Average-power mediated ultrafast laser osteotomy using a mode-locked Nd:YVO_4 laser oscillator

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Abstract. By using a novel temporal characterization technique, we determined that a threshold average laser power of 160 mW is required to drill through a 0.75-mm-thick cortical bone for a Nd:YVO_4 mode-locked laser oscillator with a peak intensity of 1.3 GW/cm^2. The ablation mechanism is identified as average-power induced carbonization followed by peak-power induced avalanche ionization in the carbonized osseous tissue. *© 2007 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.2821149]

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Surgical operation of bone slicing and drilling is usually performed with mechanical tools, such as cutting saws and hand drills. The shortcomings of those mechanical tools include high material loss, poor surface evenness, potential fragment contamination, significant tissue vibration, and so on. It is perceived that an appropriate laser source might replace those mechanical tools for bone surgery and alleviate those shortcomings. Laser ablative removal of osseous tissues and its accompanying effects have been studied in the past. For example, continuous-wave (CW) and long-pulse (ns to ms) infrared lasers, such as the CO_2 laser, Ho:YAG laser, and Er:YAG laser, were used for heating and evaporating osseous tissues near the 2.9-μm water absorption wavelength or the 10-μm calcium-phosphate absorption wavelength.[1–4] One major disadvantage associated with laser thermal ablation is significant carbonization and collateral damage to surrounding tissues. In the short pulse limit, an ultrafast laser with a ps or fs pulse width cuts or drills a dielectric material through multiphoton and avalanche ionization or hydrodynamic expansion of plasma induced by the high electric field in the laser pulse.[5] Consequently, laser machining with little heat deposition is possible when the wavelength of an ultrafast laser is tuned away from the material absorption. Recently, several papers[6–9] have reported promising hard-tissue machining by using infrared laser pulses with mJ or sub-mJ pulse energy and ps to fs pulse width at kHz repetition rates. However, the laser system used for those studies requires a fairly complex and expensive laser amplifier seeded by a mode-locked laser oscillator. In this letter, we report, to the best of our knowledge, the first experimental demonstration of laser osteotomy directly using a low-cost mode-locked laser oscillator. A mode-locked laser oscillator has a much higher pulse rate (10 to 100 MHz) and a much lower peak power (10 to 100 kW). The high pulse rate introduces Joule heating to the ablated material, and yet the kW peak power in the ultrafast pulse is still effective in introducing avalanche ionization for material removal. This study reveals an interesting cutting mechanism that combines the effects from both peak and average laser powers.

Figure 1 shows the experimental setup. The ultrafast laser used in the experiment is a 9-W mode-locked Nd:YVO_4 laser at 1064 nm (Cougar, TimeBandwidth) producing 12-ps pulses at a 54.1-MHz repetition rate. We prepared several 0.75-mm-thick flat cortical bone specimens cut from a fresh femoral bone of a pig. We polished both surfaces of the bone specimen by using a 15-μm polishing pad to mimic the typical roughness of a natural cortical bone surface. In the experiment, we fixed the laser peak power to the maximum available value of 14 kW from our laser and adjusted the laser average power by using an optical chopper with a variable aperture in the disc rotating at 30 Hz. As a result, the temporal structure of the incident laser has a train of micropulses repeating at 54.1 MHz in a macropulse envelope repeating at 30 Hz. The number of micropulses in one macropulse can be determined from the formula $N=(30\ \mathrm{Hz})^{-1}\times 54.1\ \mathrm{MHz}\times \text{average power (W)}/9\ \mathrm{W}$. Since the thermal relaxation time of a low-loss biologic tissue at 1064 nm is on the order of a second,[10] the 30-Hz macropulses provide continuous heating to the irradiated bone. With this setup, we can study the effects of both peak and average laser powers in the process of ablating the bone specimens.

We focused the laser beam to a 56-μm-diam spot by using a positive lens with a 2.5-cm focal length. In most previous studies,[6–9] visible surface damage on a scanning electron microscopic image was considered an important signature of the ablation threshold or was used to determine the material cutting rate. However, on many occasions, the cutting or drilling process can be abruptly stopped due to carbonization or plasma plume on the tissue surface. In this work, we adopt a more realistic criterion for osseous tissue removal by measuring the laser drilling time all the way through the 0.75-mm-thick bone specimen. The time required for the laser to drill through a bone specimen is equal to the signal delay time between Photodetectors A and B in Fig. 1. The drill-through time is defined to be the time difference between the two initial signals from Photodetectors A and B. The typical value of the drill-through time varies from a few tens of ms to more than a hundred ms, depending on the incident laser power. In our experiment, we define the failure of a drilling process if we detect no signal from Photodetector B 60 s after receiving a signal from Photodetector A. Figure 2 shows the drill-through time versus the average laser power for the 0.75-mm-thick bone specimen. The range of the average power between 160 and 280 mW corresponds to macropulse duration between 0.6 and 1 ms and macropulse energy between 5.3 and 9.3 mJ, respectively. Each data point in the figure was ob-

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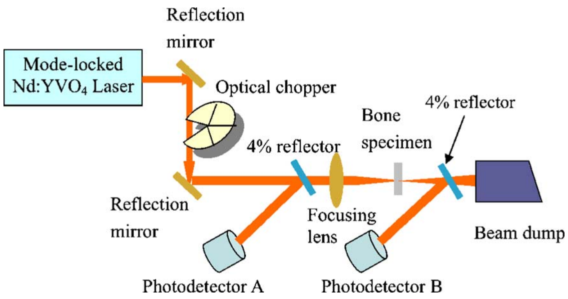


Fig. 1 Experimental setup of the bone ablation experiment by using a mode-locked $Nd:YVO_4$ laser oscillator. The laser peak power is fixed at 14 kW, but the average power is varied by the slit aperture of the optical chopper. The drill-through time is determined by measuring the time difference between the signals received by Photodetectors A and B.

tained by averaging the drill-through time measured at five different locations on a bone specimen. The error bar indicates the maximum and minimum values of the drill-through time in the five experiments. As expected, the drill-through time is decreased with an increased average power for a fixed peak laser power. However, the total number of pulses or the total laser energy for each data point in Fig. 2 is not a constant but varies with the average laser power. For example, Point A marked at 160-mW power requires 192,360 laser pulses to drill through the bone specimen, whereas Point B marked at 280 mW power requires only 112,210 pulses to drill through the specimen. This implies that, given a fixed laser peak power and a bone thickness, the laser fluence for drilling through a bone specimen of a fixed thickness decreases with the increase of the average laser power. It is also interesting to note that we failed in drilling through the bone specimen when the average power of the incident laser was less than 160 mW. That experimental evidence suggests that the laser bone drilling is an average-power mediated ablation process.

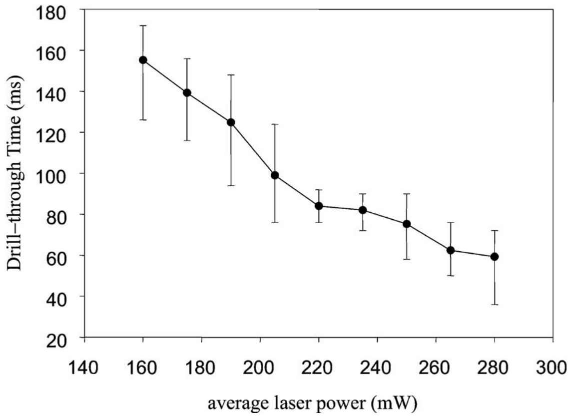
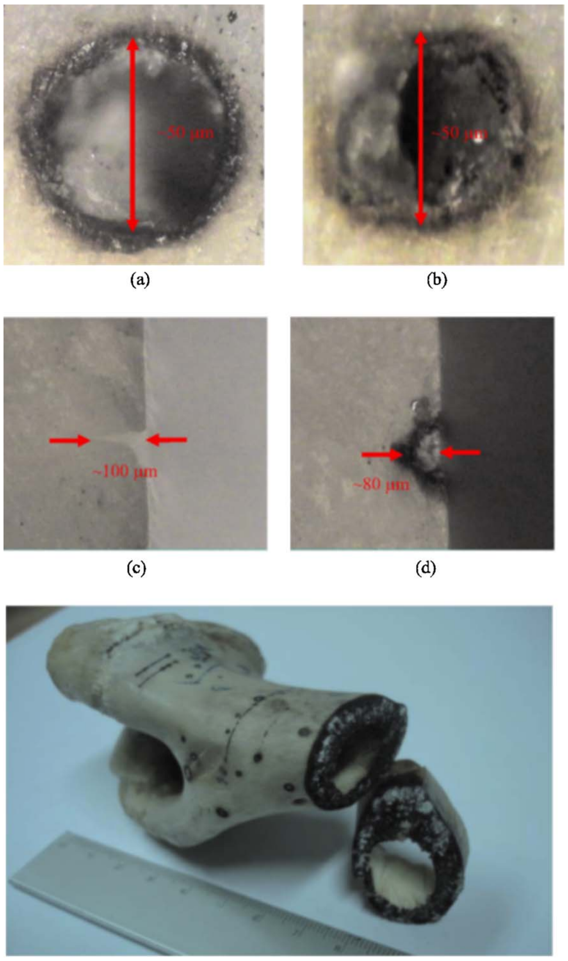


Fig. 2 The drill-through time for a 0.75-mm-thick bone specimen versus the average laser power of the mode-locked $Nd:YVO_4$ laser at a fixed peak power of 14 kW and a constant laser diameter of 56 μm. A higher average power shortens the drill-through time, but the accumulated laser fluence for each data point is not a constant.



(a) (b)

(c) (d)

(e)

Fig. 3 Ablation craters created by (a) 280-mW and (b) 160-mW average powers from the mode-locked $Nd:YVO_4$ laser. Tissue charring appears when the incident laser power is 160 mW. (c) A Q-switched laser of 100-mW average power and 200-kW peak power generated only a 100-μm deep scratch on the bone surface with negligible carbonization. (d) The frequency-doubled mode-locked $Nd:YVO_4$ laser effectively carbonized the bone surface but could not drill through the bone specimen due to its low peak power. (e) A pig femur bone was cut completely through by the 9-W mode-locked $Nd:YVO_4$ laser oscillator at 1064 nm in slightly more than a minute.

Figures 3(a) and 3(b) show the top views of the ablation craters on the bone specimen created by 280- and 160-mW average laser powers, respectively. Both craters have an ablation area well matched to the laser diameter, indicating little collateral damage to surrounding tissues. This good area match, however, is a characteristic of an ultrafast-laser or avalanche-ionization ablation process. The 160-mW crater shows obvious tissue charring in the laser irradiation area. From the two crater images, we speculate an unconventional ablation mechanism, of which the average laser power first carbonizes the osseous tissue and the peak power of the ultrafast laser subsequently removes the carbonized material through avalanche ionization. This model is first tested by using a 1-kHz-rate passively Q-switched $Nd:YAG$ laser at 1064 nm (PowerChip, Uniphase) with 100-mW average power and 200-kW peak power focused to the same laser diameter on the bone specimen. The peak and average powers of the Q-switched laser are significantly higher and lower, respectively, compared with those of the mode-locked $Nd:YVO_4$ laser. Figure 3(c) is the side view of the ablated bone specimen cut at the center of the crater. The Q-switched laser did not drill through the bone specimen but created just

Table 1 The characteristics of the laser sources used for demonstrating and verifying the unique ablation mechanism of laser osteotomy using a mode-locked laser oscillator.

	Mode-locked $Nd:YVO_4$ laser	Q-switched Nd:YAG laser	Frequency-doubled mode-locked $Nd:YVO_4$ laser	Yb fiber laser
Wavelength	1064 nm	1064 nm	532 nm	1064 nm
Pulse width	12 ps	~500 ps	~10 ps	CW
Repetition rate	54.1 MHz	1 kHz	54.1 MHz	—
Peak power	14 kW	200 kW	296 W	—
Average power	<10 W	100 mW	160 mW	10 W
Bone drilling	excellent	poor	poor	poor

a ~100-μm-deep scratch near the surface. The low average power of the Q-switched laser was unable to carbonize the osseous tissue and rendered the 200-kW peak power nearly useless.

To confirm the ablation role of the peak laser power, we focused a 10-W CW Yb fiber laser at 1064 nm (IPG Photonics) into the same laser diameter on the bone specimen. We observed only carbonization on the bone surface but could not drill through the specimen. This result unambiguously confirms the crucial role of the peak power of the mode-locked laser in drilling through the carbonized tissue.

Since a laser at visible wavelengths is better absorbed by a cortical bone than a laser at 1064 nm, we further doubled the optical frequency of the mode-locked $Nd:YVO_4$ laser to produce 160-mW and 296-W average and peak powers, respectively, at 532 nm. Figure 3(d) shows the side view of the ablation crater created by the 532-nm laser under the same focusing condition. Although the average power and better absorption of the 532-nm laser efficiently carbonizes the bone surface, the 296-W peak laser power appears too low to drill through the bone sample. This result is consistent with the conclusion derived from the test of the 10-W CW fiber laser.

In clinical applications, deep cutting in a bone is sometimes desirable. We show in Fig. 3(e) a pig femur bone cut through by the 9-W mode-locked $Nd:YVO_4$ laser at 1064 nm. The cross section of the femur bone is of approximately an elliptical shape with a 35-mm major axis and a 22-mm minor axis. The wall thickness of the bone varies between 3 mm and 12 mm. While focusing the laser onto the bone, we rotated the bone about its longitudinal axis at an angular speed of about 0.1 rad/s. The cutting process was completed in slightly more than a minute. This illustration is meant to show the deep and fast cutting ability of the mode-locked $Nd:YVO_4$ laser oscillator. In practice, tissue heating and carbonization can be further controlled by adjusting the rotation speed of the bone and the average power of the laser.

We summarize in Table 1 the parameters of the laser sources for demonstrating and verifying the unique ablation mechanism. Briefly, the test of the Q-switched Nd:YAG laser proves the need of the laser average power in the mode-locked $Nd:YVO_4$ laser for ablating a bone material. The tests of both the frequency-doubled mode-locked $Nd:YVO_4$ laser and the CW Yb fiber laser confirm that the peak power of the mode-locked $Nd:YVO_4$ laser is indispensable during the ablation process.

In summary, both average and peak laser powers play important roles in laser osteotomy using a mode-locked laser oscillator. The average laser power first carbonizes osseous tissues and the peak laser power of the ultrafast pulses subsequently removes the carbonized material though avalanche ionization. A minimum average laser power of 160-mW is required to drill through a 0.75-mm-thick cortical bone for a mode-locked $Nd:YVO_4$ laser with a 54-MHz repetition rate, 12-ps pulse width, and 14-kW peak power focused down to a 56-μm laser diameter. The 160-mW critical power indicates a threshold temperature from Joule heating at which the irradiated tissue is quickly carbonized. Above the critical average power, the high peak power from an ultrafast laser oscillator is capable of cleaning the carbonized tissues with negligible collateral damage. Our study provides a crucial understanding of using a relatively low-cost, mode-locked laser oscillator for laser osteotomy. Since most biological tissues contain carbohydrates, we expect to generalize the result of this study to most laser surgeries using a mode locked laser oscillator.

Acknowledgments

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