Original Article

A Simulation Framework for Passive Acoustic Thermometry of Homogenous Materials

Hossein Amiri [1], Bahador Makkiabadi [1,*], Ali Khani [2], Soheil Ahmadzade Irandoost [1]

[1] Department of Medical Physics and Biomedical Engineering, School of Medicine, Tehran University of Medical Sciences, Tehran, Iran

[2] School of Allied Medical Sciences, Iran University of Medical Sciences, Tehran, Iran

Received: 09 July 2019

Accepted: 23 August 2019

http://FBT.tums.ac.ir

Keywords:

Internal Temperature;

Passive Acoustic Thermometer;

Hyperthermia Therapy.

Abstract

Purpose: Passive Acoustic Thermometer (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 reported yet.

Materials and Methods: In this article (for the first time) we proposed a simulation framework for evaluating the PAT methodologies. 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.

Results: Using the proposed framework, we 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.

Conclusion: Therefore, this method enhances the possibility of examination of different conditions and algorithms. It also reduces the cost of practical experiment.

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 Infra Red (IR), Magnetic Resonance Imaging (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.

Corresponding Author:
Bahador Makkiabadi, PhD
Department of Medical Physics and Biomedical Engineering, School of Medicine, Tehran University of Medical Sciences, Tehran, Iran
Tel: (+98) 9121858679
Email: b-makkiabadi@sina.tums.ac.ir

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 studies, the PAT method is capable of reconstructing the temperature with an error of about 0.5-1 □C that is applicable for medical applications.

All 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.

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, and the temperature of the material is known, the evaluation of estimation process is easily straight forward by comparing the estimated temperature with the actual one.

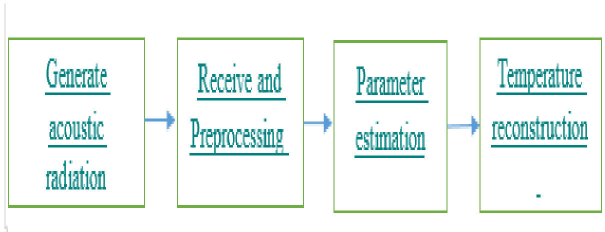

Figure 1. Global block diagram of temperature reconstruction with PAT process

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 homogeneous frame with predefined density (ῥ). Also, the propagation speed of sound in this material is assumed as V (m/s), which is consistent with the material properties. Due to the environment temperature, we defined 32 acoustic radiation sources with 25°C (according to equation 1), that these sources are randomly located and generated in simulation framework. For data analysis, the specific time sequence was selected, that the signal in this sequence is stationary and also all the grid points have nonzero energy.

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, frequency interval Δf in megahertz is formulated as

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

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

In this article we ignored the simulation of molecular motions, and just relied on the results of the previous studies such as [1, 14] for the relationship between temperature and amplitude of the acoustic pressure noise spectrum in Equation 1. In addition, according to another research [15], every material produces a specific wide band acoustic noise (below 10 MHz). Therefore, here, we used a white noise as the source.

In this study, in order to measure the acoustic signals, one receiver transducer with a center frequency of 2.2 megahertz was placed in the perpendicular to material orientation. The experimental setup is represented in the Figure 2.

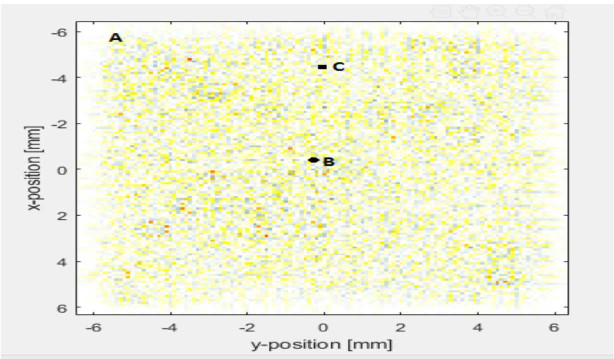

Figure 2. (A). Simulated frame, (B) Target Object with acoustic radiation, (C) receiver transducer

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°C and 29°C in the simulation environment, and then 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).

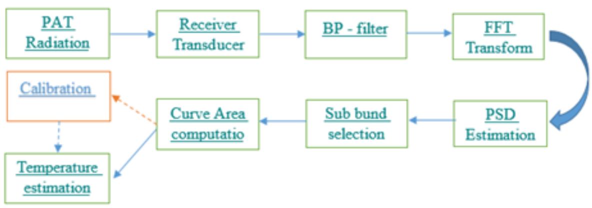

Figure 3. Detailed block diagram of temperature reconstruction

In order to reconstruct the temperature, the power spectral density (PSD) of the filtered signal is calculated. The frequency ranges are defined as f_i (_-^+)Δf(wheref_i=1,12,3,4 MHz and Δf=0.5MHz) which is measured at various frequency ranges of the area of the surface below the PSD 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 was mentioned before, using the following Equation 2 [13].

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

Where i is the number of sub-band, and 〚ΔS〛 _i (i=1,…,4) are the difference between the measured signals from the object and the black body temperature at a temperature of 28°C. Also, the term 〚ΔS〛 _bbi (i=1,…,4) denotes the difference between the measured signal from the black body at 29°C and the measured signal from the black body at 28°C.

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°C and 29°C). The aim of this process is to calculate the 〚ΔS〛 _bbi (i=1,…,4) in equation (2), so with computing the area under PSD curves of different sub-bands for two predefined temperatures, we can use the Equation (2) for temperature estimation.

From now on, the estimated parameters, 〚ΔS〛 _bbi, at the calibration process will be used to measure the temperature of the target material with unknown temperature. Then with subtracting T_exp (f_i) from actual temperature, we can calculate the error of PAT.

In order to evaluate the performance of the whole PAT process, we insert separate target materials with known temperatures as 45, 25 and 60°C in the framework.

3. Results

In this section, the results of running simulated frame according to the pervious section of water that have ṗ=1000(kg/m^3), V=1483 and N=128 are shown. The reason for choosing water as the frame substance in the environment is its negligible acoustic attenuation.

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, 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. 4.

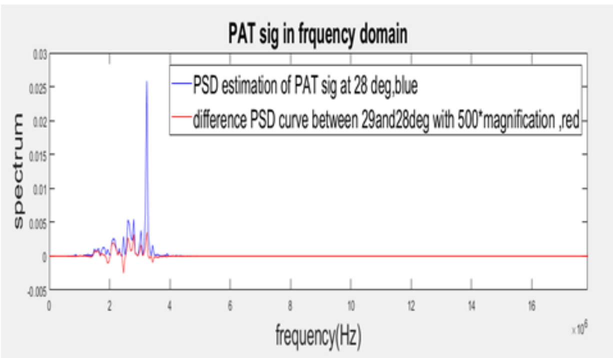

Figure 4. PSD of two black body radiation signal with a temperature of 28(blue line) and the difference between curve 28 and the spectrum of the black body with a temperature of 29 (red line) °C with 500 times magnification are shown

The same signal obtained by ANOSOV [3] in a practical experiment similar to the one mentioned in this paper that is shown in Figure 5. In that experiment, the thermal radiation of two plasticine objects (two acoustic black bodies) was measured. The two objects were immersed in the thermostatic bath at 28 °C and 29 °C, respectively. The measured spectrum of the black body with a temperature of 28 °C is shown in Figure. 5, curve 1. The difference between curve 1 and the spectrum of the black body with a temperature of 29 °C is 0.13%, but at the scale used in Figure. 5, this difference is practically invisible.

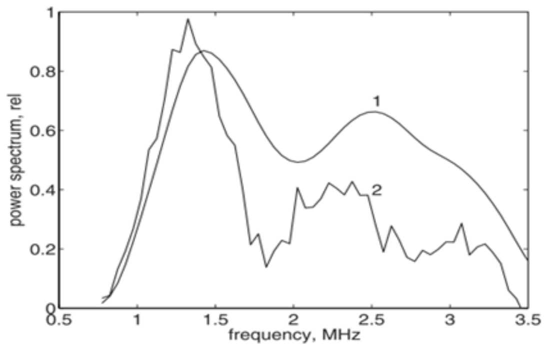

Figure 5. Spectrum of a black body with a temperature of 28 °C (curve 1) and the difference of black body spectra for temperatures of 29 °C and 28 °C (curve 2). The scales for curves 1 and 2 differ by a factor of 500 [3]

3.2. Velocity and Pressure

In the Fig. 6, the changes in speed and pressure recorded by the receiver sensor are displayed over time for a source with 28 °C.

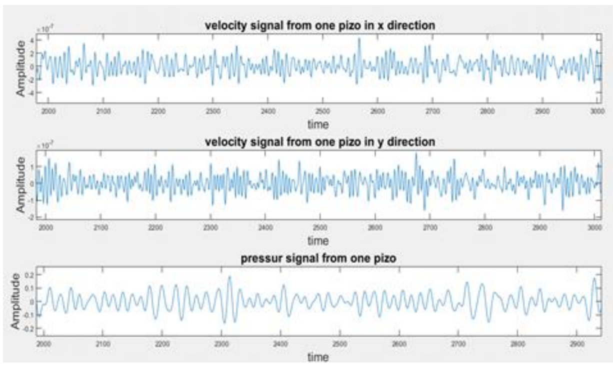

Figure 4. Velocity of acoustic signal that was captured with the transducer at x and y direction and pressure are shown

In Table 1, the reconstructed temperatures are shown for different sub-bands for objects with different temperatures.

Table 1. Result of temperature estimation at each frequency band are shown

Actual Temp (deg)	Temp.E at f_1(deg)	Temp.E at f_2(deg)	Temp.E at f_3(deg)	Temp.E at f_4(deg)
60	59.01	61.79	60.7.	61.68
45	44.73	45.49	45.19	45.46
5	4.44	5.99	5.39	5.93

4. Conclusion

Based on the results obtained in Figure 3, which is related to the acoustic signal received in the experimental experiment, which was recorded by Anosov [3] and compares it to Figure 2, which results from the PAT simulation by k-wave Toolbox, we find that there is a significant similarity between the practical results and the simulation. The similarity demonstrates the ability to use the k-wave Toolbox to simulate passive acoustic thermometers.

As can be seen from Table 1, using simulated framework, we can measure the temperature of the target object with reasonable error, which is why the ideal zero error is the consideration of all conditions such as the homogeneity of the object and the assumption of the environmental conditions that this mode is not feasible in the practical test. 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.

4.1. Velocity and Pressure

In this paper, the target objects are considered homogeneous and integrated, while in reality, we face a non-homogeneous object that should be considered for future work and we will examine this method in a practical experiment.

Acknowledgements

This research was supported by grant No. 26884 from the School of Medicine, Iran University of Medical Sciences (IUMS). Also, we thank the National Brain Mapping Laboratory of Iran for providing the MR imaging at all steps of the experimental studies.

References

1- Anosov A.A., Sharakshane AA, Kazansky A.S., Mansfel'd A.D., Sanin A.G, Sharakshane A.S, Instrument Function of a Broadband Acoustic Thermometric Detector, *Acoustical Physics*. 62 (2016)626–632. doi:10.1134/S1063771016050018

2- A.A. Anosov, A.S. Kazanskii, A.D. Mansfel'd, A.S. Sharakshane, Acoustic Thermometric Reconstruction of a Time-Varying Temperature Profile, *Acoust. Phys*. 62 (2016) 255-261. https://doi.org/10.1134/S1063771016020032

3- Anosov A.A., Kazansky A.S., Subochev P.V., Mansfel'd A.D., Klinshov V.V., Passive estimation of internal temperatures making use of broadband ultrasound radiated by the body, J. Acoust. Soc. Am. 137(2015)1667-1674.doi: http://dx.doi.org/10.1121/1.4915483

4- A.A. Anosov, R.V. Belyaev, V.A. Vilkov, M.V. Dvornikova, V.V. Dvornikova, A.S. Kazanskii, N.A. Kuryatnikova, A.D. Mansfel'd, Acousto-Thermometric Recovery of the Deep Temperature Profile Using Heat Conduction Equations, Acoust. Phys. 58 (2012) 542-548. doi:10.1134/S1063771012030037

5- A.D. Mansfel'd, Acoustothermometry: current status and prospects, Acoust. Phys. 55 (2009) 556-566. doi:10.1134/S1063771009040125

6- O.A. Godin, Retrieval of Green's functions of elastic waves from thermalfluctuations of fluid-solid systems, *J. Acoust. Soc. Am*.125(2009)1960–1970.doi: http://dx.doi.org/10.1121/1.3082101

7- A.A. Anosov, R.V. Belyaev, V.A. Vilkov, A.S. Kazanskii, A.D. Mansfel'd, A.S.Sharakshane, Dynamic acoustothermography, *Acoust. Phys*. 55 (2009) 454-462.doi:10.1134/S1063771009040022.

8- A.A. Anosov, R.V. Belyaev, V.A. Vilkov, A.S. Kazanskii, A.D. Mansfel'd, A.S. Sharakshane, Determination of the dynamics of temperature variation in a model object by acoustic thermography, *Acoust. Phys*. 54 (2008) 464-468. doi: 10.1134/S1063771008040040.

9- A.A. Anosov, Yu.N. Barabanenkov, A.S. Kazanskii, Yu.A. Less, A.S. Sharakshane, The inverse problem of acoustothermography with correlation reception of thermal acoustic radiation, *Acoust. Phys*. 55 (2009) 114-119. doi: 10.1134/S1063771009010138.

10- Anosov, A.A., Yu.N. Barabanenkov, A.G. Sel'skii, Correlation reception of thermal acoustic radiation, *Acoust. Phys*. 49 (2003) 615-619. doi:10.1134/1.1626171

11- Pouch A.M., Cary T.W., Schultz S.M., Sehgal C.M., In Vivo Noninvasive Temperature Measurement by B- Mode Ultrasound Imaging, *J. Ultrasound Med*. 29 (2010) 1595-1606. DOI: 10.7863/jum.2010.29.11.1595

12- Covaciu L., Rubertsson S., Ortiz-Nieto F., Ahlstrom H., Weis J., Human brain MR spectroscopy thermometry using metabolite aqueous- solution calibrations, *J. Magn. Reson. Imaging*. 31 (2010) 807-814. DOI: 10.1002/jmri.22107.

13- A.A. Anosov, P.V. Subochev, A.D. Mansfeld, A.A. Sharakshane. TEMPERATURE RECONSTRUCTION BY THE METHOD OF PASSIVE ACOUSTIC THERMOMETRY. *Ultrasonics*. 21 September 2017. doi.org/10.1016/j.ultras.2017.09.015

14- Robert H. Mellen. The Thermal-Noise Limit in the Detection of Underwater Acoustic Signals. *The Journal of the Acoustical Society of America* 24, 478 (1952); https://doi.org/10.1121/1.1906924.

15- Asher R. Sheppard,* Mays L. Swicord,† and Quirino Balzano. QUANTITATIVE EVALUATIONS OF MECHANISMS OF RADIOFREQUENCY INTERACTIONS WITH BIOLOGICAL MOLECULES AND PROCESSES. *Health Physics*. October 2008, Volume 95, Number 4.

