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ORIGINAL ARTICLE

A Simulation Framework for Passive Acoustic Thermometry of Nonhomogeneous Materials

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Abstract

Purpose: Internal temperature is a significant factor for medical diagnosis. There are several thermometric methods, including IR, MRI, and active ultrasonic thermometry, which have limitations for clinical applications. The new method in this field called Passive Acoustic Thermometry (PAT), which enhanced some of this limitation. PAT is a safe method for internal temperature estimation that works based on acoustic radiation of materials with a specific temperature. Several experimental studies have been carried out so far in the field of PAT. While, to the best of our knowledge, there is no simulation-based research for nonhomogeneous materials reported yet. In this article (for the first time) we proposed a simulation framework for evaluating the PAT methodologies in nonhomogeneous materials; also we proposed a new formulation for temperature estimation in PAT algorithm.

Materials and Methods: This framework supports the generation of acoustic radiation, signal processing, parameter estimation, and temperature reconstruction processes. At the moment the proposed framework estimates the temperature in the frequency domain and uses the frequency spectrum of the acquired ultrasound signals captured by a single transducer. Using the proposed framework, we tried to implement the previously practical experiments and the results of the simulation are consistent with those of the practical experiments. Also, we proposed the formulation that improves the error of temperature estimation.

Results: We study 6 scenarios, including 2 environments with a target at 3 different temperatures. The average error of the proposed formulation in two different nonhomogeneous materials for three different temperatures is less than 0.25°C.

Conclusion: The results show that the proposed formulation is the best estimation in the formula that has been introduced until now and compare with the previous study the accuracy is enhanced 54% (from 0.79 to 0.36 deg.). Therefore, the proposed formula enhanced PAT accuracy for temperature estimation. Also, the results show that it is possible to use this framework to evaluate the PAT in different scenarios. Therefore, this method enhances the possibility of examination of different conditions and algorithms. It also reduces the cost of practical experiment.

Keywords: Internal Temperature; Passive Acoustic Thermometer; Nonhomogeneous Materials.

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1. Introduction

Passive Acoustic Thermometer (PAT) is a method for measuring the thermal acoustic radiation of an object at the determination of its internal temperature. Internal temperature is a very important factor for medical applications such as diagnosis of various tumors or control temperature during hyperthermia therapy. There are several thermometric methods, including IR, MRI, and active ultrasonic thermometry, which are used for clinical applications more than MRI. Infrared thermometry is only able to measure the body surface temperature, so it cannot detect diseases such as cancerous tumors. The magnetic resonance thermometry enables measurement of internal temperatures of the human body with an error of about 0.4°C [1]. However, that method requires expensive equipment, skilled personnel, and specially prepared premises. Besides, there are groups of people for whom the application of magnetic resonance methods is unacceptable for different reasons.

The active thermometry method needs more equipment than its passive version, which leads to an increase in cost. In addition, in order to monitor the temperature in the long run using an active thermometry scenario the ultrasound exposure causes a change in the temperature of the tissue which results in having an error on estimated temperature.

On the other hand, the passive thermometry methods are very interesting because the measuring device does not emit any ultrasound wave to the target tissue and only records the inherent radiation produced by thermal chaotic movement of tissue atoms. In many types of researches [1–13], such passive measurement methods are proposed. These methods are called as PAT, i.e. by measuring the thermal acoustic radiation from tissue, in a non-invasive scenario also with low-cost hardware and easily applicable in clinical diagnosis and completely safe method because of its passive procedure. According to these articles, the PAT method is capable of reconstructing the temperature with an error about 0.5-1°C that is applicable for medical applications.

Most of the studies that have been done so far in the field of passive acoustic thermometry have examined this method in practice, but in this paper we have tried to set up a simulation framework based on the k-wave ultrasound MATLAB toolbox [14] for implementation and verifying state of the art and new algorithms on ultrasound thermometry. In [15] we studied this method in simulation for the first time at homogeneous materials.

The goal of this study is to evaluate proposed framework in pervious study [15] for nonhomogeneous materials and propose a new formula in PAT method for temperature estimation to improve accuracy of this method. Using the developed framework, it is possible to study the different algorithms and conditions for developing temperature estimation algorithms by the method of passive acoustic thermometry before developing related hardware. The details of the proposed framework and performed simulations are described in the next Section. Section 3, deals with the simulated results of the performed thermometry process and finally, Section 4 concludes the paper.

2. Materials and Methods

In this section, the required tools and formulations for PAT are described. Also, the simulated PAT process steps are provided as a protocol followed by signal processing approaches for temperature estimation.

The general steps for recovering temperature for the target material are shown in Figure 1. As it can be seen, in the first step, the acoustic signal generated by the target material is produced by the k-wave ultrasound Matlab toolbox according to Equation 1 and in the next step, the signal is received by a transducer and pre-processed. Then, in the process described in the following sections, the necessary parameters of the PAT equations are specified in a process called calibration. In the final stage, the calculated parameters are utilized to estimate the temperature of any simulated material with specific temperature in the simulation framework. Since we deal with a simulation scenario, the temperature of the material is known and the evaluation of estimation process is easily straight forward by comparing the estimated temperature with the actual one.

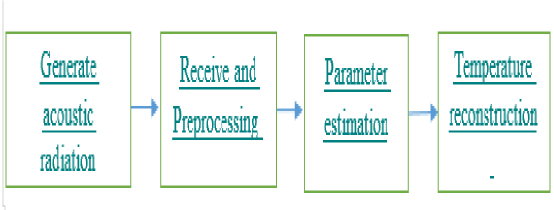

Figure 1. Global block diagram of temperature reconstruction with PAT process

2.1. Setup

In this paper, we used MATLAB software. The simulation environment size is chosen as an N*N pixels frame with 100µm resolution in both coordinates. The whole simulated material is defined as a nonhomogeneous frame that consists of different homogeneous layers with predefined density (ṗ). Also, the propagation speed of sound in this material is assumed as V (m/s), which is consistent with the material properties.

According to the Rayleigh-Jeans law, the mean of the pressure square, ⟦<p>⟧ ^{2}, emitted by an acoustic black body (target material) with specific temperature, T, at frequency interval Δf in megahertz is formulated as:

$$< p^2 >= \frac{4\pi KT\dot{\rho} f^2 \Delta f}{v} \qquad (1)$$

Where K is the Boltzmann's constant, v is the sound velocity, ṗ is the medium density and f is the radiation frequency.

In this study, in order to measure the acoustic signals, one receiver transducer with a center frequency of 2.5 megahertz was placed in the perpendicular to material orientation. The experimental setup is represented in the Figure 2.

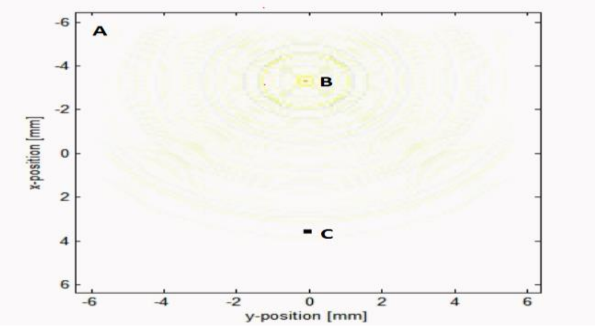

Figure 2. (A) Simulated frame, (B) Hot Object with acoustic radiation, (C) receiver transducer

2.2. Protocol

In order to achieve the unknown parameters in the temperature reconstruction process, a calibration process must be considered. In this regard, hypothetical bodies are placed at a specific temperature of 28 and 29 degrees in the simulation environment, and then the hypothetical bodies are used with an unknown temperature to generate the acoustic signals and reconstruct the temperature from the generated signals.

2.3. Temperature Estimation Process

According to the preprocessing step shown in Figure 3, the acoustic signal received by the transducer is passed through a band-pass filter with a bandwidth of 0.5-4.5 MHz (these parameters are chosen similar to those of performed practical experiment).

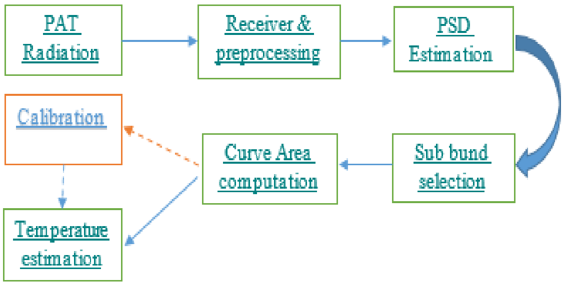

Figure 3. Detailed block diagram of temperature reconstruction

In order to reconstruct the temperature, the PSD of filtered signal is calculated. The frequency ranges defined as f_i (_-^+)Δf(where f_i=1,2,3,4 MHz and Δf=0.5MHz) which is measured at various frequency ranges of the area of the surface below the spectral curve. These bands are chosen according to the central frequency and frequency response of the measuring probe to cover its pass-band uniformly similar to the reported bands in the previously performed researches [2, 13].

The passive acoustic temperature was calculated for four frequency ranges, which were mentioned before, using the following Equation 2 [13]:

$$T_{exp}(f_i) = \frac{\Delta S_i}{\Delta S_{bb_i}} 1^\circ \mathrm{C} + 28\,^\circ\mathrm{C} \qquad (2)$$

where i is the number of sub-band, and $[\![\Delta S]\!]_{i}$ (i=1,…,4) are the difference between the measured signals from the object at the unknown temperature and the black body temperature at a temperature of 28 degrees. Also, the term $[\![\Delta S]\!]_{bbi}$ (i=1,…,4) denotes the difference between the measured signal from the black body at 29 degrees and the measured signal from the black body at 28 degrees.

At the next step, in calibration box of Figure 3, the calibration process is performed. This process is carried out for the target object at two different known temperatures (28 and 29). The aim of this process is to calculate the $[\![\Delta S]\!]_{bbi}$ (i=1,…,4) in Equation 2, so with computing, the area under spectral envelop curves of different sub-bands for two predefined temperatures, we can use the Equation 2 for temperature estimation.

From now on, the estimated parameters, $[\![\Delta S]\!]_{bbi}$, at the calibration process will be used to measure the temperature of the target material with unknown temperature. The procedure described until now that used in all practical experiment have 4 estimated temperatures for 1 actual temperature. Unfortunately, in noisy environment these 4 estimated temperatures have tolerances and error. Therefore, we proposed formula to reach one estimated temperature with high accuracy. Therefore, we proposed the fallowing formula as:

$$T_{es1}(f_i) = T_e/2\ ^{\circ}\mathrm{C} \tag{3}$$

Where T_e is:

$$T_e = \sum_{i=1}^{4} T_{exp}(f_i) - \min\left(T_{exp}(f_i)\right) - \max\left(T_{exp}(f_i)\right) \tag{4}$$

Then with subtracting estimated temperature from actual temperature, we can calculate the error of PAT. In order to evaluate the performance of the whole PAT process and proposed formula, we defined two nonhomogeneous environments and then inserted separate target materials with known temperatures as 5, 45, and 60°C in the framework.

3. Results

In this section, the results of running simulated frame according to the pervious section for different environment are shown. We assumed that N equal to 128 and material properties are according to Table 1.

Table 1. Material properties in framework simulation

	Water	Fat	Blood
Density(kg/m^3)	1000	900	1060
Velocity(m/s)	1480	140	1570

The environments are described as: Environment 1: nonhomogeneous of blood and water. Where the blood area is from 59 to 69 in row and column pixels and the properties of other pixel is based on water properties.

Environment 2: nonhomogeneous of fat and water. The primary condition is the same as environment 1 unless the blood is replaced with fat. The scheme of these two environments is shown in Figure 4.

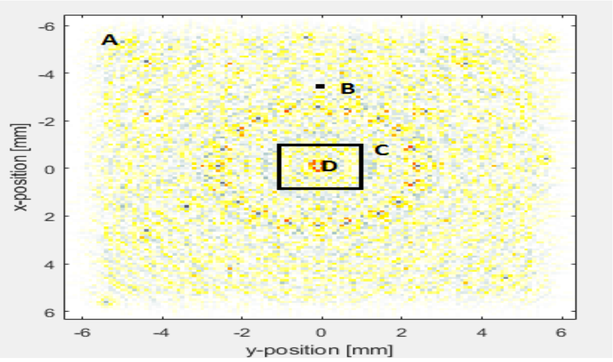

Figure 4. The simulation framework for PAT in nonhomogeneous material. A) Water area. B) Transducer. C) Fat or blood area. D) Target object

In Table 2, the calculated MU values for two energies in TPS for delivery of 200 cGy doses to the center of the CT image of phantom uploaded to the software which were obtained using multiple imaging protocols are shown.

3.1. Calibration

To obtain the temperature with Equation 2, we must obtain our unknown parameters. Therefore, in a process called calibration, the acoustic radiation of two hypothetical bodies is measured at 28 and 29 degrees, so the calculated parameter in the region in the form of the underwear, the signal obtained from the radiation of two objects with a temperature of 28 (blue line), and the difference between curve 28 and the spectrum of the black body with a temperature of 29°C (red line) with 200 times magnification are shown in Figure 5.

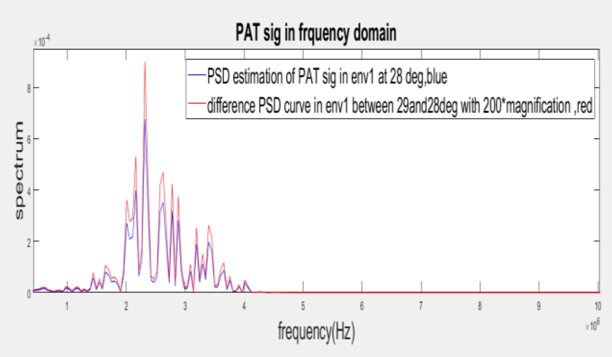

Figure 5. The simulation framework for PAT in nonhomogeneous material. A) Water area. B) Transducer. C) Fat or blood area. D) Target object

PSD of spectral radiation of two black body in environment 1 with a temperature of 28 (blue line) and the difference between curve 28 and the spectrum of the black body with a temperature of 29 (red line) °C with 200 times magnification are shown.

3.2. Temperature Estimation

In the next two Figures 6 and 7 PSD of PAT spectral radiation of target with 60°C at environment 1 and 2 are shown.

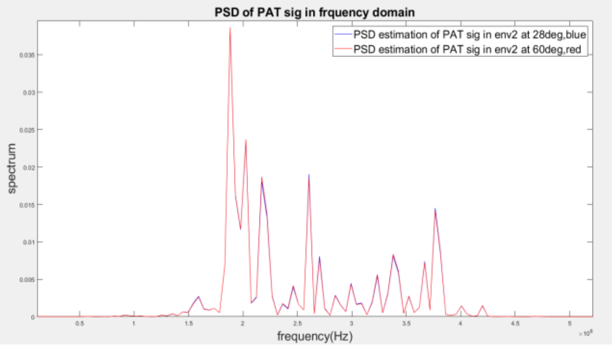

Figure 6. PSD of spectral radiation of two black bodies in environment 1 with a temperature of 28 (blue line) and 60 °C (red line) are shown

In Figure 7, the result for target with temperature of 60°C at environment 2 is shown.

In Table 2, the results of temperature estimation in environment1 are shown.

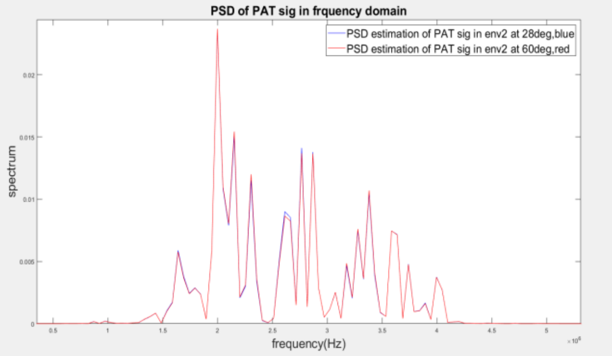

Figure 7. PSD of spectral radiation of two black body in environment2 with a temperature of 28(blue line) and 60 °C (red line) are shown

Table 2. Temperature estimation of [15] using new formula

Actual Temp	$T_{ex}(f_1)$	$T_{ex}(f_2)$	$T_{ex}(f_3)$	$T_{ex}(f_4$	T_{es1}
60 deg	63.14	60.74	58.6	59.04	59.87
45 deg	45.86	45.20	44.62	44.73	44.97
5 deg	6.75	5.41	4.22	5.21	4.93

In Table 3 the results of temperature estimation in environment 2 for 3 different temperatures are shown.

Table 3. Results of temperature estimation at environment 2

Actual Temp.	$T_{ex}(f_1)$	$T_{ex}(f_2$	$T_{ex}(f_3)$	$T_{ex}(f_4$	T_{es1}
60 deg.	63.35	60.42	58.28	55.88	59.34
45 deg.	45.92	45.12	44.53	43.87	44.82
5 deg.	6.87	5.23	4.04	2.71	4.64

4. Conclusion

Based on the results obtained in Figure 5, which results from the PAT simulation by k-wave Toolbox and compares it to Equation 2, we find that there is a significant similarity between the theoretical equations and the simulation. The similarity demonstrates the ability to use the k-wave Toolbox to simulate passive acoustic thermometers. According to Figure 6 and 7, the same results obtained for other temperature in different environment.

According to Tables 2 and 3, the results of which are from temperature estimation in environments 1 and 2 at 5, 45 and 60 degrees, the sub-band estimation, which was utilized in the practical experiment at short time duration, has a different error that makes it difficult to select true estimation. Therefore, we proposed a new formulation that provided just a single estimation for the target material.

In [15], temperature estimation for homogenous material with Equation 2 was carried out. The results of this study are shown in Table 4. The average error of this method is 0.79 deg.

Table 4. Results of temperature estimation at homogenous material in [15]

Actual Temp.	$T_{ex}(f_1)$	$T_{ex}(f_2)$	$T_{ex}(f_3)$	$T_{ex}(f_4)$
60 deg.	59.01	61.79	60.7	61.68
45 deg.	44.73	45.49	45.19	45.46
5 deg.	4.33	5.99	5.39	5.93
AVG$_E$	0.64	1.09	0.42	1.02

But by using the proposed formula in this article, the average error of [15], which is shown in Table 5, was improved to 0.36 deg. In fact, the proposed formula makes the PAT be more robust. In other words, some of the sub-bands in temperature estimation (old method) have under and overestimate than the actual temperature. In this study, we tried to reduce this effect using the proposed formula.

Table 5. Temperature estimation of [15] using new formula

Actual Temp.	T_{es1}
60 deg.	61.19
45 deg.	45.32
5 deg.	5.66
AVG$_E$	0.36

In this paper, we evaluate the proposed framework and formula for nonhomogeneous materials. As shown in Table 6, which is related to the average error of temperature estimation for environments 1 and 2 at 3 different temperatures, the proposed formula is the best estimation and has the 0.24-degree error. As can be seen from Table 6, using simulated framework, we can measure the temperature of the target object with reasonable error. So, we can use the k-wave toolbox to simulate a passive acoustic thermometer that allows for the examination of different conditions and algorithms and reduces the costs of the practical test of a hypothesis and improves the speed of the passive acoustic thermometry.

Table 6. Average error of temperature estimation in 2 different environments

	$T_{ex}(f_1)$	$T_{ex}(f_2)$	$T_{ex}(f_3)$	$T_{ex}(f_4)$	T_{es1}
AVG$_E$	1.99	0.36	0.95	1.50	0.24

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