

# The dawn of computer-assisted robotic osteotomy with ytterbium-doped fiber laser

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**Abstract** Currently, laser radiation is used routinely in medical applications. For infrared lasers, bone ablation and the healing process have been reported, but no laser systems are established and applied in clinical bone surgery. Furthermore, industrial laser applications utilize computer and robot assistance; medical laser radiations are still mostly conducted manually nowadays. The purpose of this study was to compare the histological appearance of bone ablation and healing response in rabbit radial bone osteotomy created by surgical saw and ytterbium-doped fiber laser controlled by a computer with use of nitrogen surface cooling spray. An Ytterbium (Yb)-doped fiber laser at a wavelength of 1,070 nm was guided by a computer-aided robotic system, with a spot size of 100  $\mu\text{m}$  at a distance of approximately 80 mm from the surface. The output power of the laser was 60 W at the scanning speed of 20 mm/s scan using continuous wave system with nitrogen spray level 0.5 MPa (energy density,  $3.8 \times 10^4 \text{ W/cm}^2$ ). Rabbits radial bone osteotomy was performed by an Yb-doped fiber laser and a surgical saw. Additionally, histological analyses of the osteotomy site were performed on day 0 and day 21. Yb-doped fiber laser osteotomy revealed a remarkable cutting efficiency. There were little signs of tissue damage to the muscle. Lased specimens have shown no delayed healing

compared with the saw osteotomies. Computer-assisted robotic osteotomy with Yb-doped fiber laser was able to perform. In rabbit model, laser-induced osteotomy defects, compared to those by surgical saw, exhibited no delayed healing response.

**Keywords** Bone ablation · Computer aided · Near-infrared irradiation · Saw · Wound healing

## Introduction

Currently, conventional mechanical instruments (e.g., saws, chisels, and drills) are standard tools in bone surgery. All of them are used in contact with bone tissue with a certain extent of grinding pressure, hammering or similar mechanical force, and are conducted manually. Using conventional cutting methods, the geometry is restricted: geometrically arbitrary and complex cutting shapes are not achievable [1]. Progress of computer may help to improve surgical strategies with performance of safer and faster procedures.

Laser radiation is now used routinely in medical applications to cut, shape, treat, and remove soft tissues of the body. It has many advantages over conventional cutting techniques which include high productivity, narrow kerf width, low roughness of cut surfaces, and minimum distortion. A few publications have reported preliminary success at laser bone osteotomy [2]. Both CO<sub>2</sub> laser and Er:YAG laser (with a wavelength of 10,600 nm and 2,940 nm) have been associated with a thermal mechanism of bone ablation, with resulting coagulation, carbonization, and vaporization of living tissues. For infrared lasers, including Nd:YAG, Ho:YSGG, Er:YAG, and CO<sub>2</sub> laser not only the possible mechanisms of bones ablation and tissue damage but also the healing process are reported [2–9]. Most industrial laser applications utilize computer and robot assistance. In contrast, laser radiation in medical applications is still mostly conducted manually nowadays.

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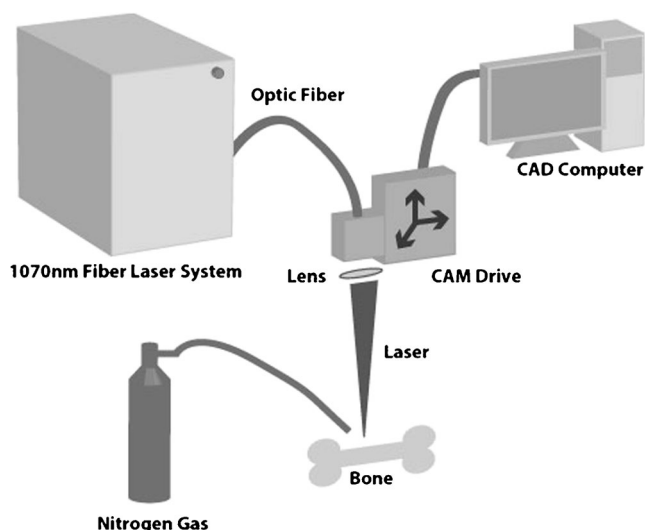
Fiber lasers are one of the fastest developing fields of optics and photonics today. Their continuous wave output power has been scaled above 100,000 W, and they are frequently used in commercial cutting and welding applications in many different industries. Fiber lasers are more compact, lighter, and more efficient than other bulk lasers. With computer assistance, accurate and precise application of the laser beam may be possible.

Recently, we developed the computer-assisted robotic Ytterbium (Yb)-doped fiber laser system with a wavelength of  $\lambda=1,070$  nm. The purpose of this study is to compare the histological appearance of bone ablation and healing response of rabbit radial bone at intervals of 0 and 21 days following creation of osteotomy defects by surgical saw and Yb-doped fiber laser with nitrogen surface cooling.

## Materials and methods

### Laser system

For laser osteotomies, an Yb-doped fiber laser at a wavelength of 1,070 nm was employed (Fig. 1). The laser produced a continuous wave and was guided by a computer-aided design (CAD)/computer-aided manufacturing (CAM) robotic system, with a minimum spot diameter of 100  $\mu\text{m}$  at a distance of 80 mm from the focusing lens. The distance between the lens and radiation field was automatically controlled with a coaligned red laser for distance measurement and visual targeting. Nitrogen gas was combined with the laser system. Based on our unpublished previous studies, which some cutting experiments using a fresh ex vivo cow femur, the laser settings were determined. The settings for bone cutting were 60 W using continuous wave system.



**Fig. 1** The schematic view of the laser system

### Surgical procedure

Twelve Japanese white rabbits at 16 weeks of age, with an average body weight of 3 kg were used in the investigation. All experimental protocols described in the present study were approved by the Ethics Review Committee for Animal Experimentation of Hyogo College of Medicine.

The rabbits were anesthetized by an intravenous injection to auricular vein of sodium pentobarbital (30 mg/kg body weight). Both the left and right radial bones of each animal were surgically exposed by means of a 5-cm incision of the medial aspect of each upper leg. Utilizing a sterile technique, soft tissue was dissected and retracted to reveal some area of bone.

The right radial bone received impact from an Yb-doped fiber laser. The laser beam was focused to an  $\varnothing 100$   $\mu\text{m}$  spot at the impact site delivered with 60 W of output power at the scanning speed of 20 mm/s scan, which means that the energy density was  $3.8 \times 10^4$  W/cm<sup>2</sup>; applied nitrogen spray level was 0.5 MPa. Laser irradiation was programmed to perform in a straight line with a single sweep. The left radial bone served as a control received an osteotomy by a surgical saw, which thickness was 400  $\mu\text{m}$ , in a straight hand piece. Following the procedure, the surgical sites were closed with 3–0 nylon sutures.

The rabbits were sacrificed by means of an overdose of sodium pentobarbital injected into the auricular vein acutely and at 3 weeks postoperatively. Twelve rabbits were randomly allocated to two groups of six. Each upper leg was dissected, removed, and placed in 10 % buffered formalin for 5 days, and then, both specimens were washed in phosphate-buffered saline. For decalcification, bones were suspended in KCX<sup>®</sup> (FALMA. Co., Ltd.) at room temperature for 7 days. Samples were then dehydrated in graded alcohols, cleared in xylene, and embedded in paraffin. Sections measuring 6–8  $\mu\text{m}$  were cut parallel with the longitudinal axis of the bones, stained with hematoxylin and eosin, cleared of paraffin in xylene, and dried. Sections through the osteotomy site were examined with an E600 Nikon microscope and photographed with DS-Fi1-U2 (Nikon) to evaluate tissue damage and healing.

In addition, muscle adjacent to the radial bone received laser impact delivered with the same parameters; muscle was dissected during the osteotomy. The muscle was removed and placed in 10 % buffered formalin immediately after the impact. They were then grossly examined for microscopic evidence of tissue damage. Following gross examination, the specimens were stained with hematoxylin and eosin for histological study.

## Results

Rabbit radial bones were examined immediately and 3 weeks after surgery. In the acute specimens, both osteotomy

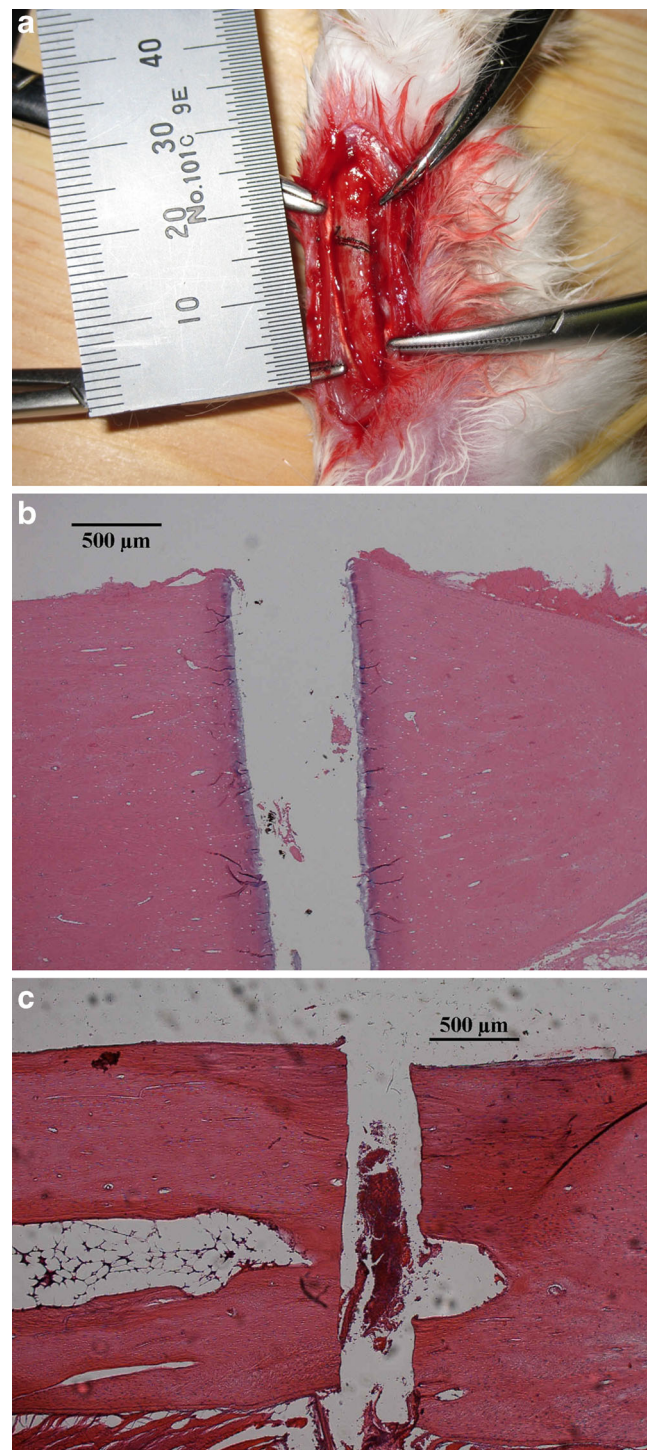
modalities produced deep cuts with sharp edges. Macroscopic observation showed some carbonization of the cut bone surface in the laser osteotomies (Fig. 2a).

Histological sections of the laser osteotomies revealed a slightly thicker pattern of ablation compared with the saw osteotomies. There was little histological evidence of charring and carbonaceous material seen in the laser osteotomies; in addition, a very thin surface of coagulated tissue was found covering the most superficial aspect of the defect (Fig. 2b, c). On the 21st postoperative day, both wounds demonstrated either complete or nearly complete healing. No evidence of a residual defect on either gross or microscopic examination was found. When evaluated histologically, these sites consisted of a solid plug of mineralized bone. The surgical site on the lased radial bone was not circumscribed at all with persistent black carbonized debris covering the surface (Fig. 3a, b).

The muscle response to the laser displayed little damage histological just after the surgery (Fig. 4). The laser was able to ablate in a straight line at a speed of 20 mm/s as we programmed in the computer.

## Discussion

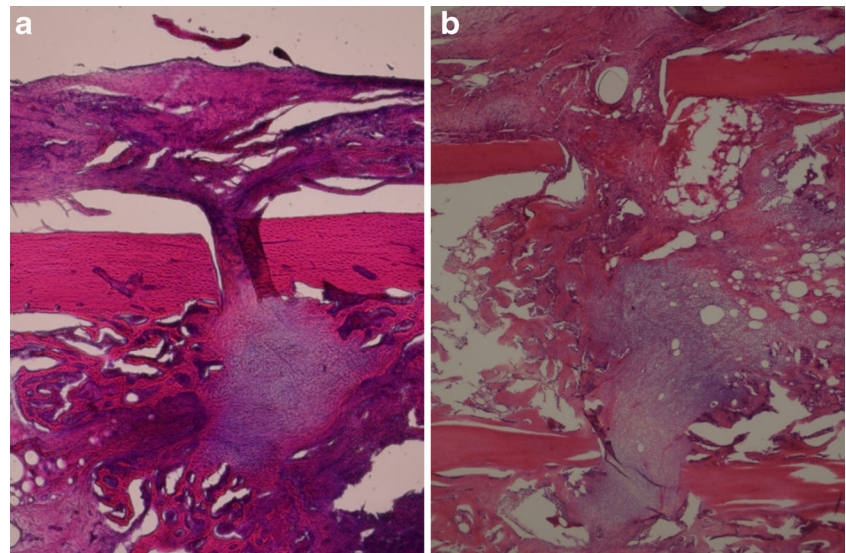
Previous studies have shown that the Er:YAG laser with a wavelength of  $\lambda=2,940$  nm has a strong absorption coefficient for water. In addition, the organic matrix and inorganic calcium salts, the major component found in bone, also have a very high absorption coefficient for Er:YAG laser irradiation [10–12]. As a result of this high absorption, thermal bone ablation is the mechanism of Er:YAG laser osteotomies. CO<sub>2</sub> laser with a wavelength of 10,600 nm also have been associated with a thermal mechanism of bone ablation [3]. The Yb-doped fiber laser has an emission band at 1,070 nm. The absorbance characteristics of a nondecalcified bone have demonstrated relatively moderate absorption of 1070 nm wavelength [3]. Heat-damaged bone is characterized by a coagulation necrosis featuring hematoxylin affinity and loss of collagen fiber orientation [13]; Yb-doped fiber laser specimens showed a little coagulated tissue covering the most superficial aspect of the defect. In addition to the thermal damage, a photomechanical effect similar to that described for Q-switched and mode locked Nd:YAG laser ( $\lambda=1,064$  nm) destruction of substrate may also play a role for bone ablation [3, 7]. When laser energy is sufficiently condensed in time and space to achieve an extremely high irradiance, a nonlinear phenomenon known as optical breakdown will occur [14, 15]. It involves the creation of plasma, which is an ionized state in which electrons have freely dissociated from their atoms. Acute specimens in this study showed little histological evidence of charring that suggests additional mechanism to thermal damage. Bone cutting was able to perform



**Fig. 2** Gross photograph of acute laser osteotomies (a). Photomicrographs of acute laser (b) and saw (c) osteotomies. Bars are equal to 500  $\mu$ m in both b and c. a Macroscopic observation of the acute lased bone. Sharp cut was performed. Some carbonization was found. b. Acute Laser: 500  $\mu$ m was the defect following laser osteotomies. Laser osteotomy appeared not to be predominantly thermal, with little histological evidence of charring and carbonaceous material. A very thin surface of coagulated tissue was found covering the most superficial aspect of the defect. c Acute saw: saw osteotomies made 400  $\mu$ m defect. Osteotomy induced by the saw consisted predominantly of mechanical disruption of tissue, which produced a pronounced operative hemorrhage



**Fig. 3** Photomicrographs of 3-week postsurgery laser (a) and saw (b) osteotomies. Both laser and saw wounds demonstrating a solid plug of mature mineralized bone

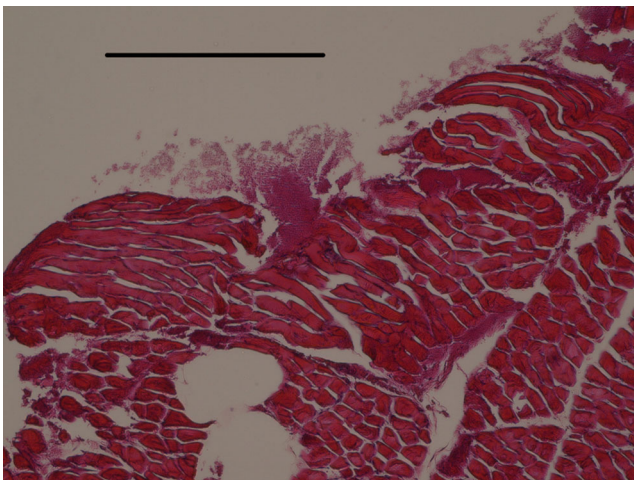


by Yb-doped fiber laser, while the potential role of these processes during bone ablation with the Yb-doped fiber laser has yet to be fully evaluated. In addition, adjacent muscle showed few damage histologically, which also needed to be evaluated.

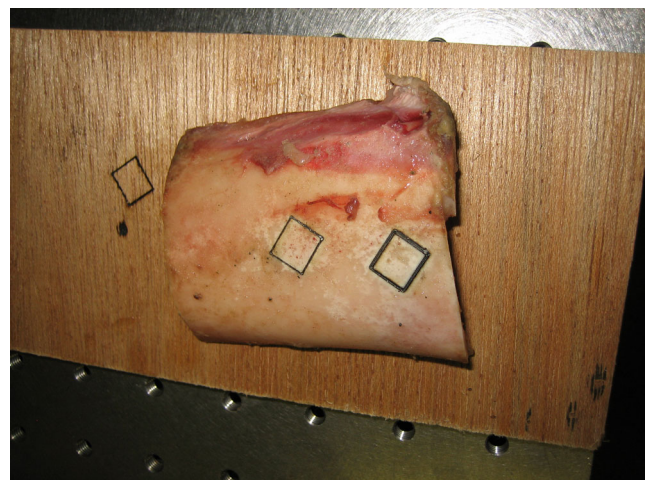
Healing of both saw and laser wound was nearly completed by the 21st postoperative day. There were no persistent defects with gross and microscopic examinations. The delayed healing response, characterized by a lack of fibroblasts and osteoblasts within the ablation defect or in contact with the char layer, has been the histological feature of the laser osteotomies [7, 13, 16–19]. In this study, the surgical site on the lased bone was circumscribed with few carbonized debris covering the surface that indicates the healing of the superficial aspect of the wound was not retarded, and Yb-doped fiber laser damage to adjacent tissue was minimal, which we hypothesize that few fibroblasts and osteoblasts were damaged

and able to participate in bone regeneration. It has been suggested that cooling of the ablation site with a jet of nitrogen gas may reduce the heat of lasing and decrease the amount of carbon char formed [8]. Although few reports combined cooling device [2, 20], we combine nitrogen gas spray for Yb-doped fiber laser. Furthermore, laser osteotomy defects were about 500  $\mu\text{m}$ , which the small gap may contribute to the healing process.

Recently, Burgner et al. has developed the world's first prototype system for robot-assisted laser bone ablation [1] and reported the need of robot-assisted laser bone ablation. We combined the Yb-doped fiber laser with CAD/CAM system for accurate and precise laser ablation, and we just planned to cut in a straight line first at a speed of 20 mm/s in this study. Cutting experiments were performed using a fresh ex vivo cow femur before this study; Fig. 5 shows the experimental cuts in rectangles. One advantage of the fiber laser is the availability of



**Fig. 4** Photomicrographs of acute laser to muscle. Bar is equal to 500  $\mu\text{m}$ . The laser-impacted muscle displayed little damage histologically just after the surgery. The wound demonstrated no evidence of charring



**Fig. 5** A fresh ex vivo cow femur was prepared, and cutting experiments were performed in rectangles

optical fibers for beam delivery, and hence, a robotic system could be less complex since no articulated arm needs to be deployed. Furthermore, fiber lasers are more compact, lighter, and easy to maintain. Laser bone ablation with CAD/CAM system has the potential to revolutionize surgery, especially in those interventions where the accuracy achievable manually is not sufficient. Cutting the bone as a dovetail joint, a technique most commonly used in woodworking joinery, may result in no use of bone plates and screws.

Our laser ablation showed fine bone cutting and healing. For laser bone ablation, precise control of localization and depth of cut is required. The change in bone type may differ in cutting and healing results [21]. Additional intimate research is necessary to evaluate proper laser setting variables with control of depth, change in bone type, and damage to adjacent soft tissue laser.

The results of this study show that the Yb-doped fiber laser will be a potentially valuable tool for bone surgery. This study has demonstrated that bone cutting using Yb-doped fiber laser is possible, and bone healing may be expected with minimal damage to surrounding soft tissue. Gross and microscopic examination revealed no additional detrimental effects upon bone. Further investigation is necessary to determine if production of larger surgical defects, increased power levels, and sustained exposure will result in a similar response.

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