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Abstract. Suture ligation of blood vessels during surgery can be time-consuming and skill-intensive. Energy-based, electrosurgical, and ultrasonic devices have recently replaced the use of sutures and mechanical clips (which leave foreign objects in the body) for many surgical procedures, providing rapid hemostasis during surgery. However, these devices have the potential to create an undesirably large collateral zone of thermal damage and tissue necrosis. We explore an alternative energy-based technology, infrared lasers, for rapid and precise thermal coagulation and fusion of the blood vessel walls. Seven near-infrared lasers (808, 980, 1075, 1470, 1550, 1850 to 1880, and 1908 nm) were tested during preliminary tissue studies. Studies were performed using fresh porcine renal vessels, *ex vivo*, with native diameters of 1 to 6 mm, and vessel walls flattened to a total thickness of 0.4 mm. A linear beam profile was applied normal to the vessel for narrow, full-width thermal coagulation. The laser irradiation time was 5 s. Vessel burst pressure measurements were used to determine seal strength. The 1470 nm laser wavelength demonstrated the capability of sealing a wide range of blood vessels from 1 to 6 mm diameter with burst strengths of 578 ± 154, 530 ± 171, and 426 ± 174 mmHg for small, medium, and large vessel diameters, respectively. Lateral thermal coagulation zones (including the seal) measured 1.0 ± 0.4 mm on vessels sealed at this wavelength. Other laser wavelengths (1550, 1850 to 1880, and 1908 nm) were also capable of sealing vessels, but were limited by lower vessel seal pressures, excessive charring, and/or limited power output preventing treatment of large vessels (>4 mm outer diameter). [DOI: 10.1117/1.JBO.18.5.058001]

Keywords: blood vessels; coagulation; fusion; hemostasis; infrared; laser; sealing.

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1 Introduction

Suture ligation of blood vessels and tissue structures during open and laparoscopic surgery is a time-consuming and skill-intensive process. Recently, the alternative use of energy-based devices in place of sutures and mechanical clips has enabled more rapid and efficient methods for vessel and tissue ligation. These energy-based devices can reduce surgical operative times and costs significantly. Several different types of energy-based instruments used in surgery today are capable of rapidly sealing blood vessels and tissue structures using thermal energy to denature proteins and reforming the material into seals that can withstand supraphysiological blood pressures. Some instruments coagulate and cut vessels through vibration, using ultrasonic frequencies to provide thermal energy. Alternatively, electrosurgical devices achieve hemostasis through the use of bipolar radiofrequency (RF) energy with electrical current generating heat resulting in thermal coagulation of the vessels. Some RF-based devices provide electrical current to the vessel followed by an actuated mechanical knife which separates the coagulum into two sealed segments. These devices expedite normally labor-intensive surgical procedures such as lobectomy,[1,2] nephrectomy,[3] gastric bypass,[4–6] splenectomy,[7,8] thyroidectomy,[9–14] hysterectomy,[15] and colectomy.[16–19]

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However, both electrosurgical and ultrasonic devices have limitations, including the potential for undesirable charring and unnecessarily large collateral thermal damage zones.[20–22] For example, more thermal energy is required to seal large blood vessels with such devices, and stray thermal energy escaping the seal area can lead to unintended lateral tissue thermal damage.

Delivery of high-power, near-infrared laser radiation may provide rapid and uniform heating of soft tissues necessary for thermal coagulation. The majority of published research performed with laser radiation has been focused on forming vessel to vessel anastomosis. The intent of the current study was to explore the use of laser radiation as an alternative energy-based method for sealing blood vessels for potential use in open and laparoscopic surgical procedures where removal of diseased tissue is required.

2 Methods

2.1 *Tissue Preparation*

Porcine renal blood vessels were used for all laboratory studies. Fresh porcine kidney pairs were obtained, and renal blood vessels were then dissected, cleaned of fat, and stored in physiological saline prior to use. Through careful dissection it was possible to surgically expose the entire vascular tree for each kidney, revealing numerous bifurcations, and multiple vessels with a wide range of diameters for testing. In this study, blood vessels were categorized as small (1 to 2 mm), medium (2 to 4 mm), and large (4 to 6 mm) samples (Fig. 1).

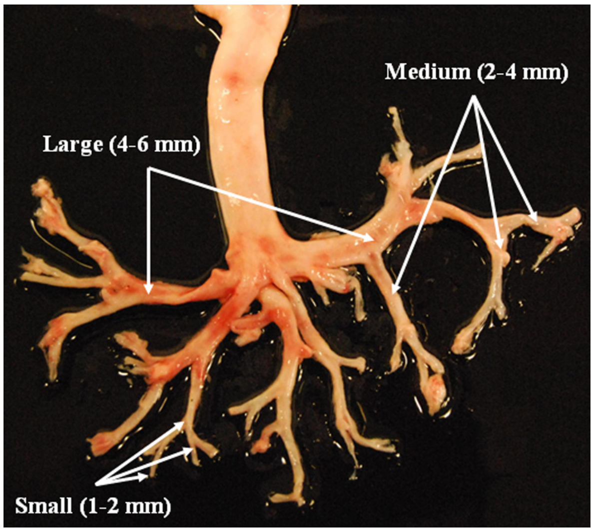

Fig. 1 Photograph of surgically exposed porcine renal vessel tree with size classifications: small vessels (1 to 2 mm), medium vessels (2 to 4 mm), and large vessels (4 to 6 mm).

Table 1 Summary comparison of continuous-wave infrared lasers used in this study.

Laser	Wavelength (nm)	Power (W)	OPD (mm)	Vessel seal
Diode	808	30	1.5	No
Diode	980	50	1.5	No
Ytterbium fiber	1075	50	3 to 4	No
Diode	1470	40	0.4	Yes
Erbium fiber	1550	30	0.9	Yes
Thulium fiber[a]	1850/1880	5.5	0.3 to 0.6	Yes
Thulium fiber	1908	100	0.1	Yes

[a]Thulium fiber laser (1850/1880 nm) was limited to low power operation.

2.2 *Infrared Laser Systems*

Seven different continuous-wave lasers spanning the entire near-infrared (IR) spectrum were tested during preliminary studies. These lasers included an 808 nm, 30 Watt diode laser (Apollo Instruments, Irvine, California), a 980 nm, 50 Watt diode laser (Edwards Life Science, Irvine, California), a 1075 nm, 50 Watt Ytterbium fiber laser (IPG Photonics, Oxford, Massachusetts), a 1470 nm, 40 Watt diode laser (QPC lasers, Sylmar, California), a 1550 nm, 30 Watt Erbium fiber laser (IPG Photonics), an 1850 to 1880 nm, 5.5 Watt tunable wavelength Thulium fiber laser (IPG Photonics), and a 1908 nm, 100 Watt Thulium fiber laser (IPG Photonics). These IR lasers were chosen because water is the primary absorber of laser radiation in the near- to mid-IR spectrum, and soft tissues are composed primarily of water (~60% to 80% water content). The optical penetration depth (OPD) in water as a function of laser wavelength is shown in Table 1 for the laser wavelengths used in this study.[23] It should be noted that visible lasers targeting blood absorption were not extensively tested because any blood normally present in the lumen of the vessel would be displaced under the applied pressure of the compressed vessel walls.

2.3 *Experimental Setup*

The benchtop experimental setup used in this study is shown in Fig. 2. This setup was intended to mimic the tissue contact aspects of a surgical instrument while providing control over the experimental variables that may impact results (e.g., applied force, gap, beam profile, etc.). Infrared laser radiation was then delivered through a 400-μm-core silica optical fiber, which was collimated using a lens. A second, cylindrical lens then converted the circular spatial beam profile to a linear beam profile. Collimating and beam shaping optical components were incorporated into the benchtop experimental setup to convert the Gaussian circular beam profile to an approximate or quasi flat-top, linear beam profile, measuring about 1 mm width by 12 mm length. This beam provided the most uniform and efficient distribution of laser power in a tight linear beam aligned perpendicular to the vessel direction for narrow, full-width thermal coagulation and sealing. The vessel sample was sandwiched between a front glass slide and a back, metal faceplate with a glass slide insert. A gap stop of 0.4 mm was used in the setup. A force meter (25 LBF, Chatillon, Largo, Florida) then monitored the amount of force on the vessel sample. Laser energy was applied for 5 s to create a thermal seal in the clamped vessel.

2.4 *Burst Pressure Measurements*

Vessel burst pressure measurements were used as the primary indicator of success. The burst pressure setup, consisting of a pressure meter (Model 717 100 G, Fluke, Everett, Washington), infusion pump (Cole Parmer, Vernon Hills, Illinois), and an iris clamp is a standard method for measuring vessel seal burst strength[24,25] and is shown in Fig. 3. Briefly, the lumen of the vessel is placed over a cannula attached to the infusion pump. An iris is then closed to seal the vessel onto the cannula. Deionized water is infused at a rate of 100 ml/h and the pressure is measured with a pressure gauge. The maximum pressure (in mmHg) achieved when the vessel seal bursts is then recorded.

2.5 *Thermal Damage Measurements*

Immediately after sealing the vessel, photographs of the vessel surface were taken for analysis of the extent of the thermal coagulation zone. Lateral thermal damage measurements were recorded as the distance measured from the center of the seal to the end of the coagulation zone, consistent with the literature.

3 Results

A general summary of qualitative vessel fusion success is provided in Table 1 for all of the near-IR lasers tested. During initial studies, several laser wavelengths were observed to produce minimal thermal alteration of the tissue and unacceptably low (<100 mmHg, which is less than systolic blood pressure) vessel burst pressures. Such wavelengths were not studied in further detail. These laser wavelengths, including 808, 980, and 1075 nm, were all similar in that they provided OPD on the

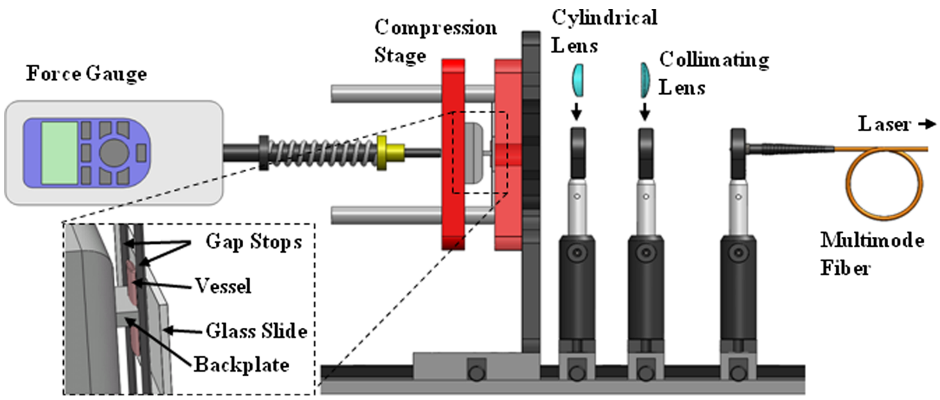

Fig. 2 Diagram of experimental setup, including a mechanical force gauge mounted onto an optical rail system, cylindrical lens for beam shaping, and laser fiber.

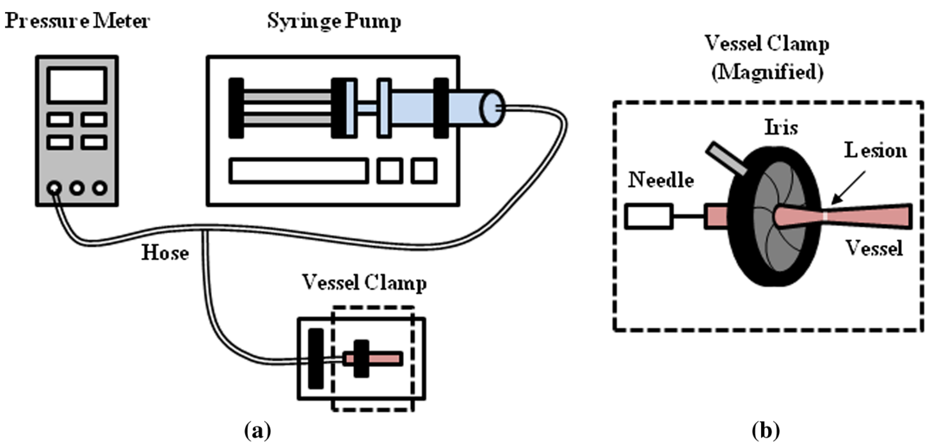

Fig. 3 (a) Diagram of burst pressure experimental setup including meter, infusion pump, and clamp. (b) Close-up view of clamp.

scale of millimeters,[23] rather than hundreds of micrometers, resulting in insufficient deposition and absorption of optical energy into the vessel during irradiation [Fig. 4(a)]. The majority of the laser energy was transmitted through the compressed, 0.4-mm-thick vessel walls, rather than absorbed in the tissue. Brief experimentation with the application of higher laser powers and/or longer laser irradiation times could not compensate for this mismatch between OPD and tissue thickness.

Extensive studies performed with several other lasers produced improved results, but were limited by lower vessel seal pressures, excessive tissue charring, and/or low power output which prevented treatment of large vessels. A comparison of the vessel burst pressures for these lasers is provided in Table 2. The 1850/1880 nm tunable thulium fiber laser was limited to operation at very low powers (5.5 W), so large vessels greater than 4 mm could not be sealed. The 1908 nm thulium fiber laser was limited by its shallow OPD (~0.1 mm), resulting in a steep thermal gradient, excessive charring on the front surface of the vessel, and borderline burst pressures for medium to large vessels [Fig. 4(b)]. It was not possible to compress the vessels down to a

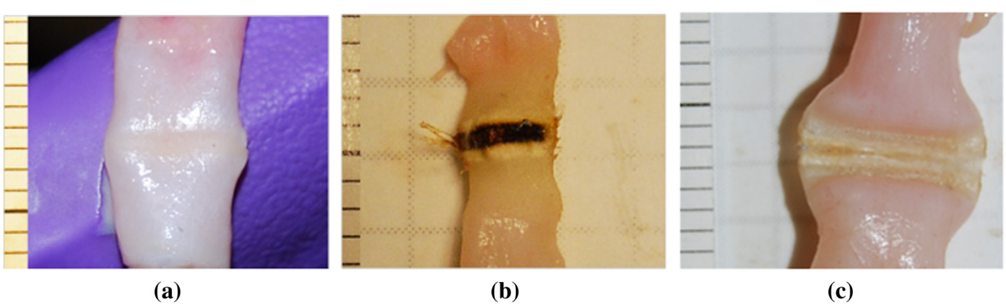

Fig. 4 Photographs of the fusion regions for the porcine renal vessel samples. Ruler scale = 1 mm increments. (a) Unsuccessful fusion of a large (6-mm-diameter) vessel using the 1075 nm laser wavelength. Minimal thermal alteration of the tissue is observed. (b) Charred (4-mm-diameter) vessel fusion zone using the 1908 nm laser wavelength. (c) Successful fusion of a large (6-mm-diameter) vessel using the 1470 nm laser wavelength. A narrow, full width thermal coagulation zone extending ~1 mm on each side of the vessel seal site is visible.

Table 2 Mean vessel seal burst pressure measurements as a function of laser power, irradiation time, and vessel size.

Wavelength (nm)	Power (W)	Time (s)	Vessel size	BP (mmHg)	N
1470	31	5	Small (1.8 ± 0.2)	578 ± 154	6
	31	5	Medium (2.8 ± 0.5)	530 ± 171	10
	31	5	Large (4.4 ± 0.3)	426 ± 174	10
1550	29	5	Small (1.9 ± 0.2)	306 ± 87	6
	29	5	Medium (3.3 ± 0.4)	275 ± 83	8
	29	5	Large (5.2 ± 0.8)	264 ± 168	13
1850	4.3	5	Small (1.9 ± 0.2)	678 ± 134	5
	4.3	5	Medium (2.5 ± 0.3)	465 ± 105	17
	NA	NA	Large	NA	NA
1880	4.3	5	Small (1.8 ± 0.3)	507 ± 389	8
	4.3	5	Medium (2.6 ± 0.3)	484 ± 145	13
	NA	NA	Large	NA	NA
1908	NA	NA	Small	NA	NA
	16	5	Medium (2.9 ± 0.4)	397 ± 117	16
	16	5	Large (4.6 ± 0.3)	357 ± 195	9

Note: Published values for radiofrequency and ultrasonic based vessel sealing devices show burst strengths ranging from a minimum of 207 mmHg to a maximum of 1261 mmHg, with values for lateral thermal damage ranging from 1 to 4 mm.[20–22,25–27]

thickness of only 0.1 mm for better matching with the OPD of the 1908 nm laser. On the contrary, the 1550 nm erbium fiber laser was limited by its large OPD (~0.9 mm) which did not match well with the compression thickness of the vessels (~0.4 mm), and also resulted in lower burst pressures for all vessel sizes. It should be noted that preliminary studies with the 1550 nm laser using a larger gap stop providing a compression thickness of ~0.8 mm to better match the wavelength's OPD did not result in improved vessel fusion, and was also unfeasible for smaller vessels which simply fell out of the larger gap stop in the experimental setup. One of our objectives was to have a single laser system and device capable of fusing all vessel sizes, which was not possible with a larger gap stop.

The 532 nm frequency-doubled Neodymium:YAG (KTP) laser was also briefly explored, but this visible laser wavelength was not included in the study. In theory, KTP laser radiation is strongly absorbed by blood and would therefore appear to be an attractive option for fusing blood vessel walls. However, during vessel sealing, the majority of blood normally located within the vessel lumen is displaced from the treatment area due to vessel compression, leaving no effective absorber for the 532 nm laser radiation, and hence, minimal thermal coagulation of the vessel was observed at this wavelength.

The 1470 nm diode laser wavelength produced rapid, precise, and strong vessel seals ($>426 \pm 174$ mmHg) over a wide range of vessel diameters (1 to 6 mm), with minimal thermal spread and charring (a lateral thermal damage width of 1.0 ± 0.4 mm including the seal was measured from the center of the seal to the end of the thermal coagulation zone) [Fig. 4(c) and Table 3)].

In this preliminary study, the 1470 nm laser wavelength produced the most consistent results over the widest range of vessel sizes with burst pressures and lateral thermal spread values similar to published values obtained with commercially available surgical devices utilizing other energy sources. In general, other energy devices produce burst pressures of about 200 to 1200 mmHg and lateral thermal damage zones of 1 to 4 mm.[20–22,25–27] Ultrasonic vessel fusion devices tend to produce less lateral thermal damage, require longer treatment times, produce lower burst pressures, and are limited to use on smaller vessels. Radiofrequency devices tend to produce greater lateral thermal damage, require shorter treatment times, produce higher burst pressures, and can be used on larger vessels.

Table 3 Mean lateral thermal damage zones as a function of laser wavelength. Lateral thermal damage measurements were measured from the center of the seal.

Wavelength (nm)	Thermal damage (mm)	N
1470	1.0 ± 0.4	15
1550	0.5 ± 0.3	21
1850/1880	0.4 ± 0.2	21
1908	0.8 ± 0.3	15

4 Discussion

In summary, a wide range of infrared lasers were tested in this study for thermal fusion of blood vessel walls. The 1470 nm diode laser was the most attractive laser due to its ability to fuse vessels ranging from 1 to 6 mm in diameter in a relatively short time period (~5 s), with a narrow zone of collateral thermal damage (~1 mm including the seal) and minimal charring. The optical penetration depth for this wavelength closely matched the vessel compression thickness (~0.4 mm), thus providing high optical absorption and heat deposition in the tissue. The 1470 nm diode laser is also a relatively compact and affordable laser system capable of emitting high powers (e.g., diode modules up to 200 W are now commercially available).

While other laser wavelengths also produced reasonable results, they suffered from significant limitations. For example, the thulium fiber laser in the wavelength range of 1850 to 1880 nm produced strong fusion of small to medium vessels at very low power. A higher power system, not available during this study, may therefore warrant further investigation. However, it is worth noting that fiber laser technology in general is less efficient than direct diodes, since the fiber lasers themselves require diode laser pump sources for operation. While the primary advantage of the fiber laser is its improved spatial beam profile for beam shaping, it is not clear whether this provides any advantages in overall performance.

Although the benchtop experimental setup described here is capable of mimicking the tissue contact parameters of a surgical device, it is not suitable for *in vivo* animal surgical studies due to its weight and size. Future work will therefore include the design and testing of a miniaturized device, consisting of a handheld instrument incorporating both the beam collimating and shaping optics and the mechanical force system for tissue compression, first for testing during *in vivo* open surgical animal studies, and then later for preclinical testing in laparoscopic surgery.

Existing energy-based devices are capable of fusing vessels with operative times as short as ~3 s.[25] It may be possible to reduce the 5 s infrared laser irradiation times during future studies by using higher laser power and/or an improved spatial beam profile.

Although the seal strengths and lateral thermal damage zones obtained in this study are consistent with those published for radiofrequency- and ultrasonic-based surgical devices, more rigorous studies may also need to be conducted to better understand the precise effect of temperature and pressure on the dynamic optical properties of the vessels during the procedure. It is well known that as soft tissues experience thermal denaturation temperatures above ~50°C, the optical scattering coefficient increases significantly, resulting in a decrease in the optical penetration depth. It has also been previously reported that the optical scattering coefficient increases as tissue is compressed[28] and for wavelengths in which scattering is already dominant, this would also translate into a decrease in optical penetration depth. However, the dynamic optical properties of blood vessels have not been well characterized, especially at some of the near-infrared wavelengths tested during this study, and therefore require further study.

5 Conclusions

This preliminary *ex vivo* tissue study demonstrates that it is feasible to use infrared laser energy to achieve rapid, precise thermal coagulation and strong seals in a wide range of blood vessel diameters with values that are in the ranges of published values obtained from commercially available radiofrequency and ultrasonic vessel sealing instruments. Near-infrared laser wavelengths producing intermediate optical penetration depths of approximately 0.3 to 0.6 mm produced the strongest seals. Future work will focus on development of a compact, handheld instrument for use during *in vivo* animal studies, and exploration of the effects of temperature and compression on the dynamic optical properties of the vessels during the procedure.

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