Development of a Robotic Laser Surgical Tool with an Integrated Video Endoscope

Takashi Suzuki[1], Youhei Nishida[1], Etsuko Kobayashi[1], Takayuki Tsuji[1],
Tsuneo Fukuyo[2], Michihiro Kaneda[3], Kozo Konishi[4], Makoto Hashizume[4], and
Ichiro Sakuma[1]

[1] Institute of Environmental Studies, Graduate School of Frontier Sciences,
The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
`{t-suzuki, nishida, etsuko, tsuji, sakuma}@miki.pe.u-tokyo.ac.jp`
`http://bme.pe.u-tokyo.ac.jp/index_e.html`
[2] Shinko Optical Co.,Ltd., 2-12-2, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
`shinko-koki@par.odn.ne.jp`
[3] Sparkling Photon Inc., 1154-1, Kotta, Tama City, Tokyo, 206-0014, Japan
`kaneda@phton.co.jp`
[4] Department of Disaster and Emergency Medicine, Graduate School of Medical
Sciences, Kyushu University, 3-1-1, Maidashi, Higashi-ku, Fukuoka, 812-8582, Japan
`konizou@surg2med.kyushu-u.ac.jp, mhashi@dem.med.kyushu-u.ac.jp`

Abstract. Integration of new surgical devices with surgery assisting robots is required by surgeons. We have developed a novel robotic laser coagulator with a charge coupled device (CCD) video endoscope and a bending joint. The endoscope visualizes the detail of the target, and bending joint realizes the irradiation in a selected direction. We adopted two laser diodes for this purpose: an infrared semiconductor laser ($\lambda = 980$ nm) for coagulation, and a visible wavelength laser ($\lambda = 635$ nm) acting as a pointer for the target. The technical originality of this work is the mounting of a laser module on the forceps without using an optical fiber or mirror guide. This reduces the danger of laser leakage at the bending joint, and realizes miniaturization in the multiarticular robot. The clinical significance is the precise positioning and intuitive operation of the laser coagulator through future integration of this tool with a master–slave robotic system. An *in vivo* study achieved necrosis of liver tissue, and demonstrated the feasibility of the robotic laser coagulator using a CCD video endoscope.

1 Introduction

Recently, laparoscopic surgery has been widely performed as a minimally invasive surgery technique. In this method, the surgeon cuts 3 – 4 holes in the abdominal wall, and the entire procedure is carried out inside the abdominal cavity. This has advantages in reducing pain, discomfort, medication, and the time needed for recovery[1]. However, this technique requires the surgeon to have much skill and experience. Various surgical instruments, such as electric cautery, ultrasonic vibration scalpels, laser knives, and laser coagulators have been developed, and

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are widely used in the operating theater. The increasing use of these devices has shown their potential advantages as new surgical tools.

On the other hand, surgery assisting robots (Zeus^{TM}, da Vinci^{TM} [2]) have been applied clinically, and have contributed to an improvement in the quality of surgery. Bending forceps with two degrees of freedom (DOF) can trace the surgeon's operational procedure, and an intuitive operation and enhanced dexterity have been realized that could not be achieved using conventional forceps.

Both new surgical devices and robots have enabled remarkable performance to be achieved. Integration of advanced surgical tools with surgical robots, however, is still not satisfactory. Surgeons have the limited options in choosing advanced surgical tools using current surgical robotic systems. Some robotized systems using lasers have been developed in prostatectomy[3,4]. Their flexibility, however, is not adequate for general abdominal surgery, as irradiation of laser light from an arbitrary direction is required to treat lesions at various locations in the abdominal cavity. Thus, providing advanced surgical instruments with additional motional degrees of freedom will enable further advancement of surgical robot technology.

We have integrated a miniaturized high power surgical laser and a CCD endoscope for target observation using robotic bending forceps. This paper discusses a prototype robotic miniaturized surgical laser and its performance as a laser surgical instrument. We also present preliminary results of animal experiments where a porcine liver was coagulated using the developed system.

2 Materials and Methods

2.1 System Configuration

We aimed to integrate robotic forceps with laser coagulator for carrying out thermal therapy resulting in a necrosis of a tumor or for abdominal surgery hemostasis. An infrared laser with an output wavelength of around $\lambda = 1\mu$m can penetrate into deep areas of an organ, resulting in coagulation and not ablation. For example, neodymium yttrium aluminum garnet (Nd:YAG) lasers ($\lambda = 1{,}064$ nm) are widely used in the operating room for photocoagulation. The infrared light is introduced into the abdominal cavity through an optical fiber. A light guiding optical fiber, however, is unsuitable for bending robotic forceps, because cracks in the fiber would occur after repeated bending at a joint. We also have to consider the bending radius that the optical fiber would be subjected to, because the laser light would leak at small radius bends.

We used an infrared semiconductor laser chip for coagulation, and mounted the laser chip on the tip of forceps. The advantages of this laser module are:(1) the need for a light guiding fiber was eliminated, and so any danger of laser light leakage was avoided; (2) any unintended coagulation associated with laser light leakage was avoided; (3) miniaturization was realized. Because infrared light is invisible, we needed a targeting device to operate the laser device. We used a semiconductor laser chip that operated in the visible spectrum, as used in laser pointers. The control box of the laser module was newly developed, based on the idea of remote control for future telesurgery. This had a serial RS232C communication interface, and thus, we could send commands (output power and coagulating time) to the unit from a personal computer.

At the same time, the problem with a conventional rigid laparoscope was highlighted: it provides a limited and narrow view for the surgeon. On laser coagulation using the bending forceps, a rigid scope may not always show the front view of the target. An inadequate view will obstruct any appropriate operation by the surgeon. Therefore, we tried to integrate a video endoscope onto the surgical instrument to provide a detailed view of the nearest point to the target and from the far-side view of the organ, which cannot be seen by a rigid laparoscope[5]. Thus, we mounted a compact charge coupled device (CCD) camera acting as a video endoscope to provide the close-up or far-side view of an organ.

A conventional laparoscope uses an optical fiber to illuminate the abdominal cavity. However, we identified the risk of cracking in the fiber, and so used a white light emitting diode (LED) for illumination, so eliminating the use of an optical fiber for the light source, and in the robotic forceps system, we integrated the above modules: laser, pointer, CCD camera, and LED.

2.2 Semiconductor Laser Module

We used an infrared semiconductor main laser for coagulation (InGaAs/GaAs, $\lambda = 980$ nm , output power = 20 W) (Sparkling Photon, Inc. Japan) that was equivalent to a normal Nd:YAG laser. We assembled a linear array of ten laser diode chips with 2 W output power each to realize a combined output power of 20 W. The alignment of the laser chips is shown in Fig. 1. The main laser bar had an area of 1×5 mm^2. The laser beam output was collimated to ensure the beams were parallel. To point to the target, we mounted a red laser ($\lambda =$ 635 nm, output power = 10 mW), as is used in a commercial laser pointing device (see Fig. 2). We circulated physiologic saline inside the base of the laser chips' mount to act as a coolant. We developed our own control unit to control the laser module(Fig. 3). This controlled the current, the coagulating time, the safety lock, the red laser for pointing, a white LED, and a foot switch, and had two input interfaces: a local mode using a nearby controller, and a remote control mode via an RS232C communication interface. This arrangement allows for future adaptation for remote control during telesurgery.

2.3 CCD Camera

We used a compact CCD camera (Shinko Optical Co. Ltd., Japan) as the second scope. The camera dimensions were: diameter = 5 mm; length = 15 mm; and weight = 3 g. The area of the CCD images was 3.30×2.95 mm^2, and this contained 410,000 pixels. In contrast to a fiberscope, the CCD camera produced good quality images. It also had the advantage of being able to be adaptable to the bending forceps, because it did not require optical fibers to function.

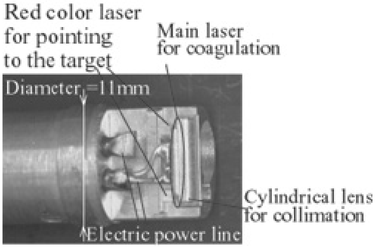

Fig. 1. Alignment of the laser chip for coagulation and pointing.

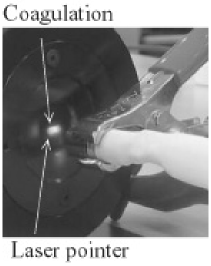

Fig. 2. The infrared semiconductor laser ($\lambda = 980$ nm) and the red laser ($\lambda = 635$ nm).

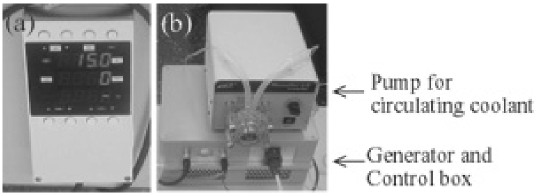

Fig. 3. The original control unit for laser module: (a) the controller; (b) the pump for circulating the coolant, and the generator.

Although optical fibers are usually used to transmit light from a light source into the abdominal cavity, we used a white LED (NSPW300BS, Nichia Corporation, Japan) as an additional light source to illuminate the target along with the main light for the laparoscope. This is because a bright light source was necessary to obtain good quality images when using the CCD camera as the second scope. We used a white LED because of its small size and the fact that no optical fiber was required. We did encounter problems with the LED color characteristics, in the red objects, such as arteries, appeared dark because of the LED's wavelength characteristics, which are different from those of conventional light bulbs[6]. In addition, the light intensity of the LED was much lower than a conventional light bulb. However, we found that the LED could be used as a light source in the limited area near the target, and that the problems associated with the spectrum would not be severe, because of the lower intensity of the LED source.

2.4 Bending Forceps and Integration

We developed the robotic forceps as an end effector of the forceps manipulator with four DOF[7,8]. The forceps required two bending joints that were equivalent to the wrist of a surgeon, so that the forceps could trace the operational procedure using six DOF. However, as the laser instrument can be considered to be symmetrical around the longitudinal axis, we eliminated one DOF (the rotational motion around the longitudinal axis). Thus, the forceps had only one DOF (the bending motion of the tip). The prototype device is shown in Fig. 4. The bending joint was driven by a linkage mechanism using a geared stepper motor (Turbo Disk P010, Portescap, USA) and a ball screw. The range of the bending joint was 0 – 90°. The tip of forceps, on which the laser module and CCD camera were mounted, is shown in Fig. 5.

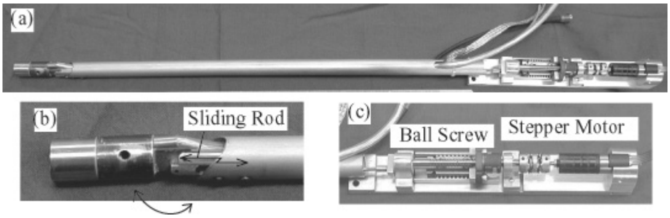

Fig. 4. The prototype: (a) full view; (b) linkage mechanism for the bending motion of the tip; (c) the driving unit using a stepper motor and a ball screw.

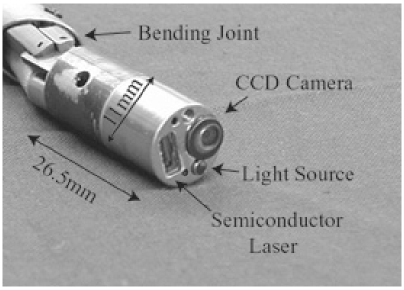

Fig. 5. The tip of the forceps: diameter = 11 mm; length = 26.5 mm; weight = 15 g.

3 Results

3.1 Laser Diode

The area of coagulation was measured to be 0.55×4.75 mm^2 at a distance of 10 mm from the tip of the forceps. This coagulation area was measured using laser alignment paper (Zap-It$^{(R)}$, Zap-It Corp., USA).

We also measured the characteristics of the input current (A), the output power (W), and the temperature of the coolant (°C), shown in Fig. 6. The initial temperature of the coolant was 22°C, and the coolant was circulated a rate of at 60 ml/s during the laser irradiation.

The maximum output power of the laser module was 20.0 W for an input current of 25 A. However, the collimating lens and the glass window in front of the lens reduced the power of the laser to 11.8 W. The temperature of the coolant increased from 22 to 43°C, a temperature of 21°C, showing that the cooling efficiency was high enough for the system to cope.

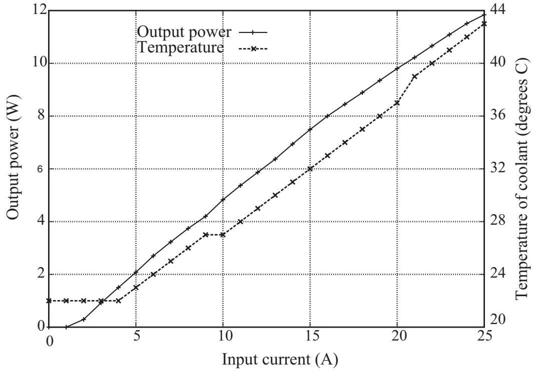

Fig. 6. The characteristicsof the input current (A), output power (W), and temperature of the coolant (°C).

3.2 *In Vivo* Experiments

We carried out *in vivo* experiments on a porcine liver under laparotomy rather than laparoscopy, because the mounting of the laser module on the robotic forceps had not been achieved at the time the experiments were conducted. The laser module was held in place using a clamp that fixed its position near the liver.

The red pointing laser was invisible under the direct high power surgical light, but as it was relatively dark inside the abdominal cavity, this would not be a problem for laparoscopic surgery. The white LED was evaluated as being a suitable point light source, but the effects of the tin white color of the LED could not be ignored, and medical doctors have commented that the color of the white LED needs to be changed.

We evaluated the coagulating performance using an output power of 9.8 W at a current of 20 A, and using an irradiation time of 10, 20, and 30 s. During coagulation, we stopped the respirator in use to eliminate any motion of the organ caused by the action of breathing; the result is shown in Fig. 7. During coagulation, laser bursts occurred in periods lasting around 15 s, and the effect of these showed that the laser had sufficient power for coagulation. On the other hand, bursts inside the abdominal cavity in this manner would cause a rapid increase in air pressure. This may be dangerous for laparoscopic surgery. Even though we will be able to determine the necrosis and carbonization of the tissue from the compact CCD camera images, an adjustment in the laser power is necessary to realize safe and stable coagulation. Thus, it is important to know the relationship between the input energy and volume of necrosis, and to quantify the appropriate input energy before bursts are carried out. As an example of how to achieve this quantification, we measured the volume of denaturation. Using the experimental conditions of power = 7.5W, current = 15 A, and the irradiation period = 20 s, the denaturation volume was 29 mm^3 (see Fig. 8). Collecting this type of data will clarify the characteristics of laser coagulation and enable us to quantify it.

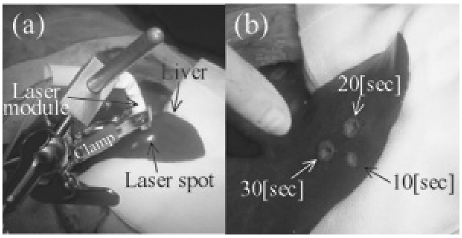

Fig. 7. The *in vivo* experiment on a porcine liver: (a) coagulation; and (b) the result.

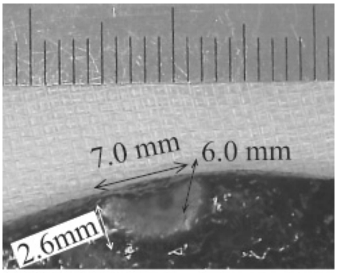

Fig. 8. A cross-sectional view of the liver. The volume was calculated using an approximated elliptical cone. Major axis length = 7 mm; minor axis length = 6 mm; depth = 2.6 mm.

4 Discussion and Conclusions

We have realized a robotic laser coagulator with an integrated CCD endoscope. The unit had mounted semiconductor laser chips for coagulation and for pointing to the target. A white LED used for lighting had sufficient light intensity, but its tin white color presented a problem. The advantages of using a semiconductor laser without an optical guide were: (1) miniaturization of the laser module; (2) elimination of laser light leakage causing unintended coagulation at the bending joint; (3) integration of the laser instrument and robotized forceps with a bending joint without any risk of laser light leakage; and (4) realization of a better maintained coherent light source that enables deep penetration into the tissue of an organ compared to a conventional laser instrument using light guiding through an optical fiber.

We have yet to fully evaluate the total sterilization of the system, but we believe that the entire system can be sterilized using ethylene oxide gas (EOG). This is because each individual module of the system, such as the laser, LED, CCD camera, and mechanical part of the forceps is able to be sterilized using EOG.

In future, we will integrate this bending forceps system with a forceps manipulator that has four DOF (rotational motion around the trocar port, and insertion into the cavity) into the slave robotic system, which can realize an intuitive operation based on commands from the surgical console.

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References

1. Daijo Hashimoto, editor. *Advanced Technique in Gasless Laparoscopic Surgery.* World Scientific., 1995.
2. http://intuitivesurgical.com/.
3. Mei Q et al. PROBOT - a computer integrated prostatectomy system. *Visualization in biomedical computing. Springer*, pages 581–590, 1996.
4. Gideon Ho et al. Computer-Assisted Transurethral Laser Resection of the Prostate (CALRP): Theoretical and Experimental Motion Plan. *IEEE Biomed. Eng.*, 48(10):1125–1133, 2001.
5. R.Nakamura et al. Multi-DOF Forceps Manipulator System for Laparoscopic Surgery. In *MICCAI2000*, pages 653–660, 2000.
6. Junichi Shimada et al. Medical lighting composed of LED arrays for surgical operation. In *Proc. of SPIE*, pages 165–172, 2001.
7. Takashi Suzuki et al. A new compact robot for manipulation forceps using friction wheel and gimbals mechanism. In *CARS2002*, pages 314–319, 2002.
8. Takashi Suzuki et al. Development of forceps manipulator for assisting laparoscopic surgery. In *CARS2004*, page 1338, 2004.