Histologic Evaluation of Blood Vessels Sealed with 1,470-nm Diode Laser: Determination of Adequate Condition for Laser Vessel Sealing

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Introduction

Energy-based devices allow for a more rapid and efficient ligation of blood vessels during operations. In the present study, we evaluated the feasibility of a laser as an alternative energy source for the vessel sealing system and determined the optimal condition of laser for an effective vessel sealing through histologic examination.

Materials and Methods

The arteries (5 mm diameter) harvested from porcine legs were compressed between two glass-slides to eliminate its luminal space and were irradiated with 1,470-nm diode laser under various sealing conditions, including laser power (5-30 W), irradiation time (5 or 10 seconds), and focus mode (focus or defocus). Subsequently, the irradiated vessels were fixed in 4% formaldehyde and then processed to paraffin block. The paraffinized sample was sectioned and stained with hematoxylin and eosin for histological evaluation.

Results

The extent of tissue change was positively correlated with duration and power of laser. In defocus mode, the irradiated vessels showed sufficient tissue denaturation for sealing effect without severe tissue destruction. Moreover, among the various conditions of irradiation, laser power between 15 and 20 W, as well as exposure time of 5 seconds were appropriate for sealing the blood vessels.

Conclusion

Adequate power and irradiation duration of laser can render blood vessels to be sealed effectively, although the higher power of laser may be required to cut the vessels.

Key words

Vessels; Sealing; Diode Laser

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INTRODUCTION

Suture ligation and hemostasis of blood vessels during surgery is a time-consuming and skill-intensive process. To reduce these burdens, several energy-based devices using ultrasound and radiofrequency (RF) have been used for blood vessel sealing system.^{1,2} Whereas ultrasonic devices make use of the thermal energy of rapid vibration for coagulation and cutting blood vessels, RF-based devices achieve hemostasis and coagulation with heat generated by electrical current.³ These energy-based devices can be rapid and efficient in blood vessel ligation, which reduce times and costs significantly in diverse surgical environment.⁴⁻⁶

However, each of the energy-based devices has some weaknesses. RF-based devices can make wider denaturation and collateral damage after blood vessel sealing compared to ultrasound devices.^{7,8} In contrast, although ultrasonic devices show less thermal spread than RF devices, the maximal temperature of those instrument tip increase over 200°C, which takes over 20 seconds to cool to usable condition.⁹ In addition, ultrasonic devices may not be easy to be flexible due to their acting mechanism.

To overcome these drawbacks, new energy sources to be installed in surgical devices are needed. Since laser has unique characteristics such as beam focusing and flexibility, laser can be made as a flexible device, cut and heat a tissue precisely. Recently, optical based systems have been studied as the new surgical instrument for vessel sealing. The infrared lasers with diverse wavelengths from 808 to 1,908 nm were investigated for coagulation and sealing for wide range of blood vessel diameters and the high-power 1,470 nm diode laser showed higher burst pressure and less thermal spread than other energy-based devices.^{10,11}

However, although these preliminary studies have shown the possibility of 1,470 nm diode laser as an alternative device, further study for the exact condition of laser-based device is needed for making one-step cutting and rapid sealing device. Thus, this study aimed at histologic and functional investigation of various condition in laser power, irradiation time and focus/defocus mode for safe and efficient vessel sealing system using 1,470-nm diode laser.

MATERIALS AND METHODS

Tissue preparation

Porcine femoral and radial arteries were used for all laboratory studies. First of all, 40 kg female pigs were

anaesthetized and euthanized with Zoletil 50 5 mg/kg, Rompun 2 mg/kg and KCl 2 mmol/kg. After obtained from front and hind legs, femoral and radial arteries with 5 to 6 mm diameter were processed by removal of fat and stored in phosphate buffered saline prior to use. Then arteries were cut into 2.5 mm length to fit laser irradiation setup.

Experimental setup

We designed a bench-top setup for testing the laser sealing and cutting of blood vessels (Fig. 1A). Using this system, we identified the optimal conditions in laser power, beam shape, and irradiation time for the effective laser surgery.

A diode laser with the wavelength of 1,470 nm (QPC laser; Laser Operation LLC, CA, USA) and output power of 45 W was coupled to the fiber with 400-μm-core diameter (People Laser Tech, Anyang, Korea). A spherical lens (People Laser Tech) with the focal length of 30 mm collimated the output beam from the fiber. A cylindrical lens (model LJ1212L1-C; Thorlabs, NJ, USA) with focal length of 100 mm was used to focus one axis of the beam such that a line beam was generated at the target plane, in which blood vessel was to be positioned. The dimension of the line beam was 0.5 mm by 10 mm. A beam dump was positioned at the downstream in order to block the transmitted beam. The arteries transected from porcine were sandwiched between two transparent slide glasses were placed at or near the focal plane of the cylindrical lens.

In order to find the optimal condition for the sealing of the blood vessels, we placed the vessels at the focal plane of the cylindrical lens (Focus mode) and at the location slighted away from the focal plane of the lens (Defocus mode). Depending on the distance from the focal plane, we could control the size of the line beam in its shorter axis and control the laser irradiation power per unit area. In short, the laser was irradiated to the compressed vessel with the laser power from 5 to 30 W, irradiation time for 5 or 10 seconds, and focus or defocus mode.

Histologic evaluation

The irradiated arteries were fixed in 4% formaldehyde and processed to paraffin block. The paraffinized samples were longitudinally sectioned along a long axis of the vessels and stained with hematoxylin and eosin for histological evaluation. After mounted using mounting medium, slides were examined with an Olympus BX51 microscope. Pictures were captured and controlled in Olympus DP72 and DP2-BSW.

Fig. 1. Experimental setup and burst pressure measurement. (A) Bench-top setup for testing the laser sealing and cutting of blood vessels. 1,470 nm diode laser, collimation lens, and cylindrical lens were used to make a line beam and the arteries were sandwiched between two transparent slide glasses. Subsequently, the line beam was irradiated to the compressed vessel with the laser power from 5 to 30 W, irradiation time for 5 or 10 seconds, and focus or defocus mode. (B) After sealing the vessels, one end of the vessel lumen was placed over a cannula attached to the infusion pump and was closed with iris clamp to seal the vessel onto the cannula. Using the syringe pump, phosphate buffered saline was fed into the vessel and the pressure was measured with the pressure meter. The maximum pressure (mmHg) just before the vessel seal bursts was regarded as the burst pressure for a given sealing condition.

The adequate condition of sealed vessels was defined as showing the even and whole denaturation from the front to back side of the vessels and both intimae were tightly stuck together without any gaps. In addition, the lateral thermal damage zone was defined from 1 to 2 mm as an adequate condition. However, when occurring an inadequate and localized denaturation of vessels or tissue destruction and detachment by severe thermal damage of vessels, we classified it as an inadequate condition.

Burst pressure measurements

We measured burst pressure of the sealed vessels to compare the sealing completeness of vessels according to the various sealing condition. Following the standard pressure measurement protocol conducted elsewhere,^{12,13} we constructed a setup composed of pressure calibrator (model 717-100G; Fluke, Everett, WA, USA), syringe pump (model Fusion 100; Chemyx, TX, USA), and Iris clamp (Fig. 1B).

After sealing the vessels, the mid-portions of those were divided with surgical scalpel and then the one end of

the vessel lumen was placed over a cannula attached to the infusion pump and was closed with iris clamp to seal the vessel onto the cannula. Using the syringe pump, PBS was fed into the vessel at a flow rate of 7.5 ml/min and the pressure was measured with the pressure meter. The maximum pressure (mmHg) just before the vessel seal bursts was regarded as the burst pressure for a given sealing condition. For control, the burst pressures were also estimated in the vessels sealed with Harmonic Scalpel® and LigaSure® Vessel Sealing System.

RESULTS

Gross images of the irradiated vessels

The blood vessels irradiated with 1,470 nm diode laser were shown in Fig. 2. The laser-irradiated regions were visible in all conditions and showed a tendency to be more charred as the power and the irradiating duration of laser increased. In particular, the char formation tended to increase when irradiating the laser with focus mode and the tissue destruction extensively occurred at an irradi-

Fig. 2. Gross findings of blood vessels irradiated with laser. The laser-irradiated regions showed a tendency to be more charred in proportion to the power and duration of laser irradiation (arrow head). The tissue destruction extensively occurred at an irradiance of 30 W for 5 or 10 seconds.

ance of 30 W for 5 or 10 seconds.

Histologic images of the irradiated vessels

The histologic findings of the irradiated vessels showed tissue denaturation and adhesion between the front and back side of vessels (Fig. 3). In terms of the completeness of tissue denaturation between the front and back side of vessels, defocus mode was more effective than focus mode, in which the laser was not effectively penetrated into the vessels and the tissue denaturation was not elicited evenly at the full-thickness of the vessels. The vessel walls were relatively more destroyed when exposed to the laser irradiation with increasing power from 25 W. In addition, the proportion of denaturation was correlated with the exposure time of laser. When exposed for 10 seconds, the irradiated vessels showed relatively wider tissue denaturation than those for 5 seconds. As a result, the adequate condition with the full-thickness and uniform

denaturation and lateral thermal damage of the vessel wall less than 1 mm was the defocus mode laser with an irradiance of 20 W for 5 seconds.

Burst pressure of the sealed vessels

Among various conditions of vessel sealing with the laser, we chose the eight conditions for estimating burst pressure; focus mode at irradiance ranging from 15 to 25 W for 5 seconds, defocus mode from 15 to 25 W for 5 seconds and focus and defocus modes at irradiance of 20 W for 10 seconds.

The mean of burst pressures, after sealing the vessels with Harmonic Scalpel® and LigaSure® Vessel Sealing System, were from 380 mmHg to 507 mmHg and 410 mmHg, respectively. Therefore, the adequate burst pressure was defined as the range between 380 and 507 mmHg of the control sealing, since it is enough to endure the blood pressure exceeding the normal systolic blood

Fig. 3. Histologic findings of blood vessels irradiated with laser. In terms of the completeness of tissue denaturation between the front and back side of vessels, defocus mode was more effective and showed tissue denaturation evenly at the full-thickness of the vessels. The adequate condition with the full-thickness and uniform denaturation and lateral thermal damage of the vessel wall less than 1 mm was the defocus mode laser with an irradiance of 20 W for 5 seconds.

pressure of 120 mmHg as well as that above 180 mmHg typically observed in malignant hypertension. Additionally, the other criterion was low standard deviation less than 100 mmHg meaning a consistent sealing of vessels. Consequently, defocus mode at an irradiance of 20 W for 5 and 10 seconds was the target condition to reveal a sufficient burst pressure (Fig. 4).

DISCUSSION

The present study demonstrated the adequate condition of laser for vessel sealing through histologic evaluation of blood vessels sealed by irradiation of 1,470 nm near-infrared (NIR) lasers. Comparing to the previous other vessel sealing systems, the sealed vessels under the conditions of defocus mode, 20 W, and irradiation time of 5 to 10 seconds elicited acceptably high burst pressure.

The previous study has suggested that NIR lasers with wavelengths producing optical penetration depths of approximately 0.3 to 0.6 mm could produce sufficiently strong sealing of blood vessels. In addition, among various wavelengths of laser, 1,470 nm diode laser elicited the ability to fuse vessels ranging from 1 to 6 mm in diameter with minimal charring and collateral thermal damage at irradiance of 31 W for a relatively short period less than 5 seconds.¹⁰ However, in contrast with this previous study,

the power of 30 W showed the excessive destruction of vessel walls in the histologic evaluation of the sealed vessels and the adequate condition for laser sealing system was 20 W, defocus mode, and 5 or 10 seconds of irradiating duration in our study. Especially, the completeness and uniformity of tissue denaturation of the front and back side of blood vessels seemed to be more associated with focus/defocus mode than laser power. Higher power of laser tends to occur more extensive tissue destruction compared to uniform tissue denaturation that ensuring a vessel sealing. Actually, In the present study, laser with focus mode or high power was not effectively penetrated into the vessels and the tissue denaturation was not elicited evenly at the full-thickness of the vessels. However, these results of our study may be associated with an impractical situation, which the laser was irradiated on the collapsed blood vessels sandwiched between two transparent slide glasses. In an actual surgical situation using energy-based devices, blood vessels are collapsed by two end-tips of the device and then cut under a slight tension. Therefore, if the compression pressure to collapse blood vessels increase and if the force pulling on both sides of the vessels is applied, the sealing and cutting of blood vessels may be elicited more effectively and easily.

In conclusion, the extent of tissue change was positively correlated to duration and power of laser. The adequate

Fig. 4. Burst pressure of blood vessels irradiated with laser. The graph and table show a comparison of the burst pressures of the blood vessels irradiated with laser and those sealed with Harmonic Scalpel® and LigaSure® Vessel Sealing System. When the adequate burst pressure was defined as the range between 380 and 507 mmHg of the control sealing, defocus mode at an irradiance of 20 W for 5 and 10 seconds was the target condition to reveal a sufficient burst pressure.

condition of 1,470 nm laser for sealing of blood vessels was the power between 15 and 20 W and exposure time for 5 seconds in defocused mode. Even if the higher power of laser may be required to cut the vessels, the adequate power and irradiation duration of laser can render blood vessels to be sealed effectively.

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