Annual Report of Iwate Medical University
School of Liberal Arts and Sciences
No. 40 (2005), 17-26.

Fundamental Experiments of Water Jet Released from Micro-tube with Micro-discharge

Makoto Komatsu

(Received October 25, 2005)

Abstract

The water jet from the canaliculus driven by electric micro-discharge was visualized. A coaxial electrode was employed for the micro-discharge. A canaliculus was a commercially available PVC tube. The inside of the canaliculus was filled with isotonic sodium chloride solution. The supply of the sodium solution was kept with syringe pump constantly. When the amount of the sodium solution supply was smaller than 100 ml/hr, a water jet traveled at a constant speed with present experimental configuration. On the other hand, the jet acceleration with the sodium solution supply larger than 100 ml/hr was faster about immediate velocity after the discharge. Additionally, it was confirmed that the water jet might be driven twice. The same phenomenon had been seen previously. Next, the bubble formed around the electrode was visualized. Many tiny bubbles were generated like a cloud. The bubbles were really different from a sphere bubble shape seen in laser using. A discharge voltage and electric current were measured at the same time. The speed of the jet became faster when there were two spikes in the waveform of the voltage. And from comparison of the visualized images and the waveforms of discharge voltage, We could anticipate that such jet acceleration was caused by discharge through water vapor or air in the bubbles. When electric discharge occurred in the sodium solution, we did not observe a similar phenomenon.

1. Introduction

The applications of water jet were used in various fields. A water jet accelerated by combination of high pressure water and a nozzle is typical and ordinary, and is applied both to small-sized devices and large-sized facilities. On the other hand, the technologies using pulse water jet are also applied to small-scaled devices in large part. There are some jet-driving methods for the pulse jet.

For example, application to the scalpel for the ophthalmology using the water jet driven by the electric micro-discharge is proposed. And the thrombolysis and a scalpel for the surgery by the laser-induced liquid jet (LILJ) are also being developed [1-4]. Additionally, rock-crushing method by using water jet including cavitation cloud is analyzed [5]. It is included compound problem underwater shock wave and micro water jet [6] in a broad sense. In usual place, the micro-jet of the ink jet printer adopts piezoelectric element as a jet driver. When the jet passes inside the material of the thin canaliculus,

Department of Physics, School of Liberal Arts and Sciences, Iwate Medical University

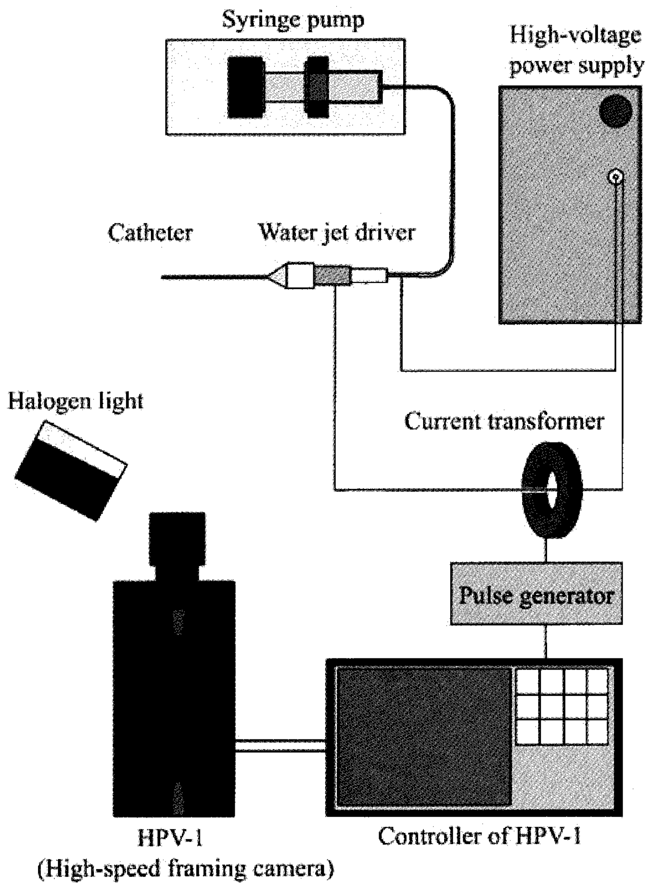


Figure 1. Whole arrangement of experimental devices for visualization.

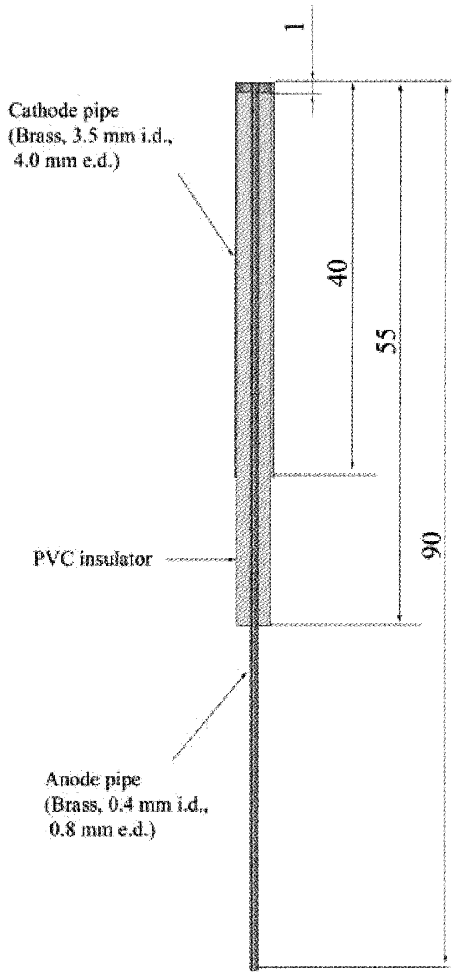


Figure 2. Longitudinal cross-section of co-axial arranged electrodes and jet driving section. Outside of the electrodes has fixer of micro-tube.

laser is most suitable energy source of jet in many cases from view on tensions around the adapters of pipes, the controllability of the jet, and combined use of the jet and a shock wave. However, the use of the laser and fiber lines is very expensive. It must be careful to the damage at the tip of the fiber line when optical fiber leads laser beam to the intratubular environment.

On the other hand, electric discharge is one of cheap and the high power energy sources for the jet. Electric discharge has tasks on controllability, an discharge medium and electrode surface deterioration. But, discharge is useful when distance between working point of jet and electrodes can be secured enough to be ignored the worse effect of the discharge. If we can change the discharge jet driver unit alone for the repair or maintenance, we can expect wide applications of it. In this regard, phenomena around electrodes might be different from generation of a single sphere water vapor bubble as the laser energy source. Therefore, we must investigate a phenomenon around the source of electric discharge.

To realize utility of this technique, it is necessary at first to perform various basic experiments and calculations for data about electrodes and jet driver. We paid attention mainly to the electric discharge drive part, and tried the acquisition of the fundamental data about behavior of the bubbles generated around the electric discharge electrode and water race released from thin micro-tube installed to a trial jet driver in this research.

2. Experimental devices

High-speed photography was used for the visualization of the phenomenon around the electrode and the race released from a canaliculus. The camera used for the high-speed photography was HPV-1 (Shimadzu Co. Ltd). Figure 1 shows the outline of the visualization system. Continuous Halogen lamp was used for lighting. HPV-1 is high-speed framing camera, and maximum framing rate is a million frames in a second. Electric discharge electrodes made of brass were arranged coaxially. A longitudinal cross section is shown in Figure 2. The positive electrode and a negative pole was an inner pipe (internal diameter 0.4 mm and external diameter 0.8mm) and outer pipe (internal diameter 3.0 mm and an external diameter 3.5 mm), respectively.

Oversized driver causes the aggravation of the energy efficiency due to the increase in the load to the connecting parts of the pipes and the loss of water race. Because of that, we must devise it from both view points of the strength of configuration and the miniaturization. The equipments used in present experiments were manufactured and miniaturized within the range of the combination of the cheap ready-made materials, and we did not employ specific manufacture in process. Note not to be the optimized result. The canaliculus which could be connected to the jet driver was made of polyvinyl chloride (PVC) which is a commercially available micro-tube (internal diameter 0.5mm and an external diameter 0.9mm). The micro-tube is fixed to metal part with epoxy adhesive, and connected to the jet driver as Figure 2.

Experiments were conducted in air and in transparent tube made of polymethylmethacrylate (PMMA) filled with the isotonic sodium chloride solution. Hence, the fixer of the tube is necessary. In present studies, PMMA transparent tube (internal diameter 5 mm and an external diameter 8mm) and water chamber (L 80 mm, W 80 mm, H 75 mm) which has connector of the PMMA tube were prepared (Figure 3).

3. The jet velocity measurement released by canaliculus

Water jet driver using electric discharge is shown in Figure 4. A charging voltage was 3.5 kV, and the amount of supply of water was made to change between 50 ml/hr to 150 ml/hr in the experiment. A commercial PVC micro-tube was adapted to tip of the driver as Figure 4. The length of the canaliculus was 100 mm. From obtained imaging data by HPV-1, a distance from the open end of the canaliculus in the horizontal direction to the jet maximum arrival point was measured with image software (Adobe Photoshop 6.0). The initialization of HPV-1 is described in the table 1.

Table 1. Camera (HPV-1) setup parameters

Frame rate [μs/frame]	250
Exposure time per a frame [μs]	62.5
Gain	×5
Trigger point after input [frames]	15
Set internal delay [μs]	10

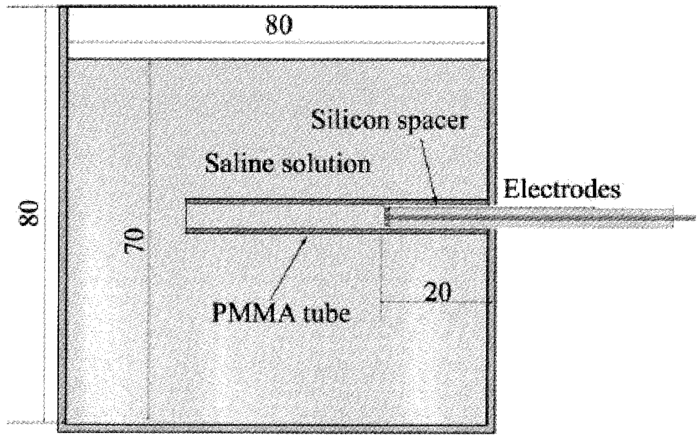


Figure 3. Fixation of PMMA tube in water chamber. The chamber is consisted of transparent PMMA plates which has 1.5 mm of thickness.

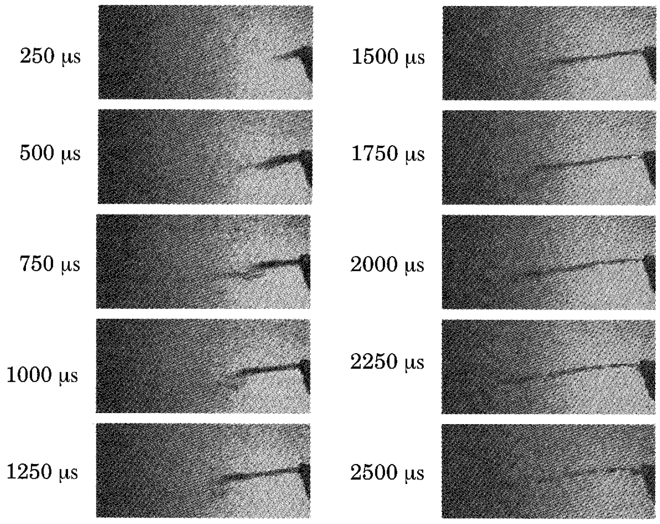


Figure 5. Time-resolved high-speed photographs of jet released from micro-tube. Condition is 150 ml/hr of isotonic sodium chloride solution flux. Precursor jet vanished on the way, and following jet appeared behind it.

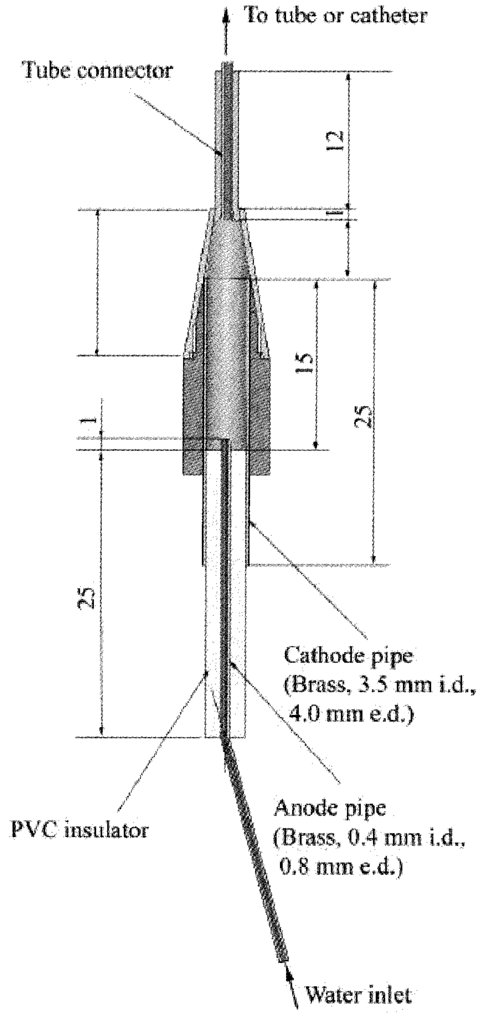
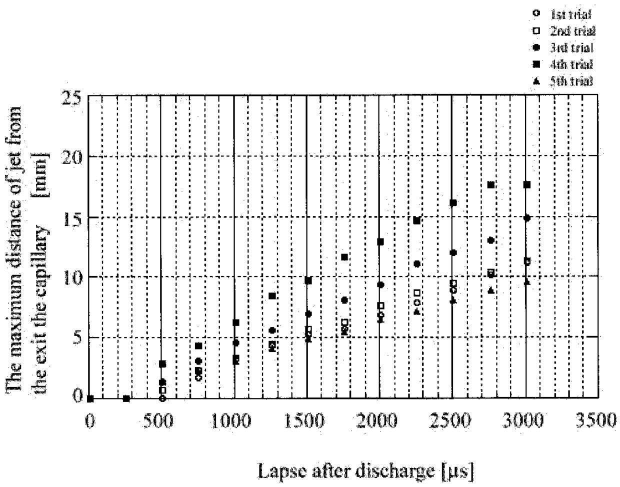
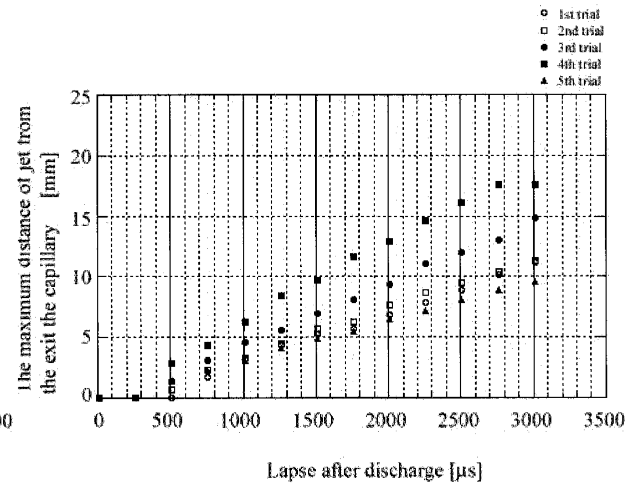


Figure 4. Connection of micro-tube to jet driver. A PVC micro-tube was glued to the metal cone parts, and the metal parts including the tube was connected to the driver.

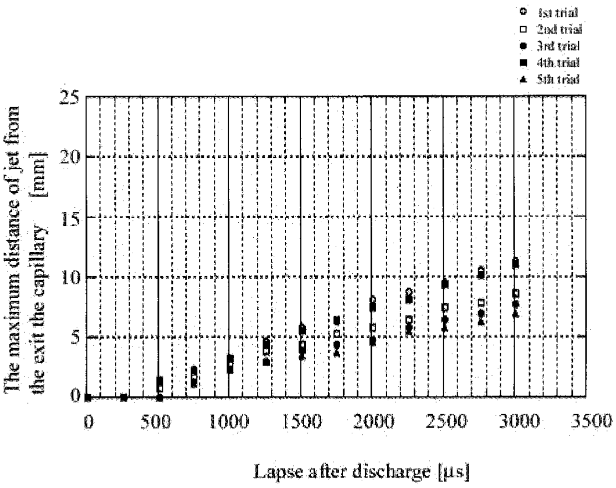
Figure 5 shows the result of high-speed photography taken with a system of Figure 2. Measured results on maximum arrival distance of the jets are shown in Figure 6. Though the maximum arrival point was almost in proportion to the lapse when the supply of water was less than 100 ml/hr, it was not in proportion in when the supply of water was more than 125 ml/hr. The number of data under the condition of 125 ml/hr is small in comparison with other conditions, because diffusion was considerable and the highest arrival point was unable to be specified. We should note this point. Moreover, the maximum arrival points decrease for a while in the case of 150 ml/hr. The decrease does not mean turn back of the jet. It was confirmed that a jet occurred from behind the precursor jet, and the arrival point was measured newly in this case. The maximum arrival point of the precursor jet at this time was



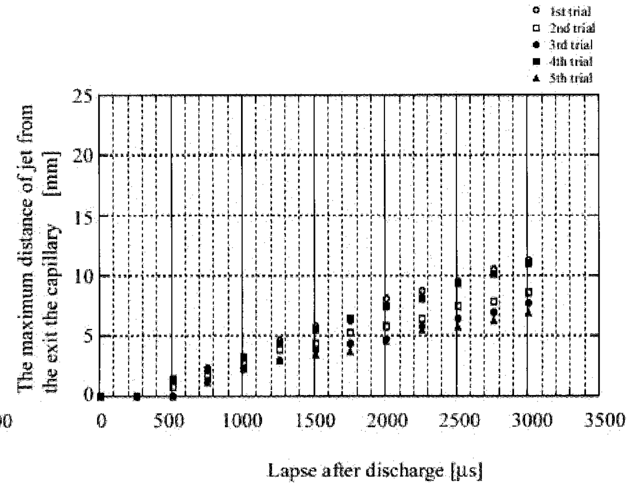
(a)



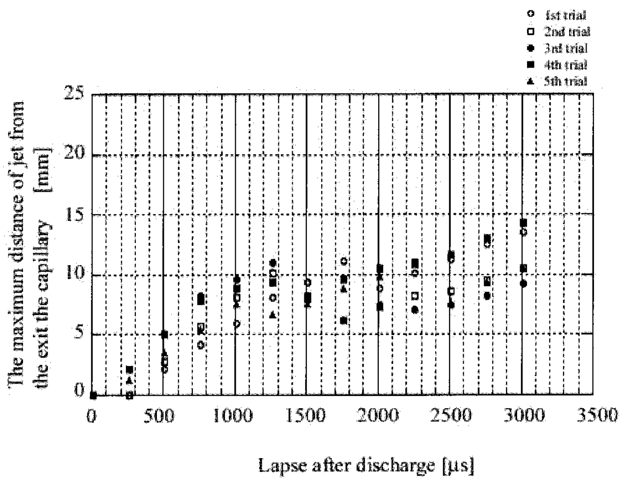
(c)



(b)



(d)



(e)

Figure 6. Plot of maximum arrival distance of jet measured from a tip of a micro-tube; (a) 50 ml/hr of isotonic sodium chloride solution flux, (b) 75 ml/hr of isotonic sodium chloride solution flux, (c) 100 ml/hr of isotonic sodium chloride solution flux, (d) 125 ml/hr of isotonic sodium chloride solution flux, (e) 150 ml/hr of isotonic sodium chloride solution flux.

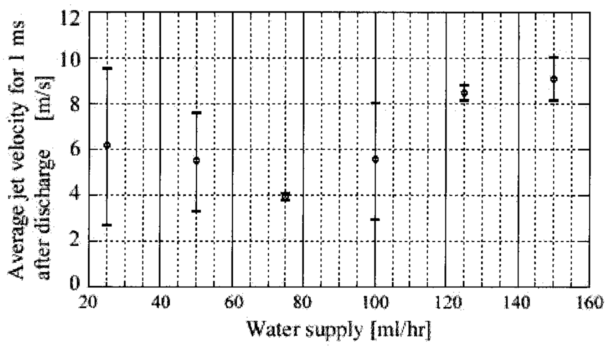


Figure 7. Average jet velocity at each isotonic sodium chloride solution flux within 1 ms after discharge. We can see data spread at 100 ml/hr of the flux. The high-flux induces high initial jet velocity.

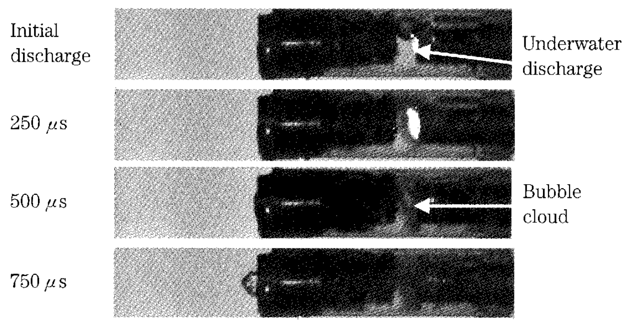


Figure 9. Time-resolved high-speed photographs of bubble around the electrodes. Charging voltage and the supplied flux was 3.5 kV and 100 ml/hr, respectively. Bubble cloud is produced which is different from a bubble with laser irradiation. Underwater discharge route was selected in this case.

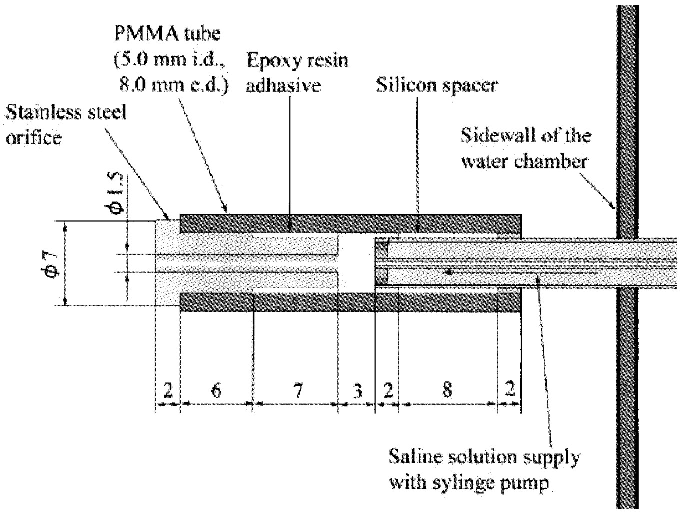


Figure 8. Schema of device for visualization of bubble generated around electrodes. Narrow tube made of stainless steel was equipped in front of electrodes to confirm influence of bubble formation in initial jet velocity.

unable to be specified in the same way as the case of 125 ml/hr.

The maximum arrival point in 3 ms after the discharge was recorded at 100 ml/hr of the sodium solution supply, and there was a case of exceeding 20 mm. However, the maximum arrival point in 1 ms after the discharge at 125 ml/hr over is larger in comparison with it at less water supply. Therefore, 5 times average velocity until 1 ms was collected in the Figure 7. Because there was delay at initiation of jet caused by many unspecified environmental reasons, a calibration curve was made with a method of least squares in the graph of Figure 6, and a speed was calculated from the inclination about each curve, and then averaged. When the flux was 75 ml/hr, the mean speed of the jet until 1 ms was minimum value at 3.93 m/s. And when water supply was 150 ml/hr, maximum value 9.09 m/s was recorded.

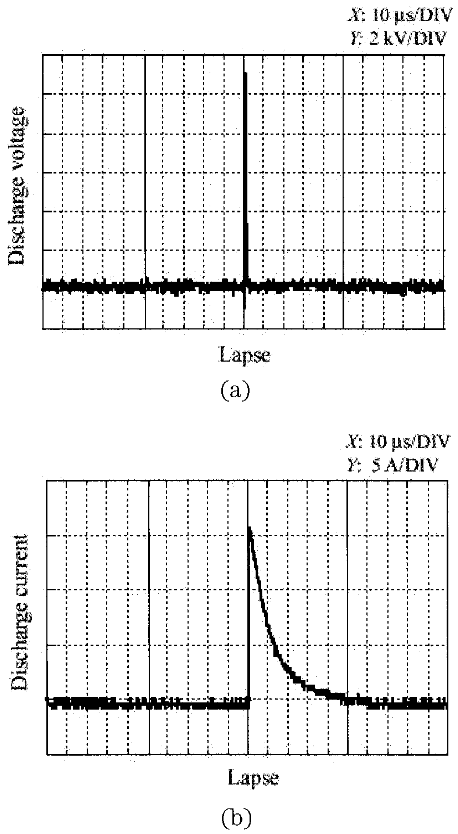


Figure 10. Waveform of discharge voltage and current measured at the same time as taking photographs of Figure 9; (a) voltage, (b) current

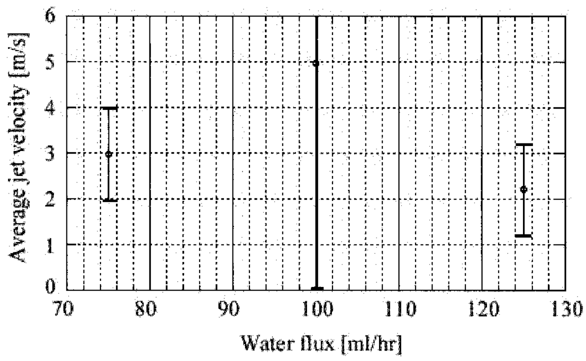


Figure 11. Plot of relationship between the isotonic sodium chloride solution flux and average jet velocity. The mean velocity was obtained 5 times of experiments. Critical data spread was seen at the flux of 100 ml/hr.

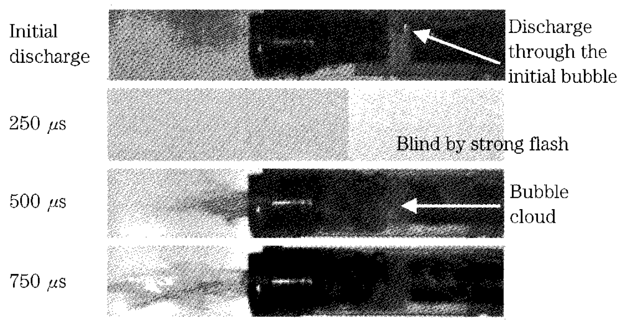


Figure 12. Time-resolved high-speed photographs of bubble around the electrodes when air bubble was put in front of the electrodes intentionally. Charging voltage and the supplied flux was 3.5 kV and 100 ml/hr, respectively. Discharge route through the bubble was selected in this case.

4. The occurrence of the bubble around the electrode

As for the device, like Figure 8, the acrylic cylinder of 5 mm inside diameter surrounded the electrode. And the cylinder of the stainless steel of 1.8 mm inside diameter was installed on 3 mm in front of the electrodes. The charged voltage was 3.5 kV, and visualization method was the same as the previous method shown in Figure 2. A discharge voltage and a discharge current were measured respectively with the high-voltage divider and the current transformer.

Figure 9 was one of results of high-speed photography. Bubble cloud was created, and such bubble formation was not same as single bubble formation with LILJ [1, 4]. Because an experiment was done in the isotonic sodium chloride solution, the water was not degassed, and a bubble remained after the phenomenon.

Figure 10 is the wave form of the discharge voltage and electric current measured at the same time. Electric current did not vibrate at decline region. On the other hand, about the jet ejected from the 1.8

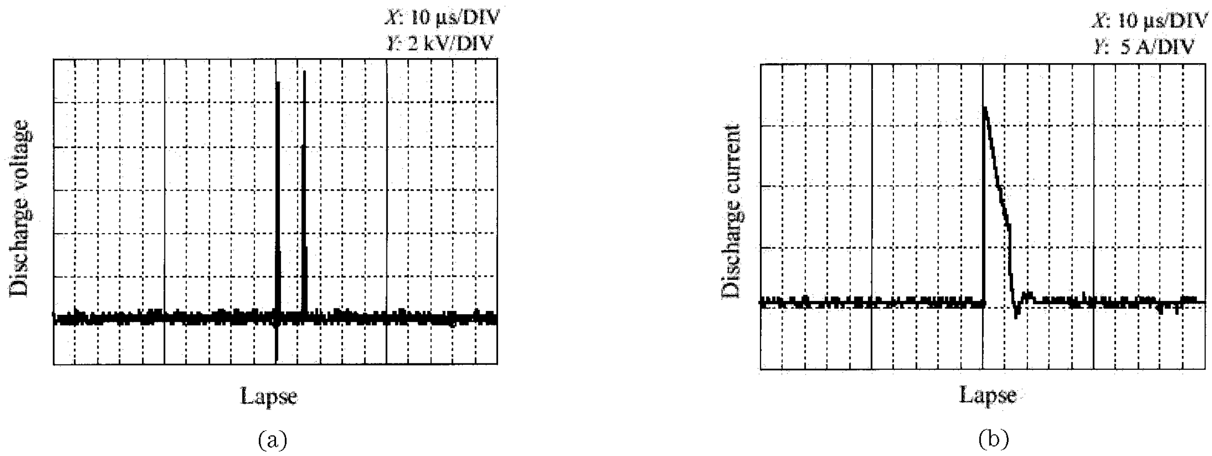


Figure 13. Waveform of discharge voltage and current measured at the same time as taking photographs of Figure 12; (a) voltage, (b) current

mm hole of the stainless cylinder, average jet velocity of 5 trials is collected in Figure 11. It was impossible to specify the relationship between water flux and jet velocity.

However, existence of a faster jet was confirmed like Figure 12. Waveforms of the voltage and current at that time are shown in Figure 13. In such case, it confirmed that two characteristic spikes existed in waveform of discharge voltage, and the current was declined rapidly.

5. Discussion

Bubble and shock wave is generated in discharges, and a jet occurs by the induced water race. When the length of the canaliculus increases, a jet becomes slow due to viscosity and various losses. On the other hand, an electric discharge current increases with a charging voltage of condenser though a discharge voltage is not change. Because of the distance between electrodes is fixed. Therefore, though a shock wave becomes strong, it is not always true that the voltage has correlation of bubble formation, water race and an influence on the jet.

Because jet formation is simple at small water flux, a maximum arrival point is in proportion to the lapse of time after the electric discharge until 3 ms. But, image analysis is difficult because a jet spreads at large flow rates of sodium solution. We should combine other measuring techniques with the high-speed photography. However, the impact of jet might be high when there is much flux because the immediate speed of the jet after the electric discharge is faster when a supply flow rate is abundant.

It is characteristic phenomenon at the flux of 150 ml/hr that a second jet is produced behind precursor spread jet. It is still difficult to conclude, but I anticipate that a jet is driven twice. It is impossible to specify cause of it just now. However, the same phenomenon often appears as driven by laser irradiation. Therefore, this phenomenon is not appropriate in using electric discharge jet driving method. A more detailed analysis is necessary from a view of physical field which is related to pressure waves as rebound of bubbles or shock waves, because this phenomenon is deeply concerned with the speed of the jet or straightability.

When a jet is used, it is asked to be high controllability with the suitable power. As for the controllability of the jet, the main factors dominating power of jet are the weight of the water and water pressure in

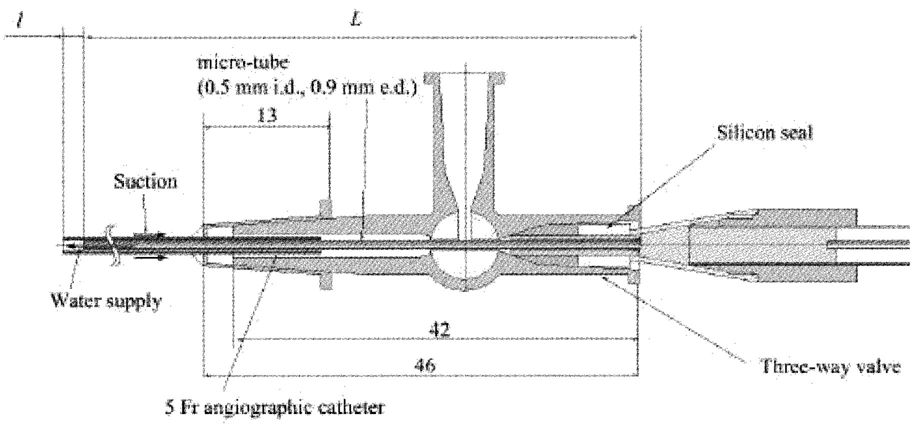


Figure 14. Description of micro-tube as jet generator with suction tube.

front of the electric discharge electrodes. The former is related to the length of the canaliculus, and the latter pertains to supply flux or the flow rate of the race. Because water mass driven with discharge is decided by length of canaliculus, the race rate is increased with the supply flux, and finally, jet can be driven easily. Accordingly, the speed of the jet increases with water flux in this device. Hence, if the power is raised, it is the easiest way to increase supply flow rates.

But, environment might not permit to increase the supply flow rate. If it gives an example of the special case on intravascular uses for the medical treatment, excessive supply causes a vascular and canaliculus explosion. Hence, the optimization of the supply flow rate is necessary. We might lead to the most effective jet devices under the limited condition if a water jet occurring in twice is available. This part is one of the fields which should be examined in detail.

On the other hand, when we pay attention to the phenomenon around the electrode, an electric discharge routes in the material which consists of a few phases also exist in each phase. Two routes exist by the electric discharge in this research because it becomes the gas-liquid biphasic fluid, a bubble and the liquid solution. When the spike of the electric discharge appears twice in the waveform of discharge voltage, the state that electric discharge happens in the bubble is caught as the figure 12. In contrast, when a spike is single, the route of the electric discharge can be seen in the liquid. Then, the speed of the jet is faster when a spike appears twice. This result is different from the case of the laser. This means that electric discharge occurs in each phase by a bubble's existing in the neighborhood of the energy source a little, and the impact of the jet may rise. As for the difference of electric discharge caused by existence of bubbles, it should be researched quantitatively due to utility of it and improvement of jet Contents of present study was mainly observation on relationship between water flow rate and jet velocity, and on behavior of bubble around the electrodes. However, there are many items which must be investigated quantitatively. For example, the experiment which has condition on the surface of the electrode, the material of the canaliculus, an shape of electrode and material of electrodes as variable parameter will be indispensable from now on.

Additionally, I am paying attention to suction system combined to micro-catheter developed by Dr. Y. Sato et al in Tohoku University. It is the system based on the developing catheter system to use for

MCA. Description of it is shown in Figure 14.

This device originally aims for cutting due to the jet and shearing by negative pressure effectively, and then can make perforation to thrombus or suck blood clots. Suction tube is arranged coaxially outside of micro-tube (narrower catheter) which is jet generator. Because it can increase flow rate easily, in hindsight, we can anticipate producing the jet effectively. It is possible to raise flow rate simply by increasing the supply flow rate with the amount of suction, and there are also few influences from the surrounding environment. In consequence, the mass of the fluid (the solution which exists in front of the electric discharge electrode) can be adjusted, and improvement controllability of jet can be expected. In addition to above-mentioned fundamental data, main future objectives are acquisition of quantitative data on the discharge, and establishment of effective jet generating method including simultaneous or combined use of existing techniques.

References

[1] T. Hirano, M. Komatsu, T. Saeki, H. Uenohara, A. Takahashi, K. Takayama, T. Yoshimoto, "Enhancement of fibrinolytics with a laser-induced liquid jet", Laser Surg Med **29**, 360-368, 2001.

[2] Topaz, ON., George V., "Laser for optical thrombolysis and facilitation of balloon angioplasty in acute myocardial infarction following failed pharmacologic thrombolysis", Carthet. Cardiovasc. Diagn. **36**, 38-42, 1995.

[3] Ansgar Berlis, Helmi Lutsep, Stan Barnwell, Alexander Norbash, Lawrence Wechsler, Charles A. Jungreis, Andrew Woolfenden, Gary Redekop, Marius Hartmann, Martin Schumacher, "Mechanical Thrombolysis in Acute Ischemic Stroke With Endovascular Photoacoustic Recanalization", Stroke **35**, 1112, 2004.

[4] Tomohiro Ohki, Atsuhiro Nakagawa, Takayuki Hirano, Tokitada Hashimoto, Viren Menezes, Hidefumi Jokura, Hiroshi Uenohara, Yasuhiko Sato, Tsutomu Saito, Reizo Shirane, Teiji Tominaga, Kazuyoshi Takayama, "Experimental application of pulsed Ho:YAG laser-induced liquid jet as a novel rigid neuroendoscopic dissection device", Laser Surg. Med. **34** (3), 227-234, 2004.

[5] K. Okumura, A. Kizaki, K. Matsuki, "Cavitation clouds induced by submerged high-pressure wayer jets under high ambient pressure", Proc. of 6th Pacific Rim International Conference on Water Jet Technology, 218-223, 2000.

[6] T. Kodama, K. Takayama, H. Uenohara, "A new technology for revascularization of cerebral embolism using liquid jet impact" Phys Med Biol **42**, 2355-2367, 1997.