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Evaluation of Frequency-dependent Ultrasound Attenuation in Transparent Medium Using Focused Shadowgraph Technique

フォーカストシャドウグラフ法による透明媒体中における周波数依存性減衰の評価

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1. Introduction

Ultrasound diagnostic equipment is widely used for noninvasive diagnosis, and various techniques of ultrasound beam forming have been developed to improve image quality. However, sharp beam forming causes a rise in temperature of biological tissue at the beam focus. Evaluation of the pressure distribution in biological tissues with ultrasound attenuation is therefore important [1].

Since a membrane hydrophone can only be used in water, the pressure waveform in biological tissue is estimated by correction of the pressure waveform measured in water considering ultrasound attenuation of a typical biological tissue. However, nonlinear propagation of ultrasound makes it difficult to accurately correct frequency-dependent attenuation of a wide band pulse.

We previously reported a focused shadowgraph technique for visualization of ultrasound fields in water [2]. In this study, the technique was applied for visualization of an ultrasound pulse propagating in a transparent medium with ultrasound attenuation, and the possibility to determine the frequency-dependent attenuation was examined.

2. Materials and methods

Castor oil (034-01586, Wako) was used as a transparent medium with ultrasound attenuation. Figure 1 shows the focused shadowgraph system used in this study. A flat face transducer (V311, Olympus) was used to generate a wideband pulse of 10 MHz in center frequency. Short pulsed laser light (wavelength: 850 nm, pulse width: 5 ns, peak optical power: 1 W) emitted by a laser diode was collimated by a convex lens to illuminate an ultrasound field from a direction perpendicular to that of ultrasound propagation. A CCD camera (BU-51LN, Bitran) placed just behind a water bath was used to capture the light transmitted through the ultrasound field. A stroboscopic imaging technique was used to visualize instantaneous ultrasound fields. The timing of visualization was determined by controlling the delay time from ultrasound irradiation to laser light illumination. Two images were captured in the presence and absence of ultrasound exposure, and sensitive detection of light deflected by the ultrasound field was realized by subtraction of the images.

Figure 2 shows the experimental setup use for hydrophone measurements of ultrasound pressure waveforms attenuated in the castor oil. A membrane hydrophone (HMB-0500, ONDA) was placed at the bottom of the water bath filled with degassed water, and a small container filled with the castor oil was placed over the hydrophone. The container has a 10-mm hole at the bottom, which was covered by a coverslip.

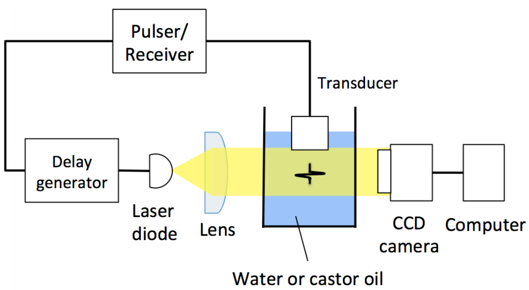


Fig. 1. Observation system of the focused shadowgraph technique.

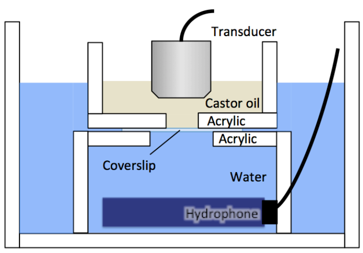


Fig. 2. Experimental setup for hydrophone measurements in castor oil.

The spatial brightness distribution on the ultrasound propagating axis was derived from a visualized field image and converted to a temporal waveform by dividing by the speed of sound. This brightness waveform was then compared with a pressure waveform measured by the hydrophone.

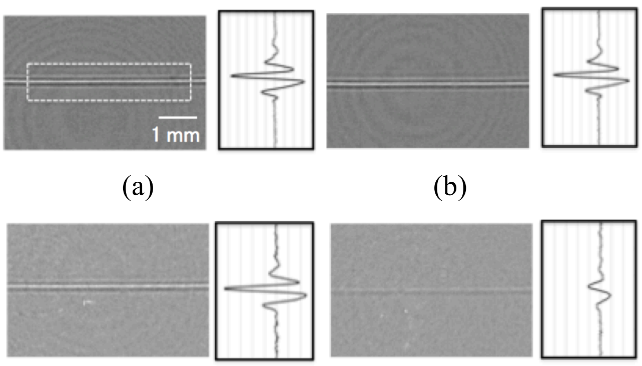
3. Results and discussion

Figures 3(a) and (b) show ultrasound fields visualized after 3- and 8-mm propagation in water, respectively, and Figs. 3(c) and (d) show those after 3- and 8-mm propagation in the castor oil, respectively. The amplitudes of brightness distributions showed no difference in water but showed a 30% decrease in castor oil, indicating that the focused shadowgraph technique can visualize the effects of ultrasound attenuation.

Frequency spectra of the brightness and pressure waveforms after 3- or 8-mm propagation in the castor oil are shown in Figs. 4(a) and (b). Each spectrum shows the average of 16 measurements. In both results, a higher propagation caused longer attenuation at a higher frequency range. The frequency-dependent attenuation curves derived by division of the 3-mm spectrum by the 8-mm spectrum are shown in Figs. 4(a) and (b), indicating that the attenuation of the castor oil in the frequency range of 4−10 MHz linearly increases with an increase in frequency. The attenuation coefficients derived from the brightness waveforms and the pressure waveforms are 4.94 and 5.02 dB/(MHz·cm), respectively, indicating the possibility of using the focused shadowgraph technique for evaluation of attenuation characteristics of a propagating medium.

4. Conclusion

The ultrasound field in the castor oil was visualized using the focused shadowgraph technique. Spectral analysis was carried out on brightness waveforms derived from visualized images and also on pressure waveforms measured by the hydrophone, indicating good agreement of the attenuation coefficients of the castor oil determined by the brightness and pressure waveforms. The results indicate that the technique is useful not only for visualization of ultrasound fields but also for simple evaluation of ultrasound attenuation.



(a) (b)

(c) (d)

Fig. 3. Ultrasound field images visualized using the focused shadowgraph technique: (a) 3 mm in water, (b) 8 mm in water, (c) 3 mm in castor oil and (d) 8 mm in castor oil.

References

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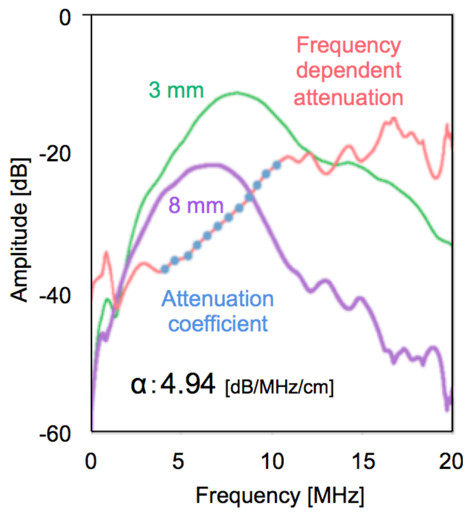
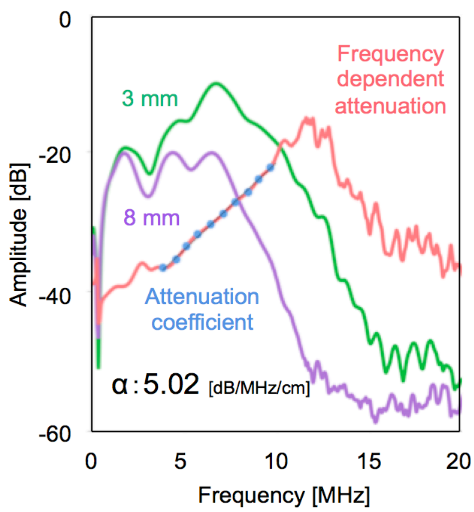
2. Kudo, N. Ultrasound Med. Biol. 41(2015). 2071-2081.



(a)



(b)

Fig. 4. Frequency spectra and frequency-dependent attenuation of brightness and pressure waveforms: (a) brightness waveforms and (b) pressure waveforms.