Study on urinary stone cutting performance of ultrasonic scalpel affected by active movement of basket mechanism

Minoru Morita[1] and Tetsuya Morisaki[2], Takahiko Katahira[1], Zhongwei Jiang[1]
[1] Graduate School of Sciences and Technology for Innovation, Yamaguchi University, Japan
[2] Department of Mechanical Engineering, National Institute of Technology, Ube College, Japan
mmorita@yamaguchi-u.ac.jp

Abstract: In this study, we investigated the effects of an actively moving basket mechanism on the cutting performance of an ultrasonic scalpel used for the treatment of urolithiasis. The active basket mechanism was able to actively move the urinary stone pressed against the scalpel by controlling the wires that make up the basket with a servomotor via a rack and pinion mechanism. In this paper, we experimentally evaluated the effects of the rotation angle, angular velocity, and motion direction of the motor on stone cutting performance.

Key-Words : *Ultrasonic scalpel, Urinary stone treatment, Actively basket mechanism.*

1. Introduction

In the treatment for urolithiasis, external shock wave lithotripsy (ESWL) is generally used, but when the stones are large and difficult to lithotripsy, endoscopic surgery, such as percutaneous nephrolithotripsy (PNL), is used. PNL is a surgical procedure in which a hole is drilled from the back to the kidney and an endoscope is inserted through the hole to crush the stone with a crushing device while viewing the inside of the hole. In the current surgery, compressed air crushers and laser scalpels are mainly used as stone crushing devices, but previous studies have shown that ultrasonic scalpels have faster stone crushing speed and stone extraction speed than the former two devices, suggesting that ultrasonic scalpels are safer [1-6]. However, there is a problem that the speed of cutting a stone with an ultrasonic scalpel decreases as the cut progresses. This may be due to the fact that the tip of the scalpel is buried in the stone and there is no space for vibration. In this study, we focused on the basket catheter, which actually plays a role in pushing stones to the scalpel inside the body and evaluated the effect on cutting performance by actively moving the basket mechanism and devising a way to push the stones.

Received: 2023/12/18, Accepted: 2024/04/19
*Corresponding author: Minoru Morita
E-mail address: mmorita @yamaguchi-u.ac.jp

2. Ultrasonic scalpel design

In order to improve the cutting ability, our laboratory uses a reverse-phase vibration scalpel. This scalpel generates longitudinal vibration in the horn part and at the same time raises opposite bending vibrations due to the bifurcated shape of the scalpel tip, making it a device that uses unprecedented combined vibration. Figure 1 is an image diagram of antiphase vibration. Opposite phase vibration is achieved by applying special processing to the tip of the ultrasonic scalpel, and in addition to the longitudinal vibration mode,

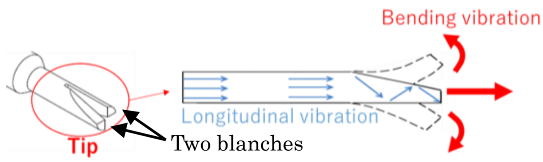

Fig.1 Combined vibration

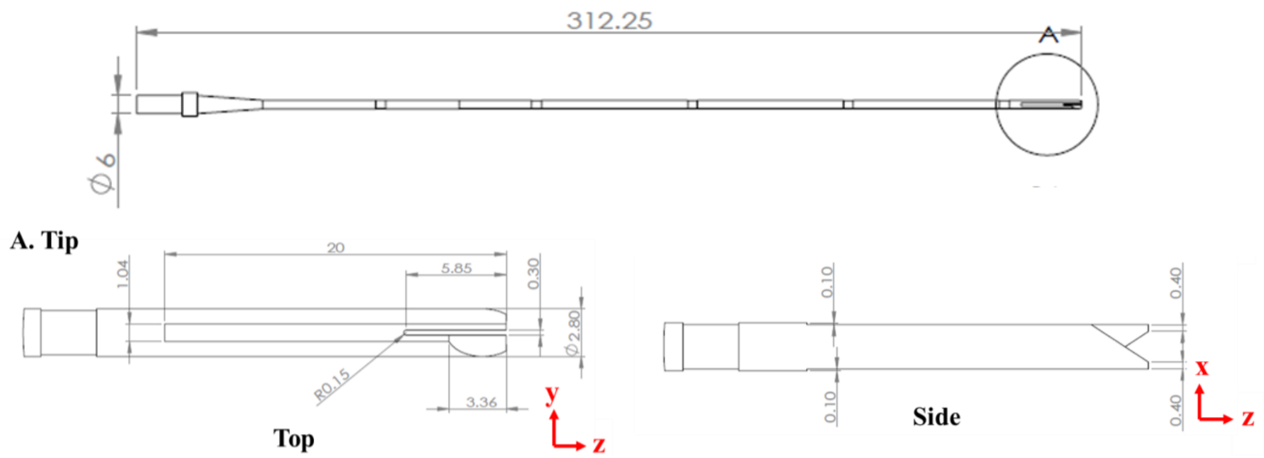

Fig.2 Structure of scalpel

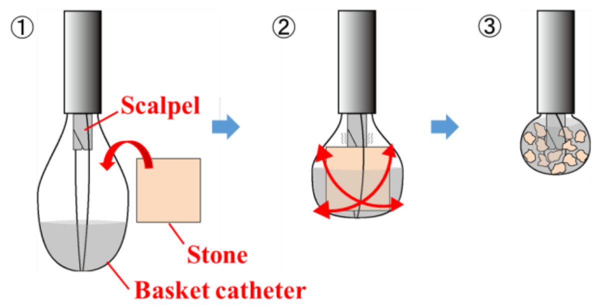

Fig.3 Assumed surgical method ①:Incorporating stones into the basket catheter ②:Actively move the basket catheter while contracting it and cut the stones ③:Remove the stone

which is the vibration mode of conventional ultrasonic scalpels, the two branches alternately bend and vibrate like scissors. Combined vibration of longitudinal vibration and bending vibration is expected to increase the shear force applied to the urinary stone surface and improve the cutting performance [7-9]. Figure 2 shows a design drawing of a blade modified to excite opposite phase vibration, and all processing was precision cutting.

3. Basket mechanism

In order to remove stones with an ultrasonic scalpel, it is necessary to press the scalpel against the stones. Therefore, we focused on a basket catheter that holds and retrieves calculi in the body, and devised a method of confining the target in a basket, contracting it, and scraping it off while compressing it, as shown in Fig. 3. In addition, by connecting both ends of the wires that make up the basket to independent motors, the wires are actively moved to arbitrarily change the contact angle of the urinary stone pressed against the ultrasonic scalpel. In the experiment, the basket part was contracted by lifting the entire basket mechanism as the load cell was raised, while it was actively moved by programmatically operating the motor through a microcomputer with a motor driver (DFRobot, Arduino Romeo BLE mini). Figure 4 shows a schematic of the experiment. A is a schematic diagram of the inside of a case that houses a mechanism consisting of a basket motor, a rack and pinion, and wires of the basket. The rotary motion of the gear attached to the motor is converted into linear motion through the rack to push or pull a thin pipe. The wires that make up the basket are glued to the thin pipe and inserted into the large pipe as shown in Fig.4 B. This structure makes it difficult to bend even if you push the wire. The black arrow in the upper left figure shows how the force that cuts the urinary stone model is transmitted from the load cell under the tank. By pulling four wires at the same time, the urinary stone model is compressed. The load cell is mounted on a linear positioning stage (Yamaden, RE2-33005C), which allows for the control of the pressing force to be constant during the cutting of the urinary stone. In a preliminary experiment using a small load cell (UNIPULSE, UCW2-20N), the difference between the actual force applied to the stone and the force measured by the load cell under the tank was about 1N in the range of 1 to 10N. The white arrows show the movements when the wires are individually controlled by moving the motors, and the four wires in the basket can be independently controlled by the four motors. Figure 5 shows an example of the movement of the basket to help understand the mechanism.

4. Experimental system

In order to make the stone cutting condition constant, an experimental system that controls the pressing force and the scalpel driving condition etc. was constructed. Figure 6 shows a schematic of the experimental system. In the experiment, the output power of the ultrasonic scalpel was controlled by the feedback control of the input current value. By feeding back control the input frequency so that the input voltage and current phase difference reaches 0, the resonance point tracking was realized. The frequency control result was around 47kHz. The input frequency and current were recorded and checked on the control PC. Total system feedback frequency was about 80 Hz.

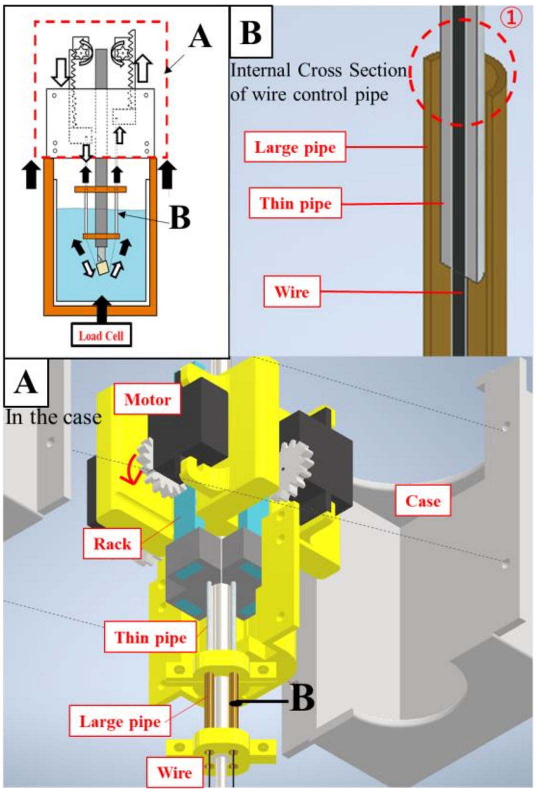

Fig.4 Outline diagram of the experiment - A is the case, pulling all four wires simultaneously as shown by the black arrows; B operates the wires individually, as shown by the white arrows; the actions of A and B can be controlled independently (①The wire is guided without wobbling by passing it through a large pipe, and near the exit of the pipe, the wire is connected to a more rigid thin pipe to enhance force conduction.)

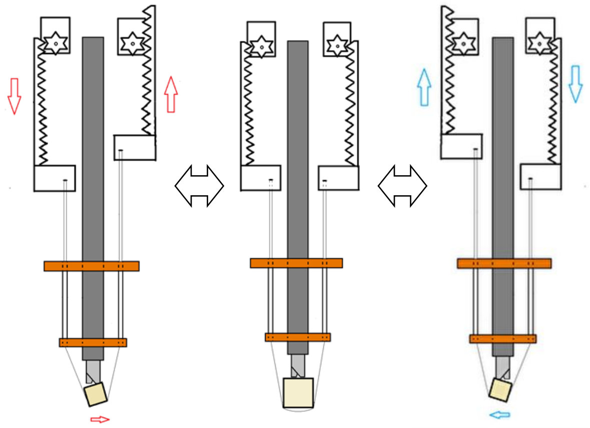

Fig.5 Schematic diagram of movement of basket mechanism.

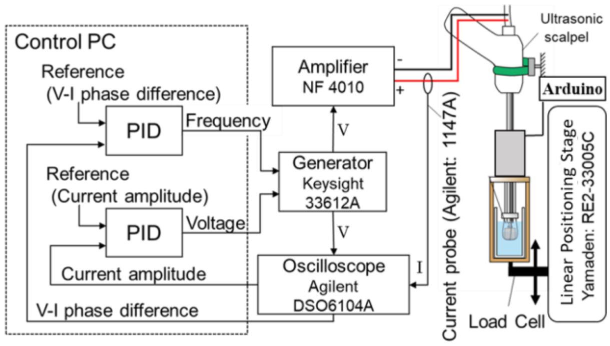

Fig.6 Scalpel control method

4.1 Experimental method and conditions.

As shown in Figure 2, the direction of the bending vibration of the scalpel tip is x and its vertical direction is y. Target current value of controlled input was set to 0.2A. The pressing force during cutting was maintained at a constant 5N by controlling the movement of the linear positioning stage, with the maximum speed of this movement set to 1 mm/s and the minimum speed being zero (stop). Therefore, if the cutting conditions are poor and the process is slow, the final cutting amount will be smaller. Conversely, if the conditions are good and the cutting proceeds quickly, the cutting amount will be larger. As a result, the cutting amount can be used to evaluate the effectiveness of the cutting conditions. The pressing time was set to 10 seconds. The urinary stone model is an 8[mm] cube made of dental cement (Zhermack, Elite Ortho), and its compressive strength is about 20MPa, which is equivalent to that of an actual urinary stone[10-12]. In the experiment, the urinary stone model was placed in water. After the experiment, the depth of the hole in the urinary stone model was measured with a laser microscope (LEXT OLS4000). It has been confirmed through preliminary experiments, conducted with the

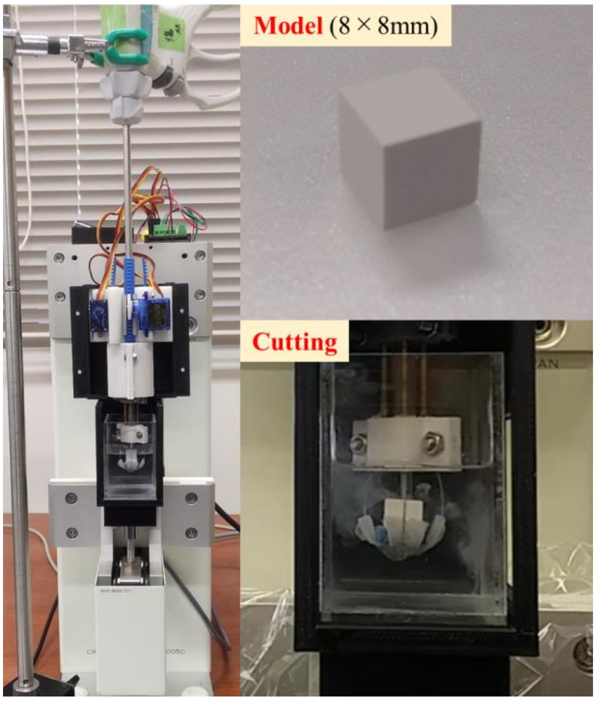

Fig.7 Overall view of the experiment

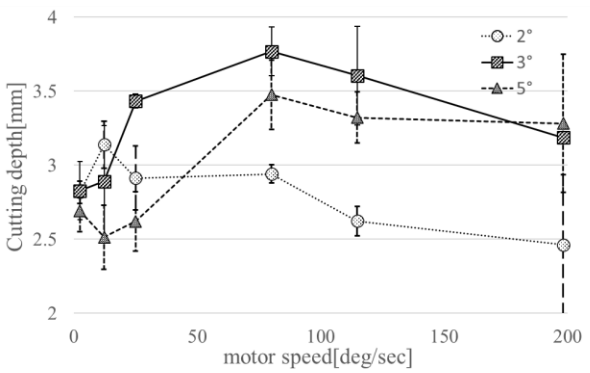

Fig.8 Result of cutting depth for each basket vibration angle and angular velocity.

ultrasonic vibration of the scalpel turned off, that the urinary stone does not undergo elastic deformation.

For the purpose of evaluating the characteristics of the active movement of basket mechanism, the rotation angles of the motor were set to 2, 3, and 5deg, and the rotation angular velocities were set to 2.44, 12.27, 25, 80.07, 114.81, and 198.24deg/s. To make the results of this study easier to understand, it would be ideal to describe the experimental conditions in terms of the tilt of the basket mechanism. However, as the cutting of the urinary stone progresses, the tip of the scalpel becomes embedded into the stone, causing the tilt of the basket to decrease. Additionally, it is challenging to accurately evaluate the tilt of the basket in the water, which becomes cloudy due to the scraped stone fragments. Therefore, this study uses the motor's rotation angle and angular velocity, which are closely related to the basket's movement and can be quantitatively controlled, as the operating conditions for the basket. The basket mechanism was periodically vibrated in x direction, and the cutting experiments were performed three times in all conditions. Figure 7 shows photographs of during the experiment. From the photograph, it can be seen that the cut urinary stone model made the water cloudy and was scraped off in powder form. Where, preliminary experiments showed that the pressure applied between the stone model and the tip of the scalpel was about 1N lower than the set value, with pressures of 4N. Figure 8 shows the results of cutting depth when the rotation angle and angular velocity are changed. The results are averages value, and the number of experiments for each condition is 3. The error bars are standard deviations. As a result, the cutting depth was less than 3 mm at almost all angular velocities at an angle of 2 degrees, which is smaller than the results at the other angles. In addition, the depth increased by about 1 mm at angular velocities of 80.07 deg/s or more for an angle of 5 degrees. The deepest result was obtained at 80.07deg/s at an angle of 3 degrees. These results suggest that the performance of the basket degraded if the movement of the basket is too slow or too fast, and that the performance improved with an appropriate speed. This is thought to be because the basket does not move when the speed of the motor slows down due to the mechanical resistance of pressing the scalpel against the stone.

4.2 Relationship between basket movement direction and cutting depth.

The opposite phase vibration type ultrasonic scalpel that we are researching in our laboratory requires a space in the bending vibration direction of the tip of the scalpel due to its cutting principle. It is thought that this is because the tip of the scalpel is buried in the hole made in the stone, increasing the contact between the stone and the side of the scalpel, making it impossible to secure a sufficient gap for vibration. Therefore, we investigated the difference in cutting depth depending on the direction in which the basket mechanism is moved. The target current value of the control input was 0.2 A, the pressing force at the tip of the ultrasonic scalpel was 3, 5, 8 N, and the pressing time was 10 seconds. The operating conditions of the basket mechanism were set at a motor rotation angle of 3 degrees and an angular velocity of 80.07 deg/s, which was the largest cutting depth in chapter 4.1. Each condition was tested three times, and the mean and variance were summarized.

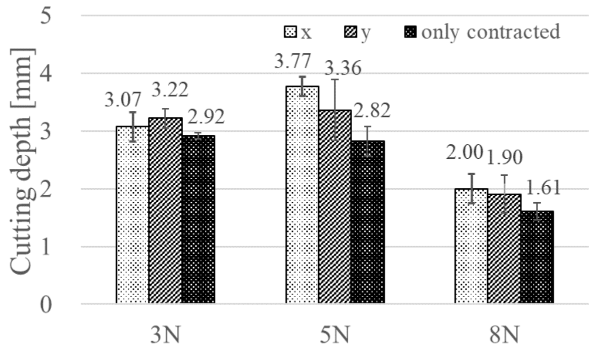

Fig.9 Differences in basket vibration direction and cutting depth.

Figure 9 is a graph showing the cutting depth of the urinary stone model measured with a laser microscope after the experiment. As shown in the figure, the amount of cutting depth was larger when the basket mechanism was vibrated periodically than when the basket mechanism was only contracted. In particular, the result of moving the basket in the x direction, which is the bending vibration direction of opposite phase vibration, tended to have a larger cutting depth than the other results. We believe that this is the result of the possibility of solving the problem that the space required for vibration due to the predicted increase in contact between the calculus and the side of the scalpel cannot be secured.

5. Conclusion

In this paper, we conducted an experiment aiming to improve the cutting performance of urinary stone by using an opposite phase vibration ultrasonic scalpel under development and using an active movement of basket mechanism. Assuming that the tip of the ultrasonic scalpel is fixed by burial as the cutting progresses and the cutting performance declines, we verified the effect of cutting while actively moving the urinary stone. In order to perform highly reproducible experiments, an experimental system was developed in which the wire of the basket that holds the urinary stone can be actively controlled by a servomotor. Using a cement model with a compression hardness equivalent to that of an actual urinary stone, cutting experiments were conducted by changing the magnitude, speed and direction of the periodic motion of the basket mechanism, and the effects were summarized. As a result of cutting for 10 seconds, the cutting depth increased by a maximum of 1 mm depending on the magnitude and speed of the movement of the basket mechanism. Within the range of the conditions in this paper, the deepest cutting was possible with a variation angle of 3 degrees and an angular velocity of 80 deg/s. By moving the basket in the bending vibration direction of opposite phase vibration, the cutting depth tended to be the largest.

Acknowledgments:

The authors would like to thank all for technical assistance with the experiments. This work was supported by JSPS KAKENHI Grant Number: 18K12107 and 22K12866

References:

[1] Kubota Masashi, Toru Kanno, Yusuke Murata, Satoshi Funada, Hiromasa Sakamoto, Ryuichi Nishiyama, Takashi Okada, Toshiya Akao, Yoshihito Higashi and Hitoshi Yamada,"The efficacy of a released ultrasonic lithotripsy in percutaneous nephrolithotomy", Acta Urologica Japonica, 63(1), pp.1-5, 2017

[2] Kursad Zengin, Nevzat Can Sener, Okan Bas, Ismail Nalbant, Inan Alisir, "Comparison of pneumatic, ultrasonic and combination lithotripters in percutaneous nephrolithotripsy". Int Braz Jurol, pp.650-655, 2014

[3] Marco L., Arman T., Constatinos A., Konstantinos P., Angelis P., Athanasios V., Despoina L., Theofanis V., Claudio S., Evangelos L., Panagiotis K., "Comparative Evaluation Between One Ultrasonic and Two Single-Probe Dual-Energy Lithotripters: In Vitro and In Vivo Experiment in a Porcine Model", Journal of Endourology, Vol.35 Issue8, pp.1229-1235, 2021.

[4] Peng Z., Xiuwu H., Xin Z., Xuhui Z., Tao L., Yansheng L., Yuanhao C., Gao L., "Clinical Observation of UreTron Single-Probe Ultrasonic Intracorporeal Lithotripter for Ureteral Calculi", International Journal of General Medicine, Vol.14, pp.4229-4237, 2021.

[5] Shah J., Fiaz A. T., Faisal M., Ijaz S., Muhammad N., "Comparison of the Intracorporeal Ultrasonic Lithotripsy and Intracorporeal Pneumatic Lithotripsy in Terms of Stone Removal and Postoperative Complications", Annals of Punjab Medical College, Vol.14, Issue4, pp.308-312, 2021.

[6] Theresa A. Z., Justin S. A., Bryan W. C., Michael R. B., Barbrina D., Mathew D. S., Jonathan D. H., Adam D. M., "Combined Burst Wave Lithotripsy and Ultrasonic Propulsion for Improved Urinary Stone Fragmentation", Journal of Endourology, Vol.32 Issue 4, pp.344–349, 2018.

[7] Minoru Morita, Jingjing Yang, Zhongwei Jiang, "Study on heat efficiency of scissor-type ultrasonic catheter device", BioMed Research International, Vol. 2021, Article ID 5543520, 15 pages, 2021.

[8] Minoru Morita, Yuichiro Danda, Shunsuke Morikawa, Zhongwei Jiang, "Study on Invitro Evaluation Method of Vascular Coagulation Performance Using Opposite Phase Vibration Ultrasonic Scalpel", International Journal of Engineering Innovation and Management, Vol. 11, Issue 2, pp.22-28, 2021.

[9] Jingjing Yang, Benyang Rong, Lei Wang, Minoru Morita, Guifang Deng, Yifan Jiang, Junbing Qian, "Analysis and structure optimization of scissor-type micro-stirrer with the most effective output performance for thrombus dissolution in interventional therapy", Actuators 2023, 12(2), No.60, pp.1-19, 2023.

[10] Esch, E.; Simmons, W. N.; Sankin, G.; Cocks, H. F.; Preminger, G. M.; Zhong, P. "A simple method for fabricating artificial kidney stones of different physical properties.", Urological Research, Vol.38, pp.315–319, 2010.

[11] Simmons, W.; Cocks, F.; Zhong, P.; Preminger, G. "A composite kidney stone phantom with mechanical properties controllable over the range of human kidney stones.", Journal of the Mechanical Behavior of Biomedical Materials, Vol. 3, Issue 1, Pages 130-133, 2010.

[12] Liu, Y.; Zhong, P., "BegoStone—a new stone for shock wave lithotripsy research", The Journal of the Acoustical Society of America, Vol.112 Issue 4, pp.1265– 1268, 2002.