Calibration of HIFU intensity fields measured using an infra-red camera

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Abstract. A trend in HIFU technologies is to use 2D phased arrays that offer electronic steering of a single focus and formation of patterns of multiple foci. Conventional methods to characterize array fields using scanned hydrophone would be prohibitively slow given the potentially large number of focusing conditions. An alternative technique for rapid qualitative assessment of intensity distributions was recently developed [1, 2]. The method is based on infrared camera measurements of the temperature rises induced by low amplitude short ultrasonic bursts in a thin absorber. Here, the method is extended to estimate the absolute values of intensity in a field of a 2D 1-MHz randomized phased array. Two approaches were implemented. In the first approach it was assumed that the measured temperature rise at the surface of the absorber is proportional to the free field intensity. The second approach correlated the temperature rise measured in an absorber and calculated from the modelled acoustic field and the heat transfer equation. Corresponding correction factors between the free field intensity and temperature was obtained and introduced in the conversion of temperature images to intensity. Free field distributions in water and focusing through ribs were recorded and simulated. Good correlation between the measured and modeled results in both spatial distributions and the absolute values of intensity was demonstrated.

1. Introduction

In recent years, there has been considerable interest in using the infrared technique to investigate thermal and acoustical fields of high-intensity focused ultrasound (HIFU) transducers [1-5]. Various other methods can be employed, such as thermocouples, MRI, and ultrasound thermometry, to measure the temperature rise and spatial temperature distribution in excised tissues. However, thermocouples are local and invasive, MRI is expensive, and acoustic methods have poor accuracy and spatial resolution. The infrared method has specific advantages in comparison with these other methods. Ultrasound field mapping in 3D is very slow, with even a single planar raster scan taking typically several hours. In addition, another trend in HIFU technologies is to use 2D phased arrays that offer electronic steering of a
single focus and formation of patterns of multiple foci. Studies of numerous intensity distributions using a scanned hydrophone would be prohibitively slow in this particular situation taking into account the potentially large number of focusing conditions. Moreover, hydrophones that are used for field mapping are expensive and can be damaged in some HIFU fields. An alternative technique for rapid qualitative assessment of intensity distributions was recently developed which enable mapping of the ultrasound field for the time comparable with units or tens seconds [1, 2]. In the present paper, the method was extended to provide estimates of the absolute values of intensity from the measured spatial distributions of temperature.

2. Experimental setup
A schematic diagram of the proposed measurements of intensity distributions is shown in Fig.1. The method is based on IR camera measurements of temperature rises induced in a thin sheet of absorber with known acoustic and thermal parameters by short ultrasonic bursts of 0.1 – 0.3 s duration and relatively low acoustic power of the ultrasound radiator (a few watts acoustic power). The low output regime provided conditions of linear acoustic propagation and less than 50°C temperature rise to avoid damage of the calibrated absorber. Short duration sonication was applied to reduce diffusion effects so that the temperature rise is proportional to the intensity.

IR measurements were carried out using a modified ThermoScope® pulsed thermography system (Thermal Wave Imaging Inc., Ferndale, MI) that included a pulsed light source, a Phoenix MWIR 9705 IR camera (FLIR Systems, Boston, MA), and a PC running EchoTherm® v6.4 software [1]. The ultrasound beam was directed vertically upwards through water onto a thin (1.8 mm thickness) layer of ultrasonic absorber (Aptflex F28, Precision Acoustics, Dorchester, UK) with a single-pass attenuation coefficient of 6 dB at 1 MHz. The reflection on the water/absorber interface was -25 dB. The other side of the absorber was air-backed (fully reflective to ultrasound) and viewed from above by the IR camera. The distance between the IR camera lens and the absorber was 40 cm, the thermal resolution was 5.6 mK. Propagation was either in the free field in water or in the presence of a phantom of ribs between the array and the absorber [2].

A randomized phased array was used as the ultrasound source [1, 6]. The array consisted of 254 circular elements, each of 7 mm in diameter and 1 MHz operational frequency. The elements were distributed on a spherical surface in a quasi-random manner. The minimum centre-to-centre spacing between the elements was 7.9 mm and the largest spacing was 9.4 mm. The radius of curvature of the spherical shell and its diameter were 130 mm and 170 mm, respectively. The array was developed according to the design and parameters described in previous publications [6, 7] and fabricated from piezocomposite material (Imasonic, Voray sur l'Ognon, France).

Acoustic power of the array was measured using the radiation force balance method [1]. Generation and control of RF signals applied to the array elements were provided by a commercially available 256 channel system (Model 500-013, Advanced Surgical Systems, Inc., Tucson, AZ). The operating frequency (1 MHz), phase (0 to 360 degrees in increments of 2.25 degrees), and relative power (8 bit control) of each element of the array were downloaded to the controller from a computer. Phase and power data for each
channel were generated using the theoretical data obtained in the modeling to produce and steer a single focus or create patterns of multiple simultaneous foci [1].

3. Calibration of IR measurement

The infrared method is primarily a relative method, since results are dependent on acoustic frequency and interference due to reflections from the air interface. Nevertheless, it is desirable to estimate intensity values if possible and two methods have been implemented. In the first approach it was assumed that the initial rate of change of IR signal distribution in the measurement plane is proportional to the free-field intensity distribution with some unknown linear coefficient:

\[ \frac{\Delta A_{IR}}{\Delta t} = \beta \cdot I_{water} \]  

(1)

where \( A_{IR} \) is the IR camera signal, \( \beta \) is the unknown coefficient, and \( I_{water} \) is the intensity distribution in the measurement plane. The IR measurements were performed in the plane that was 5 cm below the focal plane. The acoustic power was 11 W, the duration of heating was 0.2 s, all the elements of the array were active and operated in phase to create a single focus in the center of curvature of the array. No ribs were located on the beam path. The temperature distribution was measured at the surface of the absorber facing the IR camera and the power of the IR signal, \( W_{IR} \), which is proportional to the acoustic power, was calculated from the image:

\[ W_{IR} = \sum_i (\Delta A_{IR}^{i}) \cdot dS_i = \beta \Delta t \sum_i (\Delta I_{water}^{i}) \cdot dS_i = \beta \Delta t W. \]  

(2)

Here \( A_{IR}^{i} \) is the amplitude and \( dS_i \) is area of the \( i \)-th pixel in the IR camera image. The dimensions of the image were 256 x 320 pixels with a pixel size 0.43 x 0.43 mm (Fig.2). A value for the product \( (\beta \Delta t) = 80 \) levels per W cm\(^{-2} \) was obtained from IR images (such as Figure 2) using Eq. 2 and the IR images were converted to intensity distribution using Eq. 1. This calibration method includes significant experimental uncertainty because of the noise in the image data and the small number of relatively large pixels in the image which strongly contributed to the integral in Eq.(2). Heat diffusion in the absorber was also not included in the method. Knowing that \( \Delta t = 0.2 \) s and that the thermal resolution was 5.6 mK/level, the coefficient \( \beta \) can be calculated as 400 levels/s (W/cm\(^{-2} \))\(^{-1} \) or, more generally, the sensitivity in this configuration at 1 MHz was 2.2 K/s (W/cm\(^2 \))\(^{-1} \).

To evaluate the effect of diffusion and to validate the hypothesis that the temperature rise is proportional to the intensity, the second approach applied. The approach included three main steps: modelling of temperature rise in the absorber, comparison of the IR measured temperature with modelling, and correlation of modelled and IR measured temperature with free field intensity in water.

The heat transfer equation for the temperature rise \( T \)

\[ \frac{\partial T}{\partial t} = \chi \Delta T + \frac{q(x, y, z)}{\rho c_p} \]  

(3)

was solved in the absorber layer of \( l = 1.8 \) mm thickness whilst

\[ \frac{\partial T}{\partial t} = \chi' \Delta T \]  

(4)
was solved for the temperature rise in the water layer adjacent to the absorber. In the equation (3), \( q(x,y,z) \) is ultrasound induced heat deposition in the absorber, \( \chi_1 = 1.92 \times 10^{-9} \text{ m}^2 \text{s}^{-1} \) is the thermal diffusivity, \( \rho = 1010 \text{ kg m}^{-3} \) is the density and \( C_p = 1800 \text{ J kg}^{-1} \text{K}^{-1} \) is the specific heat capacity of the absorber. In Eq. (4) \( \chi_2 = 1.44 \times 10^{-7} \text{ m}^2 \text{s}^{-1} \). Equations 3 and 4 were solved using a finite difference method [7]; the boundary condition at the absorber/air interface was chosen as \( \partial T/\partial z = 0 \) assuming no heat conduction to the air. The layer of water in calculations was assumed to be thick enough so that no temperature rise, \( T = 0 \), occurs at the outer boundary of the layer. Heat deposition \( q(x,y,z) \) in the absorber, Eq. (3), was calculated using the results of modeling the array field in water, whilst that in water (Eq. (4)) was assumed to be negligible. Reflections from the water/absorber interface were ignored but total reflection from the absorber/air interface was included in modeling the intensity field in the absorber. The acoustic field in the layer thus consisted of the primary and the reflected waves, with absolute values of intensities decreasing in the corresponding direction of propagation due to absorption in the layer, \( I(x,y,z) = I_{\text{water}}(x,y,z)(\exp(-2\alpha z') - \exp(-4a_0 + 2\alpha z')). \) Heat deposition \( q(x,y,z) \) inside the layer was calculated as a combination of the absorption of the primary and the reflected waves: \( q(x,y,z) = -\frac{\partial I(x,y,z)}{\partial z} = 2a_0 I_{\text{water}}(x,y,z)(\exp(-2\alpha z') + \exp(-4a_0 + 2\alpha z')). \) (5)

Here \( \alpha = 346 \text{ m}^{-1} \) is the absorption coefficient in the layer, \( z' = z-F+l \) is the propagation distance inside the layer, \( z' = 0 \) at the water/absorber and \( z' = 1.8 \text{ mm} \) at the absorber/air interfaces. Calculation of temperature rise was performed with and without accounting for diffusion effects during the period of heating \( \Delta t = 0.2 \text{ s} \). If diffusion is negligible, then the energy deposition and temperature rise in the absorber are linearly related and the distribution of temperature rise at the surface of the layer is:

\[
T = \frac{4a_0\Delta t}{\rho C_p} I_{\text{water}}(x,y,F)\exp(-2a_0l) \quad \text{ (6)}
\]

If diffusion is included in the calculations, the intensity distributions are not exactly proportional to the temperature change, but simple corrections to the measured temperature distributions can be made. The results of temperature rise modeling in the focal plane accounting for diffusion were related to those that are proportional to the intensity, Eq. (6), and a corresponding correction factor between the intensity \( I_{\text{water}}(x,y,F) \) and temperature was obtained.

The second method was implemented when the absorber was located in the focal plane \( z = F = 130 \text{ mm} \) and the array operated so that to enable propagation of ultrasound through ribs [4]. The essence of the approach was based on switching off the array elements that are located in front of ribs. Figure 3 shows simulated spatial distributions of temperature rise in the axial plane that is perpendicular to the direction of the ribs. The upper distribution corresponds to calculations without accounting for diffusion, and the lower distribution shows the results of simulations when diffusion was taken into account. The acoustic power in the simulations was 11 W, the duration of heating was 0.2 s, and the number of active array elements was 114. The modeling was made for the case as if the ribs were located (but not physically present) at \( z_0 = 45 \text{ mm} \) from the radiator. The spatial splitting of the focus caused by the periodic spatial structure of the active array elements is seen from this figure.

In both cases, the distribution of temperature rise inside the absorber is not uniform because of the strong absorption in the layer. The temperature is higher close to the surface that is in contact with water and lower in the plane of IR measurements, \( z = F \). If diffusion is neglected, the maximum temperature rise occurs at the water/absorber interface, where intensity is the highest (Fig. 3a). If diffusion is included in the calculations, the heating moves outward from its maximum, some temperature rise in water is observed, and the maximum of temperature is shifted inside the layer (Fig. 3b).
The simulated temperature rise along the transverse y axis at the absorber/air interface is shown in more detail in Fig. 4 and compared with measurements (dots). The results of modeling were obtained without (black curve) and with (red curve) including the diffusion effect in calculations. It is seen that for 0.2 s of heating the peak temperature in the main focal lobe modeled without diffusion (i.e. proportional to intensity) is 13 % higher than the peak temperature modeled with the real diffusion taking place under experimental conditions. The broadening of the main focal lobe due to diffusion is very small for such a short period of time: from 1.40 to 1.47 mm, i.e. only 5%. Here, the width of the lobe is defined at the 1/e level of its maximum. In converting from temperature to intensity this broadening of the beam was neglected and intensity was considered to be proportional to the temperature. However, the correction factor that accounts for 13% lowering of the peak intensity due to diffusion was applied in processing the data. The results of modeling taking the effect of diffusion into account agree well with the measured data within the main focal lobe. Some differences between measured and predicted temperature data can be seen at the side foci (Fig. 4).

The correction factor to convert temperature rise to intensity was defined as the ratio of peak temperatures obtained in simulations without and with accounting for diffusion. If the diffusion is negligible, then free field intensity is related to the temperature rise as in the Eq. (6) (black curve Fig. 4):

\[
I_{\text{water}} = \frac{\rho C_p \cdot \exp(2\alpha t)}{4\alpha} \cdot \frac{T}{\Delta t}.
\]  

(7)

If the 13% difference of peak temperatures referred to above, Fig. 4, is taken into account, then the Eq. (6) is corrected as:

\[
I_{\text{water}} = K \frac{\rho C_p \cdot \exp(2\alpha t)}{4\alpha} \cdot \frac{T}{\Delta t},
\]  

(8)

where the correction coefficient \( K = 1.13 \). The equation (1) used in the first method can be rewritten in the form of Eq. (8) and the correction coefficient \( K \) can be calculated as a combination of known physical parameters and the value of the coefficient \( \beta \). This value of the correction coefficient \( K \) in the first method was found to be 0.9, which is within 20% of the value obtained using the second method, thus providing an independent test of the validity of the second modeling-based approach. In further experiments in the presence of a phantom of ribs, the second method was used to recalculate the temperature rise distribution in IR camera images to the intensity distribution.
4. Correlation of modelled and IR measured intensity distributions

An example of comparing the intensity distributions, modelled, and estimated from the measurements, is shown in Fig.5. The intensity distributions are presented in the focal plane ($z=130$ mm) in the presence of the phantom imitating the rib cage for a single focus at (0, 0, 130 mm): (a) - simulated; (b) - measured by the IR-method; (c) – 1D distributions of the corresponding quantities over the vertical coordinate $y$ perpendicular to the direction of ribs for theory (black) and experiment (red). Measurements were carried out for the acoustic power of 11 W and time of heating of 0.2 s. Theory and experiment are in reasonably good agreement. The discrepancy in the level of intensity may be caused by relatively high noise level in the IR measurements and low precision in positioning of the absorber.

![Intensity distributions in the focal plane in the presence of the phantom of ribs for a single focus positioned at (0, 0, 130 mm): (a) - simulated; (b) - measured by IR-method. (c) – 1D distributions.](image)

Figure 5. Intensity distributions in the focal plane in the presence of the phantom of ribs for a single focus positioned at (0, 0, 130 mm): (a) - simulated; (b) - measured by IR-method. (c) – 1D distributions.

5. Conclusions

Two independent methods to estimate free field intensity distributions from IR camera measurements were proposed and tested in a field of a 2D 1-MHz randomized phased array. Corresponding correction factors between the intensity and temperature were obtained and introduced in the conversion of temperature images to intensity. The results of the two calibration methods were found to agree to within 20% of each other. Good correlation between the measured and modeled results in both spatial distributions and the absolute values of intensity was demonstrated. This suggests that measurement of temperature changes using an IR-camera is a rapid and effective method to obtain spatial distributions and estimates of absolute values of ultrasound intensity in HIFU experiments.

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