Influence of scanning velocity on bovine shank bone ablation with pulsed CO_2 laser

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Received July 15, 2008

The influence of scanning speed on hard bone tissue ablation is studied with a 10.6-μm laser. The groove morphology and the thermal damage created in bovine shank bone by pulsed CO_2 laser are examined as a function of incident fluence by optical microscope following standard histological processing. The results show that ablation groove width, depth and ablation volume, as well as the zone of thermal injury, increase gradually with incident fluence. As compared to the result for high scanning speed, the lower scanning speed always produces larger ablation volume but thicker zone of thermal injury. It is evident that scanning speed plays an important role in the ablation process. In clinical applications, it is important to select appropriate scanning speed to obtain both high ablation rates and minimal thermal injury.

OCIS codes: 170.1020, 140.3470, 350.5340.
doi: 10.3788/COL20090702.0138.

Conventional methods to perform the incision or excision of hard biological tissues (e.g., bone and teeth) in today's medical practice are mechanical tools such as saw and drill. Unfortunately, the traditional mechanical tools always produce unconquerable drawbacks such as broad cut, thermal side-effect, and metal abrasion, which noticeably delay the healing processes. Thanks to the unique advantages such as free cut geometry, no vibration, haemostatic and aseptic effect, lasers as one of the most promising tools to compensate/substitute the traditional instruments for the removal of hard biological tissues have been paid more and more attentions. A number of *ex vivo* investigations and animal trials have been done with different types of biological tissue by using various laser systems[1−6]. Since the strong absorption peaks of compact bone overlap with the Er:YAG (2.94 μm) and CO_2 (9.6 and 10.6 μm) laser wavelengths, it seems that Er:YAG and CO_2 lasers may be the most suitable candidates for practical applications. However, early attempts with continuous-wave (CW) and long-pulse (pulse duration within millisecond level) CO_2 lasers always produce strong thermal side-effects. Since the importance of the pulse duration in laser medicine has been quickly realized, the so-called "superpulsed" CO_2 lasers (pulse duration $65-600$ μs) or even shorter pulse lasers ($0.1-1$ μs) were used to reduce the thermal damage. However, shorter pulse duration will lead to lower ablation efficiency or cutting speed, which of course is unsuitable for medical applications. Another recognized method to prevent dehydration of the tissue and additionally cool it during irradiation is to combine the short-pulse laser with a fast multi-pass beam scanning and using an air-water spray[7−9]. With this technique, a relatively long CO_2 laser pulse (about 100 μs) can obtain efficient and clear ablation[10]. The influence of the water content in dental enamel and dentin and the amount of water externally supplied by air-water spray on ablation has been reported[11]. However, the systematic study of the influence of scanning velocity of laser beam on ablation effects has not been reported. In this letter, we experimentally study this influence with a pulsed CO_2 laser.

The laser source used in this study is a pulsed CO_2 laser (Sharplan 30 C, Israel) with a wavelength of 10.6 μm and a pulse length of about 10 ms. The laser beam was transmitted through an articulated-mirror-arm system and focused to a spot diameter of about 510 μm on the bone sample surface directly with a 125-mm lens. The radiant exposure delivered to the tissue was set to predetermined values of $5-45$ J/cm^2 which was confirmed by reading the laser pulse energy with a pyroelectric detector and relating to the beam area. The repetition rate was 60 Hz.

Bovine shank bone obtained no later than six hours postmortem from a local slaughterhouse was used in this experiment. Areas of the bone surface exhibiting a clean, smooth cortical surface were prepared by scraping the surface with a razor blade to remove the periosteum. And then the bone was cut into rectangular blocks ($\sim 2\times 4$ (cm) with original thickness) with a diamond saw. In order to value the influence of scanning velocity on bone ablation, the prepared bone samples were divided into two groups named A and B randomly. For each group, the sample was put on a computer-controlled motorized linear driving stage and moved repeatedly through the focused beam. For group A, the sample was repeatedly moved at a rate of 20 mm/s for 6 times, while for group B, the sample was moved at 3.3 mm/s for once. We define the pulse overlap factor n as the ratio of pulse radius to the translation of the laser spot. For groups

A and B, pulse overlap factors of 0.8 and 4.6 can be obtained respectively, meaning that almost 5 pulses are placed in the space of a pulse radius for both groups (Fig. 1). In order to avoid the influence of water content, no air-water spray was used in this experiment.

After irradiation, the bone sample was fixed in 10% neutral buffered formalin, decalcified in HNO_3 solution for 5 days, and then embedded in paraffin. Serial sections with 3-μm thickness were cut transversely to the laser cuts from the embedded sample, mounted on 1×3 inch glass slides and stained with hematoxylin and eosin-y (H&E).

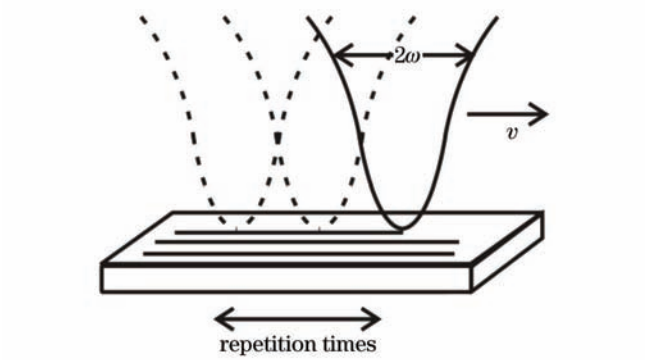

Fig. 1. Schematic illustration of the experiment. The number of pulses that acts effectively at every point along the incision can be defined as the product of the pulse overlap factor n and the repetition times.

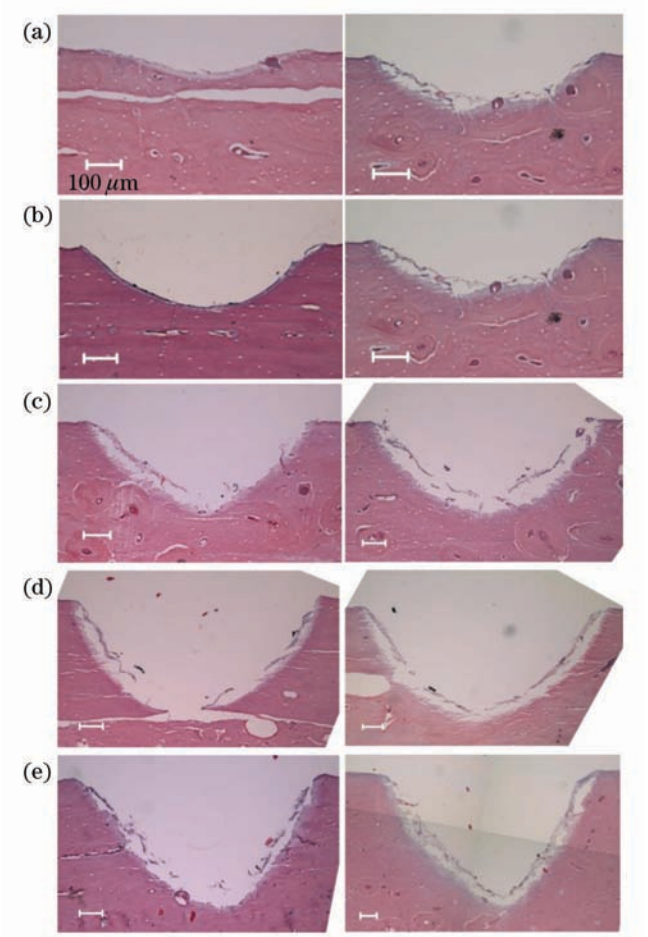

Fig. 2. Histological slices transversely to the laser incision in bovine shank bone created by pulsed CO_2 laser at different radiant exposures of (a) 5.7, (b) 15.4, (c) 33.3, (d) 41.2, and (e) 44.6 J/cm^2 for group A ($v = 20$ mm/s, left) and group B ($v = 3.3$ mm/s, right). The length of bar is 100 μm.

For analysis of crater morphology, the section of each specimen was photographed using confocal microscope (LSM 510 META, Zeiss, Germany), the width, depth, and area of the crater were measured, the zone of thermal damage at the middle sides and base of the craters were also obtained.

Micrographs of typical histological sections following ablation of bovine shank bone by using pulsed CO_2 laser at 5.7, 15.4, 33.3, 41.2, and 44.6 J/cm^2 for groups A and B are shown in Fig. 2. The cut shapes in all radiant exposures for both groups reveal almost regular U-shaped profiles, which consists with the spatial contour of the incident beam (in this study, the beam is Gaussian distribution). From the visual appearance of the cut in Fig. 2, it clearly shows that the width and depth of ablation groove increase gradually with the increasing of the radiant exposure for both groups. Since no air-water spray was used in this work, char formation always can be found at the base and both sides of the groove.

The incision geometries of bovine shank bone after irradiation, including cut width, cut depth, and cut area, versus incident radiant exposure for both groups are shown in Fig. 3. For both groups, the widths of the produced U-shaped incisions at the surface of the sample grow up with increasing the radiant exposure, which is determined for a Gaussian laser beam by the focus spot diameter and

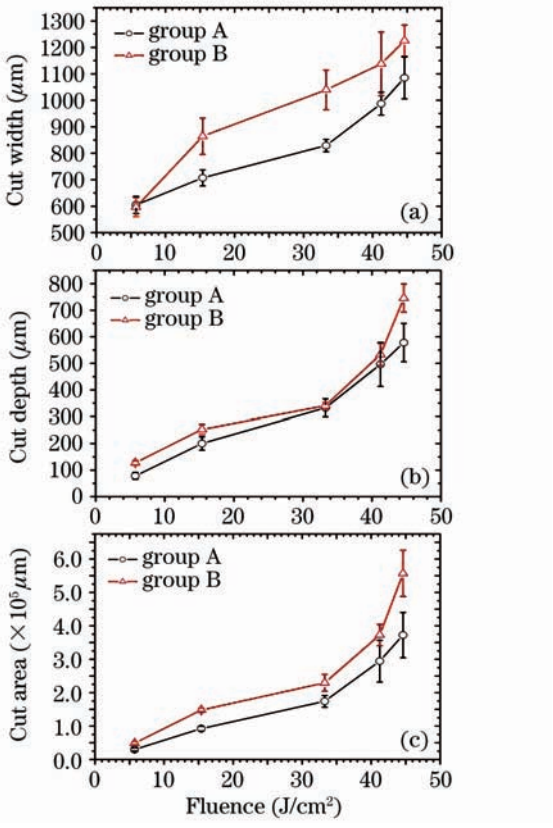

Fig. 3. Incision geometries of bovine shank bone after irradiation with pulsed CO_2 laser versus incident radiant exposure. (a) Cut width at the surface of bone sample, (b) cut depth, (c) cut area. The error bars are standard deviations of the data.

the ratio of the pulse energy density to the tissue ablation threshold. Except for the fluence of 5.7 J/cm^2, the cut width in group B is always larger than the one in group A for other four radiant exposures (Fig. 3(a)). The total cut depths of the ablation groove of bovine shank bone for both groups increase gradually with the radiant exposure, and the incision depth in group B is generally deeper than the one in group A (Fig. 3(b)). The total ablation volumes of bovine shank bone for both groups also rise gradually with fluence, and the ablation volume for group B is larger than that for group A for all radiant exposures (Fig. 3(c)).

Quantitative measurements of thermal injury at the base and both sides of the ablation cuts on bovine shank bone are provided in Table 1 (Fig. 4(a)) and Table 2 (Fig. 4(b)), respectively. The thicknesses of thermal damage zones at both the base and sides of the cuts increase gradually with increasing the radiant exposure for both groups. The thickness of laser induced thermal damage at the base of bone sample rises from 35 ± 9 μm at 5.7 J/cm^2 to 93 ± 9 μm at 44.6 J/cm^2 for group A, while from 76 ± 19 μm to 124 ± 18 μm for group B. Strong thermal injury can also be found at both sides of the cut of bone sample, which is up to 95 ± 11 μm at 44.6 J/cm^2 for group A and 142 ± 28 μm for group B.

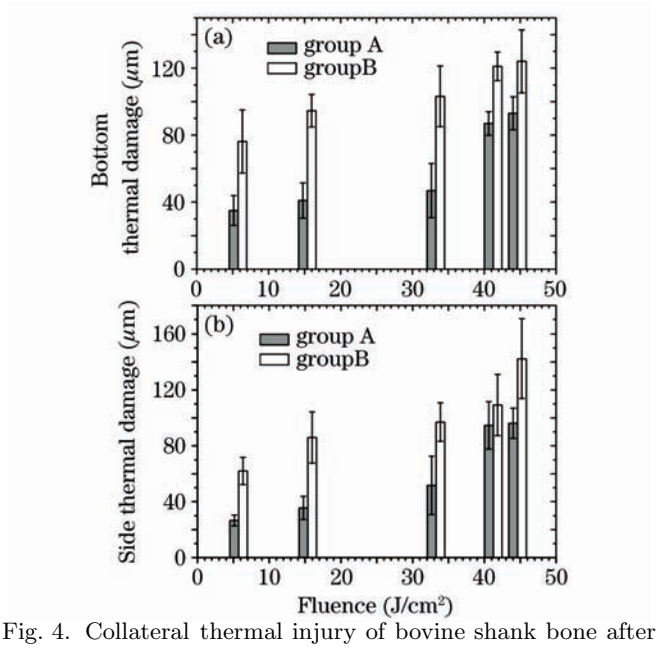

Fig. 4. Collateral thermal injury of bovine shank bone after irradiation with pulsed CO_2 laser versus radiant exposure. (a) Thickness of thermal injury at the base, (b) thickness of thermal injury at both sides of the crater. The error bars are standard deviations of the data.

Table 1. Quantitative Measurements of Thermal Injury at the Base of Ablation Groove on Bovine Shank Bone Created by Pulsed CO_2 Laser at Different Laser Fluences

Fluence (J/cm^2)		5.7	15.4	33.3	41.2	44.6
Damage (μm)	A	35 ± 9	41 ± 10	47 ± 16	87 ± 7	93 ± 9
	B	76 ± 19	94 ± 10	103 ± 18	121 ± 9	124 ± 18

Table 2. Quantitative Measurements of Thermal Injury at Both Sides of Ablation Cuts on Bovine Shank Bone Created by Pulsed CO_2 Laser at Different Laser Fluences (Mean Data of Both sides)

Fluence (J/cm^2)		5.7	15.4	33.3	41.2	44.6
Damage (μm)	A	27 ± 4	36 ± 8	52 ± 21	95 ± 17	95 ± 11
	B	62 ± 10	86 ± 18	97 ± 14	109 ± 22	142 ± 28

The results show that, although the total pulse number and total energy acting in each point along the ablated grooves is the same for both groups, lower scanning speed (group B) always produces larger cut width, cut depth, and ablation volume with thicker zone of thermal injury in the peripheral tissue as compared to higher scanning speed (group A). The laser pulse energy delivered into tissue can be divided into two parts, one is to ablate tissue, while the other is deposited in the tissue as residual heat. For the scanning speed of 3.3 mm/s (group B) in the study, the pulse overlap factor was about 5 and the repetition rate was 1, which means that 5 pulses were shot on the same point in succession. The residual energy of each pulse had no time to dissipate and thus accumulated in the tissue. This may be helpful to increase the ablation volume and induce stronger thermal injury to peripheral tissue at the same time. While for the scanning speed of 20 mm/s (group A), the pulse overlap factor was about 0.8 and the repetition times was 6. The duration between two pulses shot into the same point was long enough to dissipate the residual energy of each pulse, so that no heat accumulated between two pulses which resulted in a relative smaller ablation volume but produced smaller thermal injury.

In conclusion, the effect of scanning speed on bovine shank bone ablation by pulsed CO_2 laser was evaluated. The results show that the scanning speed has an important influence on both ablation groove morphology and thermal damage. The lower scanning speed produces larger ablation volume but thicker zone of thermal injury in the peripheral tissue as compared to the higher scanning speed. So in clinical applications, it is important to select appropriate scanning speed according to the clinical demand to obtain both high ablation rates and minimal thermal damage.

This work was supported by the National Natural Science Foundation of China (No. 60578057 and 60878062), the Natural Science Foundation of Fujian Province (No. 2008J0317), and the Project WKJ2008-2-035 supported by Science Research Foundation of Ministry of Health & United Fujian Provincial Health and Education Project for Tackling the Key Research, P.R.China.

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