Pulsed holmium:yttrium-aluminum-garnet laser–induced liquid jet as a novel dissection device in neuroendoscopic surgery

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Object. A pressure-driven continuous jet of water has been reported to be a feasible tool for neuroendoscopic dissection owing to its superiority at selective tissue dissection in the absence of thermal effects. With respect to a safe, accurate dissection, however, continuous water flow may not be suitable for intraventricular use. The authors performed experiments aimed at solving problems associated with continuous flow by using a pulsed holmium:yttrium-aluminum-garnet (Ho:YAG) laser-induced liquid jet (LILJ). They present this candidate neuroendoscopic LILJ dissection system, having examined its mechanical characteristics and evaluated its controllability both in a tissue phantom and in a rabbit cadaveric ventricle wall.

Methods. The LILJ generator was incorporated into the tip of a No. 4 French catheter so that the LILJ could be delivered via a neuroendoscope. Briefly, the LILJ was generated by irradiating an internally supplied column of physiological saline with a pulsed Ho:YAG laser (pulse duration time 350 μsec; laser energy 250–700 mJ/pulse) within a No. 4 French catheter (internal diameter 1 mm) and ejecting it from a metal nozzle (internal diameter 100 μm). The Ho:YAG laser energy pulses were conveyed by an optical fiber (core diameter 400 μm) at 3 Hz, whereas physiological saline (4˚C) was supplied at a rate of 40 ml/hour. The mechanical characteristics of the pulsed LILJ were investigated using high-speed photography and pressure measurements; thermal effects and controllability were analyzed using an artificial tissue model (10% gelatin of 1 mm thickness). Finally, the ventricle wall of a rabbit cadaver was dissected using the LILJ.

Jet pressure increased in accordance with laser energy from 0.1 to 2 bar; this translated into a penetration depth of 0.08 to 0.9 mm per shot in the ventricle wall of the rabbit cadaver. The gelatin phantom could be cut into the desired shape without significant thermal effects and in the intended manner, with a good surgical view.

Conclusions. The present results show that the pulsed LILJ has the potential to become a safe and reliable dissecting method for endoscopic procedures.

Key words • dissection • yttrium-aluminum-garnet laser • intracerebral hemorrhage • waterjet dissector • neuroendoscopy • robotic surgery • shock wave

Although various instruments have been used for dissection in neuroendoscopic surgery, including high-frequency current (using monopolar or bipolar electrodes), thermal lasers, ultrasonic probes, and mechanical dissection techniques, it is still difficult to perform controlled dissection without causing bleeding and thermal damage in surrounding tissue. Over the past two decades waterjet dissection has been introduced into medical use, and various experiments and in vivo studies have demonstrated its superiority over conventional dissection devices. The waterjet can selectively dissect tissue with preservation of blood vessels and without causing thermal damage to surrounding tissue. Recently, this method has been introduced into neurosurgery, in which a high quality of dissections and efficacy in neurological microsurgical procedures have been demonstrated. Therefore, the possibility of applying this method to a new neuroendoscopic dissection device has repeatedly been proposed. As several researchers have pointed out, however, there are issues that must be resolved before endoscopic application can be realized. These include the possible requirement of large amounts of continuous, high-pressure water and the subsequent creation of a vortex and fountain effect, with catapulting of lesion tissue together with the difficulty in assuring accurate dissection under endoscopic circumstances.

To solve the problems associated with a continuous, pres-
sure-driven waterjet, we have developed a pulsed dissection system for the neuroendoscope, which is based on a technology known as Ho:YAG LILJ.⁸ In previous studies we performed experiments, both in vitro and in vivo, showing that this pulsed LILJ can assure the advantage of a continuous waterjet while significantly reducing the problems associated with a continuous pressurized jet during open microsurgical procedures.⁹,¹⁰,¹⁷ For the present study we developed an endoscopic dissection system involving a pulsed LILJ by incorporating the system into a No. 4 French catheter, and evaluated the mechanical characteristics of the pulsed LILJ as well as its controllability, both in a gelatin phantom and a cadaveric rabbit ventricle wall, under endoscopic view.

Materials and Methods

Description of the Pulsed Ho:YAG LILJ Generating System for Flexible Neuroendoscopy

The Ho:YAG LILJ system is composed of a No. 4 French catheter (internal diameter 1 mm) for coronary angiography (Outlook, straight pigtail RQ-4SP0081; Terumo Co., Ltd., Tokyo, Japan) and an optical quartz fiber (no. QL-400-850-5; Sparkling Photon, Inc., Tokyo, Japan). The core diameter of the optical fiber is 400 μm. The distal end of the catheter is sealed with a Y connector (Amplast Cy connector, no. AP-YC2SS; Terumo Co., Ltd., Tokyo, Japan) to prevent air from entering the system, whereas a metal nozzle (internal diameter 100 μm, length 5 mm) is inserted at the tip of the catheter (Fig. 1A). The laser source used in this experiment was a pulsed Ho:YAG laser (Mid-Infrared Pulse Laser System, model MIPL-HQ; Sparkling Photon, Inc., Tokyo, Japan), whose wavelength and pulse duration were 2.1 μm and 350 μsec, respectively. The energy of the laser can be varied between 0.9 and 1.5 kV, which corresponds to 250 and 700 mJ per pulse. The LILJ is generated by irradiating internally supplied, cold physiological saline (4°C) within the catheter. This saline is supplied at a rate of 40 ml/hour. To avoid ablation of the internal surface of the catheter, a metal nozzle (internal diameter 600 μm) has been incorporated around the tip of the optical fiber (Fig. 1B). The standoff distance (the distance between the nozzle and the tip of the optical fiber) is fixed at 24 mm, which was shown to elicit maximum velocity at this energy range in a previous experimental study.⁹ To preserve flexibility at the tip of the catheter, the length of the metal tube has been limited to 5 mm. This system, therefore, can be inserted and used in the working chamber of a commercial flexible neuroendoscope.

Investigation of the Mechanical Characteristics of the Pulsed LILJ

Information on the time sequence of jet dynamics during the ejection process of the LILJ was visually analyzed using a high-speed camera (ISIS Prototype charge-coupled device camera; Shimadzu Co., Ltd., Kyoto, Japan) in framing mode. The frame rate was varied from 1.9 to 10⁸ frames per second. A commercial strobe flash with a pulse duration of 3.5 msec (full width at middle height) was used as a light source. The time sequence of observation was controlled with...
a delay circuit via a computer interface (Fig. 2A). A polyvinylidene fluoride needle hydrophone (Imotec Messtechnik, Wärendorf, Germany), with a 0.5-mm-diameter sensing element of 0.0136 V/Pa and a rise time of 45 nsec, was located 1 mm axially from the exit of the catheter in a stainless steel chamber (110 mm × 110 mm × 130 mm) on the same axis as the tip of the catheter; this hydrophone was used to monitor pressure (20 measurements for each laser energy). Measured data were stored and displayed on a digitizing oscilloscope (model DL716; Yokogawa Co., Ltd., Kyoto, Japan).

The mechanical effects of the LILJ were investigated using a gelatin phantom (by some of the authors [A.N., T.H., V.M., and T.O.]). Gelatin (Wako Pure Chemical Industries Co., Ltd., Osaka, Japan) was dissolved in pure water (Sanchemipha Co., Ltd., Sendai, Japan), at a temperature lower than 50˚C, to a concentration of 10% (w/v). This was regarded as a reasonable model for soft tissue because the Young modulus for 10% gelatin is 0.3 × 10⁴ U/m² at 21˚C, corresponding to that previously reported for soft tissue. Gelatin, which was mixed with blue ink, was molded by placing it in a thin plastic frame (3.4 × 2.4 × 1 mm).

The experiment was performed in a stainless steel chamber equipped with optical windows, a holder for the LILJ system, and a holder for the polyvinylidene fluoride needle hydrophone at a room temperature of 27˚C, under normal atmospheric pressure.

After these preparations, a single ejection of the LILJ was directed at each of 10 phantoms to evaluate the mechanical effects of the jet by using a high-speed camera. Following this, multiple ejections were produced to enucleate a circumscribed (circular) portion of the gelatin under neuroendoscopic vision (model NEU-4L; Machida Endoscope Co., Ltd., Tokyo, Japan; Fig. 2B) in each of the 10 phantoms. Each experiment was completed within 2 minutes to prevent the gelatin from melting.

Dissection of the Ventricle Wall of a Rabbit Cadaver

The dissection characteristics of the neuroendoscopic Ho:YAG LILJ in the fresh, unfixed rabbit cadaveric ventricle were examined by two authors (A.N. and T.H.). Ten male Japanese White rabbits (JW/CSK strain; Japan SLC, Inc., Shizuoka, Japan), each weighing between 2 and 2.5 kg, were killed, thereafter the brains were removed, the ventricles were exposed, and specimens (20 specimens for each energy level) were affixed to a specially designed cutting sledge. This was submerged in Ringer lactate solution in the stainless steel chamber and a single LILJ shot was ejected under endoscopic vision. All cuts were performed at a distance of 1 mm from the ventricle wall, and laser energy varied between 0.9 and 1.5 kV. After the experiment the specimens were stored overnight at 4˚C in fixative. The fixed brains were embedded in paraffin blocks and cut parallel to the direction of penetration in 5-μm-thick sections. Each section was stained with hematoxylin and eosin before examination by optical microscopy to evaluate the morphological characteristics of the dissection (general dissection structure and the quality of the dissection margins), the depth of the dissection, and vessel preservation.

All animal procedures were approved by the Institutional Animal Care and Use Committee of Tohoku University.

Results

Mechanical Characteristics of the Pulsed LILJ

Figure 3A shows the relationship between laser energy and pressure developed in the LILJ at a distance of 1 mm from the tip of the nozzle. The pressure increased, in accordance with laser energy, from 0.1 ± 0.05 to 2 ± 0.22 bar (mean ± standard deviation). Figure 3B (1–4) shows a high-speed photograph of the LILJ emanating from the tip of the catheter and penetrating the gelatin phantom. There was no distortion of the thin membrane during the penetration procedure. Figure 3B (lower right) shows the gelatin after penetration as it appeared endoscopically. During penetration no bubbles disturbed the endoscopic view and the shape and extent of the enucleated portion of the gel could be well controlled. In addition, there was no melting of the gelatin, indicating an absence of adverse thermal effects, because the melting temperature of 10% gelatin is 33˚C.8
Dissection of the Ventricle Wall of the Rabbit Cadaver

Figure 4A shows a macroscopic photograph of the dissection plane in the cadaveric rabbit ventricle wall as it appeared under endoscopic view. As already proven using a continuous waterjet, the pulsed liquid jet preserved blood vessels that had a diameter greater than 200 μm. Figure 4B shows the histological specimen, containing a sharp dissection of the ventricle wall through and including the ependymal layer. Figure 4C shows the relationship between laser energy and average penetration depth, indicating that the penetration depth increased, in accordance with a single shot of laser energy, from 0.08 ± 0.03 to 0.9 ± 0.11 mm (mean ± SD).

Discussion

There is still no common agreement on the selection of the most appropriate instrument for neuroendoscopic dissection, because each tool has its own advantages and disadvantages (possibility of causing fatal consequences mostly due to damaging small vessels, difficulties in estimating the extent of dissection while viewing the target tissue via the video monitor, results of incomplete procedures, and possibility of thermal damage to surrounding tissue). Waterjets—either conventional or laser-induced—are alternative methods for dissecting soft tissue. Input energy is mostly converted into the kinetic energy of flowing water, which is ejected by a small nozzle at the tip of the delivery device. The waterjet transmits its kinetic energy to the tissue surface and ejects particles of tissue, creating a corridor through the surface of the organ. Exploiting the differing tensile strengths of various tissues allows the waterjet to be used for selective dissection. Conventional continuous pressurized waterjets powered by compressed air have been used to dissect brain parenchyma while preserving vessels and have also been used in liver, ophthalmological, and vascular surgery. The waterjet device possesses several dissection-related qualities that are superior to conventional instruments, such as selective tissue dissection with vessel preservation. In addition, in liver surgery some researchers have also demonstrated that the use of waterjets leads to less blood loss and parenchymal trauma than the use of ultrasonic aspiration or blunt dissection. Another notable advantage of such a technique is the avoidance of thermal damage to surrounding parenchyma, which occurs with bipolar or monopolar high frequency current, ultrasonography, and laser coagulation. Moreover, in their excellent reports on the investigation of tissue selectivity in porcine cadavers, Oertel, et al., reported that the ependyma is amenable to waterjet dissection.

Although effective at an air–tissue interface, it is possible that the continuous flow of fluid may not provide precise control of the cutting depth when applied in liquid media. Moreover, such devices may not be suitable for endoscopic surgery; because of the use of relatively large amounts of high-pressure liquid, an increase in intracranial pressure may occur. We have presented information in a pulsed liquid jet, which is driven by the transient expansion of a laser-induced vapor bubble inside a No. 4 French catheter. The three-dimensional expansion of the confined vapor bubble, directed by the Ho:YAG laser, is used to drive a one-dimensional liquid jet through a fine nozzle at the tip of the catheter. In an earlier work we described a pulsed jet with a diameter smaller than 1 mm and an initial jet velocity that could be controlled between 8 and 54 m/second by changing the laser energy. The ejected volume of fluid can, therefore, be limited to within the order of 0.4 to 1.5 μl per shot (unpublished data), because the expanding laser-induced bubble pushes a small amount of liquid, the quantity of which is mainly determined by the amount of laser energy through the exit hole. The results for velocity, pressure, and...
related tissue depth in the cadaveric rabbit brain showed that these are well correlated with laser energy. The incision test on a 1-mm thickness of 10% gelatin demonstrated that the gelatin was perforated without adverse mechanical and thermal effects, and that the intended shape could be obtained with a good surgical view. In particular, the temperature of the ejected LILJ was maintained at a lower level (melting point of 10% gelatin is 33°C) than that used in an open surgical procedure (≈ 41°C); this was probably due to underwater usage. Therefore, the present study shows that the Ho:YAG LILJ possesses the advantages of a conventional continuous waterjet, while avoiding its disadvantages by implementing a jet in pulsed mode. Although the actual pressures were not as high as those reported by Oertel, et al.19 (most cuts were performed under a preset pressure of 3–13 bar), our liquid jet was able to dissect a sufficient depth of tissue under low pressure. We believe that this is because of differences in the dissection mechanisms of these two waterjet modalities and that the present mechanism is more strongly related to the water-hammer effect (or impact), in which jet velocity and the sharpness of the jet influence its effectiveness.14,15 Regarding the effect on intracranial pressure, the present experiment showed a pressure elevation of between 0.1 and 2 bar 1 mm away from the nozzle exit. As a slight increase in intracranial pressure can produce an adverse effect,6 however, one should evaluate the effect of pressure in a closed system in live animals before clinical application.

It is expected that an alternative application of LILJ will be useful during neuroendoscopic removal of an intracerebral hemorrhage because we originally investigated LILJ for the removal of a blood component, with special interest in the enhancement of fibrinolysis for acute cerebral embolic stroke.8

Although a selective, controlled dissection with the assurance of a clear endoscopic view has been demonstrated by this experiment, sequelae of the mechanical impact and further assurance of the endoscopic view should be investigated in experiments in living animals prior to clinical application of this promising instrument.
Conclusions

We have presented a waterjet device suitable for neuroendoscopy, in which the jet is produced in a pulsed mode, simultaneously reducing the required amount of water, improving the surgical view, and ensuring safety. The controllability and safety of the system were evaluated by investigating the mechanical characteristics of the instrument and by performing in vitro experiments with 10% gelatin and a cadaveric rabbit ventricle wall. The present results show that the pulsed LILJ has the potential to become a safe and reliable dissecting method for neuroendoscopic procedures.

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References


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