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Cavitation Inception by Dual-Frequency Excitation in High Intensity Focused Ultrasound Treatment

強力集束超音波治療における周波数重畳照射によるキャビテーション発生

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1. Introduction

There have been reports that ultrasonically induced cavitation bubbles locally enhance the heating in the tissue in High Intensity Focused Ultrasound (HIFU) treatment [1]. In this study field, it is important to create cavitation bubbles reproducibly and efficiently, and control them appropriately for the efficacy and safety of the treatment.

In our previous study, “Triggered HIFU” treatment was suggested [2]. In “Triggered HIFU” treatment, a high intensity burst (named “a triggering pulse”) was irradiated just before the CW ultrasound (named “heating waves”), at an intensity level and with duration, typical for conventional HIFU ablation. By using this method, the acoustic energy of HIFU should be converted to heat efficiently at the cavitation site, and the tissue around the site should be coagulated efficiently. However, it is hard to generate highly negative acoustic pressure over the cavitation threshold by ultrasonic focusing because of the nonlinear propagation of focused ultrasound. Some new method needs to be developed for triggering cavitation efficiently.

It has already been found that acoustic cavitation can be generated efficiently by superimposing the second harmonic onto the fundamental [3]. In this study, cavitation threshold was investigated in the case of dual-frequency exposure with second-harmonic superimposition as well as the case of single frequency exposure using spherically curved PZT transducer.

2. Experimental procedure

An air-backed ultrasound transducer for second-harmonic superimposition consists of two co-focally aligned spherically curved PZT ceramic elements. The outer and inner elements have resonance frequencies of 1.11 and 2.28 MHz and curvature radii of 80 and 72 mm, respectively.

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Fig. 1 shows the experimental setup. Transducer was placed in a PMMA water tank. The focus was located at the surface of the aluminum wall to generate cavitation bubbles. A broadly focused hydrophone was located 20 mm from the HIFU focus to pick up the acoustic emission. The water tank was filled with deionized water. Its DO level was maintained 80-90%. The temperature of the water was kept 23-26°C.

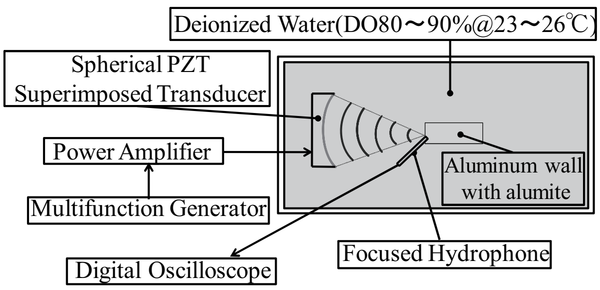

Fig. 1 Schematic of the experimental setup.

Fig. 2 shows that the diagram of the fundamental wave and the sum of the fundamental and second harmonic waves at the focal point. The second harmonic phase emphasizing the negative pressure was obtained by properly tuning the phase relative to the fundamental in the ultrasonic intensity range of 5-6 W/cm^2 using a broad-band hydrophone, and used in the exposure experiments ignoring the potential phase shift due to nonlinear propagation. The fundamental and second-harmonic frequencies of 1.14 and 2.28 MHz, respectively, were used.

Fig. 3 schematically shows the procedure of this experiment. First, a high intensity burst (named “a triggering pulse”) was irradiated for 100 µs. Immediately after the triggering pulse, low intensity CW ultrasound (named “a sustaining pulse”) was irradiated for 10 ms in order to sustain the cavitation for detection. During the sustaining pulse was irradiated, the 1/2 subharmonic signal amplitude in the acoustic emission from the focus was detected and analyzed [4]. Exposure experiments were carried out using a triggering pulse either at a single frequency or with second harmonic superimposition, as shown in Fig. 2. Cavitation threshold was investigated for both cases by varying the triggering pulse intensity from 100 to 13000 W/cm^2 at a fixed sustaining pulse intensity of 12 W/cm^2. The experiments were repeated 5 times at the same condition.

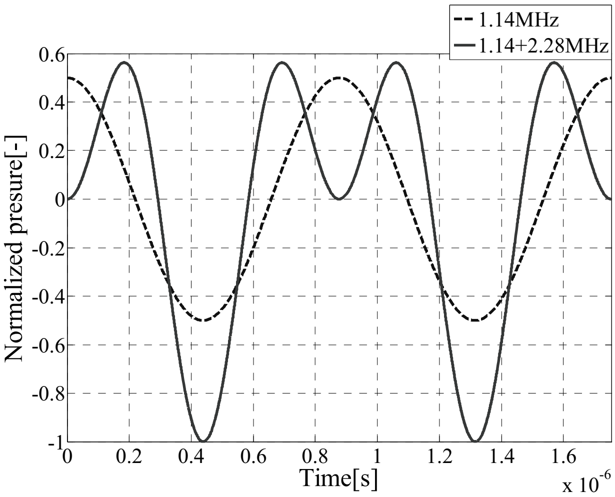

Fig. 2 Diagram of fundamental wave for single frequency exposure and second harmonic superimposed wave for dual-frequency exposure.

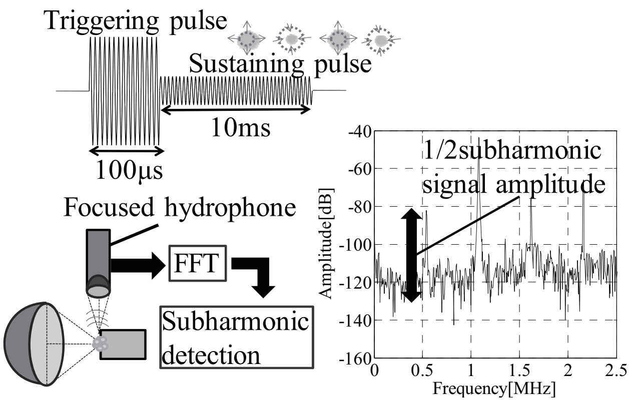

Fig. 3 Schematic of experimental procedure.

3. Results and discussion

Fig. 4 shows the relationship between the intensity of the triggering pulse and the 1/2 subharmonic signal amplitude for both single frequency and dual-frequency exposure experiments. In the single frequency exposure experiment, the 1/2 subharmonic signal was detected for the intensity of the triggering pulse above 3000–4000 W/cm^2. This means that cavitation bubbles were generated above this range of intensity. On the other hand, the 1/2 subharmonic signal was detected for the intensity of the triggering pulse above 1500-2000W/cm^2 in the case of dual-frequency exposure.

The results indicate that the ultrasonic intensity needed to trigger cavitation can be reduced to approximately half by using a triggering pulse with second-harmonic superimposition. The results are consistent with the principle of superposition, in which the same peak pressure can be achieved at a half acoustic intensity by using two harmonic frequencies.

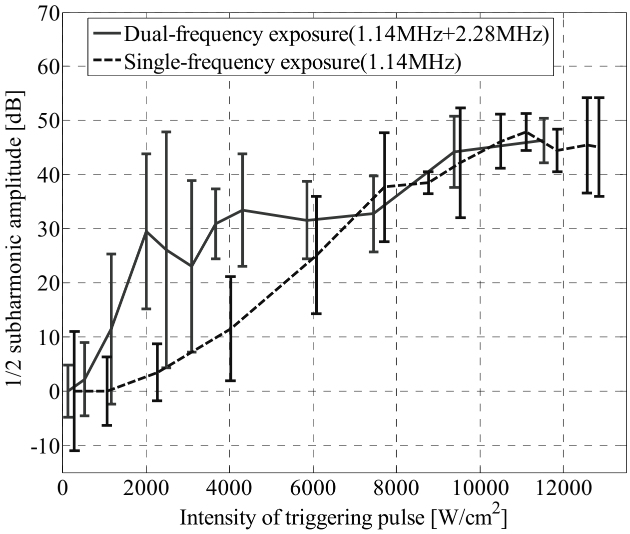

Fig. 4 Relationship between the intensity of triggering pulse and 1/2 subharmonic signal amplitude.

4. Conclusion

In this study, cavitation threshold was investigated in the case of dual-frequency exposure in comparison with single frequency exposure by detecting the subharmonic emission from cavitation bubbles. The experimental results show that cavitation bubbles can be generated more efficiently by superimposing the second-harmonic onto the fundamental.

The second harmonic superimposing method may have a potential to be applied to triggering pulses in the "Triggered HIFU" treatment.

5. References

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