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Comparison of laser-assisted damage in soft tissue using bi-directional and forward-firing optical fiber

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ABSTRACT

Laser-assisted endoscopic surgery is made possible by employing optical devices such as fiber optics and hollow wave-guides. In some applications of laser-assisted endoscopic surgery, it is necessary to change the direction of the light emission. Our group reported a new fabrication method for bi-directional firing fibers. The conical surface of the fiber tip made the bi-directional emission of the laser light at the distal end of the fiber. In this study, we employed the bi-directional firing fiber for laser-assisted coagulation of soft tissue. The developed fiber and the normal forward-firing fiber are used for the endoscopic delivery system of a continuous IR laser into an in vitro porcine liver. The ablation and coagulation pattern were compared for two distinctive fiber systems. Regardless of the laser's parameters, the bi-directional firing fiber produced a cavity and coagulation zone with more or less a circular shape, while the forward fiber produced an elongated cavity and coagulation region. The bi-directional firing fiber produced wider and shorter coagulation and cavity zones compared to that of the forward-firing fiber. We expect the bi-directional firing fiber to be an excellent optical delivery system for endoscopic laser-hyperthermia when used against various tumors in the liver, breast and thyroid.

1. Introduction

Laser-assisted surgery is a less invasive treatment modality than traditional procedures and uses a coherent laser source to remove, stimulate, and injure normal and abnormal tissue. By localizing the laser energy absorption within the laser-affected zone, the laser can treat or correct diseased tissue in a controlled and precise manner. Since the first application of ruby lasers on malignant tumor tissues in hamsters [1], laser-assisted surgery has been studied and employed in various fields that include photorefractive keratectomy, laser lithotripsy, laser prostatectomy, dental cavity treatment, and cosmetic surgery [2–6]. Since the light absorption and scattering inside the tissue limit the laser penetration into deep tissues, the application of laser energy into deep tissue and internal organs is made possible by employing optical devices such as fiber optics and hollow wave-guides [7]. Laser-assisted endoscopic surgeries such as lithotripsy, prostatectomy, herniated disk surgery, varicose vein surgery, and liposuction are conducted based on this optical delivery system along with an endoscopic vision system. The less-invasive nature of laser-assisted surgery makes it favored over conventional surgery, especially for simple and less complicated disorders and diseases.

Most optical fibers for endoscopic surgery are designed to be forward-firing in that the beam exits the distal end of the fiber along the optical axis. In some applications, such as the laser prostatectomy and Photo Dynamic Therapy (PDT), it is necessary to change the direction of the light emission. A side firing fiber is used to enlarge the lumen of the prostate during a prosectomy and a diffusing fiber tip is employed for the uniform delivery of laser light for endoscopic PDT [8,9].

Recently, our group reported the fabrication of a bi-directional firing fiber. The distal end of an optical fiber with a 125 μm core diameter was machined conically by a combination of femtosecond laser machining and the arc-discharge process. The mirror-like conical surface of the fiber tip made possible the circumferential emission of the laser light at the distal end of the fiber [10]. In contrast to the femtosecond laser and the arc-discharge process for a small fiber, a tip structuring for large core fibers (core diameter > =400 μm) was conducted by employing CO_2 laser machining and femtosecond laser machining [11]. We were able to modify the tip of large core fiber into a conical shape. The emission profile of the modified tip clearly demonstrated a bi-directional light emission (circumferential emission and forward emission).

In this study, we employed the bi-directional firing (circumferential emission and forward emission) fiber for laser-assisted damage

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of soft tissue. The developed bi-directional firing fiber and a normal forward-firing fiber were used for the endoscopic delivery system of a continuous IR laser into an in vitro porcine liver. The ablation and coagulation patterns are compared for the two distinctive fiber systems and the potential application of the bi-directional firing fiber for the soft tissue treatment is discussed.

2. Materials and methods

A semiconductor diode laser (DONONA Inc., LAS-30AB) with a wavelength of 980 nm was used as the light source for the soft tissue ablation. The output powers of the laser were 3 W and 5 W in continuous mode and laser irradiation times of 3 and 5 min were used. Porcine livers obtained from a local slaughter house were used as the irradiation target of the CW diode laser. The porcine livers were extracted from young and fresh pigs and they were stored in a closed ice container prior to the experiment. The temperature of the tissue was maintained at room temperature before the irradiation of laser light. The laser irradiation was conducted within eighteen hours after the extraction of the liver. The extracted livers were cut to a uniform size of $7 \times 7 \times 5$ cm^3 (width, length, and height). The prepared samples were placed on top of a 3 cm thick heat insulator in order to prevent heat loss to the metallic table during the irradiation of the laser.

The CW laser light was delivered into the porcine liver using ultra low –OH optical fibers (Polymicro technologies, FIP 600660710) with an outer diameter of 710 μm, a core diameter of 600 μm and a numerical aperture (NA) of 0.22. In order to investigate the effect of the firing direction from the fiber tip, we employed two distinct fiber systems. The forward-firing system was implemented using the conventional optical fiber tip. The tip of the ultra-low –OH fiber was cleaved manually and the buffer was stripped using the heat from a lighter. After the cleaving and the stripping, the tip was cleaned with optical cleaning paper soaked with acetone. The bi-directional firing system was implemented with the home-made fiber featuring a conically structured surface at the distal end of the fiber. The tip of the ultra-low –OH fiber was conically micro-machined with a femtosecond laser system along with CO_2 laser processing. The details of the manufacturing process can be found in literature [11] and the typical optical microscopy image of the bi-directional firing fiber tip and the light emission pattern in the air is presented in Fig. 1. The conical structure of fiber distal was observed in Fig. 1a. The emission profile was imaged by coupling a low power He: Ne laser into the proximal end of the fiber. The emission profile in Fig. 1b clearly demonstrates a bi-directional light emission (circumferential emission and forward emission) from the conical fiber tip. We employed the NIR laser with the 980 nm for the laser tissue ablation. The NA of the fiber dominates the beam profile and the NA is depending on the wavelength. Thus, the beam emission profiles for the He: Ne laser and 980 nm laser were compared. Although the sensitivity for wavelengths differ, a typical digital camera detects the 980 nm wavelength. The images of the beam emission pattern were taken using a typical digital camera after coupling a He:Ne laser and 980 nm laser into the proximal end of same bi-directional fiber. The resulting profiles of both beams were similar. (Fig. 1b, c)

The power of circumferential emission and forward emission were measured in our previous study [11]. The ratio of the forward emission was measured to less than 40% of the total emitted power and the ratio of the radial emission was measured to more than 60% of the total emitted power.

After the liver was cut to a uniform size (Fig. 2a), an eighteen gauge stainless steel needle was used in order to guide the irradiation fiber tips inside the porcine liver. The guiding needle was inserted 3 cm into the prepared porcine liver sample (Fig. 2b). Once the needle was placed inside the liver, the irradiation fiber was guided into the liver through the guiding needle so that the fiber tip was also placed 3 cm into the liver (Fig. 2c). The needle was then exclusively pulled backward so that the tip of the guiding needle remained at a depth of 1 cm from the surface and 2 cm away from the tip of the fiber (Fig. 2d). This 2 cm gap was introduced between the fiber tip and the guiding needle to minimize heat accumulation in the metallic guiding needle as well as heat transfer through it.

The proximal end of the fibers was coupled to the laser source with an SMA connector and the laser light was irradiated into the porcine liver. Three different cohorts of laser power setting were tested (three minutes continuous irradiation with a laser power of 3 W, five minutes continuous irradiation with a laser power of 3 W, three minutes continuous irradiation with a laser power of 5 W) and 5 samples were irradiated for each laser cohort and fiber type. Upon the completion of each laser irradiation, both the optical fiber and the guiding needle were pulled out of the porcine liver. Fibers were then soaked in acetone in order to clean the tip and the output power from the fiber distal was measured after the cleaning. The measured laser power was in the range of $\pm$10% of the pre-set laser power for all tested irradiation**s**.

The laser-affected zone inside the liver tissue was imaged with a digital camera after dissecting the laser-induced damage zone with a surgical scalpel. The geometrical dimensions of laser-induced regions were measured based on the digital camera images for all laser power cohorts and both fiber tip types. The length and width of cavity regions as well as the coagulation zones were measured with a blind test by five individuals who had no knowledge of the laser parameters or fiber types. The length was defined as the axial extension of the

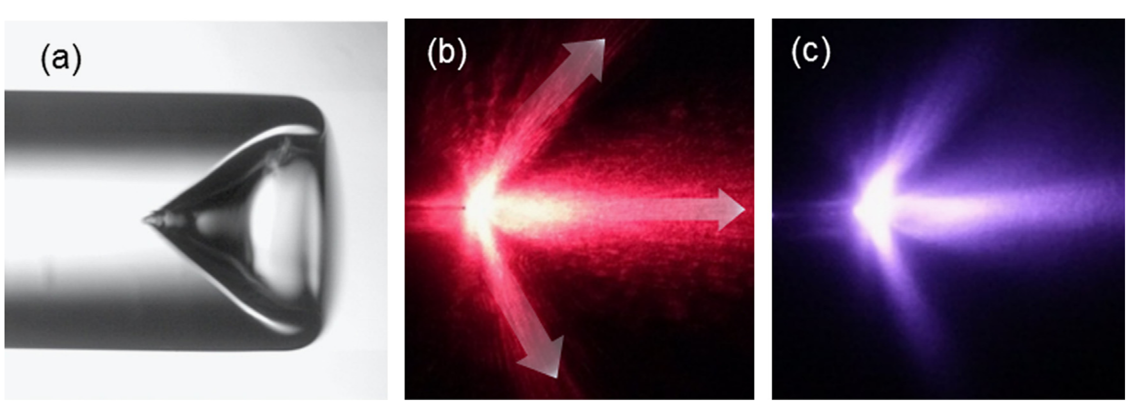

Fig. 1. (a) Optical microscopy image of the bi-directional firing fiber tip. (b) Image of visible light emission (633 nm) at the tip of the bi-directional fiber. (c) Image of near infra-red (NIR, 980 nm) emission at the tip of the bi-directional fiber.