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Laser-based pulsed liquid microjet for surgery

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Abstract

A water microjet device that can be used for precise dissection of soft tissue in surgical procedures has been developed. The water jet is generated by irradiating a pulsed Ho : YAG laser, through an optical fiber, into a thin tube/catheter filled with water or a physiological saline solution. Pulsed laser irradiation within the tube evaporates the water generating a vapor bubble, whose rapid expansion drives a microjet of water out of the tube through a micronozzle of 100 ~ 200 μm exit diameter. This laser-induced microjet can readily penetrate a soft tissue in human body. The jet is applicable to neuroendoscopic surgery, treatment of cerebral thrombosis, intravascular drug delivery, etc. The thermal effects and the controllability of the jet were first investigated on a 10% gelatin layer that simulates a soft tissue, and then the jet was used to dissect the ventricular wall of a cadaver rabbit. The experimental results indicated a well-controlled incision, preserving capillary blood vessels thicker than 0.2 mm in diameter, and the collateral damage to the tissue was negligible.

Keywords: Laser, liquid, microjet, surgery.

1. Introduction

Microjets are of interest in a variety of engineering applications such as combustion or heat-transfer systems, microthrusters for miniature satellites, divert and attitude reaction control systems in the case of space vehicles to perform maneuvers during flight [1], etc. On the other hand, we have been developing applications of laser-driven liquid microjets to medical treatment such as intravascular drug delivery, and also as a substitute to lasers for dissecting soft tissues. Lasers have widely been used for precise incision of soft tissue containing water, but in such a case, the absorption of laser energy by the surrounding water results in its evaporation and formation of a water vapor bubble that could cause serious damage to the neighboring tissues/blood vessels during its growth and collapse [2, 3]. Laser-induced liquid microjets, in which the energy is deposited mainly in the direction of flow, can be used for precise incision of soft tissue without any thermal effects and collateral damage to the tissues. Continuous liquid jets powered by compressed air have successfully been used for tissue dissection [4, 5], but when applied in liquid media it is difficult to control the penetration depth with a continuous flow of the jet fluid, and also the splash of blood caused by this method is not desirable. Hence for microsurgical procedures, a pulsed water jet is a unique method that can achieve moderate penetrations in soft tissue by preserving capillary blood vessels of diameter thicker than 0.2 mm.

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An electric discharge-induced pulsed liquid microjet generator was developed for creating incisions in soft tissues in surgical procedures [6]. The device generated a 30 μm diameter liquid jet with a peak velocity of 90 m/s, which created incisions of about 150 μm deep in a polyacrylamide gel after a series of discharges. This was the first pulsed liquid microjet device that had a potential to become a surgical tool, but, it uses a high voltage for its operation and the structure of it may not be flexible enough to be miniaturized and integrated with surgical devices like endoscopes.

With an intention of applying the pulsed liquid microjet concept to endoscopic surgical procedures, we have developed a Ho:YAG laser-induced pulsed liquid jet device for soft tissue incision in neuroendoscopic surgery [7]. The present study had the following objectives:

(1) To analyze the dynamics of the jet by measuring its pressure, velocity and temperature.
(2) To assess the feasibility of using this jet for some medical applications such as soft tissue dissection and intravascular drug delivery.
(3) To study the laser-induced bubble dynamics inside a thin tube by means of photography.

The liquid microjet device, extracted mechanical information on the jet and the bubbles, and the physical interpretation of the soft tissue dissection are briefly discussed in this paper.

2. Experimental methods

Figure 1 shows a schematic of the Ho:YAG laser-based pulsed liquid microjet device. A catheter or a thin flexible tube of 800 μm ~ 1 mm internal diameter was filled with a physiological saline solution or water, and an optical fiber connected to the laser was drawn into it. The end of the catheter was fixed with a metallic nozzle with an exit diameter of 100~200 μm. A standoff distance (gap) was maintained between the optical fiber end and the nozzle exit, in which sufficient volume of water was accommodated such that a portion of it was discharged as a water jet during the operation. Explosive bulging of the water vapor bubble on laser irradiation displaced the water ahead of the optical fiber through the micronozzle as a jet. The tip of the optical fiber was covered with a hollow metallic tube of 800 μm inner diameter in order to prevent ablative damage to the catheter inner wall. The Ho:YAG laser beam had a wavelength and a pulse duration of 2.1 μm and 350 μs, respectively, and this wavelength was quite suitable for the water to absorb the laser energy. The laser energy could be varied from 250 to 800 mJ/pulse, depending on the core diameter of the optical fiber. In the present study, an optical fiber of 400 μm core diameter was used and the laser pumping lamp voltage was fixed at 1.5 kV, which was equivalent to an energy level of 433 mJ/pulse.

3. Mechanical analysis of the liquid microjet

Release of the water microjet in air from the micronozzle was visualized using a high-speed video camera (ISIS Prototype, CCD Camera: Shimadzu Co. Ltd., Kyoto, Japan.) at a speed of 31,250 frames/s. The experiment was performed in a stainless steel chamber of dimensions $110 \times 110 \times 130$ mm, with observation windows on its sidewalls. A commercial

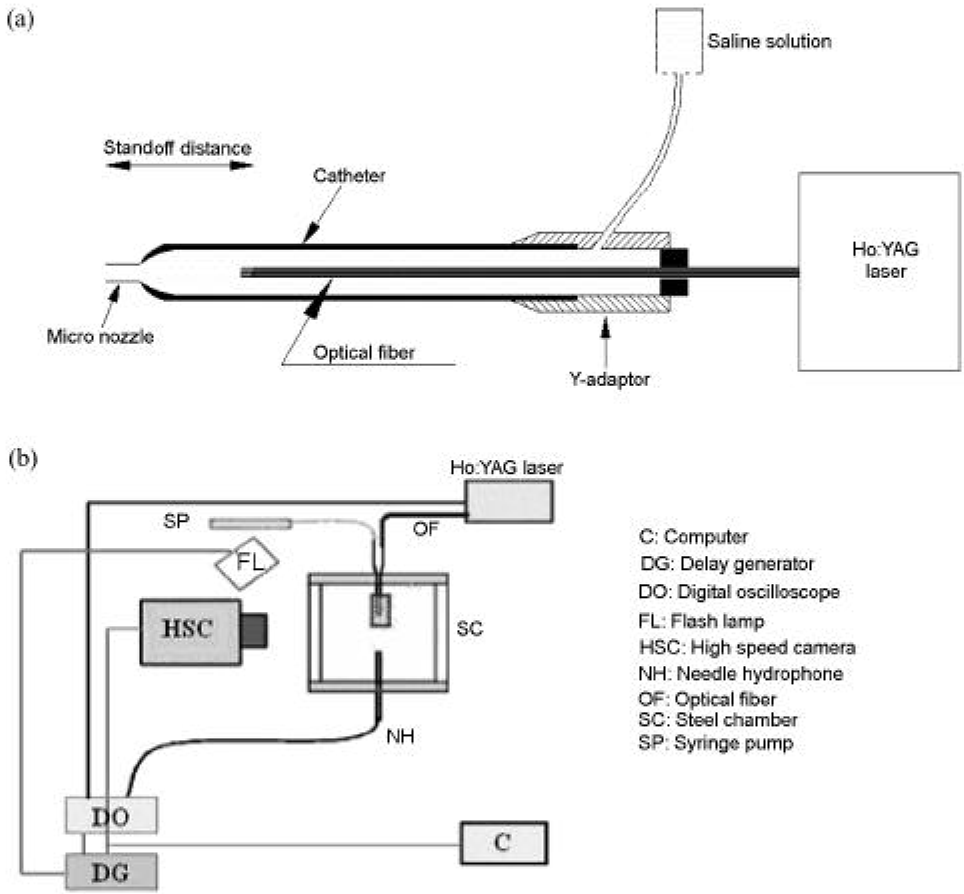

FIG. 1. Schematic of the Ho:YAG laser-based pulsed liquid microjet device: (a) the jet knife, (b) the experimental setup for inspection of the jet.

strobe flash with a pulse duration of 3.3 ms was used as a light source. Typical, time-resolved images of the microjet discharging in air at atmospheric pressure are shown in Fig. 2. The catheter nozzle-exit diameter and the standoff distance were 200 *m*m and 45 mm, respectively. The peak average velocity of the jet measured from the initial frames of these time-resolved images was about 50 m/s. A polyvinylidene di-fluoride (PVDF) needle hydrophone (Imotec Messtechnik, 0.5 mm diameter sensing element with a sensitivity of 0.00144 volt/bar) located axially opposite to the catheter nozzle, at a distance of 1 to 2 mm, was used to record the stagnation pressure of the impinging microjet. Figure 3 shows the microjet stagnation pressure signal for a standoff distance and a laser energy of 45 mm and 433 mJ/pulse, respectively, which is corresponding to the jet peak velocity of 50 m/s. The maximum recorded stagnation pressure of the jet was about 12 atmospheres.

An expanding vapor bubble that is formed by laser energy deposition in water drives the microjet. The vapor bubble collapses after reaching the limits of its expansion, releasing the

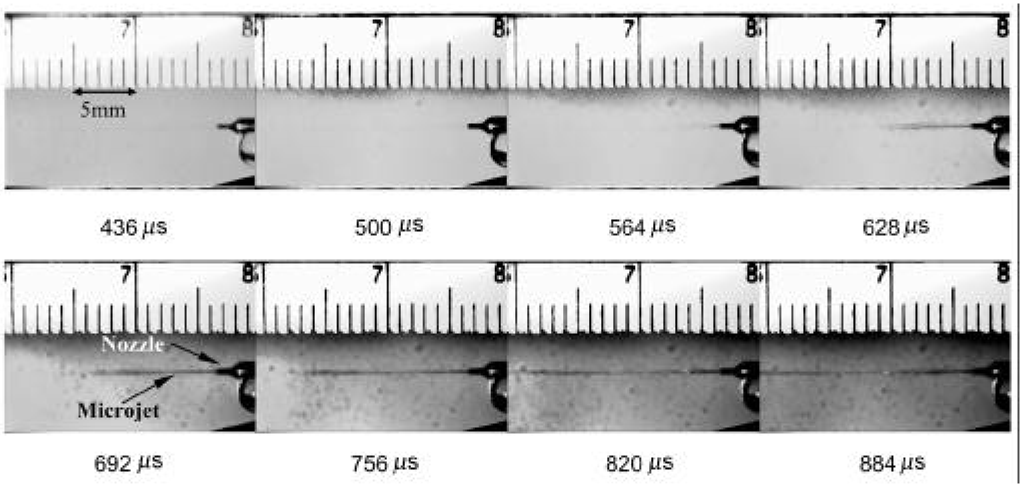

FIG. 2. Time-resolved images of the microjet, emitting into atmospheric air from a nozzle of 200 *m*m exit diameter.

hot steam that may flow out of the catheter nozzle and come into contact with the target. This gave rise to a faint doubt that the local temperature at the spot of jet impingement could rise. In order to have a precise idea of these thermal effects, we measured the temperature of the impinging jet using a *k*-type thermocouple, assembled with a PC-based data acquisition unit MX100 of Yokogawa make. The shortest measurement interval on the thermocouple was 10 ms and the minimum temperature it could sense was 0.1°C. The size of the thermocouple hot junction was about 0.5 mm. A typical temperature history recorded by the thermocouple at the spot of jet impingement is shown in Fig. 4. A temperature rise of about 20°C was noticed at the point of jet impingement for the maximum jet velocity. The temperature change did not exceed 20°C even after a continuous use of the jet for a few minutes. While the pulse width of the microjet is much shorter than the response time of the thermocouple, the output of the thermocouple represents only an average temperature.

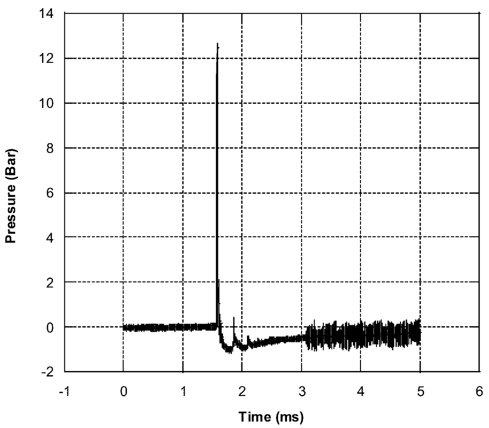

FIG. 3. Stagnation pressure of the microjet in atmospheric air, corresponding to a laser energy of 433 mJ/pulse.

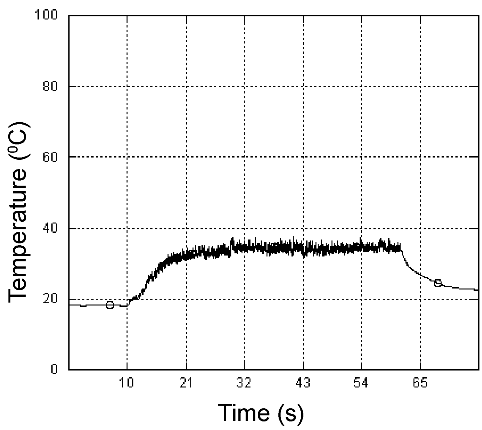

FIG. 4. Typical temperature history at the point of microjet impingement, corresponding to a laser energy of 433 mJ/pulse.

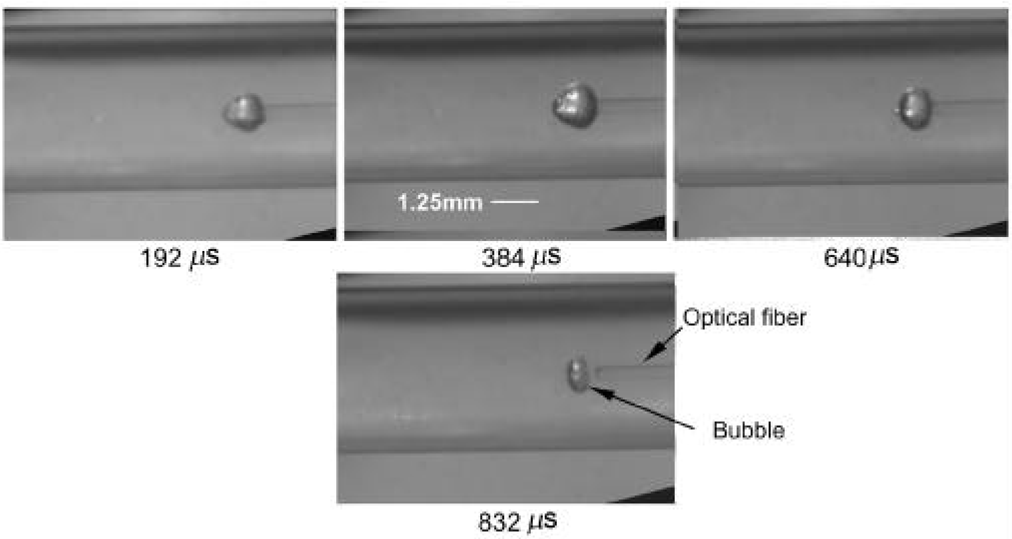

FIG. 5. Generation and collapse of a vapor bubble on laser irradiation (433 mJ/pulse) in liquid in a glass tube of 8 mm internal diameter.

It was also attempted to look into the generation of vapor bubbles that drove the liquid jet. The bubble generation was visualized using the same high-speed video camera (Shimadzu) in transparent glass tubes of 8 and 1 mm inner diameters. Figure 5 shows the growth and collapse of a typical vapor bubble on absorption of the laser energy by water in the 8-mm diameter tube. Since the tube inner diameter was large in comparison with the bubble size, the bubble was confined to the center of the tube and grew spherical in shape. Figure 6 shows the growth and collapse of a micro-vapor bubble in the 1-mm diameter tube. In this case, the bubble occupied the entire inner diameter of the glass tube and expanded longitudinally. This quick longitudinal growth of the vapor bubble pushed the liquid ahead of it, forming a jet through the catheter nozzle.

4. Results on medical applications

The dissecting ability, the thermal effects and the controllability of the jet were first investigated on a 10% gelatin slab of 1 mm thickness, which simulated a soft body tissue. Figure 7(a) shows the liquid jet penetrating the 1-mm thick gelatin slab held (moulded) in a thin plastic frame. The jet penetrated the gelatin slab without causing any distortion in the surroundings, and there were no occurrences of the bubbles during the penetration. The shape and the extent of gelatin enucleation could be controlled well. Figure 7(b) shows the gelatin slab after enucleation. There was no melting of the gelatin slab, which indicated the absence of the thermal effects.

The dissecting ability of the jet was also investigated on the ventricle wall of the brains of a cadaver rabbit. Figure 8(a) shows the picture of an incision made in a cadaver rabbit ventricle wall using the liquid microjet, under the endoscopic vision, keeping the jet-generator nozzle at a distance of 1 mm from the ventricle wall. After the incision, the ven-

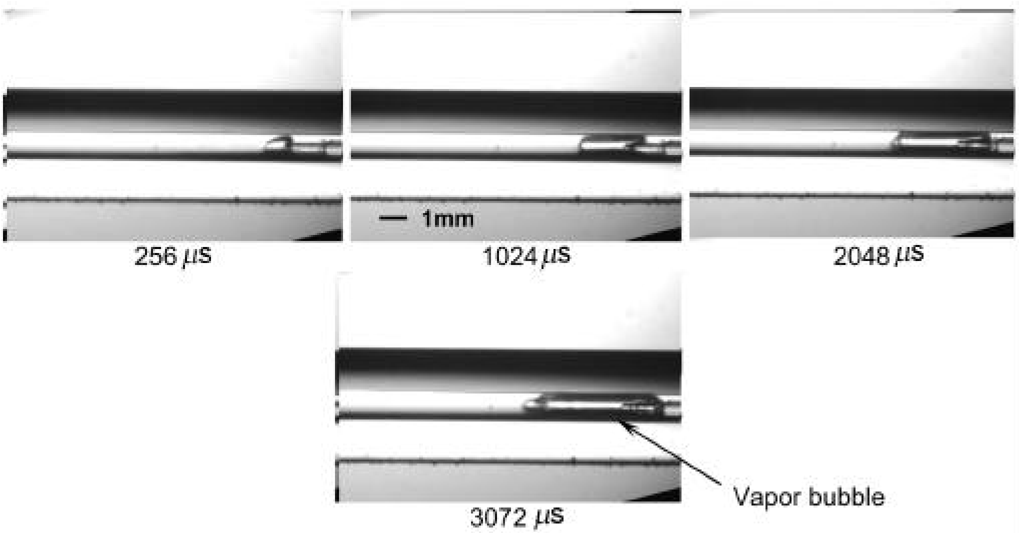

FIG. 6. Generation and expansion of a micro-vapor-bubble on laser irradiation (433 mJ/pulse) in liquid in a glass tube of 1 mm internal diameter.

tricle of the rabbit brain was opened to take this picture. The incision was done across a capillary blood vessel and the blood vessel was preserved during the operation, as shown in the figure. It was observed that the blood vessels over a size of 200 *m*m were preserved by the liquid jet while performing the incision. Figure 8(b) shows a micrograph of the dissection plane of the cadaver rabbit ventricle wall, cut across the incision performed by the microjet. Sections of 5 *m*m thickness were cut, stained with hematoxylin and eosin, and were examined under an optical microscope to evaluate the dissection morphology, dissection

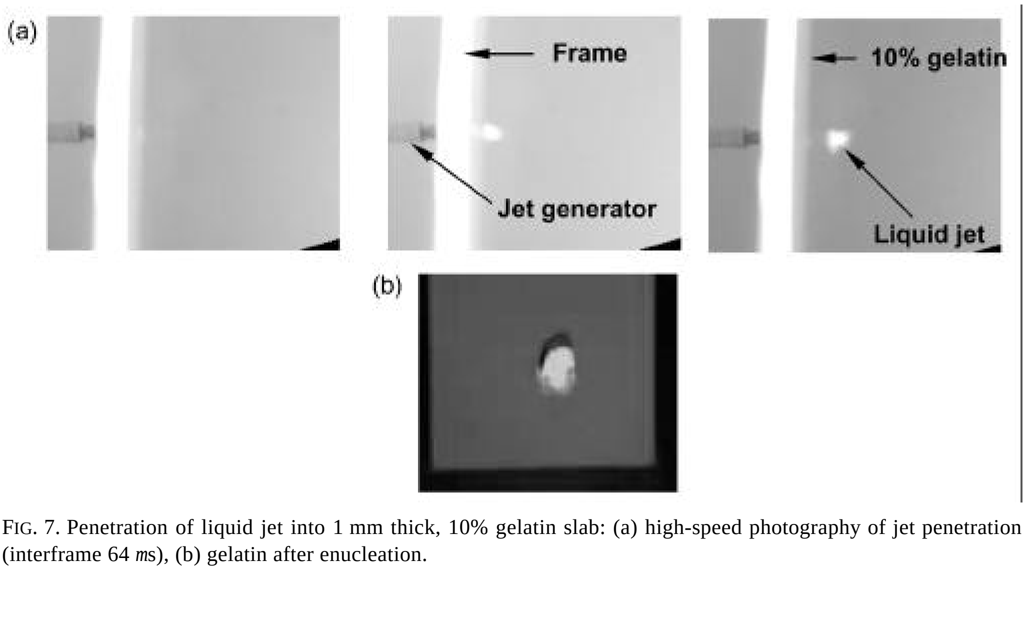

FIG. 7. Penetration of liquid jet into 1 mm thick, 10% gelatin slab: (a) high-speed photography of jet penetration (interframe 64 *m*s), (b) gelatin after enucleation.

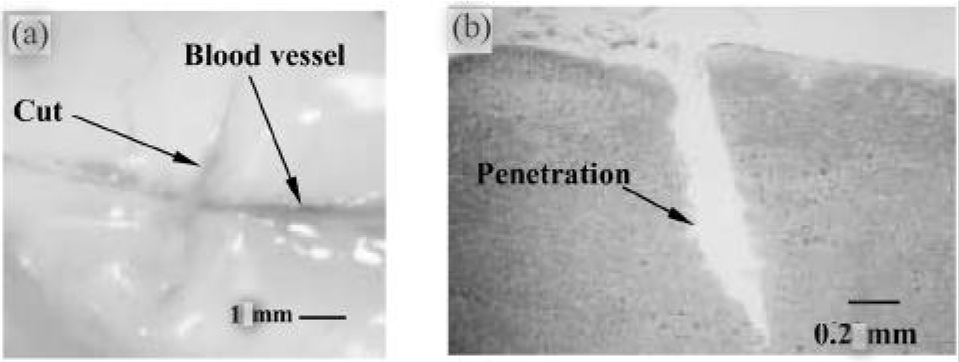

FIG. 8. Dissection of cadaver rabbit ventricle wall under endoscopic view: (a) macrograph showing the dissection with the preservation of blood vessel, and (b) micrograph of the dissection plane.

depth and vessel preservation. The maximum penetration depth observed in this case was 1.3 mm, for a laser energy of 433 mJ/pulse.

The positive inference on the thermal effects of the microjet, drawn from the temperature measurements, prior to the physiological investigations was only a priori. Since the microjet pulses were much shorter than the response time of the thermocouple, the temperature readout of the sensor was exclusive of the instantaneous temperatures, which were believed to be higher than the recorded ones, and if existed, were believed to cause an irreversible damage to the target. But, the physiological and histological investigations did not reveal any such adverse thermal effects of the jet on the target.

5. Conclusion

A laser-induced pulsed liquid microjet device that can be used in neuroendoscopic surgery has been developed. The physical properties of the jet have been analyzed for a jet of 200 μm diameter and for a laser energy of 433 mJ/pulse. The dissecting ability of the jet, its controllability and safety have been investigated by carrying out experiments on 10% gelatin and cadaver rabbit ventricle wall. Results show that the pulsed laser-induced liquid jet (LILJ) has a good scope to become a safe and reliable dissecting method in endoscopic procedures.

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