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# Analysis of liquid reservoir effect induced by pulsed laser liquid jet

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*Abstract*— **A pulsed-laser-induced liquid jet (LILJ) is a new device used in neurosurgery to simultaneously crush, incise, and aspirate tissues and tumors, preserving blood vessels and nerves. In addition, a feature of a pulsed LILJ is its ability to excavate tissue at constant depth while a liquid jet is being repeatedly focused at the same point. To clarify the mechanisms of constant depth of excavation, we employed a gelatin phantom and extracted brain tissue using a high-speed camera, and we then confirmed that the liquid-reservoir-induced LILJ played an important role in enabling the safe usage of an LILJ.**

## I. Background

In all medical surgeries, there is a focus on having high rescue rates and ensuring both the maximum extraction of tumors and the minimum effect on nerves and blood vessels. To improve the likelihood of both tumor rejection and preserving nervous function in brain surgeries, we developed a laser-induced liquid jet (LILJ). The power source for an LILJ is a pulsed Ho:YAG laser. The LILJ intermittently shoots out a micro-liquid with high speed, and the liquid crushes the tumor. Our device has met the abovementioned medical specification and has also performed the function of automatic dissection, separation, and crushing. In clinical cases and difficult treatments such as brain pituitary surgery, there have been reported improvements in surgical time, bleeding, and prognosis [1, 2]. Pulsed liquid jets have the characteristic that when liquid jets are repeatedly focused on the same location in the brain tissue with moderate parameters of an LILJ, the depth at which the tissue is excavated remains constant. This characteristic is the difference between a pulsed liquid jet and a continuous-flow liquid jet. However, the crushing ability of a pulsed liquid jet is lesser than that of an ultrasonic aspirator. This characteristic is a safety feature that prevents the excessive crushing or penetration of tissue in the cases of precision brain tumor rejection near the blood vessels or nerves. However, the mechanism of the constant depth excavation remains unclear. This study aims to clarify this characteristic of an LILJ using an imitation sample and brain tissue.

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## II. Pulsed Laser Induced Liquid Jet

An LILJ is constructed using a silica optical fiber, a metal tubule, and water (saline). A stainless tubule (inside diameter = 1.0 mm) is filled with water, and a silica optical fiber is inserted into the middle of the tubule. When water is irradiated by a pulsed Ho:YAG laser, the water in front of the fiber edge evaporates and expands instantaneously. To harness this rapid cubical expansion, a micro-liquid is ejected from the stainless tubule at high speed (10–30 m/s), and the tissue or tumor is crushed. In this manner, the laser drive voltage and pulse frequency can be controlled. For brain pituitary surgery, settings of 0.7 kV and 3–5 Hz were used, respectively. The principle behind a pulsed LILJ is shown in Fig. 1.

## III. Phantom Experiments

### A. Gelatin specimen preparation

In our experiments, to limit the use of biological samples for basic verification, we mainly used gelatin, which has the same hardness and properties as brain tissues. First, we measured the excavation depth of extracted pig brain tissue crushed with an LILJ, and the settings of the laser drive voltage were 0.5–1.0 kV (increasing in increments of 0.05 kV), a pulse frequency of 3 Hz, and the number of shots to 10 at the same point on the brain surface. Then, gelatin blocks were prepared with 4–20 wt% gelatin in increments of 2 wt%. The gelatin phantoms were shot by an LILJ having the same parameters as in the brain tissue experiments, and the excavated depths were measured. The results are shown in Fig 2. From this result, 4–6 wt% gelatin was assumed to have the same property as the pig brain tissue. In our basic experiments, we used gelatin having similar constituents.

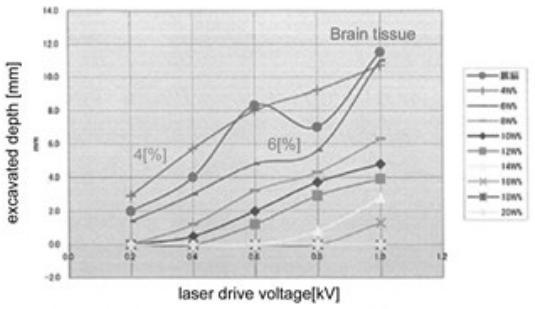



Figure 2. Relation between laser drive voltage and excavated-depth-induced LILJ.

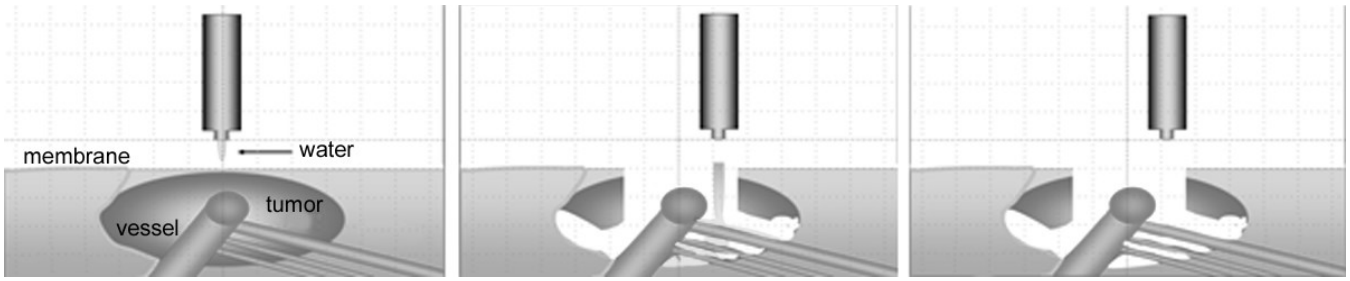



Figure 1. Principle of a pulsed LILJ..

### B. Experimental setup

The experimental setup is shown in Fig. 3. The system was constructed using a gelatin phantom set on a 3D stage, an LILJ, trigger-timing generator, illumination light source, and high-speed digital video camera. For visibility purposes and ease of off-line image processing, the saline of the LILJ had a dark purple color due to aqueous ink. The axis of the LILJ applicator was set vertically against the surface of the gelatin block.

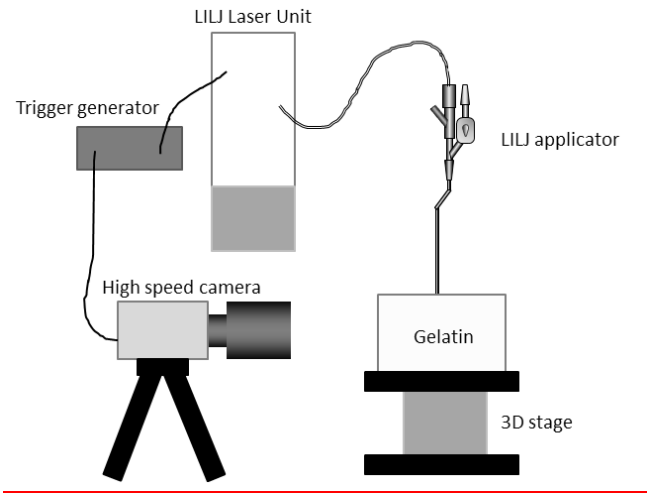



Figure 3.Measurement system setup in phantom experiments.

### C. Experimental protocol

LILJ's setting parameters were as follows: 0.7 kV, a pulse frequency of 3 Hz, and the number of shots to 10 at the same point on the brain surface. The distance between the tip of the LILJ and gelatin surface was set at 0–4 mm by every 1 mm. The camera-recording trigger was synchronized with LILJ's laser driving timing and was measured with 384 × 288 pixels, the recording speed was 30000 fps, and signal dynamic range was 12 bits (4096 gray gradation).

### D. Results

The liquid jet attained a depth of about 6.3 ± 1.1 mm and made a liquid reservoir having a diameter of 2.2 ± 0.3 mm (Fig. 4). In subsequent shots of the LILJ, the liquid jet attained a depth greater than the first shot, and it instantaneously enlarged the liquid reservoir. However, it did not crush the gelatin under the liquid reservoir, which was only elastically deformed. Between the different LILJ shots, micro-amounts of liquid jets were evacuated from the gelatin in small amounts, and using a high-speed camera, we observed that the volume of the liquid reservoir was reduced before the next shot. For all values of distance between the LILJ and gelatin, we confirmed the formation of a liquid reservoir and the micro-ejection of liquid after the shots.

### E. Discussions

From the results obtained from the phantom experiments, the mechanisms behind the constant excavated depth caused by the pulsed LILJ were as shown below

*1) The liquid jet formed a liquid reservoir that is located at a depth of 6 mm under the surface.*
*2) The inner pressure of the liquid reservoir was dispersed in accordance with Pascal's principle, and the size of the liquid reservoir became stable due to the equilibrium between the internal and external pressure of the liquid reservoir.*
*3) After the second shot of an LILJ, the liquid jet induced only the elastic deformation of gelatin around the liquid reservoir and did not crush the gelatin. An increased amount of liquid was ejected slowly before the next shot (0.33 sec after the previous shot)*
*4) In the subsequent shot of an LILJ, there was no sufficient pressure to crush the gelatin under the liquid reservoir; thus, the excavated gelatin maintained a constant depth.*

## IV. In-vitro experiments

We performed in vitro phantom experiments to confirm the liquid reservoir phenomenon in the in vitro brain tissue experiment.

### A. Experimental setup

To clarify the liquid reservoir phenomenon in the extracted pig brain tissue, sliced tissue specimens were obtained by the following protocol. Sliced tissue blocks were cut from the surface of the extracted brain, and their sizes were 10 mm × 10 mm × 2 mm. The strip preparations were sandwiched by 5 wt% transparent gelatin, which had a thickness of 3 mm. Then, the specimens were sandwiched between transparent acrylic boards having a thickness of 2 mm. The specimen and measurement system setup are shown in Fig. 5.

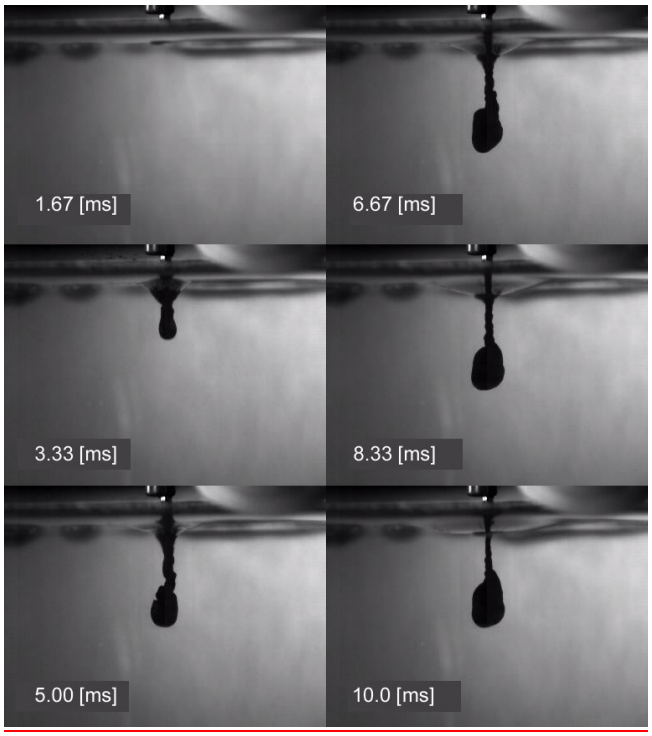



Figure 4.Liquid reservoir in the gelatin phantom induced by a LILJ

*B. Experimental protocol and signal processing*

The experimental setup is shown in Fig. 5. The sliced specimens were illuminated from one side using a constant voltage illuminator. A high-speed video camera recorded measurements from the counter side of the specimen. An LILJ was set vertically against the top surface of the tissue. The liquid jet was colored by aqueous ink. The behavior of the inserted liquid jet was captured as a shadow picture. The pulsed LILJ parameters were set to be the same as in the phantom experiments.

The measured movies were inverted, and normalized images were processed by off-line processing. The measured movie data were 12 bit gray-scale independent format avi files that were first saved on a PC. Then, to emphasize the subtle changes of brightness values, gradation reversal processing and gradation normalization processing were applied against all pixels of all frames in the measured movie files. The processed mathematical formula is as shown below.

$$fp(x, y) = (1/(brd + brh)) * (f(0)(x, y) + brd - f(n)(x, y)) * 256$$

f(n)(x, y): brightness value of n[frames] at coordinate (x, y)

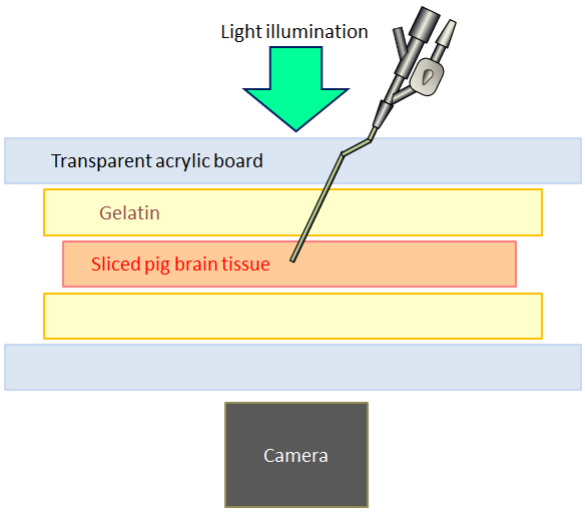
f(0)(x, y): basic brightness value at coordinate(x, y)

fp(n)(x, y): processed brightness value of n[frames] at coordinate (x, y)

brd: variation in width at the side of low gradation against basic brightness value

brl: variation in width at the side of high gradation against basic brightness value

(In this study, brd was set as 10, and brl was set as 25.)



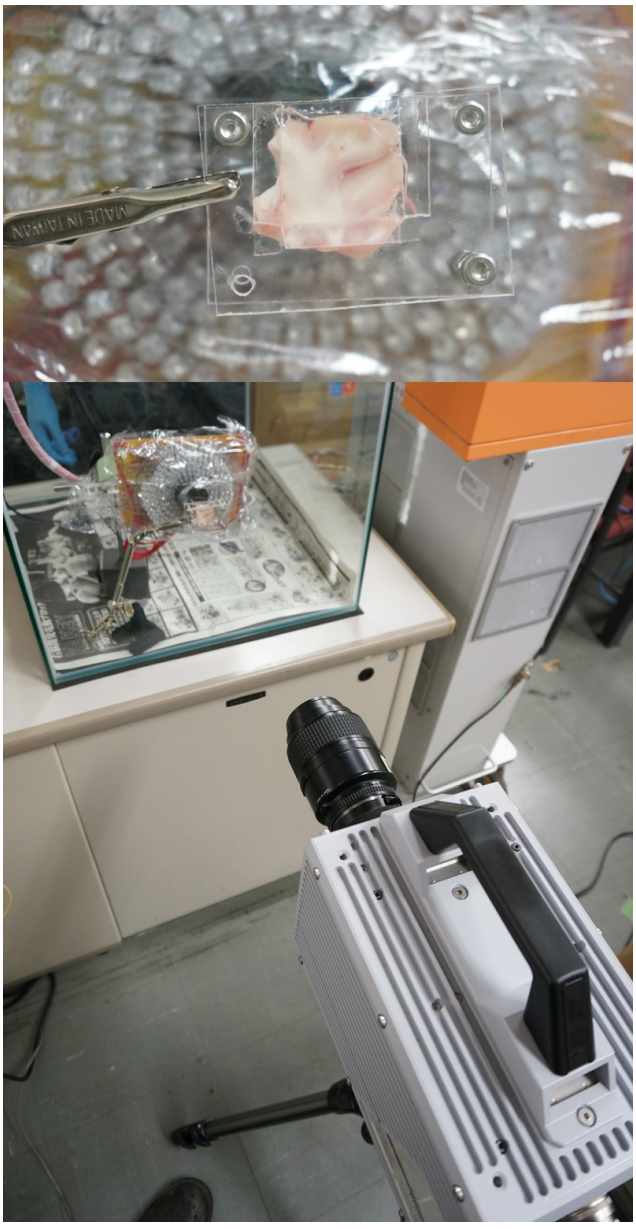



Figure 4. System setup of brain tissue experiment and sliced specimen preparation.

### C. Results

Fig 6 shows the processed data of the first and second shots of an LILJ on the same sliced specimen and same episode of shots. The orange and yellow regions of the image indicated that opaque liquid jets were inserted in the region of the sliced brain tissue. These results showed that the liquid reservoir induced by the pulsed LILJ on the sliced brain tissue was formed in the same manner as in the gelatin phantom experiments. The corresponding liquid reservoir induced on the brain tissue maintained the same volume and depth of the excavated location after the second shot of an LILJ was applied.

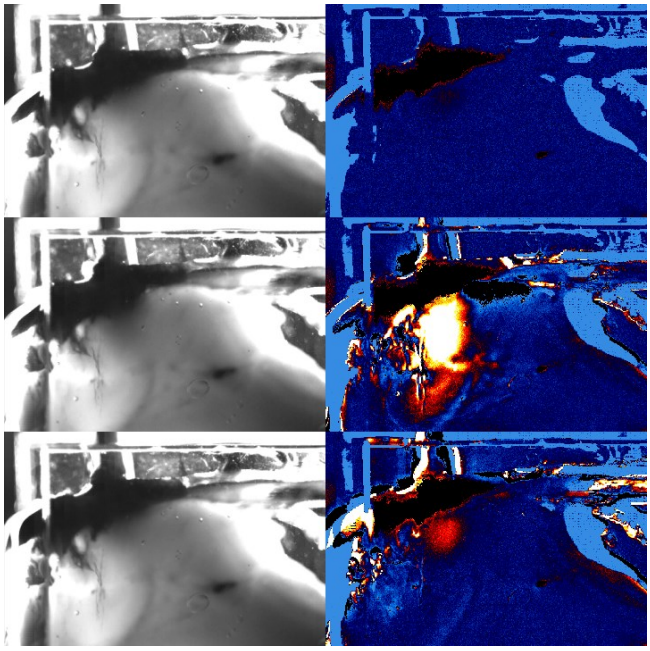


Figure 5. Processed images of liquid reservoir in brain tissue induced by LILJ. Left gray images were original captured 12[bit] grayscale images. Right colored images were normalized data. Orange to yellow to white color change meant that became dark in original image. These pictured showed that opacity liquid was injected and liquid reservoir formed in sliced brain tissue.

## V. Discussions

After the front tip of the high-speed liquid jet approached the surface of the brain tissue, it became slow while excavating the tissue. Thus, the ejected liquid jet was a long train of water, and when the front tip slowed, the latter side of the train maintained its speed and increased the internal pressure. Then, a liquid reservoir was formed with a diameter that was larger than the internal diameter of the first liquid jet. About 20 ms after the liquid jet shot, the inner pressure of the liquid reservoir and stress of the external brain tissue reached an equilibrium, and the liquid reservoir functioned as a buffer material that regulated the internal pressure within limits that would not crush the external brain tissue. However, the increased liquid on the reservoir was slowly ejected to the outside of the tissue, and the interval through the next shot was 333 ms (pulsed LILJ was driven at 3.0 Hz). This interval was sufficiently long to prepare for the next shot of excess water. The abovementioned mechanism assumed that the pulsed LILJ maintained constant excavated depth.

## VI. Conclusion

Using a high-speed video camera, a phantom specimen, and extracted pig tissue, we analyzed the phenomenon of constant excavated depths induced by a pulsed LILJ focused at the same point on a tissue. We clarified that the liquid reservoir inside the tissue induced by the pulsed LILJ served an important role in this phenomenon.

## References


[1] T. Ohki, A. Nakagawa, T. Hirano, T. Hashimoto, V. Menezes, H. Jokura, H. Uenohara, Y. Sato, T. Saito, R. Shirane, T. Tominaga, and K. Takayama, "Experimental application of pulsed Ho:YAG laser-induced liquid jet as a novel rigid neuroendoscopic dissection device.," Lasers in surgery and medicine, vol. 34, no. 3, pp. 227–34, Jan. 2004.

[2] Y. Ogawa, A. Nakagawa, K. Takayama, and T. Tominaga, "Pulsed laser-induced liquid jet for skull base tumor removal with vascular preservation through the transsphenoidal approach: a clinical investigation.," Acta neurochirurgica, vol. 153, no. 4, pp. 823–30, Apr. 2011.