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Reconstruction of nonlinear ultrasound field of an annular therapeutic array from acoustic holograms of its individual elements

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Acoustic holography method has been shown to provide accurate reconstruction of 3D ultrasound fields generated by various medical transducers including multi-element arrays as well as to set a boundary condition for nonlinear field modeling at high pressure levels. Here an approach of measuring holograms of individual array elements for modeling of an entire array field is proposed and tested for a 3 MHz 16-element annular array (48 mm diameter and 35 mm radius of curvature). The array is a part of a high intensity focused ultrasound system with magnetic resonance guidance used for developing thermal and mechanical methods of tissue ablation in mouse tumors. The holograms measured separately for each array element were combined together to obtain a boundary condition for the array with all operating elements. Modeling results were compared to low-amplitude beam scans and good agreement was demonstrated. Then, nonlinear field simulations were performed at increasing power outputs based on the 3D Westervelt equation. It was shown that the transducer is capable to produce focal waveforms with 140 MPa shock amplitude at 110 W acoustic power and thus is well suited for evaluating shock-based ablation therapies in small animals.

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1. INTRODUCTION

Acoustic holography method has been shown to provide accurate reconstruction of 3D ultrasound fields generated by various medical transducers including multi-element phased arrays.¹ However, multiple holograms should be acquired for reconstructing various focusing configurations of the array fields which can be unpractical. Here an approach of measuring holograms of individual array elements for modeling an entire array field is presented and tested for a 3 MHz annular transducer (Fig. 1a,b). The transducer (16 elements, 48 mm diameter, and 35 mm radius of curvature) is a part of a high intensity focused ultrasound system with magnetic resonance guidance (Image Guided Therapy, Pessac, France) used for evaluation of thermal and mechanical ablation methods in mouse tumors.^{2,3}

The holograms measured separately for each array element were combined together to obtain a boundary condition for the array with all operating elements and simulate its linear 3D field. The results were compared to simulations when the hologram of the entire array was used as a boundary condition and to low-output experimental field scans. At high power outputs, measurements of nonlinear acoustic field generated by such high-frequency strongly focused transducer was technically challenging because of its high frequency, fine spatial structure of the field, small dimensions of the focal lobe, and limited hydrophone bandwidth. Here, nonlinear field simulations based on the 3D Westervelt equation with holographic boundary conditions were performed at increasing power outputs to determine shock-forming conditions and acoustic pressure levels for the system.^{4,5}

2. MATERIALS AND METHODS

A. ACOUSTIC HOLOGRAPHY MEASUREMENTS

2D measurements of acoustic pulses were conducted with a needle hydrophone (0.2 mm active size, Precision Acoustics, Ltd., UK) in the plane xy perpendicular to the array axis and located at the distance z = 15.2 mm from its center (Fig. 1c). Pressure waveforms were measured in a 50x50 mm square field of view using 0.2 mm steps, i.e. a 250 x 250 matrix; pulse duration at each scanning point was 100 µs. Sixteen individual holograms from each array element operating with the same phase as well as the hologram of the entire array with all operating elements were acquired at low power output of the system.

Pressure magnitude and phase then were determined from the acoustic waveform at each scanning point. Spatial spectrum of the field was calculated by performing a 2D spatial Fourier transform and the angular spectrum approach was used for setting two boundary conditions in a plane z = 0 by back-propagating numerically the pressure fields from the scanning plane.^{4,5} Either holography measurements of the entire array or holograms measured separately for each element and combined together were used in these low-power output simulations.¹

To test how different the array elements are operated when being excited either separately or all together, which can be caused by the electronics of the system, a comparison was made of the resulting boundary conditions. Then linear simulations of the pressure field were performed at the array axis and in the focal plane for both cases and validated by the corresponding linear scan measurements.



Figure 1. A photograph (a) and sketch (b) of the array and a diagram of the holography measurements (c).

B. MEASUREMENT-BASED MODELING OF NONLINEAR ARRAY FIELD

Nonlinear field simulations were performed at increasing power outputs of the array based on the 3D Westervelt equation. Numerical solutions were obtained using a previously developed algorithm validated for various high power HIFU transducers.^{4,5} The method of fractional steps with an operator splitting procedure of the second-order accuracy over the propagation distance z was employed. The diffraction operator was calculated for the amplitudes of each harmonic in the waveform spectrum using the angular spectrum method. A Godunov-type shock-capturing scheme was employed for modeling the nonlinear operator. Absorption operator was calculated in the frequency domain using an exact solution for each harmonic. Physical parameters of the propagation medium in simulations were chosen as follows: the sound speed - 1485 m/s, nonlinear parameter - 3.5, density 998 kg/m³, and thermoviscous absorption 4.33 $\cdot 10^6$ m²/s. Shock-forming conditions at the focus as well as maximum achievable pressure levels and shock amplitude were determined.

3. RESULTS

Shown in Fig. 2 are distributions of acoustic pressure magnitude (a, b) and phase (c, d) reconstructed in the plane z = 0 from the combined holograms of the individual elements and from the hologram of the entire array Fig. 2b, d. The distributions are in a good agreement, both showing an annular structure of the array and boundaries between four pieces of the composite ceramics from which the array was assembled (Fig. 2a, b). Small differences can be noticed such as finer spatial structure of the pressure magnitude distribution obtained from the combined holograms. Performance of each array element was therefore not exactly the same when operating alone or together with all other elements. However, these differences did not noticeably affect the array field simulated using these distributions as a boundary condition. Validation of the linear simulations results *versus* measurements is presented in Fig. 3a, b. Modeling results obtained with the two holographic boundary conditions and with nominal parameters of an annular array consisting of ideal rings are compared to the measurements conducted at low power output on the beam axis (Fig. 3a) and in the focal plane (Fig. 3b). The results agree very well, which demonstrates the accuracy of the proposed method and that the array performs in accordance to its nominal parameters.

Focal waveforms simulated based on the Westervelt equation at increasing power level of the array are shown in Fig. 3c. Gradual steepening of the waveform that leads to formation of high amplitude shock fronts is illustrated. Red dashed curve corresponds to the waveform containing a developed shock, which is a characteristic parameter of the system to be used when planning shock-based therapies. Following the definition introduced recently, the shock front is developed when its lower pressure is located at the zero level.⁵ The amplitude of the developed shock here is 140 MPa, which is reached at 110 W acoustic power of the array when focusing in water. Longitudinal and transvers dimensions of the focal region defined at this power at -6 dB are 1.7 and 0.3 mm for the peak positive and 2.6 and 0.6 mm for the peak negative pressure, respectively. According to the nonlinear derating approach, for *in situ* conditions when focusing at specific depths in tissue, the developed shock will form at the array power increased by an amount that in the linear approximation compensates for the attenuation losses over the beam path to the focus.⁶



Figure 2. Comparison of boundary conditions for the pressure magnitude (a, b) and phase (c, d) obtained by combining holograms from individual elements (a, c) and from the hologram of the entire array (b, d).



Figure 3. Pressure magnitude distributions modeled and measured at low power output on the beam axis (a) and in the focal plane (b). Focal waveforms simulated for increasing pressure at the array elements (c).

4. CONCLUSIONS

An approach of measuring acoustic holograms of individual array elements for modeling the entire array field at low and high power outputs is presented and tested for a 3 MHz 16-element highly focused annular array (48 mm diameter and 35 mm radius of curvature) of a preclinical MRgHIFU system. A boundary condition for modeling the array field was set from the holograms obtained either separately for each array element and then combined together or with all elements operating simultaneously. Good agreement was demonstrated between the linear modeling results of the array field and experimental low-amplitude beam scans. Further studies are planned to evaluate the accuracy of the approach when additional phases are applied to the array for electronic steering of the focus along the axis.

Nonlinear simulations based on the 3D Westervelt equation showed that the transducer is capable to produce focal waveforms with 140 MPa shock amplitude at 110 W acoustic power and thus is well suited for evaluating shock-based ablation therapies in small animals.

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