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A novel waveguide design that produces an elongated laser beam output for soft tissue ablation

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ABSTRACT

In this work, we have fabricated and experimentally demonstrated a purpose-built 365 μm optical fibre device that produces an elongated laser beam output for efficient tissue ablation. The proposed fibre device has several advantages and potential for application in surgery. The off-axis firing beam from the fibre lowers the risk of past-pointing injury as compared to forward-firing laser fibres. A pulsed Holmium:YAG (Ho:YAG) laser at a wavelength of 2.1 μm at a repetition rate of 6 Hz was used in this experiment. The fibre was angle-polished at ~25° to create a deviated beam that resulted in a longer ablation length ~1 cm; it was five times longer than the forward-firing laser output and had sufficient energy intensity to perform an ablation rate of 7.7 μm per pulse. Fresh squid (*Cephalopod Theutida*) was used as the biological tissue to determine the ablation length and crater. The threshold radiant exposure, Φ_{th} for tissue ablation was estimated to be 1.84 J/cm^2 and the effective divergence angle was ~24° by using the highest pulsed energy of 1.8 J.

1. Introduction

Laser is one of the most exciting technology in the field of surgery today. The first investigation on the laser ablation on biological tissues dated back to the 1960s. [1]. A few years later, the use of pulsed lasers for medical applications was developed and reported [2]. The earliest surgical applications and publications were in Ophthalmology due to the inherent advantages of lasers in precision and photocoagulation in tissue ablation [3]. The advancement in laser technology and understanding in the laser-tissue interaction have further catalysed the use of laser for other medical specialties such as dermatology, urology, and dentistry [4]. Since then, much progress has been made and lasers have become essential tools for many surgical procedures [5].

When laser is being used in surgery, it is important not only to consider the source-target power/energy delivery efficiency but also absorption of the laser energy by the target tissue [6], ablation efficiency [7], collateral damage to surrounding tissue, associated surgical technique [8]. In the current practice, the optical fibre is the most effective material for laser energy delivery for the purpose of tissue ablation [9].

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Numerous types of materials had been used for making optical fibres in surgical applications. Generally, silica based optical fibres are the most commonly used fibres because they are economical to produce, bio-compatible, transparent and have low loss for laser wavelengths in most surgical situations. Nonetheless, other fibre glass materials for surgical use had also been reported. These include fluoride glass [10] and chalcogenide glass [11] for mid-infrared lasers and germanium dioxide glass [12] for mid- and far-infrared wavelength.

The forward-firing fibre type is the commonest design used in surgical applications [13] and laser ablation. The fibre tip design is a simple flat end facet, which can be easily produced by using the conventional fibre cleaving method. There are also cylindrical fibre diffuser designs that comprise of a short fibre segment with embedded diffusing element that are intended to produce an omnidirectional beam. This fibre design is suitable for large area treatment such as photodynamic therapy.

There are shaped end fibres with off-axis beam emission such as side-firing fibres and radial-firing fibres [14] for specific surgical procedure such as prostatectomy [15], endodontic and periodontal applications in dentistry [16] for the hard-to-reach areas.

However, it would be technically challenging to incorporate forward-firing and radial beams with the jaws of a forceps that surgeons are used to for gripping and cutting tissue. Without the jaws of the forceps impeding the trajectory of the laser beam, forward-firing laser beams risk causing unintended past-pointing injury of vital anatomical structure. Radial beams on the other hand would not have the intensity to cut through tissue, thus rendering it a poor candidate for this objective.

Therefore, a side-firing laser beam would be the most appropriate design for purpose of creating a surgical cutting device. To the best of our knowledge, all the side-firing laser fibres presently available for clinical use produce a round or short elliptical beam [17]. We aimed to produce an optical wave-guide that could produce a side-firing laser beam that is both elongated and able to deliver high energy intensity.

In this work, we designed a novel purpose-built fibre end that could produce off-axis firing with a small deviation angle from the fibre axis. The produced laser beam has an elongated beam length with an intensity high enough for soft tissue ablation. The off-axis firing beam is achieved by the angled fibre facet fabricated using mechanical polishing. The polished end of the fibre was encapsulated by a fuse silica glass tube which served as protection shield for the fibre tip. The projection of the deviated beam on one side of the glass tube had a beam length longer than its width by a factor of $\sim$5. In the ablation test with Holmium-YAG (Ho:YAG) pulsed laser, this fibre device produced an ellipsoidal crater on our test biological tissue. We found that this fibre device was capable of making long ablation on the biological tissue with minimum mass loss and collateral damage.

2. Motivation

Most of the surgical energy devices that are currently available commercially are rigid and bulky. A next-generation flexible and miniaturized surgical energy device would enable better reach when operating in tight spaces. This could potentially be achieved by employing laser energy because it could be delivered via fine and flexible optical fibres. It is hoped that such a device would help simplify very complex surgery and reduce the risk of blood loss. As was earlier mentioned, forward-firing fibre poses an inherent risk of past-pointing injury. In order to overcome this problem, we propose an optical fibre wave-guide in the form of a purpose-built fibre end to manipulate and reshape the laser beam.

The proposed fibre wave-guide has an angled-facet with a polish angle of $\sim 25^{\circ}$ and the firing beam is deviated from the fibre axis by small angle of 13°. Unlike the forward-firing fibre, the projected beam is long and narrow, and it produces an ellipsoidal cavity when used to ablatebiological tissue. The side-firing fibre can be more readily incorporated into forceps-like instrument such as a laparoscopic or endoscopicgrasper that a surgeon would commonly use in surgery. In general, this optical wave-guide has low handling power. A wave-guide with larger cross-sectional area should have a high damage threshold. The potential for this technology to be used to produce a flexible surgical energy device is very attractive. The flexibility offers superior reach over currently available rigid energy device, thus improving the surgeon to work in tight operative fields.

3. Methodology and instrumentation

3.1. Laser source

The Ho:YAG laser (Lumenis Pulsed 100 H), which operates at the wavelength of 2.1 μm, is highly absorbed by water and it has a shallow penetration depth of approximately 0.4 mm per pulse [18]. As a pulsed mode laser, the Ho:YAG laser produces less charring which are more prevalent compare to continuous wave laser like the Thulium laser. The shallow penetration depth minimizes the coagulation zone and collateral damage to sensitive surrounding tissue for clean and precise incision and tissue ablation. The combination of the controlled penetration depth and the water absorption characteristics reduce the energy that can reach the non-target tissue, contributing to the safety profile of the procedure. Hemostasis is achieved by modulating laser parameters and focal distance. Pulsed lasers are widely used in surgery because of their ability to rapidly and precisely coagulate, incise and ablate tissue. Several properties of biological tissues are relevant to pulsed laser ablation. The tissue composition and morphology are properties that determine the internal volumetric energy distribution; and this in turn dictates the ablation process within the tissue environment. Current theoretical models of pulsed laser ablation