Ultrasound temperature control during short-term local heating of a test object by focused ultrasound

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Abstract. High Intensity Focused Ultrasound (HIFU) is widely used in modern medicine. One of the important applications is the ablation of internal organ tumors under the HIFU heating. During this procedure, it is necessary to monitor the temperature in healthy adjacent tissues. Ultrasound thermometry (UST) is a promising non-invasive method of temperature control. The paper presents implementation of the UST technique in case of short-term local heating. A new algorithm suggested for ultrasound data processing improves the accuracy of the ultrasound thermometry technique to 2 °C.

1. Introduction

High-intensity focused ultrasound (HIFU) is one of the promising modern therapeutic procedures [1]. The main advantage of this method is the non-invasive heating of internal organs and tissues. The first experimental studies of HIFU began in the 1950s. Now HIFU therapy is widely used to solve various medical problems: in cosmetology, for bleeding stop, Parkinson's disease treatment [2], ablation of internal organs tumors [1].

During the HIFU tumor ablation, the temperature of healthy adjacent tissues is monitored. This is necessary to prevent them from overheating. For monitoring of tissue temperature, various sensors are used, such as thermocouples and fiber-optic sensors [3]. However, they are invasive and, besides, provide only local measurement data. In contrast, magnetic resonance imaging [4] allows measuring the temperature field. This method has high accuracy, but at the same time requires expensive and bulky equipment. Its up-to-date alternative is the ultrasound thermometry (UST) technique [5-7].

The UST method is based on the temperature dependence of the speed of sound in a medium. The latest research is aimed at improving the method accuracy, animals testing [8], and numerical simulations [9].

The paper presents the author's implementation of the UST technique for the case of short-term local heating. The computer program supporting the method operation has been implemented in the HIFU-therapy apparatus "Diater" developed by SPbPU and Shvabe (RostechCorp.). The new ultrasound data processing program includes an additional algorithm for smoothing and approximating UST data. This algorithm is based on an analytical solution for the problem of instantaneous spot heating of a material. The new algorithm testing was carried out with a tissue-mimicking test-object using reference measurements with a thermocouple.
2. Data approximation based on a mathematical model of HIFU heating

Due to the temperature dependence of the speed of sound, a cumulative time delay of the echo signal arises. Let’s Δτ indicate the delay corresponding to the depth z, due to a local change in temperature T. The transition from the temporal to the spatial domain is made by multiplying Δτ by speed of sound c in the medium at its initial temperature: Δτ = cΔτ/2. Thus, the depth-dependent derivative of the shift between the signals obtained at different temperatures characterizes the local changes in the medium temperature: ΔT(z) = Kε, where z is the depth, ε = d(Δd)/dz is the deformation of the echo signal, K is the coefficient, which is found for each material by calibration according to the temperature field model.

In the present work, an algorithm has been developed that receives ultrasound raw RF data at the input, and provides a reconstructed temperature increase field ΔT at the output. The algorithm includes two steps: the weighted average method for calculating the echo shift and a method of approximating the measured temperature increase field by applying an analytical solution of the heat conductivity equation.

The weighted average method previously developed by the authors was successfully tested on slow heating of a test-object with a heated wire [10]. This method is aimed at finding weighted average values of the echo signals at half-periods and at evaluating the depth shift between the corresponding weighted average values. To calculate the deformation of the ultrasound shift, the measurement data are firstly approximated using the arctangent function by the least squares method. Then the echo signal deformation field is calculated by differentiating of the found approximating function. After processing the echo signal deformation field by a median filter and by Laplace smoothing, the deformation field is multiplied by the temperature deformation coefficient of the ultrasound field, K. The result is a temperature increase field that is termed below as the original measured temperature increase field. The detailed description of the algorithm is given in [11].

Let’s describe now the method serving for approximation of the originally measured temperature increase field. This method based on using a solution of the unsteady heat conductivity equation has been developed allows improving the accuracy of the original algorithm. It consists of the following.

The temperature field is described by the equation

$$\frac{\partial T}{\partial t} = a\Delta T + S(t, x, z)$$

where T is temperature, a is thermal diffusivity, S(t, x, z) denotes an axisymmetric source of HIFU-heating, x is coordinate perpendicular to the ultrasound beam, and z is coordinate along the ultrasound beam.

In a cylindrical coordinate system S(t, x, z) = Q(t)exp[−x²/βx]exp[−z²/βz]. As a result, one can express a solution in the following form

$$T(t, x, z) = \int_0^t Q(\tau) \frac{\exp[-x^2/(4a(t-\tau)+\beta_x)]\exp[-z^2/(4a(t-\tau)+\beta_z)]}{\sqrt{4a(t-\tau)+\beta_x}(4a(t-\tau)+\beta_z)} d\tau$$

In case of a short ultrasound pulse, the density of the ultrasound source is expressed through the delta function, Q(t) = qδ(t), then

$$\Delta T(t, x, z) = q \frac{\exp[-x^2/(4at+\beta_x)]\exp[-z^2/(4at+\beta_z)]}{\sqrt{4at+\beta_x}(4at+\beta_z)}$$

To calculate the unknown value of the source density, q, we can use the original measured field of the temperature increase, rewriting equation (3) as:
\[ q = \Delta T_{mc}(t,x,z) / \left( \frac{\exp[-x^2 / (4at + \beta_x)]\exp[-z^2 / (4at + \beta_z)]}{\sqrt{4at + \beta_x} (4at + \beta_z)} \right). \quad (4) \]

In the developed algorithm, reconstruction of the initially unknown \( q \)-value is carried out using the found original temperature increase values at points \( x_i \) (\( i = 1 \ldots N_x \), where \( N_x \) is the number of rays) on the center line \( z = z_0 = 0 \) for several time instances \( t_k \) at the phase of material cooling \( (k = 1 \ldots N_k) \), where \( N_k \) is the number of processed ultrasound files: \[ q = \frac{1}{N_x N_k} \sum_{k=1}^{N_k} \sum_{i=1}^{N_x} \Delta T_{mc}(t_k,x_i,z_0) / \left( \frac{\exp[-x_i^2 / (4at_k + \beta_x)]\exp[-z_0^2 / (4at_k + \beta_z)]}{\sqrt{4at_k + \beta_x} (4at_k + \beta_z)} \right). \quad (5) \]

As a result, substitution of the \( q \) value given by (5) into analytical expression (3), produces an approximation function for final evaluation of the temperature increase field:

\[ \Delta T(t,x,z) = q \exp[-x^2 / (4at + \beta_x)]\exp[-z^2 / (4at + \beta_z)] / \sqrt{4at + \beta_x} (4at + \beta_z). \quad (6) \]

The constants \( \beta_x \) and \( \beta_z \) are established empirically. In particular, in case of using tissue mimicking material and HIFU apparatus described in Section 3, \( a = 0.13 \text{ mm}^2 / \text{s} \), \( \beta_x = 3 \text{ mm} \), \( \beta_z = 25 \text{ mm} \).

The algorithm presented has been implemented in the ultrasound thermometry program. The program is written in C++ in Visual Studio 2007 and works with ultrasound data recording window of 20 x 20 mm. The ultrasound data file from the recording window contains 26 beams and 575 samples per beams (for the used phased array ultrasound probe).

To calculate the temperature increase, the UST program needs a set of input data including the temperature deformation coefficient of the ultrasound field, \( K \), for the measured material, the frequency of ultrasound files processing and the time instance from the end of the heating, where the ultrasound recording is performed.

3. Ultrasound thermometry testing facility and technique

Testing of the new UST program was carried out with a tissue-mimicking test-object (figure 1). 128-element transducer H-302 (Sonic-Concepts) (1) creates a short-term heating of the tissue-mimicking material (TMM) in the focus area (2). TMM is made of agar-agar with graphite. Heating for 250 ms with ultrasound intensity in the focus area of 40 kW/cm² can provide a temperature increase in TMM (3) to 70 °C. Ultrasound scanning of the heating area was performed by a phased US probe (4), which was installed in the transducer (5) central hole. During measurements, the probe was located at a distance of 70 mm from the focus center. US probe operating frequency is 3.5 MHz. Thermocouple (6) B57560G1 (NTC) of \( D = 1 \text{ mm} \) was installed in the TMM for the reference measurements.
Figure 1. Ultrasound thermometry testing facility:
1 – multi-element HIFU transducer H-302, 2 – focus area, 3 - tissue-mimicking material, 4 – ultrasound diagnostic probe MC4-2R20N at measuring position, 5 – water filled cone, 6 – thermocouple B57560G1, 7 - HIFU-therapy device Diater

US transducer heated the TMM in the focus area for 250 ms. The focus area center was located at a 20 mm distance from the TMM upper surface. US signals were not recorded during heating to avoid interference from the transducer. The US probe was located outside the water-filled cone. After heating, the US probe was lowered to the working position and US data recording was started from 15 s to 5 min. The center of the US data recording window 20x20 mm (ROI) was located at a 70 mm distance from the US probe and was coincided with the focus center. The thermocouple measured the temperature during and after heating at the depth of the focus area center and at the 3 mm distance from the transducer axis. The thermocouple position was determined by the B-mode image.

Recorded US data were processed using the new UST program algorithm. The temperature increase field was calculated for the entire US recording window. The calculated temperature increase was compared with the reference thermocouple measurements to evaluate the algorithm accuracy.

4. Test results
Shown in figure 2, results of applying the developed temperature increase approximation method demonstrate the features of filtering random splashes.

Figure 3 illustrates the temperature increase fields calculated with the new UST program. The temperature increase field approximation is presents at instances of 5, 10 and 15 s after pulse heating. The fields show an ellipsoidal shape of the heated area, which center is coincided with the window center. A rapid temperature decrease after heating is illustrated as well: the temperature in the area center decreases by 15 °C in the time interval from 5 to 10 s. Besides, the heated area expands and becomes more rounded. The point of thermocouple measurements is marked in the fields by a black dot.
Comparison of the UST results and thermocouple measurements at a distance of 3 mm from the heated center is shown in figure 4. The time is counted from the end of heating. Data is averaged over five measurements. The greatest deviation of the results is observed for the instant immediately after heating. It may be due to the thermocouple setting accuracy (± 0.5 mm) and/or directly to UST algorithm errors at the initial time instance. In fact, there is a delay before US measurements made after heating due to the US probe movement from the transducer housing. After 5 s from the end of heating the difference between the UST measurements and thermocouple data is about 2 °C and it decreases during cooling time.

Figure 2. UST calculated temperature increase fields in the HIFU-heated tissue-mimicking material (40 s after heating): before (a) and after (b) approximation

Figure 3. UST calculated temperature increase fields in the HIFU-heated tissue-mimicking material: at 5 s (a), 10s (b), 15 s (c) after heating, black point - thermocouple location
5. Conclusions
A new algorithm of US data approximation to be applied for ultrasound thermometry technique in case of short-term local heating is presented. The algorithm is based on using an analytical solution of the unsteady heat conductivity equation at spot heating.

The technique was tested with a facility supplied by a multi-element HIFU-transducer for heating of tissue-mimicking material. This powerful transducer created short-term heating in the local area. The temperature change in the focus area was close to values used for HIFU-therapy in the clinic. During testing performed for comparison of UST results with reference thermocouple measurements, the errors of the ultrasound thermometry technique did not exceed 2°C.

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