Optimization Overlapping Ratio of Erbium: YAG Laser Irradiation for Less Thermal damaged Bone Cutting with Water Cooling

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Abstract
Lasers have the capability to remove or cut bone precisely without large reaction forces. However, surgeons have had many difficulties with using lasers during operations because of the thermal damage. In this paper, we propose an optimization the overlapping ratio, using water cooling; for the efficiency of laser bone ablations per unit time without thermal damages for operational application. A water-cooling Er: YAG laser (18.5 J/cm², λ = 2.94 μm, 20 Hz, 200 μs) using optical fiber was operated at 0.5 – 3.0 mm/s moving velocities and repetitions. We focused specifically on the overlapping irradiated area and the interval time between the laser irradiations. Swine scapulae were ablated and its rate and performance were evaluated. The water-cooling Er: YAG laser obtained optimal ablation results when the moving velocity was set at 2.0 mm/s; the overlapping ratio is 0.89, and the ablated area along the troughs per unit time was optimized to 0.50mm²/s. Carbonization was not evident at this velocity. Controlling of the laser’s moving velocity, we can optimize the ablation ability to 0.50mm²/s at 2.0 mm/s. At this velocity, the mass removal efficiency was at 208 μg/J. This result was almost same with previously conducted results accomplished by free running without water cooling.

Key words
Ablation, Bone cutting, Laser, Water cooling.

1. INTRODUCTION
Laser osteotomy has potential advantages over conventional bone cutting with mechanical sawing and drilling thanks to precise cutting capability. Accurate osteotomy can avoid unnecessary damage to surrounding tissue and nerves thus lowering the risk of implant failure and complications.

Erbium: YAG (Er:YAG) laser, among other laser modalities, is most suitable for osteotomy that requires least thermal damage to the bone tissues and most cutting efficacy. Numerous reports were made to evaluate thermal damages and cutting efficiency of laser osteotomy, comparing Excimer (1)–(4), CO₂ (5)–(9), Hol: YAG (10)–(13), and Er: YAG (12)–(24) lasers. Er: YAG produces less thermal
damage than Hol: YSGG laser\(^{16}\) does, while it has higher removal efficacy than CO\(_2\)\(^{7,8,20}\) and Excimer laser do.

Other studies also indicated the suitability of Er:YAG laser-based osteotomy over conventional mechanical approach by measuring the thermal damage, temperature increase, and healing delay. Cross-sectional cutting area by Er:YAG laser showed comparable post-operative healing to that by mechanical drill\(^{22}\). These studies concluded that the Er: YAG laser is appropriate for clinical application if fracture strength is prioritized over amount of periostal callus after surgery.

In all previously published studies, efficiency of evaluated cutting by Er:YAG-laser were evaluated by consented measuring standards: the ablated depth, volume, and mass per unit energy. While these standards are significant when one wants to control the ablation rate by energy, the efficiency per time is more significant for osteotomy to avoid the lengthy operation time in clinical applications.

The objective of this paper is to introduce the novel measuring standard, the efficacy per time, and use the proposed standard to optimize the deposition parameter of Er:YAG laser in bone cutting. The parameters for optimization include velocity of contact tip running over the bone surface and number of irradiation repetitions. The experiments were conducted by using specially designed mechanism to maintain the distance between the contact tip and bone surface 1.0 mm and by using water cooling to hold temperature increase of bone.

2. MATERIALS AND METHODS

2.1 Tissue Preparation

Adult swine scapulae were obtained after slaughter, and kept fresh for 2 days by freezing before being used in experiment. The sample density was 1.73 g/cm\(^3\) (measured value) and was kept in a hydrated condition until experiments were concluded. We did not treat or modify the sample in any manner to avoid any property change. This includes sanding, polishing or cutting.

2.2 Laser Parameters

The experiments were performed with a multi-mode Er:YAG laser (Prototype: HOYA Photonics Co., \(\lambda = 2.94\) µm, pulse duration \(\tau_p = 200\) µs, \(f = 20\)Hz). The laser was guided by a glass fluoride optical fiber (IR-FGF: HOYA Photonics Co.). The laser energy was fixed at 400 mJ at the power generator.

A sapphire contact tip (Prototype: HOYA Photonics Co.) was used at the head of the laser mechanism. It was chisel-shaped and its area at the tip was 1.4 \& 0.45 mm\(^2\). A water-cooling system was used to prevent the bone from carbonization, and the temperature of the water to cool the bone being ablated was 17°C. We fixed the water flow to 3–4 ml/min. The water flow was at a reasonable rate to avoid carbonization\(^{19}\).

2.3 Experimental Setup

To magnify the efficiency of laser bone ablations per unit time for operational application, we controlled the irradiation energy. We prepared equipment to manipulate the laser movement during the experiments. The equipment to control laser moving consisted of a sensing mechanism and a manipulator with 3 Degrees of Freedom (DOFs).

The sensing mechanism is designed to maintain the distance between the bone and the contact tip. Based on literature\(^{13}\), we set the distance to minimum 1.0 mm and hold any temperature increase below 5°C\(^{24}\). The sensing mechanism is shown in Fig. 1. The manipulation system is designed to control of the laser irradiation's movement velocity. It has 3 DOFs, and a margin of error during position repeatability at 0.02 mm.

2.4 Overlapping Ratio Optimization

As a standard for defining the irradiation energy, we adopted the Overlapping ratio\(^{6,19}\). As shown in Fig. 2 (a), the Er: YAG laser diffused at an angle of \(\alpha\). The irradiated...
Fig. 2  Pulse Overlapping Factor: (a) Mechanical parameters. The fluence at the surface of the bone is 18.5 J/cm². (b) When the contact tip moves with a velocity v, the overlapping ratio $\eta$ becomes $x/w$. v is inversely proportional to $\eta$.

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Fig. 3  Charring in troughs: A distinct char layer was observed when (a) v = 0.1 mm/s (b) v = 0.3 mm/s. To avoid charring on the bone, laser movement must have a velocity over 1.0 mm/s.

(a) $v=1.0\text{ mm/s}$ (b) $v=0.3\text{ mm/s}$

(a) $v=1.5\text{ mm/s}$ (b) $v=2.0\text{ mm/s}$

(a) $v=2.5\text{ mm/s}$ (b) $v=3.0\text{ mm/s}$

Fig. 4  Ablation rates measured with laser moving velocity of 1.0~3.0 mm/s (n= 5). The ablated depth increases linearly, and the deviations of each velocity become smaller as repetition times increase. The fluence at the surface of the bone was measured of 18.5 J/cm².

(a) $v=1.0\text{ mm/s}$ (b) $v=1.5\text{ mm/s}$

(c) $v=2.0\text{ mm/s}$ (d) $v=2.5\text{ mm/s}$

(e) $v=3.0\text{ mm/s}$

The irradiated area was overlapping when we manipulated the laser. We defined the overlapping ratio $\eta$, as shown in Fig. 2 (b). When we manipulated the laser along the laser beam moving direction with an overlapping ratio, the velocity was became:

$$A = W_a \times W_b$$

$$W_a = a + 2d \cdot \tan \frac{\alpha}{2}, \quad W_b = b + 2d \cdot \tan \frac{\beta}{2},$$

where $d$ is the distance between the bone and the tip.
\[
\eta = 1 - \frac{v}{W_b \cdot f}
\]  

(2)

\(f\): the pulse frequency of the Er: YAG laser

As the diffusion angle of the contact tip \(\alpha\) was 8°, \(\beta\) was 25°, \(d\) was 1.0 mm, \(a\) was 1.4 mm, and \(b\) was 0.45 mm, so \(W_a\) became 1.5 mm and \(W_b\) became 0.90 mm. Note that the distance between the bone and the laser \(d\) was 1.0 mm and the frequency \(f\) was 20 Hz. When we moved the laser at a velocity of 3.0 mm/s, the overlapping ratio became 0.89. This means that a given area was irradiated 6 times with given fluency.

Tissue samples were mounted on a flat table, and the laser was activated. We ablated a given place to 5 times at different velocities to clarify the effect of the repetition of irradiation. As we observed carbonization under the velocity 0.5 mm/s (Fig. 3), we ablated bones with velocities 1.0 mm/s to 3.0 mm/s. After ablation, a microscope interfaced to a digital CCD camera (VH-7000: KEYENCE) with an automatic scaling was used to determine the width and depth. Simultaneously, we also checked the existence of charring (a black area in images) in the troughs.

2.5 Data Analysis

We repeated ablation the same place of the bone to 5 times with each velocity. As a final standard, ablation efficiency was defined as the ablated area along the troughs per unit time at a given heat fluence based on the measured depth, and movement velocity. With this definition, we could determine the total time to ablate or cut a bone sample. Results from multiple experiments are expressed as means \(\pm\) the standard deviation.

3. RESULTS

The Er: YAG laser ablation rates conducted at various velocities are shown in Fig. 4. We calculated the cross-sectional ablated area with the width and the depth. Although there were some local peaks in the results, the depth and the ablated area increased as the number of repetitions increased. In addition, as the movement velocity slowed, the depth and the ablated area were increased.

As we considered the ablation efficiency in terms of time, we recalculated the ablated area along the troughs by multiplying the velocity to the ablated depth. As shown in Fig. 5, when the velocity was 2.0 mm/s; the overlapping ratio is 0.89, the efficiency per unit time was optimized to 0.52 mm²/s, although ablated depth was maximized when the velocity was 1.0 mm/s. This optimization applies when the amount of bone to be cut is over 0.15 mm.

The surface views and the cross-sectional views when the velocity was 1.0 mm/s and 2.0 mm/s are shown in Fig. 6. Some thermal damage appeared after ablation when the velocity was under 0.5 mm/s; the overlapping ratio is 0.96. The char was at the bottom of cut troughs. In addition, there was no thermal damage after ablation when the velocity was between 1.0 mm/s and 3 mm/s.

4. DISCUSSION

The objective of this paper was to propose new efficacy measure of Er:YAG laser-based bone cutting: the efficacy per time, unlike efficacy per energy proposed in related studies. We then used the proposed standard to optimize the irradiation parameters: velocity of contact tip running over the bone surface and number of irradiation repetitions.

We found that the ablation efficiency per unit time was best when the movement velocity was at 2.0 mm/s overall. At this velocity, the overlapping ratio became 0.89, indicating that the overlapping bone was irradiated 9 pulses (duration time 200 \(\mu\)s) with a pulse energy fluence of 18.5 J/cm². When the velocity was faster than 2.0 mm/s, the ablation was not as effective because the energy accumulation to ablate bone was insufficient. However, when bone is ablated shallowly under 0.15 mm, then the optimal velocity should to be reconsidered. At a velocity under 2.0 mm/s, the ablation was not effective. In this case, the troughs were deep enough to retain high temperature and pressure, and, as a result, the energy intended to ablate the bone created plasma instead.

In addition, at the velocity of 0.3 mm/s, there appeared to be charring at the bottom of the trough. In this point, we considered the four regimes of ablation as reported by Majaron. With the thermal relaxation time \(\tau\) is 0.85 \(\mu\)m, there is a possibility of transforming the state into a ‘hot’ ablation regime. We believe that we could get a no carbonization on the bone with water cooling and control of the laser beam moving velocity.

In addition, we believe that there is another parameter to determine the ablation regime. With our results, we believe that the accumulation of the irradiation energy per
Fig. 5 Ablation rate of cross-sectional area along the troughs per unit time at a given heat fluence of 18.5 J/cm². The ablation rate is obtained by multiplying \( \nu \) to the ablated depth. A higher ablation rate means a faster cut. Note that although the ablation rate of the depth at the velocity of 2.0 mm/s is smaller than the ablation rate of the depth at the velocity of 1.0 mm/s, the ablation rate of cross-sectional area considering cutting time at the velocity of 2.0 mm/s is at the peak in this graph.

unit time and the interval time between the pulses to diffuse the accumulated energy are parameters of determine the ablation regime. At this time, the exact regime parameters cannot be clearly established in our results. With further study, the possibility of other regime parameters maybe found. A critical aspect may be located in the overlapping repetition and the pulse interval. There is a possibility to increase the rate of ablation if the pulse frequency is greater than 20 Hz with the same heat fluence, in other words, if the movement velocity of the laser could be faster with the same overlapping ratio.

When we consider the ablation efficiency as the mass removal efficiency as like Li \(^{20}\), the efficiency becomes 208 \( \mu g/J \) at the fluence of 18.5 J/cm² with the value 1.73 g/cm³ and the 20Hz frequency. Interestingly, the mass removal efficiency had a similar value regardless of material type 270 \( \mu g/J \) \(^{21}\), and Walsh reported 250 \( \mu g/J \) when the density of the bone was 2 g/cm³ \(^{13}\). In our study, the mass removal efficiency was at 208 \( \mu g/J \) at the 2.0 mm/s, almost same with previously conducted results accomplished by free running without water cooling.

Fried reported results of 40 \( \mu m/pulse \) with Q-switched (\( \tau_p = 0.5 \mu s \)) and 70 \( \mu m/pulse \) (\( \tau_p = 300 \mu s \)) without water-cooling on bovine skull \(^{19}\). Li also reported a result of 32 \( \mu m/pulse \) (\( \tau_p = 200 \mu s \)) on rat femur \(^{24}\). Telfair had a result of approximately 60 \( \mu m/pulse \) (\( \tau_p = 100 \mu s \)) with a water-cooling on bovine femur compacta \(^{20}\). Walsh reported 66 \( \mu m/pulse \) \(^{13}\), and Nuss had a result of 60 \( \mu m/pulse \) (\( \tau_p = 250 \mu s, 2 Hz \)) \(^{16}\) with guinea pig skull calvaria. Although the experimental conditions (the material, frequency, pulse duration time, and cooling method) were not exactly same, our result 22.2\( \mu m/pulse \) was absolutely smaller than the past works. If we remind that the mass removal efficiency were virtually equivalent, the result means that we ablated broader area.

At the velocity of 1.0 mm/s to 3.0 mm/s, the troughs showed no charning. There are many previous studies regarding thermal damage and healing after ablation. Many studies have identified the appearance of periostal callus or tissue regeneration. For clinical application, if fracture strength is prioritized over amount of periostal callus after surgery, then to examine the fracture strength after a period of time is crucial, as was noted by Buchelt \(^{23}\).

For a future work in laser ablation, it is necessary to record local temperature increase and its effects on regeneration. In order to cut bone precisely and quickly, it is necessary to use a robot for the precise control of the velocity and the distance between the bone and the laser.
5. CONCLUSION

In summary, controlling of the laser’s moving velocity, we can optimize the ablation ability to 0.52 mm²/s. Even though the laser was guided by an optical fiber, the results were almost identical with results accomplished by free running without water cooling.

References