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Acceleration of Lithotripsy Using Cavitation Bubbles Induced by Second-harmonic Superimposition
高周波重畳法によって生成したキャビテーション気泡を利用した結石破砕治療の高速化

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1. Introduction

Shock Wave Lithotripsy (SWL) has been one of the several first-line treatments for crushing kidney stones. However, SWL suffers from the fact that it tends to produce residual stone fragments too large to flow away through the ureters. Damages of surrounding kidney tissue, apparently caused by cavitation, have also been reported.

High-intensity focused ultrasound (HIFU) is a noninvasive treatment method, in which ultrasound is generated outside the body and its energy is focused on to a target tissue. Around the focal region of HIFU, acoustic cavitation bubbles can be generated because of highly negative pressure by focusing. Ikeda, et al. reported that using the collapse of cavitation bubbles caused by HIFU resulted in the production of small stone fragments from disruption via cavitation erosion.[1] However, the erosion rate of proposed method is significantly lower than SWL.

The control of cavitation bubble behavior is important because the erosion rate may be significantly reduced by ultrasound attenuation due to excessively generated bubbles clouds. Yoshizawa, et al. demonstrated on a surface of aluminium blocks that the behavior of cavitation bubbles and clouds can be controlled by using the peak-positive enhanced (PPE) waves and the peak-negative enhanced (PNE) waves obtained by superimposing the second harmonic to the fundamental.[2] In this study, we tested the PPE-waves and the PNE-waves to control cavitation bubbles behavior at the surface of kidney stone and the erosion rate was measured and compared between these waves.

2. Materials and Methods

2.1 Experimental Setup

Fig. 1 shows a schematic of experimental setup. A 128-channel array transducer was placed in a water tank containing degassed water. The O_2 concentration is controlled to be within 3 or 5 ppm. The geometric focus of the transducer was located on the surface of a model stone, made from cement powder and tap water mixed at the ratio of 10:6 (g:mL). The Vickers hardness of the stones was measured with a 50 *g* load to be 80.6±19.5, which is consistent with the previous measurements of the natural and model stones.[3]

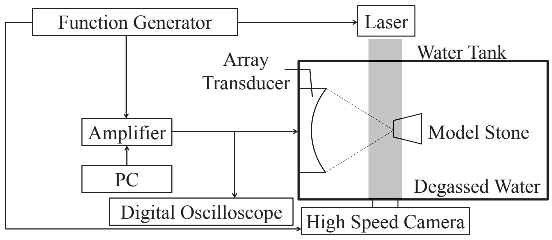

Fig. 1 Schematic of experimental setup

2.2 Waveform and sequence

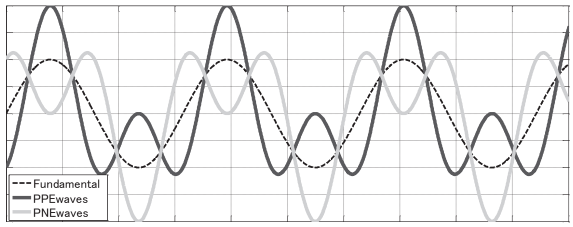

Fig. 2 Waveforms of dual-frequency ultrasound

Fig. 2 shows waveforms of the PNE- and PPE-waves. In this study, 1.6 MHz ultrasound was superimposed on 0.8 MHz ultrasound to generate the PNE- and the PPE-waves. These frequencies were chosen because the power efficiencies of the transducer were similar and reasonably high at the two frequencies. **Fig. 3** shows a schematic of the ultrasound waveform used in the experiments. In order to accelerate the sonication, the focal point of dual-frequency ultrasound pulses were electronically scanned sequentially at each apex of a regular hexagon on the focal plane. Ultrasound was sonicated 20 μs at an intensity of 24 kW/cm^2 at each focal point and ceased for 30 μs before next sonication, to reduce the thermal load on the amplifiers. This results in an overall duration of the

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sequence of 300 μs. The sequence repetition frequency (PRF) was varied by adjusting a rest period between each consecutive sequences. The sequence was repeated for 2 min at a PRF of 0.2, 0.5, 1, 2 and 3 kHz.

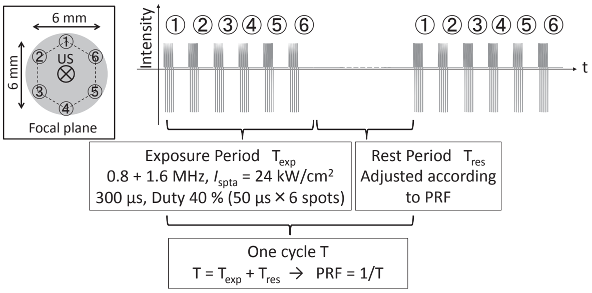

Fig. 3 Schematic of ultrasound sequence

3. Results and discussion

3.1 Erosion rate measurements and high-speed optical images

High-speed optical images near the model stone during exposure with the PNE and PPE waves are shown in **Fig. 4.** With the PPEwaves, cavitation clouds were formed toward the transducer, while with the PNEwaves, cavitation bubbles were generated only on the stone surface. The results indicate that the peak negative pressure of the PNEwaves was enough to generate cavitation bubbles on the stone surface but its peak positive pressure was not enough to form a bubble cloud by shock-scattering.[4] **Fig. 5** shows the stone erosion rate plotted as a function of PRF in the case of eroding model stones. The erosion rate of PNEwaves was higher than that of PPEwaves at all PRFs. From 2 kHz to 3 kHz, the erosion rate was increased in the case of PNEwaves but reduced in the case of PPEwaves apparently because ultrasound was shielded before reaching the stone surface by the cavitation clouds formed and grew toward the transducer. The erosion rate which Ikeda, et al. achieved using HIFU was about 10 mg/min.[1] In addition, the erosion rate of lithotripsy using histotripsy pulces was about 90 mg/min and that using piezoelectric SWL was about 110 mg/min according to the results of Duryea, et al.[5] The erosion rate, achieved by PNEwaves at 3 kHz, of 301 mg/min was higher than these rates from literature by more than 3 times.

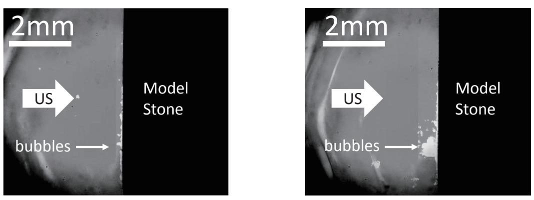

Fig. 4 High speed images of the PNE- and PPE-waves near a model stone

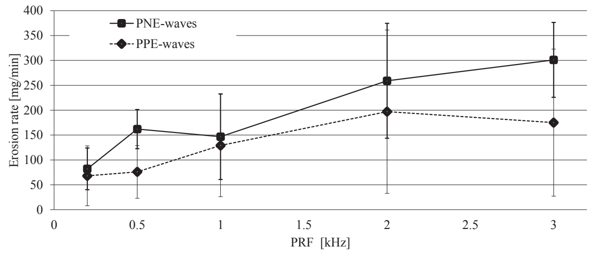

Fig. 5 Erosion rate plotted as a function of PRF

3.2 Size of erosion fragments

Fig. 6 is the distribution of equivalent diameter of erosion fragments. Traditional clinical perspective deems erosion fragments less than 2 mm as clinically insignificant because they are likely to pass through ureters with minimal difficulty.[6] Fig. 6 shows that all fragments were smaller than 2mm.

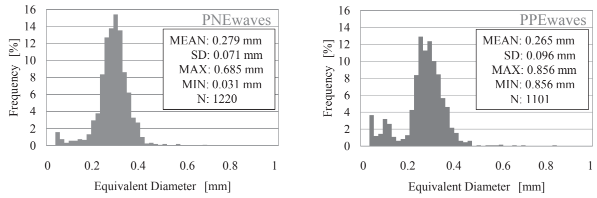

Fig. 6 Size-frequency of a number size distribution of fragments diameter

4. Conclusion

In this study, cavitation bubbles behavior near the surface of a model stone in a focal region were observed by a high speed camera and the erosion rate was measured. With PNEwaves, bubbles were generated only on stone surface and the maximum erosion rate reached approximately 300 mg/min, which is higher than the results of several previous works more than 3 times. In addition, all the fragments was smaller than 2 mm, which will make them pass through ureters naturally. The proposed method may have the potential to significantly improve both speed safety of lithotripsy.

References

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