33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

New Approach for Quantitative Measurement of Ultrasonic Cavitation Yields

Si Cheol Noh, Ju Young Kim, Jin Su Kim, Jung Hun Kang, Hong Ki Min, and Heung Ho

Abstract—**In this study, we propose the use of the bubble cloud ellipsoid volume as the quantitative evaluation parameter to monitor the ultrasonic cavitation yield. The bubble cloud ellipsoid volume was calculated by using the bubble cloud image and attenuation characteristics in bubble cloud. The usefulness of this parameter was verified by observing the change in the bubble cloud under various conditions. Under all sonication conditions, the bubble cloud volume was increased in proportion to the rise in sonication intensity (R^2: 0.9283, 0.8817, and 0.9439). On the basis of these results, we consider that the bubble cloud ellipsoid volume is a very useful evaluation parameter for quantitatively assessing the cavitation yield. Furthermore, this new approach may form the foundation of future studies on cavitation applications.**

I. Introduction

Ultrasonic cavitation is the formation and collapse of microbubbles in a high-intensity ultrasonic field. The cavitation effect has non-linear characteristics; the creation and extinction of a single bubble or bubble cloud influence the surrounding environment. In addition, the mass and lifecycle of a bubble are sensitive to the environmental conditions. Consequently, although many studies have been conducted on cavitation, the researches in this field are facing many difficulties.

In order to investigate the effects of cavitation, researchers have focused on aspects such as cavitation yield measurements, lifecycle monitoring, and numerical modeling. In particular, the use of sonoluminescence, sonochemistry, spectrum analysis, image analysis, and acoustic characteristic analysis has been proposed to evaluate the cavitation yield [1-4]. However, sonoluminescence, sonochemistry, and spectrum analysis have some disadvantages because they involve complex and indirect measurement methods. In contrast, image analysis and acoustic characteristic analysis can explain the cavitation yield directly and in a simple manner. In fact, image analysis can describe the real state of a bubble. However, this method gives results with substantial errors, because each image represents a transient state of the bubble distribution during cavitation. In addition, although the acoustic attenuation is a major factor used for describing the nature of cavitation, it cannot be used to explain the overall characteristics of the cavitation yield because it provides only partial data about a bubble cloud.

In this study, we propose the use of the bubble cloud ellipsoid volume as the evaluation parameter to overcome the abovementioned limitations. The use of this parameter can make it possible to measure the cavitation yield quantitatively and accurately.

II. Materials and Methods

A. Reconstruction of Bubble Cloud Ellipsoid

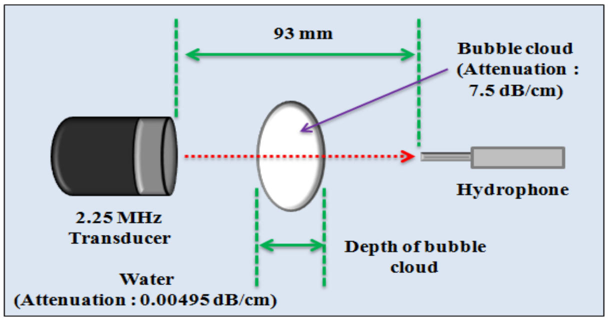
We assumed that the bubble cloud has an ellipsoid form. Based on this hypothesis, the cavitation yield was evaluated by calculating the volume of the bubble cloud ellipsoid under the various sonication conditions. The lateral cross-section of the bubble cloud ellipsoid was calculated using the measured area of the bubble cloud. The depth of the bubble cloud ellipsoid was estimated by the attenuation of the interference wave. After forming a square of the same area as that of the measured bubble cloud, we form an ellipse with the same area and set the minor axis as the side length of the square. In general, the ultrasonic attenuation of the 2.25 MHz frequency is about 0.00495 dB/cm in water, and 7.5 dB/cm in air. Furthermore, the distance between the 2.25 MHz transducer and the hydrophone was measured as 93 mm. We calculated the depth of the bubble cloud ellipsoid under these attenuation and sonication conditions. Figure 1 shows the process of the bubble cloud ellipsoid reconstruction, and figure 2 shows an example of this process (25 mm^2 of bubble area, -2.5 dB/cm of attenuation).

B. Area and Attenuation of Bubble Cloud

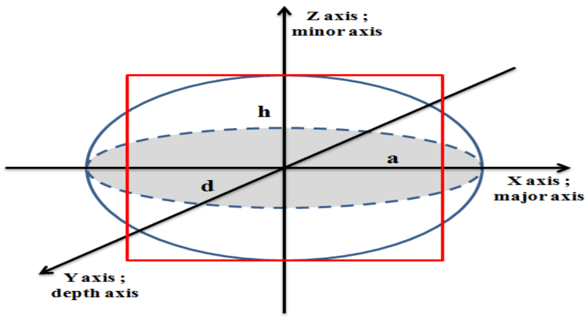
In this study, the bubble cloud image and attenuation characteristics were analyzed in order to calculate the bubble cloud ellipsoid volume. Two concave-type ultrasonic transducers (H-101 and H104 model, Sonic Concepts, USA) for high-intensity focused ultrasound (HIFU) were used to induce cavitation. The center frequency of the transducer was

Manuscript received March 27, 2011. This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MEST) (No. 20090059682).

Si Cheol Noh is with the Dept. of Radiological Science, International University of Korea, Jinju, CO 660759, Korea (e-mail: nscblue@iuk.ac.kr).
Ju Young Kim is with the Dept. of Biomedical Engineering, Inje University, CO 621749, Korea (e-mail: kjy96@bse.inje.ac.kr).
Jin Su Kim is with the Dept. of Biomedical Engineering, Inje University, CO 621749, Korea (kjs03@bse.inje.ac.kr).
Jung Hun Kang is with the Dept. of Biomedical Engineering, Inje University, CO 621749, Korea (e-mail: kjh03@bse.inje.ac.kr).
Hong Ki Min is with the Dept. of Information & Telecommunication Engineering, University of Incheon, CO 406772, Korea (e-mail: hkmin@incheon.ac.kr).
Heung Ho Choi is with the Dept. of Biomedical Engineering, Inje University, CO 621749, Korea (phone: +82-55-320-3639; fax: +82-55-327-3292; e-mail: hhchoi@inje.ac.kr).

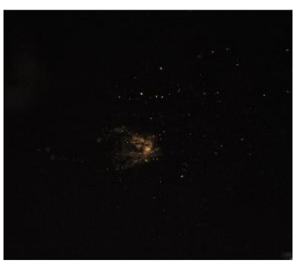


(a) Depth of bubble cloud calculation concept

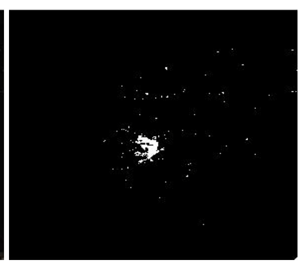


(b) Schematic of ellipsoid volume

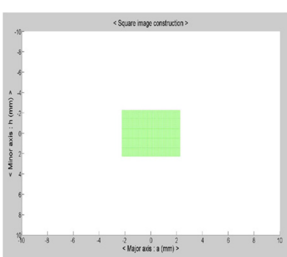
Fig. 1. The concept of bubble cloud ellipsoid reconstruction



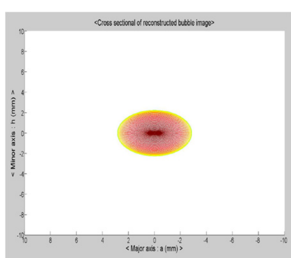
(a) Original image



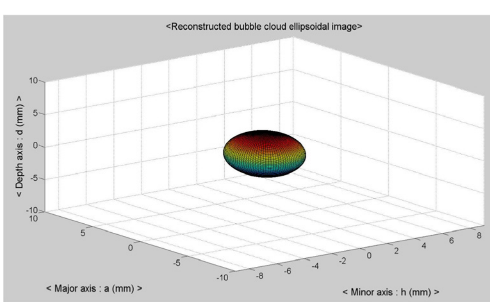
(b) Binary image



(c) Square image



(d) Elliptical image



(e) Reconstructed cloud ellipsoid image

Fig. 2. Bubble cloud ellipsoid construction process

1.1 MHz in the H-101 model and 0.5 MHz in the H-104 model. Each transducer has a diameter of 81.8 mm, and a maximum output power of 400 W, and a geometric focal length of 62.6 mm. The shape of the focal zone has a diameter of 1.26 mm and an axial depth of 11 mm of in the H-101 model, and a diameter of 2.93 mm and an axial depth of 28.3 mm in the H-104 model. The frequency bandwidth is ±250 KHz in H-101 and ±100 KHz in H-104 [5]. The ultrasonic sonication was controlled by a function generator (33220A model, Agilent Technologies, USA) and an RF amplifier (AG1016 model, T&C Power Conversion Inc., USA). The sonication intensity was set in the range of 20 – 100 W using a 3.5 $V_{P\text{-}P}$ burst wave (with 10 cycles and 10 KHz of PRF).

The shape and yield of the bubble cloud were monitored with a digital camera (D90 model, Nikon, Japan, with a maximum resolution of 12.3 million pixels) and two 75 W halogen light sources (75PAR30/FL model, General Electric, USA) with continuous mode. The type of the obtained image was set as an 8 bit JPEG with a 4,288 × 2,048 pixel size. We used an 18–55 mm VR lens and a Nikon Camera Control Pro2 (Nikon, Japan) software to archive the image and control the digital camera. The aperture was set at F4, the shutter speed at 1/4,000 s, and the ISO sensitivity was set at 3,200. Under these conditions, four images were obtained within a second. After converting the acquired image to binary using MATLAB 8.0, the cavitation yield was estimated using the calculated pixel size and count of pixels. The choice of the binarization coefficient is very important in the binarization process. For these reasons, we compared the original image and binarized image with various binarization coefficient. Furthermore we performed the same process with negative image of measured bubble image. By using these results, the binarization coefficient was taken as 0.15 considering the loss of data, the error by the image noise, the focus depth, and the field depth. Figure 3 shows the block diagram for measuring the bubble cloud area.

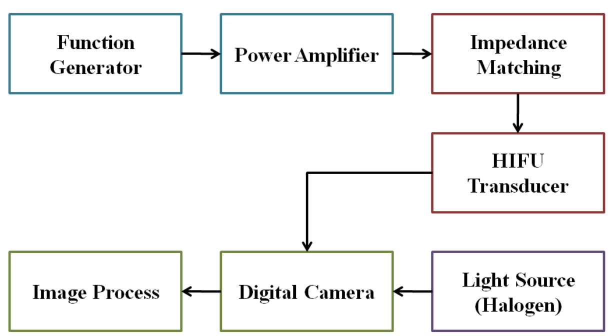


Fig. 3. Block diagram of bubble cloud image acquisition setup

According to the ultrasonic linear theory, the ultrasonic attenuation coefficient and phase transmission speed are sensitive to changes in the fluid [6]. Therefore, the presence or absence of bubbles can have considerable impact on the transmission speed because of the large difference between the inner density of bubble and the density of the medium (water). For these reasons, the acoustic characteristics of the bubble cloud were analyzed by measuring the attenuation in the bubble cloud. First, we cause cavitation using a concave-type single ultrasonic transducer. Subsequently, we transmit the ultrasound beam across the center of the bubble cloud. The transmitted ultrasound is generated by a 2.25 MHz single transducer (AeroTech Co., Netherland, Φ=15 mm) and an ultrasonic pulse/receiver (MKPR-1030 model, MKC KOREA Inc., Korea). The received signal is detected by a hydrophone (NHA-0400 model, ONDA Co. Ltd., USA) and it is stored by a digital oscilloscope (Wave-runner 6100 model, LeCroy, USA) with 10 GS/s. Figure 4 shows the experimental setup for measuring the bubble area and the attenuation characteristics in the bubble cloud. Figure 5 shows the block diagram for measuring the attenuation characteristics in the bubble cloud, and figure 6 shows the transducer alignment for attenuation measurement.

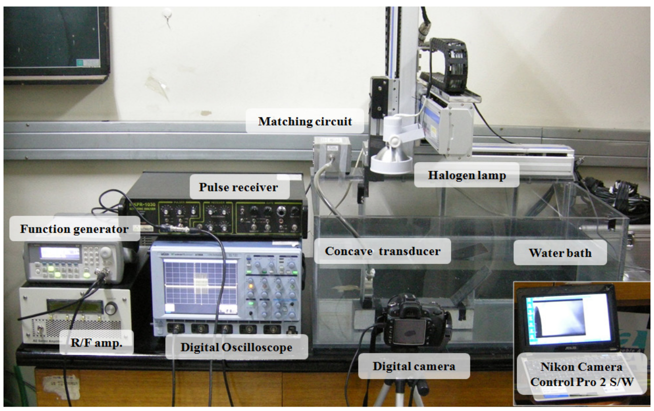


Fig. 4. Experiment setup

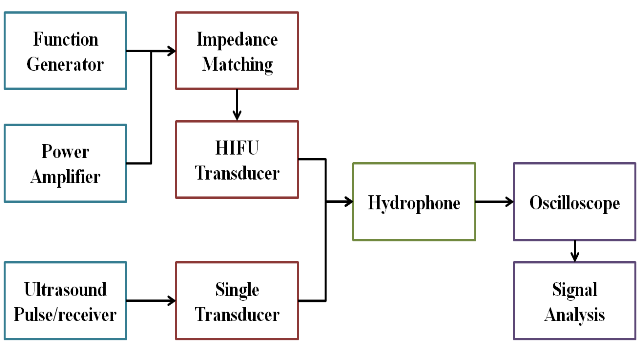


Fig. 5. Block diagram of attenuation measurement setup

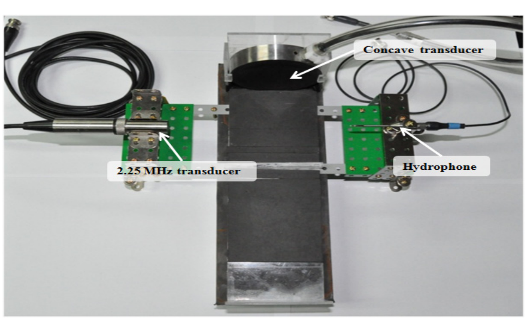


Fig. 6. The transducer alignment for attenuation measurement

III. Result and Discussion

The shape of the generated bubble cloud was assumed to be an ellipsoid. The volume of the reconstructed bubble cloud ellipsoid was measured by the attenuation of the interference wave and the generated bubble areas for each sonication condition.

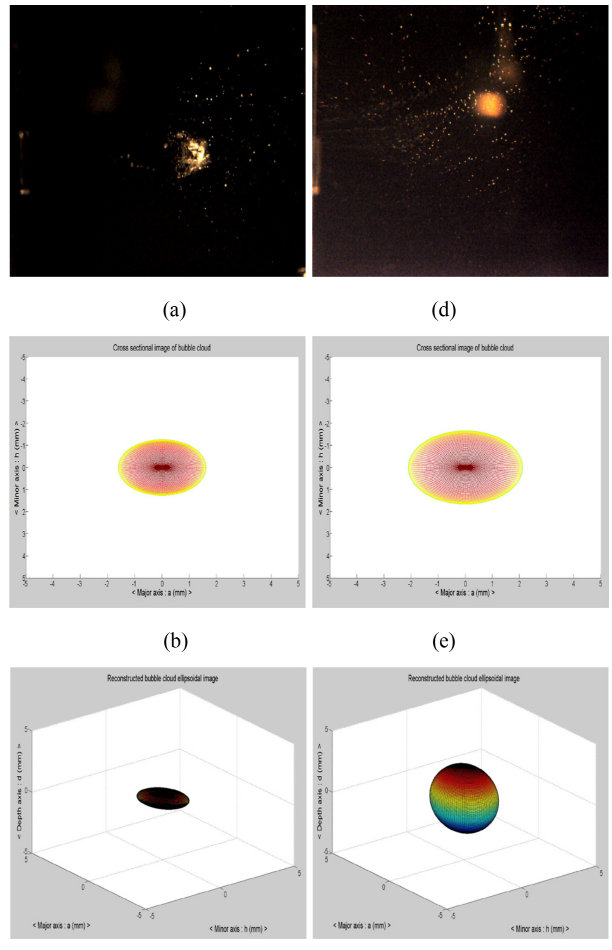


Fig. 7. Bubble cloud ellipsoidal image construction; (a)-(c) 500 KHz 70 W, burst wave, area: 6.45 mm^2, attenuation: -0.24 dB/cm, volume: 1.13 mm^3, (d)-(f) 500 KHz 100 W, square wave, area: 11.03 mm^2, attenuation: -2.03 dB/cm, volume: 19.43 mm^3

Based on the experimental results, the cavitation yield was synthetically estimated under the various sonication conditions. Figure 7 shows the process of the bubble cloud ellipsoid image reconstruction using the bubble image and the attenuation for each condition (500 KHz, 1.1 MHz burst wave, 500 KHz continuous wave)

The measured volumes of the bubble cloud ellipsoid increased with increasing power. When a burst wave and a single concave-type transducer were used, the volume change in the 1.1 MHz burst wave was bigger than that in the 500 kHz burst wave (coefficients of determination: 0.9283 and 0.8817). In the 500 kHz sonication, the volume change in the square wave was bigger than that in the burst wave (coefficients of determination 0.9439 and 0.8817). Figure 8 shows the changes in the bubble cloud ellipsoidal volume at the 500 kHz and 1.1 MHz burst wave. Figure 9 shows the change in bubble cloud ellipsoidal volume in the burst and square waves when the 500 kHz concave-type transducer was used. Figure 10 shows the correlation of the sonication condition and the bubble cloud ellipsoidal volume in each case.

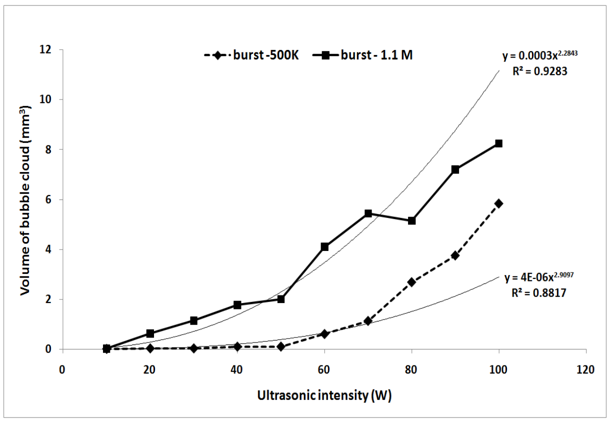


Fig. 8. Bubble cloud ellipsoid volume trend by ultrasonic intensity; 500 KHz, 1.1 MHz burst wave single sonication

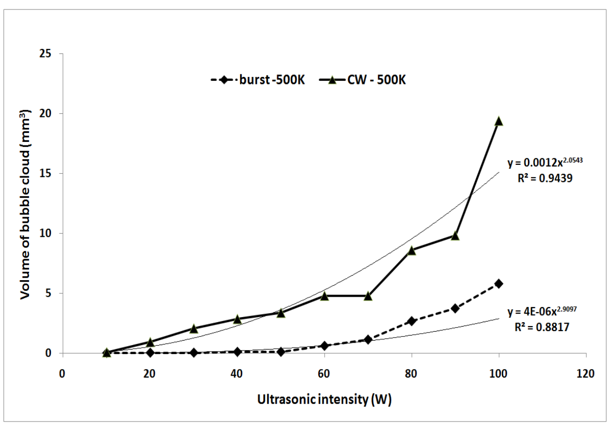


Fig. 9. Bubble cloud ellipsoid volume trend by ultrasonic intensity; burst wave, square wave single sonication

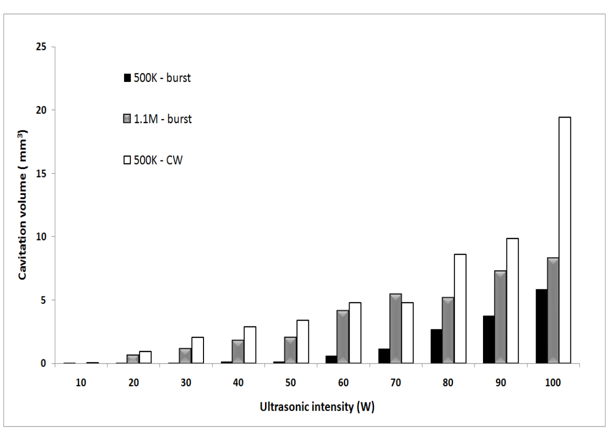


Fig. 10. Bubble cloud ellipsoid volume trend by ultrasonic intensity

IV. CONCLUSION

In this study, the bubble cloud image and attenuation characteristics were analyzed for the evaluation of ultrasonic cavitation. The bubble cloud ellipsoidal volume was presented as a new parameter for evaluating ultrasonic cavitation. The usefulness of this parameter was verified by observing the change in the bubble cloud under various conditions. Under all sonication conditions, the bubble cloud volume increased with an excellent correlation coefficient of 0.9. On the basis of these results, we consider that the bubble cloud ellipsoid volume is a very useful evaluation parameter for quantitatively assessing the cavitation yield. Furthermore, this new approach may form the foundation of future studies on cavitation applications. And as the cavitation effects on the ultrasonic heating of tissue are considered variable, the usefulness of this parameter could be confirmed by verifying the correlation and ultrasonic heating characteristics.

REFERENCES

[1] Christopher E. Brennen, "Cavitation and Bubble Dynamics", New York: Oxford University Press Inc., 2005, pp. 113-133.

[2] E. A. Neppiras, "Acoustic cavitation thresholds and cyclic processes", *Ultrasonics*, vol. 18, pp. 201-209, 1980.

[3] G. Iernetti, P. Ciuti, N.V.Dezhkunov, et al, "Enhancement of high-frequency acoustic cavitation effects by a low-frequency stimulation", *Ultrasonics sonochemistry*, vol. 4, pp. 263-268, 1997.

[4] Ruo Feng, Yiyun Zhao, Changping Zhu, et al, "Enhancement of ultrasonic cavitation yield by multi-frequency sonication", *Ultrasonics sonochemistry*, pp. 231-236, 2002.

[5] http://www.sonicconcepts.com

[6] M. R. Bailey, V. A. Khokhlova, O. A. Sapozhnikov, et al., "Physical Mechanisms of the Therapeutic Effect of Ultrasuond (A Review)", *Acoustic Physics*, vol. 49, pp. 437- 464, 2003.

[7] Ruo Feng, Yiyun Zhao, Changping Zhu, et al, "Enhancement of ultrasonic cavitation yield by multi-frequency sonication", *Ultrasonics sonochemistry*, pp. 231-236, 2002.

[8] B. Krasovitski, H. Kislev, E. Kimmel, "Modeling photothermal and acoustical induced microbubble generation and growth", *Ultrasonics*, vol. 47, pp. 90-101, 2007.

[9] K. Wojs, T. gudra, R. redzicki, "Experimental research into the cavitation noise spectrum in water solutions of high molecular weight polymers", *Ultrasonics*, vol. 44, pp. 350-359, 2006.

[10] Amir H. Barati, Manijhe Mokhtari-Dizaji, Hossein Mozdarani, et al, "Effect of exposure parameters on cavitation induced by low-level dual-frequency ultrasound", *Ultrasonics sonochemistry*, vol. 14, pp. 783-789, 2007.