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● *Original Contribution*

QUANTITATIVE ASSESSMENT OF ACOUSTIC INTENSITY IN THE FOCUSED ULTRASOUND FIELD USING HYDROPHONE AND INFRARED IMAGING

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Abstract—With the popularity of ultrasound therapy in clinics, characterization of the acoustic field is important not only to the tolerability and efficiency of ablation, but also for treatment planning. A quantitative method was introduced to assess the intensity distribution of a focused ultrasound beam using a hydrophone and an infrared camera with no prior knowledge of the acoustic and thermal parameters of the absorber or the configuration of the array elements. This method was evaluated in both theoretical simulations and experimental measurements. A three-layer model was developed to calculate the acoustic field in the absorber, the absorbed acoustic energy during the sonication and the consequent temperature elevation. Experiments were carried out to measure the acoustic pressure with the hydrophone and the temperature elevation with the infrared camera. The percentage differences between the derived results and the simulation are <4.1% for on-axis intensity and <21.1% for −6-dB beam width at heating times up to 360 ms in the focal region of three phased-array ultrasound transducers using two different absorbers. The proposed method is an easy, quick and reliable approach to calibrating focused ultrasound transducers with satisfactory accuracy. (E-mail: shenguofeng@sjtu.edu.cn) © 2013 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Acoustic intensity, Focused ultrasound, Infrared imaging, Temperature elevation, Hydrophone, Beam width.**

INTRODUCTION

An emerging medical treatment that uses high-intensity focused ultrasound (HIFU) has been recognized as a potential non-invasive technique for cancer therapy. HIFU has been successfully used to ablate solid tumors within the breast, prostate, pancreas, liver, bone, brain and uterine fibroids in clinical trials (Al-Bataineh et al. 2012; Hynynen 2011; Kennedy et al. 2003; Mason 2011; Ter Haar and Coussios 2007).

Quantitative characterization of the acoustic field is important for the development and pre-clinical validation of HIFU devices, as well as in the planning of clinical procedures. Several techniques have been applied and accepted by national and international standards (GB/T 19890-2005; IEC 62555 Ed. 1.0; IEC 62556 Ed. 1.0). Poly(vinyl difluoride) membrane and needle (Lewin et al. 2005) or fiber-optic (Zhou et al. 2006) membranes with good sensitivity, broad bandwidth and a small active element are used to measure the acoustic pressure waveform, from which acoustic intensity is derived. The acoustic power from the ultrasound transducer can be measured with the radiation force balance. However, it is hard to obtain the value and distribution of the acoustic intensity. Schlieren imaging could characterize the ultrasound beam within minutes by Raman-Nath diffraction of light in water non-invasively without disturbing the acoustic field (Neumann and Ermert 2006). Quantitative acoustic pressure or intensity can be derived after calibration with a hydrophone in the linear acoustic range (Charlebois and Pelton 1995; Schneider and Shung 1996). In recent years, an infrared (IR) camera has been used to measure the temperature elevation at the surface of an absorber, from which the relative distribution as well as the absolute intensity value of the HIFU transducer can be determined (Bobkova et al. 2010; Giridhar et al. 2012; Hand et al. 2009; Myers and Giridhar 2011; Shaw and Hodnett 2008; Shaw and Nunn 2010; Shaw et al. 2011). One of the attractive features of this method is the rapid assessment of 2-D and 3-D ultrasound beams.

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Quantitative assessment is challenging, however, because of the complicated physical phenomena involved in sonication. There are three media in the acoustic wave propagation path (water, absorber, air). Because of the limited transmission of infrared energy through liquid, an air layer should be located between the IR camera and the acoustic absorber. The ultrasound beam will be reflected from the absorber/air interface with nearly equal amplitude but opposite phase with respect to the incident beam. Thus, the net intensity at the interface, but not inside the absorber, is approximately zero. Although the absorber used for IR measurements is thin (usually ~ 2 mm thick), the thermal diffusion of absorbed acoustic energy toward the top should be considered and compensated for (Bobkova et al. 2010; Shaw et al. 2011). The intensity profiles of ultrasound beams under the assumption of a Gaussian shape were derived to further compensate the axial and radial diffusion of heat (Myers and Giridhar 2011). However, there is ~10% error between focal intensities and beam widths determined *via* the IR approach and those determined with hydrophone measurements (Giridhar et al. 2012), which are likewise dependent on the duration of sonication duration. In addition, in the quantitative assessment of acoustic intensities, the acoustic and thermal parameters of the absorbers must be known.

In this study, the distribution of acoustic intensities was determined using a hydrophone and an IR camera, with no prior knowledge of the acoustic and thermal parameters of the absorber or the configuration of the phased-array elements. A three-layer model was developed to calculate the acoustic field in the absorber, the absorbed acoustic energy during the ultrasound exposure and the consequent temperature elevation. An experiment was performed to measure acoustic pressure with a hydrophone and temperature elevation with an IR camera. Then the distribution of acoustic intensities derived with our proposed method was compared with theoretical simulations using three phased-array transducers and two different absorbers at heating times up to 360 ms. The differences between derived and simulated results are <4.1% for axial intensity and <21.1% for −6-dB beam width in the focal region of the ultrasound transducer. The proposed method provides an easy, quick and reliable approach to calibration of focused ultrasound transducers.

METHODS

Acoustic and thermal field in the absorber

When an acoustic absorber is positioned normal to the transducer axis with its anterior and posterior surfacea immersed in de-gassed water and air, respectively, there are three layers of media in the acoustic propagation path, as shown in Figure 1. The temperature at the absorber/air interface is dependent on the acoustic field in the absorber, which is the sum of the waves emitted from interfaces I and II and the properties of the absorber (*i.e.,* dffusivity, conductivity and attenuation) (Fan and Hynynen 1992, 1994; Li et al. 2011).

For a phased-array transducer, each circular piston was divided into finite elements that are typically smaller than one-sixth of the wavelength and can be regarded as point sources. The complex acoustic velocity potential in a homogenous medium is calculated using the Rayleigh-Sommerfeld diffraction integral (Fan and Hynynen 1994; O'Neil 1949)

$$\psi = \sum_{m=1}^{M} u_m \frac{1}{2\pi} \sum_{n=1}^{N} \frac{e^{-jkr_{mn}}}{r_{mn}} S_{mn} \quad (1)$$

where S_{mn} is the area of finite element, N is the number of elements of the mth piston, M is the number of pistons, $u_m = u_0\, e^{j\omega t}$ is the complex particle velocity normal to the surface of the mth piston, $k = 2\,\pi f/c - j\mu$ is the complex wavenumber, f is the frequency, c is the speed of sound in the medium, μ is the attenuation coefficient and r_{mn} is the distance between the point of interest and the source. The particle velocity, u, in the propagation direction is given by the derivative of the velocity potential (Fan and Hynynen 1994)

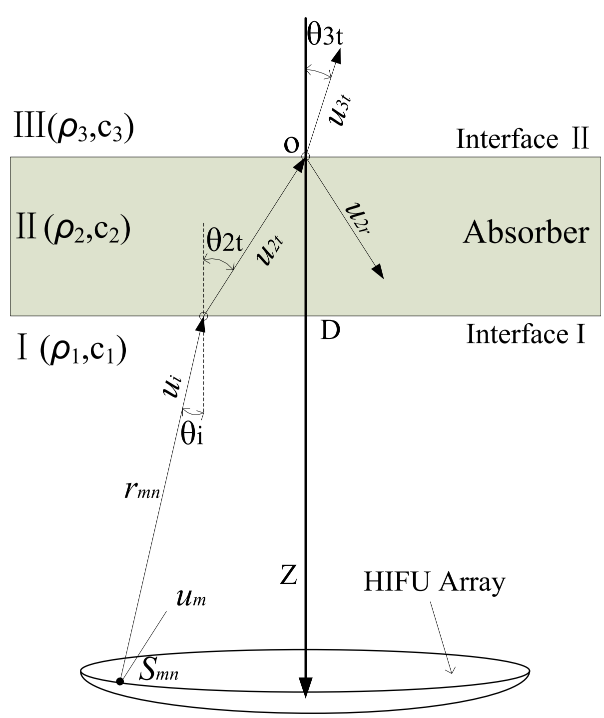

Fig. 1. Schematic drawing of acoustic wave propagation and focusing in a three-layer model (water, absorber, air). HIFU = high-intensity focused ultrasound.