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A Simple Technique for Evaluation of a High-intensity Focused Ultrasound Field Using Focused Shadowgraphy

フォーカストシャドウグラフを用いた強力集束超音波音場の簡易評価法

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1. Introduction

High-intensity focused ultrasound (HIFU) treatment is a non-invasive technique for ablation of canceous tissues. Volumetric evaluation of a high-intensity pressure region around the focus is important to determine the extent of tissue ablation.

A membrane hydrophone, which is widely used for measurements of diagnostic ultrasound fields, is not suitable for evaluation of HIFU fields because the hydrophone is easily damaged by HIFU irradiation. Optical techniques such as Schlieren and shadowgraphy have been used for HIFU fields; however, it is still difficult because higher inensity causes larger light deflection, resulting in larger distortion of field images.

We previously reported a focused shadowgraph technique designed for visualization of ultrasound fields [1,2], which can reduce image distortion by introducing focusing optics into a shadowgraph system. In this study, the technique was applied for visualization of a HIFU field, and its usefulness was investigated by comparing the profile of a ultrasound beam with that derived using a non-linear simulation of high-intensity ultrasound.

2. Materials and methods

Figure 1 shows the focused shadowgraphy system used in the present study. Short pulsed 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 the ultrasound propagation. A CCD camera (BU-51LN, Bitran) placed just behind a water bath captured the light transmitted through the ultrasound field. To minimize image distortion caused by light deflection, a focus plane of the camera was placed at a distance of 5 mm from the transducer axis to the light source side.

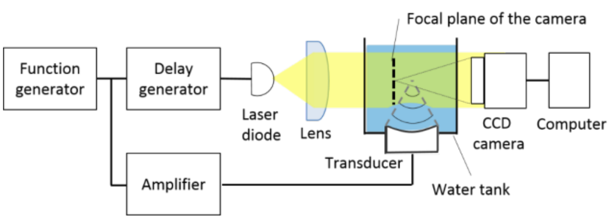

Fig. 1. Experimental system of the focused shadowgraph technique.

A stroboscopic imaging technique was used to visualize instantaneous fields of propagating ultrasound. The timing of visualization was determined by controlling the delay time from ultrasound irradiation to laser light illumination. Two images were taken 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.

A HIFU transducer (inner diameter: 40 mm, outer diameter: 110 mm, focal length: 100 mm, resonant frequency: 1.58 MHz) was driven by a burst pulse of a 20-cycle sinusoidal wave. Electric input power was changed in the range from 10 W to 100 W.

The HIFU field was also evaluated using a simulator developed by FDA [3], which can consider non-linear propagation of high-intensity ultrasound in water. The electromechanical coupling coefficient of the piezoelectric element was set to 0.25, which was determined so that the peak positive and negative pressures measured under the condition of 10 W using a hydrophone (80-0.5-4.0, IMOTEC) would become the same as those determined by the simulation. Acoustic intensity estimated using the electromechanical coupling coefficient of 0.25 was 2500 W/cm^2 under the condition of electric input of 100 W.

3. Results and discussion

A basic Schlieren technique can take a time-averaged field image, which it is convenient for evaluation of a beam profile. In this study, a maximum intensity projection (MIP) method was used to make a similar image using shadowgrams. Ten shadowgrams captured at increasing time-delay settings in steps of 60 ns (λ/10) were used to create the image shown in Fig. 2, which maps p-p value of brightness. In the image, a region with higher brightness indicates higher ultrasound intensity. Convergence of ultrasound to the focus is visualized in the image; however, the first null between main lobe and the side lobe is not clear.

Figure 3 shows a tomography image of the ultrasound beam in the x-y focus plane, which was reconstructed using the filtered back-projection method assuming axisymmetry of the field. The brightness profile determined from the boxed region in Fig. 2 was used for the projection. The brightness of the pixels in the region was averaged in the z direction with a thickness of 0.2 mm, and the profile was smoothed in the y direction using a simple moving average with a window size of 0.5 mm. The main lobe and surrounding first side lobe are clearly separated as shown in Fig. 3.

The brightness profile derived from the MIP image (Fig. 2) and that derived from the reconstructed image (Fig. 3) are compared in Fig. 4 with a pressure profile derived by the simulation. While the average of normalized amplitudes at the two first nulls was 0.40 in the MIP image, those in the reconstructed and simulated profiles were 0.11 and 0.07, respectively. Furthermore, full widths at half-maximum of the main lobe derived from the reconstructed and simulated profiles were 0.75 mm and 0.95 mm, respectively, indicating the usefulness of the focused shadowgraph technique to evaluate a beam width of HIFU fields.

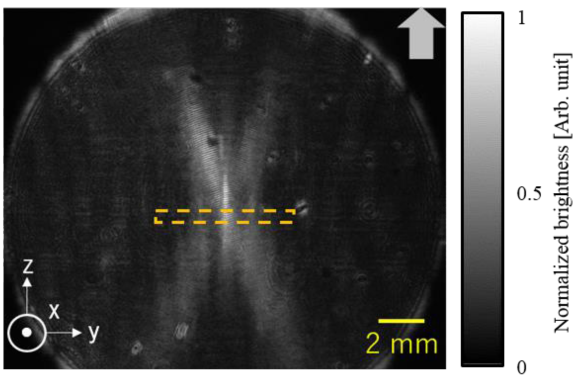

Fig. 2. MIP image of a HIFU field visualized by the focused shadowgraph technique (y-z plane).

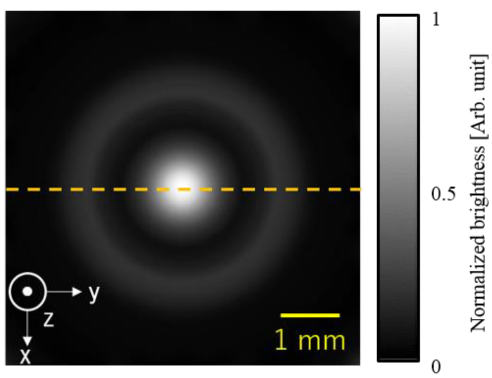

Fig. 3. Tomography image of a HIFU field reconstructed by filtered back projection (x-y plane).

Large image distortion in a shadowgram is emphasized in visualization of HIFU fields; however, good agreement was found between the beam profiles derived by the reconstruction and simulation (Fig. 4). This result indicates the important role of focusing optics in shadowgraphy for minimizing image distortion. This is also important to secure effectiveness of the back-projection algorithm that assumes straight propagation of light.

Even with the focusing optics, tomographic reconstruction was essential for finding the correct profile. This is reasonable since light deflection is integrated over the light path, and a light ray therefore experiences deflection both in the first side lobe and main lobe before incidence on a focus plane of the camera.

4. Conclusion

The HIFU field was visualized using the focused shadowgraph technique. Good agreement was confirmed between the brightness profile derived from the tomography image reconstructed by back projection of focused shadowgram and the pressure profile calculated by nonlinear simulation, indicating applicability of the focused shadowgraph technique for visualization of HIFU fields.

References
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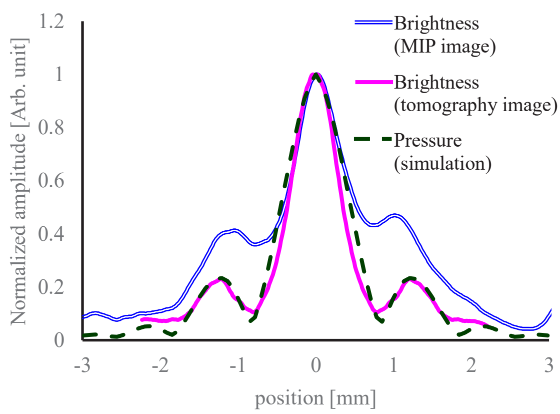

Fig. 4. Brightness profiles in the y-direction evaluated by the focused shadowgraph technique and pressure profile calculated by non-linear simulation.