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ORIGINAL ARTICLE

Thermal Simulation and Detection of Breast Tumor Using Passive Acoustic Thermometry

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Abstract

Purpose: For over three decades, various researchers have aimed to construct a model of breast cancer. Most of them have used an infrared thermal model to stimulate breast cancer, but in this study, a novel estimation methodology is presented to detect the breast cancer tumor using the surface measurement obtained by Passive Acoustic Thermometer (PAT). PAT is a safe method for internal temperature estimation that works based on acoustic radiation of materials with a specific temperature.

Materials and Methods: This article uses a simulation framework for breast tissue simulation and tumor detection using the PAT methodologies in different scenarios. This framework supports the generation of acoustic radiation, tissue modelling, signal processing, parameter estimation, and temperature reconstruction processes. 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, PAT has been evaluated in breast cancer detection.

Results: According to the results, obtained from the temperature estimation in scenario 3, the sub-band estimation method, which is utilized in practical experiments in this field, shows different errors in each sub-band, making it difficult to select the true estimation. Therefore, a novel formulation is proposed that provides only one estimated temperature for breast tissue with a reasonable error (1.28 degrees) for tumor detection.

Conclusion: The results show that it is possible to use this framework to evaluate the PAT in different scenarios for tumor detection. In fact, this method enhances the possibility of examination of different conditions and algorithms. It also reduces the cost of practical experiments.

Keywords: Internal Temperature; Passive Acoustic Thermometer; Breast Tumor Simulation.

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1. Introduction

Breast cancer, the most common invasive cancer among women, is an international concern. Every year, about 200 000 new cases of the disease are identified, and it is estimated that there are more than 1 million women with undetected breast cancer. Breast cancer is highly treatable if it is diagnosed at an early stage [1]. The most widely used procedure for breast cancer detection is mammography, but it has some significant limitations, including radiation exposure, high cost, patient discomfort, and more importantly, a high false-positive rate. As an alternative, it is also possible to detect cancerous lesions using thermal imaging, a noninvasive and more comfortable technique for patient [2]. Among various techniques to detect breast cancer, infrared (IR) imaging has been widely applied since the late 1950s [3]. The accuracy of this method is not perfect; therefore, new methods have been proposed such as passive acoustic thermometer (PAT). 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 the diagnosis of various tumors or temperature control during hyperthermia therapy. There are several thermometric methods, including Infrared thermometry (IR), Magnetic Resonance Imaging (MRI), and active ultrasound thermometry, among which MRI is the most widely used in clinical applications.

IR is only able to measure the body's surface temperature with high accuracy, so it cannot detect diseases such as cancerous tumors. The magnetic resonance thermometry enables the measurement of internal temperatures of the human body with an error of about 0.4℃ [4]. However, that method requires expensive equipment, skilled personnel, and specially prepared premises. In addition, there are groups of people for whom the application of magnetic resonance methods is unacceptable for different reasons. The active ultrasonic thermometry method needs more equipment than its passive version, which leads to an increase in cost. In addition, to monitor the temperature, in the long run, using an active ultrasonic thermometry scenario, the ultrasound exposure causes a change in tissue’s temperature, resulting in an error on estimated temperature.

On the other hand, the passive thermometry methods are very interesting because the measuring device does not emit any wave to the target tissue and only records the inherent radiation produced by the thermal chaotic movement of tissue atoms. In many types of studies [4-11], such passive measurement methods are proposed. These methods are called 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.

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, a simulation framework based on the k-wave ultrasound Matlab toolbox [12] for implementation and verifying state-of-the-art algorithms on ultrasound thermometry is set-up. In [13, 14] this method has been evaluated in simulation for the first time on homogeneous and nonhomogeneous materials.

Using the developed framework, it is possible to study the different algorithms and conditions for developing temperature estimation algorithms by the passive acoustic thermometry method before developing their 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 tumor simulation based on 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 breast tissue are shown in Figure 1. As can be seen, in the first step, breast tissue is simulated. Then, the acoustic signal generated by the breast tissue is produced by the k-wave ultrasound Matlab toolbox according to Equation 1. In the next step, the signal received by a transducer is pre-processed. The necessary parameters of the PAT equations are then specified in the calibration process, described in the following sections. In the final stage, the calculated parameters are utilized to estimate the temperature of the breast tissue with a specific temperature in the simulation framework. Since we deal with a simulation scenario, the temperature of the tissue is known, and the evaluation of the estimation process is straightforward by comparing the estimated temperature with the actual one.

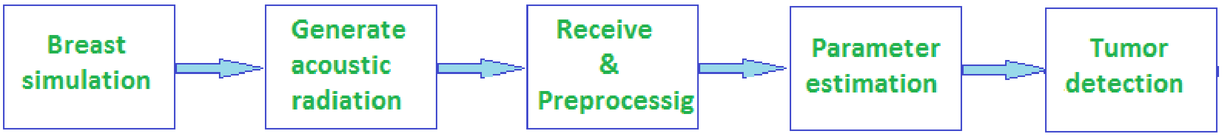

Figure 1. Global block diagram of the breast temperature reconstruction with PAT process

2.1. Setup

In this study, MATLAB software as a powerful scientific tool, especially in simulation tasks, has been used. The simulation environment size is chosen as an N*N pixels frame with 100µm resolution in both coordinates. The simulated material is defined according to breast tissue structure with predefined density ($\dot{\rho}$). Also, the propagation speed of sound in this material is assumed as V (m/s), which is consistent with the material properties. In fact, the breast tissue structure is defined similarly to the breast phantom introduced in [15, 16].

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. Also, v, $\dot{\rho}$, and f are sound velocity, medium density, and radiation frequency, respectively.

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

In Figure 2, the simulated framework, indicated with A, is water. The breast tissue consists of three parts (B, C, and D), each of which has a thermal source with a specific temperature. As can be seen, the tumor region, fibro glandular tissue, and subcutaneous fat have one, four, and twelve thermal sources, respectively, indicated with red points (E).

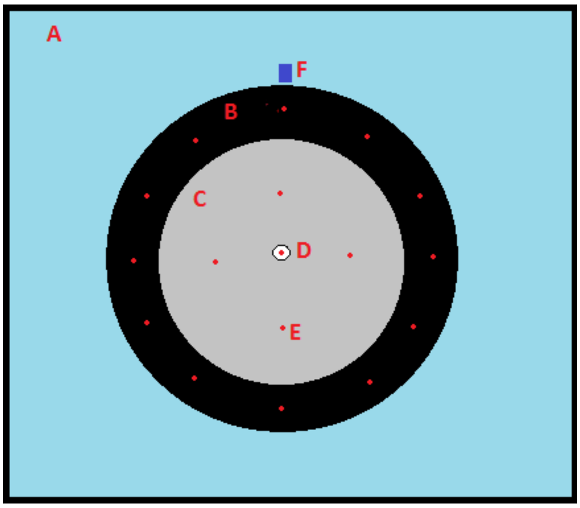

Figure 2. (A). Simulation framework, (B) Subcutaneous fat, (C) Fibroglandular tissue (D) Tumor region (E) Thermal source with acoustic radiation (F) Transducer

2.2. Protocol

To achieve the unknown parameters in the temperature reconstruction process, a calibration process for breast tissue must be considered. In this regard, at the normal breast tissue, a hypothetical thermal source at a specific temperature is placed in the simulation environment. Then, thermal sources related to the tumorous breast 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.

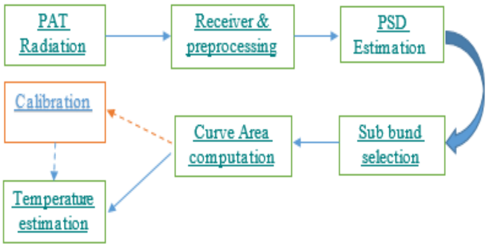

Figure 3. Detailed block diagram of temperature reconstruction

To reconstruct the temperature, the Power Spectral Density (PSD) of the filtered signal is calculated. The frequency ranges are defined as $f_i \pm \Delta f$(where $f_i = 1,2,3,4\ MHz\ and\ \Delta f = 0.5MHz$), 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 conducted researches [4, 10].

The passive acoustic temperature, already mentioned, is calculated for each frequency range using the following Equation [14]:

$$T_{exp}(f_i) = \frac{\Delta S_i}{\Delta S_{bb_i}} * (temp2 - temp1)^\circ C + temp1\ ^\circ C \qquad (2)$$

Where i is the number of sub-bands and $\Delta S_i$is the difference between the measured signals from the tumor location at the unknown temperature and the breast tissue at a temp 1. Also, the term ΔS_{bbi} denotes the difference between the measured signal of the breast tissue at the temp 2 and temp 1.

At the next step, the calibration process is performed. This process is carried out for the target object (i.e. thermal source located in the center of the simulated framework) at two different known temperatures, temp 1 and temp 2. In fact, this process aims to calculate the ΔS_{bbi}, the area under spectral envelop curves of different sub-bands for two predefined temperatures. Now, Equation 2 can be applied to estimate the temperature.

From now on, the estimated parameters, ΔS_{bbi}, at the calibration process will be used to measure the temperature of the breast tumor with unknown temperatures. According to [17], the main algorithm for temperature estimation, used until now, has been based on Equations 1 and 2 with four estimated temperatures for an actual one. However, noisy environments can cause errors in these four estimated temperatures. A noisy environment is a heterogeneous environment the specifications of which, such as density and the propagation speed of the wave, are varied or dissimilar. In this study, for instance, the whole layer defined as a subcutaneous fat does not have a specific density and in some points of it, there is a small difference in that. Therefore, an accurate formula to obtain one estimated temperature is proposed here:

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

Where T_e is:

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

Then, by subtracting the estimated temperature from the actual one, the error of PAT can be calculated. To evaluate the performance of the whole PAT process and proposed formula, three different scenarios for breast tissue that two of them related to the calibration process and the last scenario is tumor detection.

Table 1. Breast tissue temperature at a different scenario

	Tumor Location	**Fibro Glandular**	**Subcutaneous Fat**
Scenario 1	Temp1	37.3° C	36.8° C
Scenario 2	Temp2	37.3° C	36.8° C
Scenario 3	Temp3	Temp4	36.8° C

3. Results

Based on the information presented in Section 2, the specifications of the simulation environment are as follows: N = 128 (the simulation is performed in a 128 x 128 space). Given that in clinical applications of the ultrasound probe there must be used an impedance matching between the probe and the tissue, in the simulation environment, it is assumed that the breast tissue is surrounded by water. It is also supposed that breast tissue is composed of three parts, including tumor, gland, and fat, which have the characteristics listed in Table 2. The simulation environment has been performed in three different scenarios. In the first and second scenarios, the goal is to achieve the parameters in Equation 2.

Table 2. Material properties in framework simulation [15, 16]

	Tumor Location	Fibro Glandular	Subcutaneous Fat	Water
Density (kg/m^3)	1090	1041	911	1000
Velocity (m/s)	1549	1515	1470	1480

In the first scenario, according to Table 1, the temperature sources are considered as tumor tissue with a temperature of 37.6 degrees Celsius, glandular tissue with a temperature of 37.3 degrees Celsius, and subcutaneous fat with a temperature of 36.8 degrees Celsius. These sources will emit acoustic waves in the simulation environment based on Equation 1, as shown in Figure 4. The emitted acoustic waves are received by the transducer and are used to estimate the temperature.

In scenario 2, all conditions are the same as scenario 1 except tumor temperature, in this case, considered 36.8 degrees.

Figure 4 shows an image of the running simulation environment. As explained in Section 2, the characteristics of different parts of this environment are in accordance with Figure 2 and Table 2, which cause the propagation of acoustic waves at different speeds in different parts.

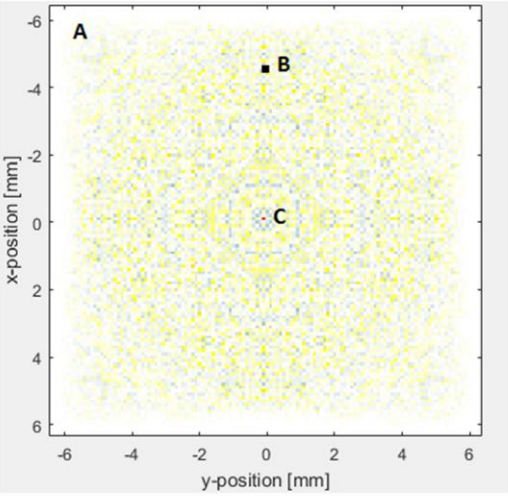

Figure 4. the simulation framework for PAT in breast tissue. A) Water area. B) Transducer. C) Thermal acoustic radiation from the tumor region

To evaluate the proposed method in tumor detection, scenario 3 has been proposed. In fact, three different conditions have been designed for temperature estimation, in all of which the subcutaneous fat temperature is constant and equal to 36.8 ° C. But, the tumor temperature (temp3) and the fibro glandular tissue temperature (temp4) in the three different cases have been selected (38.6, 37.6), (38.8, 37.7), and (39, 37.8) for (temp3, temp4), respectively.

3.1. Calibration

To obtain the temperature based on Equation 2, the unknown parameters must be first calculated. Therefore, in a process called calibration, the acoustic radiation of breast tissue is measured in scenarios 1 and 2. Then, the acquired parameters in the region in the form of the underwear, the signal obtained from the radiation of breast tissue in scenario 1 (blue line), and breast tissue at scenario2 (red line) are shown in Figure 5.

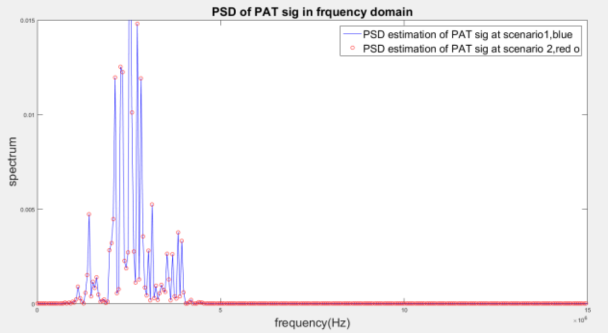

Figure 5. PSD of spectral radiation of breast tissue in scenario 1 (blue line) and scenario 2 (red line)

It should be noted that the only difference between the first and second scenarios is the temperature difference in the tumor area. In the first scenario, which is shown in blue, the temperature of the tumor area is 37.6 ° C, and in the second one, which is shown in red, it is 38.6 ° C. In both scenarios, after receiving the acoustic signals, they are processed according to what has been described before. In Figure 5, the frequency domain PSD of the processed signals are shown, and they can be compared with each other. As can be seen in the figure, the signals of these two scenarios are very similar and differ only slightly in amplitude. Considering Equation 1, it is many because of the direct relationship between the temperature and pressure, resulting in an increase in the amplitude of PSD signal with temperature growth.

3.2. Temperature Estimation

After the calibration process, the temperature estimation parameters are obtained. Now, the designed framework is ready to measure the temperature of the target tissue. To evaluate this framework, scenario 3 has been designed. This scenario has been applied with 3 different temperature modes to obtain the average accuracy of the proposed method for temperature estimation. For the case where temp3 is 38.6, after receiving the PSD of the processed acoustic signal received by the transducer is shown in Figure 6 by the red color. Also, the received signal in scenario 1 is distinguished by blue in the figure. In the next Figure, the PSD of PAT spectral radiation of the target is shown.

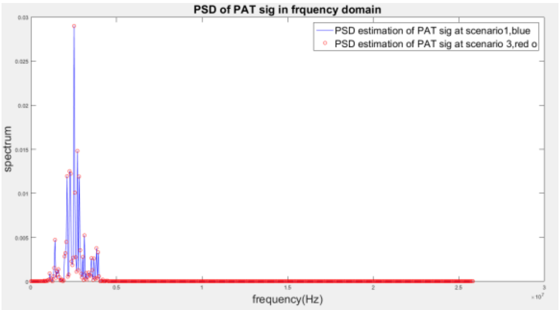

Figure 6. PSD of spectral radiation of breast tissue in scenario 1(blue line) and scenario3 with temp 38.6° C (red line)

Finally, after completing Scenario 3 for all supposed cases, the results of the estimated temperatures can be shown as in Table 3. In the first column of this table, the actual temperature of the tumor, based on which acoustic waves are generated in the simulation environment, is shown. In the next four columns, the estimated temperature in each sub-band is illustrated. Also, the estimated temperature of breast tissue, using the proposed formula, is shown in the last column.

In order to more accurately evaluate the proposed formula, Table 3 has been prepared. In this table, the average temperature estimation error in four sub-bands and the proposed formula are calculated for 3 different cases considered in Scenario 3.

Table 3. Results of temperature estimation at scenario 3

Actual Tumor Temp	$T_{ex}(f_1)$	$T_{ex}(f_2)$	$T_{ex}(f_3)$	$T_{ex}(f_4)$	T_{es1}
38.6 Deg	36.23	40.23	38.13	37.93	37.64
38.8 Deg	35.64	40.98	38.18	36.86	37.52
39 Deg	35.05	41.73	38.22	36.58	37.4

4. Conclusion

Based on the results shown in Figures 5 and 6, obtained by using the PAT simulation by k-wave Toolbox and comparing it to Equation 1, it is found that there is a significant similarity between the theoretical equations and the simulation results. In other words, according to Equation 1, the temperature is proportional to the mean of the pressure square, and it can be seen that in Figure 5 and Figure 6, the obtained curves in different scenarios are similar, and they are just slightly different in amplitude, caused by temperature changes in different scenarios. This result has been observed in simulation and practical studies [4, 10, 17]. The similarity demonstrates the ability to use the k-wave Toolbox to detect breast tumor activity with passive acoustic thermometers. In some studies [10, 14, 17], the PAT method for estimating the temperature in the sub-bands has been applied by practical experiments and simulation. This method calculates one estimation temperature of the target in each sub-band; therefore, several estimated temperatures are obtained for a target material. If the target material is not homogeneous, these estimated temperatures will be different. According to Table 3, obtained from temperature estimation in scenario 3 at different temp3 and temp4, the sub-band estimation, utilized in the practical experiment, has a different error, making it difficult to select true estimation. Therefore, we proposed a new formulation that provides only one estimation for the target material. In Table 4, the average error of temperature estimations for scenario 3 is shown.

According to a clinical study [18], the temperature difference between healthy tissue and cancerous tissue is between 2.6 -5.6 ° C. Therefore. As shown in Table.4, which is related to an average error of temperature estimations obtained in scenario 3 with three different tumor temperatures, the proposed formula for the 4 sub-band algorithm has an error equal to 1.28° C. Based on the results obtained in the previous section, using a simulated framework, it is possible to measure the temperature of the target object with a reasonable error. Hence, the k-wave toolbox can be utilized to measure a breast tissue temperature using the passive acoustic thermometer, allowing the examination of different conditions and algorithms. Also, it can reduce the costs of the practical test of a hypothesis.

Table 4. The average error of temperature estimation in scenario3 with 3 different tumor temperatures

	$T_{ex}(f_1)$	$T_{ex}(f_2)$	$T_{ex}(f_3)$	$T_{ex}(f_4)$	T_{es1}
AVG_E	3.16	2.18	0.62	1.68	1.28

5. Limitation

In this paper, we proposed a new formulation that is examined in simulation, but in future work, it must be evaluated in the practical experiment.

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