Application of ultrasound thermometry technique in case of local HIFU heating of test-object

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Abstract. The present work is aimed at development of a method for estimation of the accuracy of ultrasound thermometry (UST) when applying during local HIFU heating of a tissue-mimicking material (TMM). The method is based on comparison of the ultrasound measurement results with a temperature field reconstructed inside the TMM using data of the infrared (IR) camera surface measurements. In the case presented, the HIFU transducer heated up the TMM by 30 °C for 10 s in the focus area. Ultrasound signals were processed using an in-house UST application software. A 3D temperature field inside the TMM was reconstructed using a method based on the neural network approach. As a result, it has been achieved a good agreement between the UST measurement data and the reconstructed temperature field, especially for the points along the HIFU transducer axis.

1. Introduction

Human internal tissues are exposed to heat to destruct cancerous tumors and treat other diseases. High-intensity focused ultrasound (HIFU) is a non-invasive method of thermal exposure [1]. During focused ultrasound procedures, it is necessary to monitor temperature in real time to prevent overheating of surrounding tissues. Currently, a non-invasive magnetic resonance imaging method is used in conjunction with the HIFU procedure for temperature control [2].

There is an increasing interest in development of another non-invasive method known as ultrasound thermometry (UST). This method is under development in a number of research centers. It is more mobile and cheaper compared with the magnetic resonance imaging. The UST method is based on the temperature dependence of the speed of sound in a medium [3]. Due to this dependence, the ultrasound signal reflected from the heated medium is shifted in depth relative to the signal reflected from the unheated medium. Thus, the shift of the ultrasound signal can be used for calculation of the temperature change.

The UST method is tested on test objects with tissue-mimicking materials (TMM) [4] and on biological objects, such as the liver [5], chicken breast [6], and others. During the tests, the temperature change (increase) obtained with the UST method is compared with reference measurements of the temperature increase carried out with temperature sensors or an infrared camera [7].
The purpose of this work is to explore a possibility of estimating the accuracy of the ultrasound thermometry when applying during local TMM HIFU heating by means of comparing the ultrasound measurements results with a temperature field reconstruction based on the infrared (IR) camera surface measurements.

2. Methods
The TMM temperature field was measured using the UST method on an experimental setup (figure 1), where the TMM was heated locally by a focused-ultrasound transducer with a focal distance of 50 mm and a central frequency of 1.5 MHz. The transducer could provide the material heating up to 50 °C. The TMM, made from agar-agar with the addition of graphite, simulates the density, sound speed, attenuation coefficient, heat capacity and thermal conductivity of biological tissue.

A sample of TMM (1) being a parallelepiped of 80x80x17 mm was installed over the transducer (2) filled with water. The center of the transducer focus was located near the upper surface of the working material.

Figure 1. Experimental setup with HIFU heating: 1 – tissue-mimicking material, 2 - HIFU transducer, 3 - generator, 4 - power supply, 5 - ultrasound diagnostic probe, 6 - ultrasound scanner, 7 - control computer, 8 - infrared camera

An ultrasound diagnostic probe (5) was installed close to the side face of the TMM sample so that its scanning plane was perpendicular to the axis of the HIFU transducer. The linear 80-element ultrasound probe, 20 mm wide, had a central frequency of 6 MHz. The probe scanning plane was located at a depth of 4 mm from the upper surface of the TMM sample. This distance was chosen according to results of a special investigation aimed at evaluation of effects produced by changing the distance from the TMM upper surface to the scanning plane on the ultrasound thermal shift strain. This investigation has shown in particular that at the selected depth of 4 mm, the presence of the TMM surface had almost no effect on the ultrasound probe measurements. The center of the raw ultrasound data recording area (20x10 mm) of the diagnostic probe was always positioned on the HIFU transducer axis.

An ultrasound signal reflected from the TMM in an unheated state was recorded before heating. Then, for 10 s, the HIFU transducer was heating up the TMM by about 30 °C in the focus area. After that, the HIFU transducer was turned off and ultrasound signals were registered during the material cooling phase (over 50 s). Ultrasound signals were not recorded during heating due to disturbances produced by the HIFU transducer.

Ultrasound signals were processed using an in-house application software for the UST [8]. This program calculates the ultrasound signal shift strain \( \varepsilon \) (the derivative of the signal shift in depth), which is related to the temperature change by the following expression:
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\[ \Delta T = K \varepsilon \] (1)

Next, some filtering and smoothing algorithms are applied to the obtained temperature change field.

The tissue-mimicking material K factor that is necessary to recalculate the ultrasound signal shift strain deformation into a temperature change has been previously determined in calibration experiments [8]. According to these experiments \( K = 540 \, ^\circ C \).

An infrared camera, Thermal Expert Q1 (8), was installed above the TMM sample. It has a temperature measurement accuracy of 2 \(^\circ C\), a resolution of 384x288 pixels, and a frame rate of 9 Hz. The TMM sample was fully captured in the camera recording area.

Using data from the temperature surface measurements, the 3D temperature field inside the TMM was reconstructed with a method, based on the neural network approach. This method [9] implies minimization of the functional difference between the surface measurement data and the solution of the unsteady heat-conductivity equation for half-space in the presence of a constant power heat source in the form of an ellipsoid. The task was solved in the Wolfram Mathematica software package. The reconstructed temperature distribution over the plane positioned 4 mm under the TMM upper surface was compared with the UST measurement results for the same plane.

3. Results

Figure 2a illustrates the results of TMM temperature change surface measurements by the infrared camera 10 s after start of the cooling phase (all subsequent figures are also related to this instant). As seen, the temperature change at the focus (the map center) was about 12 \(^\circ C\) at this instant, whereas it reached 30 \(^\circ C\) at stop of the heating. The axial symmetry temperature distribution obtained confirms, in particular, the TMM isotropy. The temperature dependence on the radius has a shape that is close to the Gaussian distribution, this fact was discussed previously in [9].

Figure 2b shows the temperature change surface distribution that followed from the 3D reconstruction with the neural network method. This distribution can be treated as a sort of approximation of the measurement data. At the area of main interest, near the heating center, the approximation has the best accuracy. Figure 2c presents the difference between the measured and approximated temperature change surface distributions. At distances less than 5 mm from the focus center, the difference does not exceed 1 \(^\circ C\). At larger distances, the difference increases and reaches 3 \(^\circ C\) at the periphery of the measured zone.

Figure 3 shows the difference between the neural-network approximated surface temperature distribution and the distribution reconstructed at a depth of 4 mm. The largest difference is observed in the central area, where reduction of the temperature increase reaches 3 \(^\circ C\).

Figure 2. The temperature change on the tissue-mimicking material surface measured (a) by the infrared camera 10 s after stop of the heating, and approximated (b) with the neural network method, as well as the difference (c) between the measured and the approximated distributions.
Figure 3. Difference between the temperature change distributions at the TMM surface and at a depth of 4 mm, as given by the reconstructed 3D field

The measured temperature change distribution at a depth of 4 mm. Here, figure 4a shows the field obtained after application of equation (1) where the shift strain is calculated with the previously described algorithms [8], implemented in the in-house software. Figure 4b presents a map obtained after application of procedures of Gauss filtering and Laplace smoothing (these procedures have been also implemented in the in-house software).

Figure 5 presents the difference between the temperature change distribution measured by the UST method at a depth of 4 mm and the distribution reconstructed at the same depth based on the surface IR measurement data. One can see that in the central area, being of the major interest, the difference is less than 1 °C. However, at the periphery of the measurement area, the difference reaches 4 °C that is of the same order as the temperature increase at this place. It seems that this deficiency of the present realization of the method under development is originated mostly from insufficient quality of the 3D temperature reconstruction at the larger radii, as illustrated in figure 2c.

Figure 4. Results of the UST measurement of the temperature change at a depth of 4 mm: (a) the field obtained after application of equation (1), (b) a smoothed field
Figure 5. Difference between the temperature change measured with the UST method and that reconstructed from the IR surface measurements, plane at a depth of 4 mm

4. Conclusions
The present study has confirmed that it is possible and reasonable to use IR measurements of the TMM surface temperature when developing methods for assessment of the UST method accuracy in case of local HIFU heating. This assessment can be carried out by comparison of the temperature change field measured with the UST method and the temperature change field reconstructed inside the tissue-mimicking material sample based on IR surface measurements.

In the present realization of this approach, difference between the temperature change measured with the UST method and that reconstructed from the IR surface measurements is evaluated as 1 °C, if consider the most heated (up to extra 12 °C) zone, being in fact of the major interest. Far away of the HIFU transducer axis, the difference reaches 4 °C that is of the same order as the temperature increase at this place. It gives a motivation to improve performance of the neural network method suggested in [9] for reconstruction of a 3D temperature change field inside the TMM sample.

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