EDITORIAL

A Review of Ultrasound Thermometry Techniques

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Abstract

Acoustic thermometry is one of non-invasive methods to measure the temperature inside tissue area. Especially, when using the thermal therapy techniques such as High Intensity Focused Ultrasound (HIFU) and other thermal based methods, thermal assessment of heated area seems to be necessary. Some of acoustic properties of medium are temperature dependent; therefore, evaluation of temperature dependent parameters will be an indirect and non-invasive approach in thermometry. In this paper some of thermometry methods based on changes in acoustic properties of medium have been reviewed. The published methods are classified in two main categories: passive and active thermometry. In the passive thermometry, the thermal measurement probes, induced no acoustic signals to the medium, but they receive the radiated signals from the heated medium. In active method, the thermometry probe transmits a signal into the heated region and receives the echoes, then the received RF signals are processed in order to measure the temperature.

1. Introduction

Ultrasound-Based thermometry methods are divided into two main categories: Active and passive. In active thermometry, the ultrasound probe transmits an acoustic wave to the heated region, and then the echo signals are received. Afterwards, proper RF data processing methods can be applied to extract the desired temperature dependent parameter. In this review the published studies in active thermometry are classified in five groups based on the mentioned parameters. Beside the active methods, the passive ones are another field of studies. In this approach, the radiated signals from heated region are acquired when the thermometry probes transmit no acoustic signals to the region. Therefore, the radiated signal contains the thermal information. The block diagram of Thermometry methods is shown in Figure 1.

2. Materials and Methods

2.1. Active Thermometry

As it is mentioned we categorized the active thermometry methods into five groups employing speckle tracking and the methods based on measuring changes in backscattered energy, changes in statistical properties of medium, changes in non-linear parameter of medium, and change in attenuation parameter are described in this section as follows.

1) Echo shift or speckle tracking methods: The focus of these methods is on the local changes of speed of sound and thermal expansion of medium due to heating. The basic idea behind these studies is the difference between time delays of echo signals received from scatters. The speed of sound is temperature dependent and the mentioned time delay is a function of sound speed. As mentioned in [1], the echo shifts or speckle tracking methods refer to the change in sound speed due to temperature changes. According to the [1], the echo shift methods are sensitive to body motion when using the method in-vivo. Another drawback of using the speckle tracking methods is the inhomogeneity of medium. Sharp temperature gradients as the effect of acoustic lens is another difficulty of the echo shift methods [1].

$$t(z) = 2 \int_0^z \frac{d\xi}{c(\xi, \theta(\xi))} \tag{1}$$

$$\theta(\xi) = \theta_0 + \delta\theta(\xi) \tag{2}$$

In Equation 2, $\theta(\xi)$ is the temperature at depth of ξ and θ_0 is the initial temperature of medium before heating. If the substituted by $(1+\alpha(\xi)\delta\theta(\xi))d\xi$, $t(z)$ will be changed into:

$$t(z) = 2 \int_0^z \frac{(1 + \alpha(\xi)\delta\theta(\xi))d\xi}{c(\xi, \theta(\xi))} \tag{3}$$

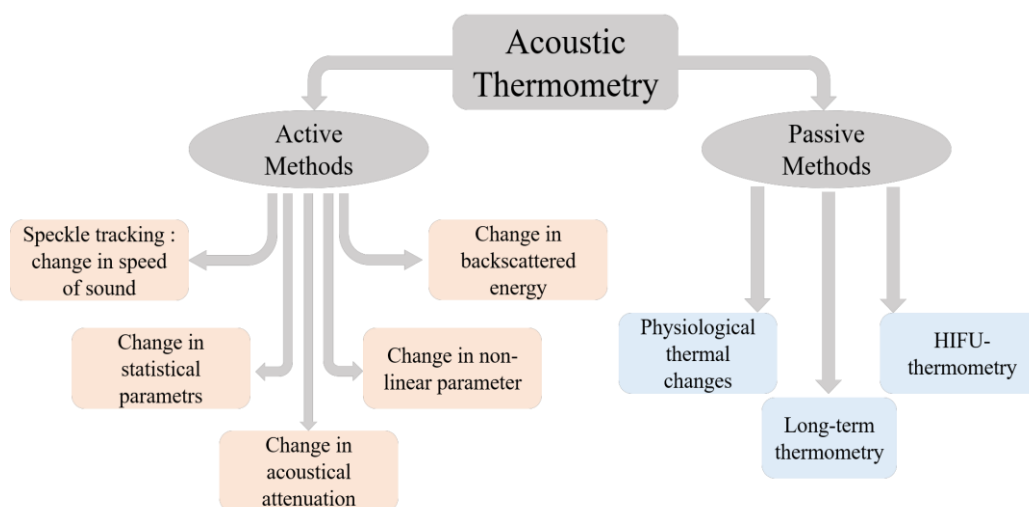The time delay of echo in initial time t_0 is as Equation 4.

Figure 1. The block diagram of thermometry methods

$$t_0(z) = 2\int_0^z \frac{d\xi}{c(\xi, \theta_0)} \tag{4}$$

$$\delta t(z) = t(z) - t_0(z)$$
$$= 2\int_0^z \frac{\left(1 + \alpha(\xi)\delta\theta(\xi)\right)d\xi}{c\left(\xi, \theta(\xi)\right)}$$
$$- 2\int_0^z \frac{d\xi}{c\left(\xi, \theta(\xi)\right)} \tag{5}$$

$$\frac{\partial}{\partial z}\left(\delta t(z)\right) = 2\left[\frac{1 + \alpha(z)\delta\theta(z)}{c(z, \theta(z))} - \frac{1}{c(z, \theta_0)}\right] \tag{6}$$

$$c(z, \theta(z)) = c_0(z)(1 + \beta(z)\delta\theta(z) \tag{7}$$

$$\delta\theta(z) = \frac{c_0(z)}{2}\left(\frac{1}{\alpha(z) - \beta(z)}\right)\frac{\partial}{\partial z}\left(\delta t(z)\right) \tag{8}$$

Using an analytical model can be useful to figure out the relation between temperature and sound speed changes. Authors in [2] derived this relation. They find that during temperature changes the behavior of echo shifts will be linear. Consequently, the results show that the distribution of echo shifts is a function of temperature distribution. The feasibility of temperature prediction using time delay of echo signal is reported in [2]. In this study the authors tried to predict the temperature distribution in turkey muscle during HIFU exposure. In the experiments the HIFU exposure was removed during temperature estimation. In [1] the echo shifts in the consecutive frames are estimated using cross correlation method. The axial derivation of the echo shifts is proportional to the thermal change. In this study, to suppress the ripples due to the lens effect, Axial and lateral filtering is applied. The accuracy of method in tissue mimicking phantom is 0.5°C and the spatial resolution is 2mm.

In another study authors use the axial displacement data to extract the temperature [3]. The cross-correlation algorithm is applied to digital sonographic images. The average error of temperature estimation is 0.5°C with the standard deviation of 0.19°C.

Another echo shift method is reported in [4]. In this study the echo shifts are considered as the changing in signal phase during heating process. The zero crossing method is applied to estimate the local instantaneous frequency. The computational efficiency of method is six fold better than the cross-correlation based methods.

Combining both zero-crossing method and cross-correlation in [5] improves the accuracy of thermal estimation. The computational efficiency is similar to fast cross correlation algorithm. Bayat *et al*. proposed a new model for echo shift method based on a recursive filtering method that spatially differentiates and integrates the echo shifts [6]. In this study the authors applied an adaptive filter for motion compensation. As mentioned before, the drawback of echo shift methods is the ripples due to the acoustic lens, but using the proposed method in-vivo shows better suppression of the ripples. Other active thermometry methods based on the echo shifts or speckle tracking are reported in [7-14].

2) Change in backscattered energy (CBE-based methods): Backscattered energy is another temperature dependent acoustical parameter that is considered in thermometry methods. In [15] the authors developed an expression for the average backscattered energy of the scatterers, which are randomly distributed in a small volume. According to [15,16] the C B E value in the temperature θ is as Equation 9:

$$CBE(\theta)$$
$$= \frac{\alpha(\theta_R)}{\alpha(\theta)}\frac{\varepsilon(\theta_R)}{\varepsilon(\theta)}\frac{(1 - e^{-2\alpha(\theta)Z})}{(1 - e^{-2\alpha(\theta_R)Z})} \tag{9}$$

$$\frac{\varepsilon(\theta)}{\varepsilon(\theta_R)}$$
$$= \frac{\frac{\rho_m c(\theta)^2{}_m - \rho_s c(\theta)^2{}_s}{\rho_s c(\theta)^2{}_s} + \frac{1}{3}\left(\frac{3\rho_s - 3\rho_m}{2\rho_s + \rho_m}\right)^2}{\frac{\rho_m (c(\theta_R)^2{}_m - \rho_s c(\theta_R)^2{}_s}{\rho_s c(\theta_R)^2{}_s} + \frac{1}{3}\left(\frac{3\rho_s - 3\rho_m}{2\rho_s + \rho_m}\right)^2} \tag{10}$$

Where in Equation 9, α and ε are acoustic attenuation and backscattering coefficient of the medium, respectively. θ_R is the reference temperature of medium and z is the scattering depth. The ratio of backscattering coefficient can be approximated as a function of sound speed c and density ρ [15,16].

In Equation 10 the subscripts s and m denote the scattered and the medium, respectively. In [16] the authors used CBE method to estimate the temperature distribution for multiple scattering region and single scatterer. The experimental results show that the proposed method can be used in tissue medium with inhomogeneities. Using proposed method, the prior knowledge about the speed of sound as a temperature

dependent parameter is not necessary. In another study [17], authors used the cross correlation algorithm for motion compensation and displacement tracking. Temperature estimation using CBE along with the motion compensation method is in a good agreement with theoretical findings. Authors in [18] used the CBE method for 30 estimation of temperature in motion compensated images. The estimation error is below 0.53°C. Temperature estimation without motion compensation is reported in [19]. The results demonstrate that the motion compensation is not necessary for temperature estimation using CBE method.

Since the conventional CBE based methods do not have acceptable performance in temperature estimation, Jingjing Xia *et al.* proposed a new approach in [20]. In this paper, polynomial approximation of CBE combined the sliding window is proposed. The square windowing is applied to the envelope image. The suggested approach can overcome the difficulties of conventional CBE in non-uniform heating. Using the polynomial approximation results in the better Contrast to Noise (CNR) than CBE images.

3) Change in statistical properties of medium: As mentioned in previous section, the backscattering of ultrasound wave is a random process and the probability distribution of backscattering signal is temperature dependent. Therefore, by fitting an appropriate distribution to the histogram of backscattered signal, thermal changes can be extracted [21].

Some of the used distributions in published studies are as follows. Rayleigh distribution: The Probability Density Function (PDF) of Rayleigh distribution is [21]:

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{-\left(\frac{x}{\sqrt{2}\sigma}\right)^2}, x \geq 0 \quad (11)$$

Nakagami distribution: The PDF of Nakagami distribution is [21]:

$$f(x;m,\Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} x^{2m-1}; x \geq 0, m \geq \frac{1}{2},$$
$$\Omega > 0 \quad (12)$$

K-distribution: The PDF of K-distribution is [21]:

$$f(x;k) = \frac{4x^\alpha}{(2\sigma^2)^{\frac{\alpha+1}{2}}\Gamma(\alpha)} k_{\alpha-1}\left(\sqrt{\frac{2}{\sigma^2}}x\right) \quad (13)$$

In Equation 11 to 13, σ_m, and Γ are scale parameter, shape parameter and Euler Gamma function, respectively. α and K are shape parameter and modified Bessel function, respectively.

In [22], Bayra *et al.* used non-parametric statistics for temperature visualization. They used the two types of distances contain: Kolmogorov Smirnov distance and Kulback-Leiber divergence. With these criteria the distance and divergence between the statistical distribution of RF signals amplitudes in two different temperature can be calculated. The heating and cooling rate is similar and the accuracy is up to 3%.

Since the envelope of Rf signals are random distributions, in [21], authors propose three types of distributions and according to the two different criteria (mean square error and shape parameter), the k-distribution is in better agreement with the distribution of Rf signal envelopes. The authors claim that the shape parameter of k-distribution can be used as a thermometer. In [21], the ratio of change in Nakagami parameter as a matrix is obtained and the polynomial approximation is applied to the absolute value of matrix. The obtained images using the proposed method can be suitable to obtain the thermal distribution contour.

4) Change in non-linear parameter of medium: The non-linearity of medium as described in wave equations is another temperature dependent parameter that itself is a function of sound speed. As mentioned in [23], the non-linear parameter $\frac{B}{A}$ is:

$$\frac{B}{A} = 2\rho C \frac{\partial c(p,\theta)}{\partial p}\Big|_{p_0,\theta_0}$$
$$+ \frac{2\alpha_\theta c\theta}{c_p} \frac{\partial c(p,\theta)}{\partial \theta}\Big|_{p_0,\theta_0} \quad (14)$$

In 1986, the authors determined the non-linear parameter and sound speed in biological medium when the temperature changed from 20 to 37°C [24].

The dependence of non-linear parameter to the temperature changes in porcine liver is reported in [25] as the first experiment. The goal of second experiment, the authors used the focused transducer for heating an

object, and then the temperature rise is derived using non-linear parameter. At the third experiment, the authors focused on the reconstruction of temperature distribution in biological sample. The authors compared the results of this study with the previous study [24]. This study presents higher values for non-linear parameters than previous one. The authors explain that the difference between the two studies was due to systematic errors and uncertainties of liver kinds. Some of disadvantages of the method are described in [25]. The first one is the small bubbles effect on measurements due to non-linear properties of bubbles. The second one is the sensitivity of estimation to the tissue types and patients. Finally, motions of patient can influence on accuracy of measurements.

In [23], the authors reported the possibility of temperature prediction using non-linear parameter of medium. According to the measurements, they claimed that the non-linear parameter is more sensitive to the temperature changes compared to the other parameters. For a homogeneous medium, the ratios between amplitudes of various harmonic components is computed in simulations and compared with the ratios in measurements. Repeating the measurements led to the several temperature predictions. Therefore, averaging method is used to noise suppression.

A estimation in bovine liver is reported in [26] during HIFU ablation. Using finite amplitude insertion method makes it possible to estimate the attenuation and sound speed. The results show better signal to noise ratio compared to the previous studies. According to the results, the authors mentioned that for detecting the inclusions in tissue medium, the non-linear parameter should be under the large changes.

In another study, the amplitude and energy of fundamental, the second and third harmonic components are measured in tissue mimiking phantoms and ex-vivo [27]. Since the mentioned parameters are temperature dependent, the average amplitudes and energies decreased with temperature changes from 26°C to 46°C. The authors claim that the nonlinear parameter can be effectively used in order to estimate the temperature in tissue medium. Temperature dependence of harmonics in different frequency ranges is reported in [28]. In this study the opposite dependency of nonlinear parameter to the

temperature is detected in frequency ranges of 1, 3.3 MHz and 13, 20MHz. Using commertial pulse echo system, the previous study [27] is repeated in [29].

5) Change in attenuation parameter: Another temperature dependent acoustic parameter is attenuation or absorption of medium. Absorption can be described as the amount of incident energy to the medium that is absorbed by the particles and changed into the heat. Some of studies focused on the absorption-based methods in thermometry. Some of them are mentioned here. In [30], the dependency of acoustic attenuation parameter to the temperature is discussed in dog muscle during HIFU exposure. Estimation of attenuation map in 20 is reported in [31]. In this study the authors used three different types of tissue for experiments. Higher attenuation was observed in high temperature ranges. In another study [32], dependency of sound speed and attenuation coefficient is estimated. The experiments are done on the tissue mimiking phantom and two different tissue types.

2.2. Passive Thermometry

As mentioned before, the passive thermometry methods are based on the radiated signals from the area under heating or cooling due to the motions of atoms of tissue medium. In passive methods, the thermometry probe is only in receive mode without transmitting any wave to the medium. The radiated acoustic wave is as a result of chaotic motions of atoms in heated area [33]. Acoustic thermometry methods have some advantages in comparison with microwave or magnetic resonance thermometries. According to the [34], Mansfel'd mentioned that the passive acostothermometry can measure the internal temperature of body with lower side effects. He claimed that the passive method can provide high spatial resolution compared to the other thermometry methods. Higher sensitivity of method to the temperature changes can be another benefit of passive acoustiothermometry methods. Mansfel'd in [34] categorized the problems of thermometry in three main categories. 1) Thermometry when an organ inside the body is under the physiological temperature changes. 2) Thermometry during HIFU exposure or hyperthermia due to an external thermal source. 3)

Long term thermometry for on-line monitoring of temperature changes inside the body.

When the area is considered homogeneous, the absolute temperature can be estimated using the mean of squared pressure.

$$T \propto P^2 \qquad (15)$$

Where in Equation 15, T, p are absolute temperature acoustic pressure, respectively. For an inhomogeneous medium, the derived temperature from acoustic pressure denotes the acoustic brightness temperature [33].

$$T_A \propto P^2 \qquad (16)$$

In Equation 16, TA is the acoustic brightness temperature, which is considered as the temperature of an idealized medium that absorbs all incident acoustic radiations (black body). Physically, the radiated thermal acoustics from this area is similar to the heated tissue medium [33].

According to the mentioned categories, in presented review the passive thermometry methods are classified as follows:

Another application of passive thermometry is reported in [35]. In this study, the temperature reconstruction for deep brain is investigated. The experiments are done on the brain of two patients. Due to the attenuation in brain scalp, in study the selected subjects are with brain injury and some parts of their scalp is missed. The results of thermometry for the two patients are around 37°C with standard deviation of 0.7°C and 0.3°C.

The application of passive thermometry is reported in drug delivery [36]. During heating process, the phase transition in liposomes occurs during heating process. When the liposome is destroyed, the temperature of phase transition can be measured. According to the results, temperature monitoring using passive method can be useful in determining the lipid destruction moment.

In [37], the authors used two different arrangements of pizo-electric elements to measure the temperature of plasticine object. A planar array consisting of 14 elements and a pair of perpendicular arrays are used, each of which has seven elements. Using the two mentioned models resulted in the estimation of

temperature brightness with the accuracy of 1 degree and a thermal distribution map for heated and cooled plasticine object.

The effect of physical pressure on the temperature of forearm is studied in [38]. Using passive thermometry, the authors illustrate that the temperature rise of forearm in presence of physical force and blood flow compared to the rest condition is 2°C. In [39], the time varying profile of temperature for human hand in heating and cooling process is investigated. The error of thermal estimation is 0.6°C.

In [40], the authors reconstruct the temperature profile of forearm and plasticine object using broadband acoustic thermometers. The average error is about 0.5K in plasticine object. Forearm experiments are done with and without physical pressure that the maximum reconstructed temperatures are 38.3°C, and 36.3°C, respectively.

In another study published in 2010 [41], the authors used 4 elements in front of the plasticine object. The cross-correlation method is applied to measure the temperature distribution of object. For non-correlation method perpendicular arrangement of acousto-thermometry elements is used. 3D real time mapping of thermal distribution is as a result of non-correlation method. The aim of another study is the reconstruction of temperature profile for plasticine object and human hand [42]. The results show around 0.5K error for plasticine object. The experiments on hand are done using a planar array with 14 elements. In [43], the previous study [42] is repeated for broadband acoustic thermometers. The reconstruction error for plasticine object was about 0.6K.

Another study on passive thermometry used the heat conduction equation in order to estimate the time varying thermal profile of deeper objects [44]. In this study, the effect of acoustic non-uniformity in plasticine medium is investigated. The results show 17% and less than one degree error in estimation of heat conductivity coefficient and initial temperature, respectively.

The application of Neural networks for temperature reconstruction is reported in [45]. Four acoustic thermometer received the radiated signals and these waves were applied as Neural network input and three dynamic temperatures are the output of mentioned

Neural network. The mean square error of temperature recovery in bovine liver is less than 0.5°C.

In [33], the authors reported the 2D temperature reconstruction using experiment and simulation. If the depth of measurement is about the inverse of absorption coefficient, then the optimal reconstruction can be achieved. The least squares method combined with the Tikhonov's regularization method leads to the best results. The error value in temperature determination was about 0.25K.

Another study determines the dependency of internal temperature or absolute temperature on the thermal difference between radiated part of object as the passive source and transducer as the receiver [46]. The authors experimentally proved that this dependency is linear.

Thermometry method during the tumor treatment using radiofrequency heating is reported in [47]. The aim of the paper is to map the temperature distribution of the heated area. Simulation and experiments on human hand using Tikhonov's regularization method result in 0.4K squared error.

In [48], the authors calculated correlation function of radiated signal from a narrow plasticine object in heating and cooling process spatially. In this paper the dependency of correlation function to the absolute temperature and the difference between the heated plasticine and the passive receiver is investigated. Heating and cooling of plasticine source can change the sign of correlation. Other studies on the correlation of radiated signals from heated plasticine are reported in [49] and [50]. Anosov *et al.* in 2005 used acousto-thermometery for measuring the temperature distribution of biological tissue [51]. In [57], the authors in this study consider that the measured temperature should satisfy the heat equation. Accordingly, estimation of initial temperature and thermal diffusivity can be sufficient in temperature estimation problem. The efficiency of algorithm is tested experimentally. The estimation error in this study is about 0.5 to 1 K. Other acousto-thermometry methods and applications are reported in [52-56].

The newest study on acousto-thermometry is reported in 2019 [58]. The authors in this study propose a simulation framework for evaluating the PAT methodologies. This framework supports the

generation of acoustic radiation, signal processing, parameter estimation, and temperature reconstruction processes. Using the proposed framework, they tried to implement previously practical experiments and the results of the simulation are consistent with those of the practical experiment. The mean error of temperature estimation was below 0.45 °C. The results show that it is possible to use this framework to evaluate the PAT in different scenarios.

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