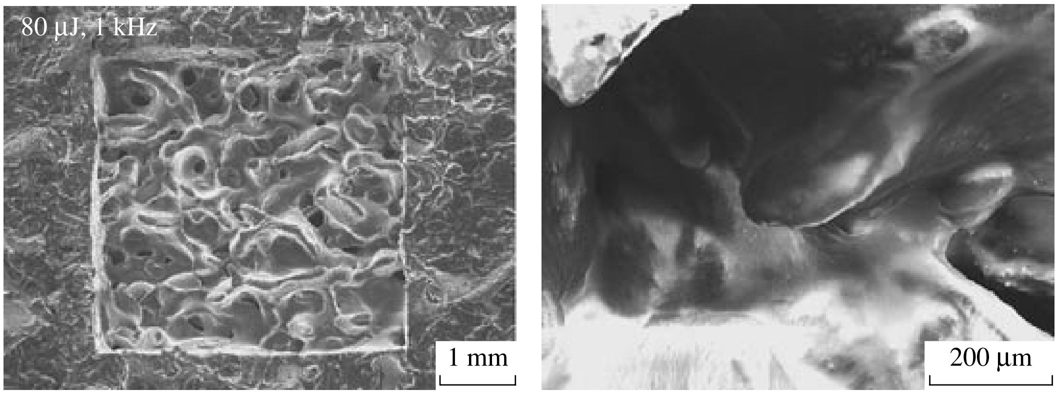

Fig. 4. Left: USPL ablated cavity in spongy tissue. A rectangular scan algorithm has been applied. Right: Magnification of a cut border on a single trabeculum. The absence of bubble-like structures is an indicator of melting-free ablation.

where a_{eff} is the effective absorption coefficient, is valid.

Nevertheless, compared to the Er, Cr:YSGG system, the obtained ablation rates per pulse are very small. For example, when a power density of ~1000 W/cm^2 is applied for both systems, the Erbium laser ablates 0.157 mm^3/s of compacta while the USPL ablates 3×10^{-4} mm^3/s giving a ratio of 474. For cartilage, the situation is similar. The Er, Cr:YSGG laser ablates 0.140 mm^3/s and the USPL removes 5×10^{-4} mm^3/s. That means that the Erbium laser ablates 279 times more material per second than the USPL system. To enhance the ablation speed of the USPL system, higher pulse repetition rates combined with higher scan velocities have to be applied. Adjusting the scan parameters according to the laser setting is necessary to avoid accumulation effects. By doing so, even higher PRR yield excellent results concerning the morphology of the remaining cavities as earlier morphological studies of dental tissue conducted in our workgroup revealed. This is also expected for bone tissue. Ablation of bone tissue with higher PRR will be the subject of further studies.

Morphology

Although the ablation speed of USPL with the available PRR is not that favorable, the morphology of USPL treated cavities is very convincing. In Figs. 3 and 4, the morphology of Erbium and USP laser prepared cavities in spongiosa are shown. Fig. 3 depicts the view of the cavity walls of an Er, Cr:YSGG laser ablated cavity. The cavity was sectioned through the center line using a diamond saw. The outermost parts on the left and right side of the picture reveal the cut surfaces. Just the inner part of the picture should be considered when evaluating the ablation performance. At first sight, the remnants from laser treatment do not look that bad as the trabecular structure is preserved. Yet, a more detailed analysis reveals cracks as a sign of dehydration due to overheating and melting on the cut borders. Additionally, the cut borders are very rough. This is a result of the quite rough ablation process with its microexplosions.

These unwanted side effects cannot be identified in Fig. 4, which captures a rectangular USPL cavity. The left ESEM picture gives an overall impression of the cavity, whereas the right side depicts the magnification of a single trabecula cut by the laser. The natural structure of spongiosa remains untouched, whereby the rims of the cavity are smooth and well-defined. The magnification shows no evidence of cracks, melting, or carbonization. It must be emphasized that USPL ablation in contrast to Erbium laser ablation was performed without the cooling effect of an air–water spray and that even in this case superior features of the morphology have been obtained. When scanning the USPL beam in the shape of a rectangle, overheating and, therefore, melting may appear at the corners of the cavity because of accumulation effects. This can be avoided by using a shutter that blocks subsequent laser pulses from impacting onto the same tissue spot.

If too high pulse energies are applied, melting occurs for Erbium as well as for USPL ablation. But, in case of Erbium laser, whole trabeculae may be removed so that the natural structure of the tissue is completely destroyed. This is not the case for USPL ablation. That means that, if inappropriate laser parameters are erroneously used, the risk of destroying whole areas of tissue can be drastically reduced by using USPL.

List of obtained ablation thresholds of the Yb:glass USPL for bovine spongiosa, compacta, and cartilage

Material	Ablation threshold, J/cm^2
Spongiosa	0.82
Compacta	0.78
Cartilage	0.54

Morphological analysis of compacta and cartilage ablated with Erbium and USPL, respectively, shows similar features as discussed within this paragraph.

CONCLUSIONS

Using USPL for bone tissue treatment has shown several advantages over Erbium lasers. In addition to the lower ablation thresholds for spongiosa, compacta, and cartilage which are less than 0.8 J/cm^2, the morphology of the remaining cavities convinces us of the usefulness of scanned USPL for bone preparations. Some advantages of USPL osteotomy are listed in the following:

- gentle and contact-free preparation technique,
- no external forces, which is especially useful for porous and brittle bone tissue,
- hygienic and sterile,
- almost no melting, carbonization or microcracks,
- the nearly complete absence of collateral damage,
- selective ablation,
- precise cavity preparation, and
- minimal invasive treatment.

All of these promise better healing conditions while the disadvantages may only include the low ablation rates compared to Erbium lasers. Nevertheless, the ablation procedure can be accelerated by applying higher PRR using improved USP laser models and more appropriate scan parameters.

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