Analysis of the short-pulsed CO$_2$ laser ablation process for optimizing the processing performance for cutting bony tissue

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ABSTRACT

Recently we established an experimental setup for robot-assisted laser bone ablation using short-pulsed CO$_2$ laser. Due to the comparable low processing speed of laser bone ablation the application in surgical interventions is not yet feasible. In order to optimize this ablation process, we conducted a series of experiments to derive parameters for a discrete process model. After applying single and multiple laser pulses with varying intensity onto bone, the resulting craters were measured using a confocal microscope in 3D. The resulting ablation volumes were evaluated by applying Gaussian function fitting. We then derived a logarithmic function for the depth prediction of laser ablation on bone.

In order to increase the ablation performance we conducted experiments using alternate fluids replacing the water spray: pure glycerin, glycerin/water mixture, acids and bases. Because of the higher boiling point of glycerin compared to water we had expected deeper craters through the resulting higher temperatures. Experimental results showed that glycerin or a glycerin/water mix do not have any effect on the depth of the ablation craters. Additionally applying the acid or base on to the ablation site does only show minor benefits compared to water. Furthermore we preheated the chemicals with a low energy pulse prior to the ablation pulse, which also showed no effect. However, applying a longer soaking time of the chemicals induced nearly a doubling of the ablation depth in some cases. Furthermore with this longer soaking time, carbonization at the crater margins does not occur as is observed when using conventionally water spray.

Keywords: laser bone ablation, short-pulsed CO$_2$ laser, catalyzing fluids

1. INTRODUCTION

Since the beginning of studies with a CO$_2$ laser for ablation of hard tissue it was recognized early that irradiation with a continuous or long pulsed (in the range of ms) produces the best results. The intuitive chosen laser parameters, long pulse durations to deposit high intensities in a technical easy way, caused severe thermal damage to the adjacent tissue with charring and carbonization and finally led to delayed healing. This first attempts did not indicate feasibility of CO$_2$ laser to perform bone cutting.$^{1,2}$

Since the late 1980s several publications have again addressed CO$_2$ laser ablation of hard tissue. The first publication addressed the delayed healing problem due to carbonization, but also encouraged the use of CO$_2$ lasers for hard tissue processing due to several advantages.$^3$ Different short pulsed laser systems were utilized (in $\mu$s range) and since the beginning of the 90s, experimental and histological results have verified that pulse durations well below the thermal relaxation time of hard tissue components combined with the strongly absorbed wavelength of the CO$_2$ laser, allows hard tissue ablation with an acceptable level of thermal damage.$^4$

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The wavelength of a CO$_2$ laser, at 10.6 µm, is strongly absorbed by the two main components of bony tissue, i.e. hydroxiapatite and water. With high pulse intensity and short pulse duration, the energy is deposited quickly into the tissue. As the thermal dispersion is avoided before the ablation process starts. By focusing this highly absorbed radiation onto the bony tissue, its superficial layer is heated up immediately while inertia prevents thermal expansion. The pressure within the irradiated volume increases. The speed at which this pressure increase occurs results in the thermal induced mechanical tissue ablation (thermo-mechanical process) being inferred to as microexplosions. The overheated water in the tissue is vaporized and solid tissue fragments are carried away with the vapor during the micro explosions. The largest amount of the deposited heat is removed by the vapor and only a small amount diffuses into the adjacent tissue. To prevent tissue dehydration an air-water spray is applied, which additionally cools the surrounding tissue. In addition to fine water spray, fast scanning of the laser beam avoids cumulative thermal effects by multi-pass irradiation.

Investigations on hard tissue ablation using a long-pulsed Er,Cr:YSGG laser under different liquid environments were carried out by Kang et al. Comparing five successive 150 µs pulses applied to fresh bovine tibia by using a dry layer, a distilled water layer, a perfluorocarbon layer and water spray showed that the ablation was optimal when using the water spray. Even though perfluorocarbon reduces the energy loss due to lower IR absorption and the resulting ablation volume was approximately 15% higher, undesirable thermal damage was caused (characteristically black carbonization of the crater). Using water spray to support the ablation process achieved clean cuts with smooth crater surfaces without thermal damage. Water inhibits the temperature rise and the rapid vaporization of interstitial water promotes additional mechanical impact on the crater wall. Additionally Kang et al. assume that the water flow has an additional cleaning effect by removing debris. Characteristically formed craters (narrow, sharp-cone) are explained by forward scattering of the laser beam. Scattering effects also lead to limitations of the ablation volume.

From the medical point of view, cutting bony tissue using laser is favorable in comparison to mechanical instruments like burrs and saws are currently common practice. The contact-free cutting process allows arbitrary and sophisticated incision geometries even in regions which are difficult to access with mechanical cutting tools. Furthermore the absence of cutting by-products, e.g. metal abrasion, has a positive effect on the healing. The strongest advantage of laser bone ablation is the considerably smaller incision width which can be achieved (in the range of the laser spot size).

Narrow incisions with only a few hundred microns necessitate precise guidance and application of the focused laser beam. To achieve such accuracy manually is beyond the human capabilities. Hence, the combination of this new cutting technique with the methods of computer and robot assisted surgery is indispensable. To this extent we established world’s first system for robot-assisted laser ablation. Beside the application in microsurgical interventions (e.g. robot assisted laser based cochleostomy), our research is focused on robot assisted laser osteotomy. However, the main drawback of short-pulsed CO$_2$ laser ablation of bone is the comparably long processing time compared to conventional cutting methods. In this paper, we describe our experimental evaluation of short-pulsed CO$_2$ ablation in order to characterize the process and increase the bone removal rate.

For medical applications speed and feasibility is a very critical point, because if the usage of such a device or method is not faster and more practical than the currently used device or method it will not be accepted by the patients or surgeons. The benefits of the laser bone ablation will get shot down by the long time it would need for processing. This paper presents the analysis of single and multiple pulsed laser bone ablation including modelling of the depth development in the ablation and an overview of how to increase the processing speed of the laser bone ablation by using chemical additives.

2. METHODS

Even though the laser bone ablation process comprises complex physical and chemical interactions the result from application of a single laser pulse is reproducible and corresponds with a crater formed by several microexplosions. For our case, with our laser and beam intensity profile, this crater is Gaussian shaped. From the geometrical point of view one can say, that several of these single laser pulses applied result in the concatenation of craters.
2.1 Experimental setup
Our CO\textsubscript{2} laser source is a Rofin Sinar SCx10 slab laser (Rofin Sinar Technologies Inc., Plymouth, USA) with a wavelength of 10.6 \(\mu\text{m}\) and a maximum output power of 100 W. This compact laser guarantees an excellent beam profile with \(M^2 < 1.2\). In order to allow the user to survey the process optically a red laser diode (Rofin Sinar SC x10 External laser diode option) is utilized. The laser beam is focused onto the bone by a single element ZnSe lens (48TSL100, ULO Optics, Stevenage, United Kingdom), with a specified focal distance of \(F = 101.3 \text{mm} \pm 0.5\%\), this is mounted to the scan head. The lens has f-theta characteristics, i.e. the laser beam is focused onto a plane. In order to distribute the laser pulses fast over the tissue, a laser scanning system is utilized. The two-dimensional galvanometric scan head (Colibri, Arges GmbH, Wackersdorf, Germany) has an aperture of 11 mm and an accuracy in deflecting the laser of 20 \(\mu\text{rad}\) in its working area (70x70 mm\(^2\)). The laser beam is delivered through a passive articulated mirror arm (Laser Mech Inc., Michigan, USA) to the galvanometric scan head. The scan head is attached to the flange of a Stäubli RX90B CR robot (Stäubli Tec Systems GmbH, Bayreuth, Germany). The robot is used to position the scan head in respect to the bone. For the described setup the laser beam has a diameter of 200 \(\mu\text{m}\) at its waist.

For our experiments we also used a simpler setup, where the scan head is fixed, while the bone is positioned by a hexapod (M-850, Physical Instruments, Karlsruhe, Germany). Registration of the hexapod to the scan head is performed by using a measurement arm (Microscribe G2X, Immersion Inc., San Jose, USA). Acquiring points on the hexapod platform and the underside of the scan head allows parallel adjustment of the focal distance. For the application of laser pulses the user can acquire the target point on the specimen, which is then brought into the right position in respect to the scan head. Figure 1 illustrates the experimental setup.

![Figure 1. Experimental setup. Bony specimen is fixated on a hexapod platform for automatic positioning in respect to the scan head. A measurement arm is utilized for definition of the target point for the laser pulse.](image_url)

2.2 Measurement methods
Two measurement methods were used. For pulse measurement a confocal microscope was used while the incision measurement was done with a digital microscope.
2.2.1 Pulse measurement

For precise quantitative measurement of laser pulses a confocal microscope (µsurf explorer, NanoFocus AG, Oberhausen, Germany) is utilized. A measurement field of 800x800 μm² with resolution in x- and y-direction of 1.6 μm and resolution in z-direction of 6 nm was utilized. The microscope allows measurement of ablation craters with a maximum depth of 1000 μm. The resulting 3D topometry data is used for further analysis.

2.2.2 Incision measurement

For qualitative assessment of incisions deeper than that possible of the confocal microscope, a digital microscope (VHX-600, Keyence Corp. Osaka, Japan) is utilized. In comparison to a conventional optical microscope the digital microscope provides a depth of field at least 20 times larger.

2.3 Catalyzing fluids

The ablation performance is strongly dependent on the amount of bone ablated by a single laser pulse. From our experience the ablation performance utilizing fine air-water spray is not optimal. As an example, a laser pulse of 22 mJ removes a bone piece which is corresponding to a 2D Gaussian function with diameter of 200 μm and peak at 120 μm in average. Further, the overall processing speed for cutting bony tissue becomes longer for deeper cuts. Hence, our idea was to apply catalyzing fluids other than water onto the bone in order to enhance the ablation performance. A few chemicals were taken into account, which are described in the following sections.

2.3.1 Non reactive fluids

As a non-reactive fluid glycerin was used in a glycerin water mixture. The glycerin does not react with the bone but it has a much higher boiling point then water. The idea was that the normally used water spray will be replaced by the glycerin because it needs much longer to evaporate then the water. This should bring more heat from the laser into the bone in the area where the glycerin was applied.

2.3.2 Acids

For these experiments acids were chosen which build complexes with the calcium in the bone. The goal was to weaken the bone by altering the inorganic properties. The rest of the inorganic and the organic parts are then removed by the laser. The intend is that with less energy of the laser the same volume can be vaporized or alternating with the same energy more volume.

2.3.3 Bases

The bases have the same function as the acids. They should solubilize the calcium atoms out of the bone and build complexes with them.

2.3.4 Nanoparticles

A different experiment was established with gold nanoparticles. The particles had an average diameter of 1-3 nm. Gold nanoparticles with this diameter are absorbing infrared light with the wavelength of our CO₂ laser. The aim with the nanoparticles was to bring more heat to the bony tissue. Additionally the particles were applied in an acidic environment which should also increase the volume of bone removal.

3. EXPERIMENTS

In order to characterize the ablation performance, we conducted experimental series. As specimen we utilized fresh ex-vivo femoral cow bone, which was cut into parts and frozen. Shortly before the experiments we defrosted the bone in water and fixated it in modeling clay onto supporting material. In the following the experiment series are described.
3.1 Depth development

In order to generate reference data for our comparative analysis of the impact of catalyzing fluids, we evaluated the depth development for short-pulsed CO$_2$ laser ablation under usage of a fine air-water spray. Using the system setup with the hexapod described in Section 2.1, we moved the bone to the correct final distance from the scan head. Single laser pulses were applied with a pulse duration of 80 $\mu$s (corresponding to 22 mJ pulse energy). The number of laser pulses applied onto the same position was increased from one pulse up to one hundred pulses. A further experimental series was conducted with the bony specimen positioned 6 mm out of the focal distance. Figure 2 illustrates the specimen after the experiment.

For this analysis we conducted confocal measurements. For the ablation craters that exceed the measuring range of the confocal microscope, we modified the experiment. Here, the bony specimen was precut using a band saw and single laser pulses were then distributed along a cutting line over the gap (cp. Figure 2 right). This allowed us to determine the ablation depth by evaluation of the cross section. Precutting was necessary since slicing the bone after applying cutting lines would smear over the ablation with sawdust and distort the measurement. The depth of these line cuts was measured under the digital microscope.

3.2 Experiments with fluids

For the experiments with the fluids four different setups where used. In the following paragraphs these setups will be described in detail. For every setup a reference pulse was set on the bone. This is necessary because bone properties can differ very much from piece to piece. To be able to compare the results this reference pulse can be used as norm for the actual pulses on the fluids. To evaluate the depth change three single pulses were placed side by side. To evaluate deeper pulses two, three, five, and ten pulses were placed.

3.2.1 Short soaking time

For this experiment the fluids were applied on the bone with a Q-tip. This is not a very accurate method but for the first experiments it was enough to see if there is any difference compared to water spray or to applied laser pulses without any additions. After application, the fluid was immediately wiped away leaving only a thin film. The laser pulses were applied to the film immediately.

3.2.2 Middle soaking time

The fluid was applied with a Q-tip on the bone. The liquid was left for one minute. After this minute it was again wiped away leaving a thin film.

3.2.3 Long soaking time

For the long soaking time experiments the bone pieces were put completely into the chemicals. The experimental setup changed during the three different experiment passes because very long soaking times did not show great differences. During the first pass a soaking time of 30 minutes per pulse was used. The second pass used soaking times of 1, 2, 3, 5, 10, 15, and 20 minutes. This leads to an overall soaking time of 56 minutes. For the third pass the laser was applied after every minute for ten minutes. After the last single pulse was applied two, three, five, and ten pulses were placed side by side on the weakened bone.
3.2.4 Preheating experiments

A different experiment examined the effect of preheated fluid on the bone. Using the premise that commonly a reaction processes faster with higher temperatures. We used a pulse of $10 \mu s$ for the first experiment and $5 \times 10 \mu s$ for the second experiment. Currently the results are inconclusive with no indication of faster processing time. The first thought on to why there was no increase is that it cannot get be determined if $10 \mu s$ are enough time for the laser to fire. Therefore this point is mentioned for completeness and until it is not proved whether or not the laser is able to fire in the defined $10 \mu s$ pulses no results are presented here.

3.3 Qualitative analysis

Figure 3 shows an image acquired with the microscope. The brighter ring around the crater indicates the plateau which occurs while using acids or bases. The second image (b) shows the surface reconstruction of this specific crater where this plateau can easily be seen (arrow).

![Figure 3](image)

Figure 3. Figure (a) shows a microscope image of one crater. The bright ring is a plateau which only occurs while using acids or bases. Figure (b) shows the confocal reconstruction of the surface where the plateau can be seen.

Other experiments showed some kind of membrane covering the crater. Figure 4 shows this membrane and how this shows up in the reconstruction of the measurement. Part (a) shows the microscope image of this membrane. In the middle of the membrane it has a breakthrough where the depth is as expected. Part (b) of the image is the side view of the reconstruction of the measured points. The membrane can be clearly seen at the outsides of the crater where the depth is much lower than expected. Part (c) is the top view of the crater. The membrane can be seen inside the crater around its border as very shallow parts of the hole. Actually this hole should be nearly circular which it is not as shown on the picture. It is not completely clear which effects cause this membrane and why it is not always present.

4. RESULTS

This section is separated into two parts. The first part states the results of the analysis of conventionally applied laser pulses. The second part is concerned with the ablation under the usage of catalyzing fluids.

4.1 Depth development for conventional ablation

The ablation depth is plotted against the number of applied laser pulses in Figure 5. In order to approximate the depth development we applied a logarithmic fitting function. The first laser pulses result in a fast depth development. With increasing number of pulses, more and more energy of the laser is lost. This is due to the ablation debris on the one hand and to the increasing surface area of the incision on the other hand. The experiment also proved that the depth development is similar for different pulse energies.
Figure 4. The microscope image of the membrane is shown in part (a). Parts (b) and (c) show the reconstruction of the measurement points where the first image is the side view and the latter one the top view of this reconstruction.

Figure 5. Ablation depth plotted against the amount of applied laser pulses (pulse duration 80 µs) with logarithmic fitting function. The upper curve and points indicate ablation performed in the focal point of the beam, while the lower curve and points show pulses which were applied out of focus (i.e. less intensity).

4.2 Depth results with catalyzing fluids

The first experiments let us infer that the use of bases will not achieve results as good as those where we applied acids. Therefore we concentrate more on the acids, without completely discarding the bases.

One interesting observation was the outline of some craters. Similar to impact craters, this “popcorn effect” is caused by the mass expelled by the explosion. But this is loose mass and therefore it is interesting that this happens here as well. Another explanation could be the increasing pressure inside the bony tissue under laser irradiation. The laser beam with TEM$_{00}$ shows a Gaussian energy distribution. Hence, the laser intensity in the
Table 1. Mean ablation crater depths with standard deviation for different fluids. All values in µm.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Short</th>
<th>Reference</th>
<th>Middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycerin</td>
<td>58.8 ± 4.68</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Glycerin/water</td>
<td>69.1 ± 3.94</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A1</td>
<td>55.7 ± 4.27</td>
<td>63.25</td>
<td>52.27 ± 10.25</td>
</tr>
<tr>
<td>B1</td>
<td>64.4 ± 12</td>
<td>52.75</td>
<td>52.2 ± 2.51</td>
</tr>
<tr>
<td>A2</td>
<td>42.4 ± 7.25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B2</td>
<td>57.74 ± 1.61</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A3</td>
<td>74.43 ± 7.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A4</td>
<td>123.9 ± 33.7</td>
<td>114.6</td>
<td>154.02 ± 2.52</td>
</tr>
<tr>
<td>A5</td>
<td>123.34 ± 10.21</td>
<td>118.24</td>
<td>125.53 ± 5.35</td>
</tr>
<tr>
<td>A6</td>
<td>139.97 ± 10.08</td>
<td>122.16</td>
<td>141.16 ± 2.62</td>
</tr>
<tr>
<td>A7</td>
<td>125.12 ± 28.04</td>
<td>139.1</td>
<td>145 ± 21.93</td>
</tr>
</tbody>
</table>

The center of the irradiated spot is higher, than at the borders. Therefore, the tissue at the border of the irradiated circular area is heated up less.

Additionally it is interesting that not every crater has this outline, only a few of them. More investigation has to be done on this phenomenon. Table 1 lists the results for short, middle, and long soaking times. The list below shows which acids and bases were used.

- A1: citric acid (0.5 M)
- A2: hydrochloric acid and citric acid (0.5 M)
- A3: citric acid (0.01 M) and gold nanoparticles
- A4: oxalic acid (1.0 M)
- A5: nitric acid
- A6: sulfuric acid
- A7: nitric acid and sulfuric acid
- B1: ethene diamine tetraacetate di sodium salt dihydrate (0.5 M) and sodium hydrate (1.0 M)
- B2: ethene diamine tetraacetate di sodium salt dihydrate (0.5 M) and sodium hydrate (5.0 M)

Figure 6 shows the depth development for the long soaking time. The depth is plotted against the soaking time in minutes. Due to the absent carbonization of some pulses some values are missing because they could not be found under the confocal microscope.

5. DISCUSSION AND FUTURE WORK

With this contribution we presented our efforts in order to enhance the ablation performance. Analyzing the ablation depth development for the concatenation of laser pulses revealed, that we are facing a logarithmic development. Hence, the ablation depth increases very fast for the first pulses, while it converges with cumulative depth. As already reported by other research groups, the maximal ablation depth for laser bone ablation is limited, if no widening of the incision is performed.\textsuperscript{10}

Our experiments with catalyzing fluids other than water did not show significant increase of the ablation performance. However, we anticipate that following the approach is worth the effort, since the major drawback of laser bone cutting is the comparably low processing speed.
Figure 6. The figures show the depth development for the long soaking time of fluids. The depth is plotted against the soaking time. The first value is the reference pulse without the fluid. From (a) to (g) the following fluids were used: A1, B2, A3, A4, A5, A6, A7.

It is very important to notice, that all the presented results of the catalyzing fluid experiments are treated as pretest results. They should only show a tendency towards the fluids, which should be investigated in detail in future work. There are a lot of parameters, which were not taken into account, e.g. bone curvature, surface appearance or the amount of fluid applied. Hence, the results are not inter-comparable. However, they indicate the trends on the same bone compared to the reference pulse. Due to the absent carbonization some pulses could not be found under the confocal microscope. For the experiments done by now, the specimen was manually adjusted. In future experiments this should be automated by utilizing our robotic setup. This allows to place the laser pulses at defined positions on the bone and makes it possible to find them again under the confocal microscope, even if there is no carbonization.

For future work it is foreseen to determine histological information about the effects of the fluids on the bone itself. Furthermore the application of the fluids is not very accurate. This makes the results also not comparable.
It is planned to use a printer cartridge to place discrete amounts of fluid accurately on predefined positions on the bone. On the resulting fluid spots, the laser beam will be applied. The surrounding bone will also not be damaged by any excess fluid.

To conclude, laser ablation using short-pulsed laser is a very promising method for cutting bony tissue. Application in microsurgical interventions which require accurate bone removal is already feasible. Surgical applications which necessitate ablation of larger bone volumes (e.g. orthopedic surgery, cranio-maxillofacial surgery) require an enhancement of the processing speed.

REFERENCES


