33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Medical Thermal Imaging of Electrically Stimulated Woman Breast: a simulation study

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Abstract— **Tissues have different electrical conductivity and metabolic energy consumption values depending on their state of health and species. Since metabolic heat generation values show differences from tissue to tissue, thermal imaging has started to play an important role in medical diagnoses. Temperature differences of healthy and cancerous tissue may be changed by means of frequency dependent current stimulation within medical safety limits, and thus, depth dependent imaging performance can be increased. In this study, a three-dimensional realistic model of a woman breast and malignant tissue is generated and frequency dependent feasibility work for the proposed method is implemented. Temperature distributions are obtained by solving Pennes Bio Heat Equation (using finite element method). Temporal and spatial temperature distribution images are obtained at desired depths for two cases; with and without current application. Different temperature distributions are imaged by altering the frequency of the applied current and the corresponding conductivity value. Improvement in the imaging performance can be provided by current stimulation, and the temperature difference generated by 40 mm^3 tumor at 1.5 cm depth can be detected on breast surface with the state-of-the-art thermal imagers.**

Index Terms— **medical diagnostic imaging, thermal infrared imaging, breast cancer diagnosis, bio-heat equation.**

I. Introduction

Infrared thermal imaging had initially started to be used for military purposes in research area. Medical studies with the thermal imaging have begun in the year of 1970's. At that time period digital infrared cameras had lower spatial resolution (128 x 128 pixels), limited thermal resolution (approximately ± 1°C) and slow response time due to single detector scanning. [2] However, the sensitivity of infrared thermal imaging systems has significantly increased in recent years. "Very fast focal plane array cameras in the 8 mm region (> 100 frames/sec, 256 x 256 pixels or more per frame) and high resolution fast scanning cameras were developed." [11] Temperature differences can be detected up to 20 m°C's with the recent thermal imagers. [10]

The imaging techniques used in the determination of the masses found in the breast are; mammography, ultrasound, computed tomography, magnetic resonance imaging and positron emission tomography. Mammography and ultrasound are the most common methods for the breast screening. Nevertheless, they have some disadvantages. Mammography has some diagnostic accuracy problems especially for smaller tumors and is not comfortable for patients. Ultrasound imaging cannot show micro calcifications and cannot monitorize deep areas of the breast. [5] On the other hand, thermal imaging is risk free, non-ionizing, patient - friendly and has better price to performance ratio compared to other imaging systems.

A three dimensional model of woman breast with embedded tumor is developed in this study. Cancerous tissue is placed in the healthy tissue. To solve the problem, bio-heat equation is figured out using finite element method. Applying current to the object at different frequency values, different temperature distribution images are obtained for the same object.

"Our objects in simulations are: 1) to be able to obtain temperature distribution of cancerous tissue at specific depths with recent thermal imagers, 2) by applying various low frequency currents in medical safety limits how much we can improve the temperature differences of cancerous and healthy tissue."[11] In our study, whether the following inequality (1) is correct or not is investigated.

$$T'o(x,y) - T'(x,y) > To(x,y) - T(x,y) \qquad (1)$$

TABLE I
Abbreviations of Thermal Image

T(x,y)	Thermal image of healthy tissue
T_0(x,y)	Thermal image of malignant tissue
T'(x,y)	Thermal image of healthy tissue when current is applied
T_0'(x,y)	Thermal image of malignant tissue when current is applied

"Performance improvement due to current application ((T'o-T')/(To-T)) refers to how much we can improve the temperature difference between the cancerous tissue and the healthy tissue." [11]

Manuscript received April 18, 2011. This work was supported from Turkish Government Planning Organization with BAP-08-11-DPT.2002K120510-BIL-7 project in the name of Akdeniz University.

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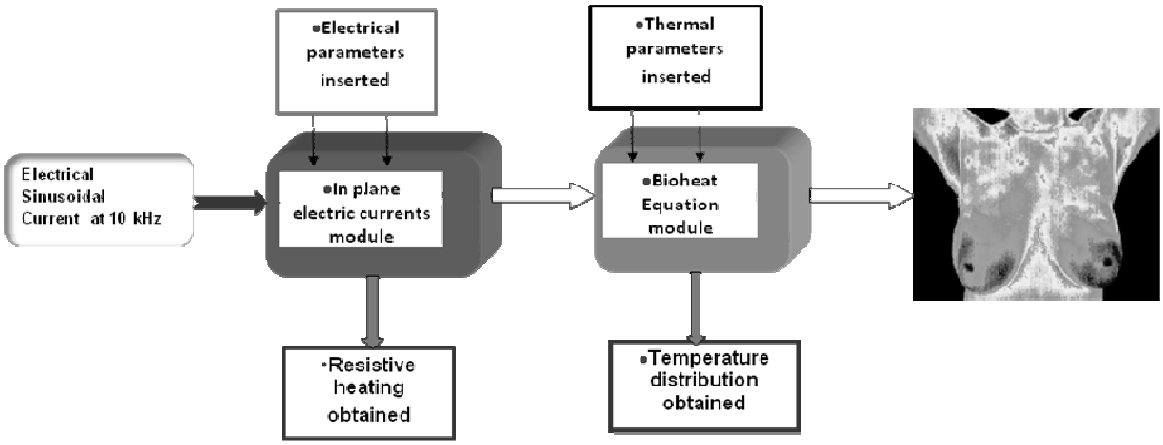

Figure 1. Flowchart of the Electrically Stimulated Thermal Imaging System

TABLE II
HEALTHY AND MALIGNANT TISSUE ELECTRICAL AND THERMAL CHARACTERISTIC VALUES [1], [3], [9], [11]

	Healthy Tissue	Malignant Tissue
ρ (kg/m^3)	920	920
ρ_B (kg/m^3)	1000	1000
C_B (J/kg°K)	4200	4200
W_B (1/s)	0.0018	0.009
T_B (°K)	310.15	310.15
Q_{met} (W/m^3)	450	29000
k ($W/m°K$)	0.42	0.42
σ(S/m)	0.0283	0.1804

Where ρ is density (kg/m^3),
C_B is blood specific heat (J/kg°K),
ρ_B is blood mass density (kg/m^3),
W_B is blood perfusion rate (1/s),
T_B is ambient blood temperature (°K),
σ is electrical conductivity (S/m),
k is thermal conductivity (W/m°K).
Q_{met} is metabolic heat generation (W/m^3).

Thermal and electrical conductivity parameters, metabolic heat values, blood perfusion rates used in simulations are real values (Table II) taken from the literature.

II. Problem Analysis and Modeling

A. Problem Definition and Analysis

Applied low frequency currents generate electric field in the breast environment. Electric field intensity is calculated with Maxwell Equations. After the electromagnetic field problem is solved, spatial heat value which is formed due to electric field intensity is obtained using Joule Heat Equation (Equation 5).

To be able to obtain temperature distribution of the tissue, Pennes proposes a method which describes the effects of metabolic generation and blood perfusion over energy balance. The most common approximation method to figure out heat problems in biological tissues is Pennes Bio Heat equation. This work explains the thermal interaction between tissues and perfused blood in detail.

$$\rho C \frac{\partial T}{\partial t} = \nabla . k \nabla T + Q_{met} + Q_B \quad (2)$$

$$Q_B = \rho_B C_B W_B (T_B - T) \quad (3)$$

Where C is specific heat (J/kg°K),
T is temperature (°K),
Q_B is heat source due to blood perfusion (W/m^3).

When there is no current stimulation, existing state can be called as thermal equilibrium state. Current application causes an additional heat source and finishes this state. In this case, a new heat source is generated in the tissue and temperature values will reach a new equilibrium state in a certain period of time. After having reached the steady state, contrast between the cancerous and the healthy tissue increases. This yields to be able to detect malignant tissue, even if, it is located at deeper locations. Due to the external source which is formed by the current that we apply, a new term should be inserted to the bio-heat equation. A modified version of the bio-heat equation is figured out to obtain images which have different temperature distributions. We decided to call this modified form of the equation "*Electrically Stimulated Pennes Bio Heat Equation*".

$$\rho C \frac{\partial T}{\partial t} + \nabla.(-k\nabla T) = Q_B + Q_{met} + Q_{ext} \quad (4)$$

Where Q_{ext} is the external heat source (W/m^3).

Natural convection on skin surface was also taken into account as a convective boundary condition and the heat transfer coefficient value which includes also radiation was taken as 5 W/m^{2}K.

In the meanwhile, at constant current values, different temperature distributions can be obtained at different frequencies for the same object.

$$Q = \frac{1}{\sigma}|J|^2 = \frac{1}{\sigma}|\sigma E|^2 = \sigma|\nabla V|^2 \quad (5)$$

Where J is current density (A/m^2),
σ is electrical conductivity (S/m),
E is electrical field (V/m),
V is electrical potential (V).

Finally, temperature increase is obtained with respect to time and space using Electrically Stimulated Pennes Bio Heat Equation.

B. Modeling

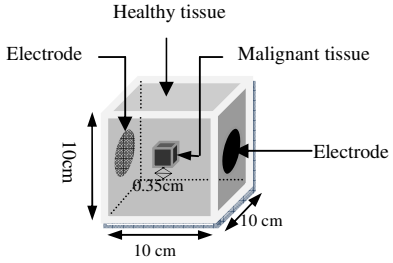

Fig. 2. Simulation Model

The designed model is objected to be closer to the real case. Woman breast is modeled by a large cube which has 10 cm x 10 cm x 10 cm dimensions and malignant tissue is modeled by a smaller cube which has 0.35 cm x 0.35 cm x 0.35 cm dimensions (approximately 40 mm^3).

Current is applied from left and right side surfaces with circular electrodes located at the center. Applied current values are within medical safety limits [6]. In the simulation study, Comsol Multiphysics Program is carried out to figure out bio heat problems [7]. In plane electric currents module and bio heat module are used simultaneously to solve the problem. Spatial heat source due to applied current is calculated using in plane electric currents module. Then, this value is inserted to the second module, 'bio heat equation module', and temperature distribution images of the tissue are obtained. Healthy and malignant tissue parameters used in simulations are found in Table 2. Figure 1 explains the numerical procedure schematically.

III. Temperature Distribution Images

A. Temperature Increases of Malignant Tissue at Different Depths

To be able to model the ideal situation, thermal camera looks at object is considered at the top and current is applied from right and left surfaces within medical safety limits. Tumour depths were changed in between 1 and 8 cm and corresponding temperature increases and performance improvements due to current application were obtained. In this simulation study, the dimension of tumor was selected as 3.375 mm^3 and 5 mA current at 10 kHz was applied for 300 second. 3.375 mm^3 tumor dimension was selected particularly because enhancement quantification (dynamic MR) allows detection of tumors to ~ 3 mm. [8] Here, performance improvement shows the increase of the temperature difference between the cancerous tissue and the healthy tissue when there is a current stimulation. Current application increases the temperature contrast in between the malignant and the healthy tissue.

TABLE III
Temperature Increases and Performance Improvements Due to Current Application

Tumor depth (cm)	Temperature (°C)	Performance improvement (%)
1	38.241	10.9
2	38.167	9.5
3	38.150	8.7
4	38.142	7.4
5	38.135	5.7
6	38.122	4
7	38.086	2.6
8	38.074	1.9

As it can be seen from Table III, whenever malignant tissue is getting closer to the surface, more temperature increases occur. Current application increases the temperature difference between the healthy and the malignant tissue, and a 1.5 - 11 % improvement in the performance (see Table III) was obtained depending on the location of the cancerous tissue. This tumour creates more than 20 m°C temperature increase at 8 cm depth. Therefore, it can be possible to detect malignant tissues up to 8 cm depth with today's modern thermal infrared imagers.

B. Temperature Increases of Malignant Tissue on the Breast Surface at Different Frequencies

In this simulation study, the dimension of tumor was selected as 40 mm^3 and 10 mA current was applied at various frequencies. Temperature distribution on the outer surface of the woman breast was obtained when the malignant tissue was located at a depth of 1.5 cm.

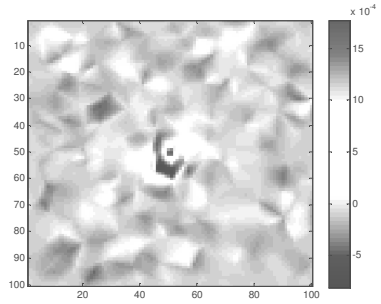

Fig.3. Temperature distribution image of tumor on the breast surface when there is no stimulation, color bar indicates the temperature difference (°C)

The temperature distribution image of a healthy tissue was provided when there is a tumor and when there is no tumor. Then, the difference of these two images was taken. Figure 3 shows the image of 40 mm^3 tumor on the breast surface when there is no current application. These shown images are barely the tumor itself (figure 3, 4, 5). The cancerous tissue was located at 1.5 cm depth. Without current stimulation, 2 m°C temperature difference can be obtained. This amount of difference cannot be sensed with today's technology. In figure , 10 mA current is applied at 100 kHz.

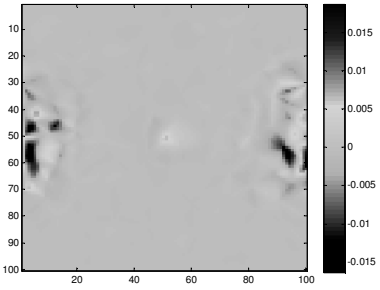

Fig.4. Temperature distribution image of tumor on the breast surface when there is 10 mA current stimulation at 100 kHz, color bar indicates the temperature difference (°C)

As it is seen, tumor is clearer at the center when it is compared to no current case (figure 3) and temperature difference was in between 10 and 20 m°C. However, current artifacts due to electrodes still exist at 100 kHz but they were removed at 800 MHz frequency value. The best contrast and the clearest image were obtained at 800 MHz (figure 5). Tumor dimension is very important parameter in tumor detection. 40 mm^3 tumor can be detected from 1.5 cm depth. On the other hand, this depth decreases to 0.9 cm for 3.375 mm^3 tumor. Bigger tumors lead to more temperature increases and hence, can be detected from deeper locations. By the help of the current application at different frequencies, cancerous tissue had emerged very clearly, and almost 60 m°C temperature increase occurred at the center.

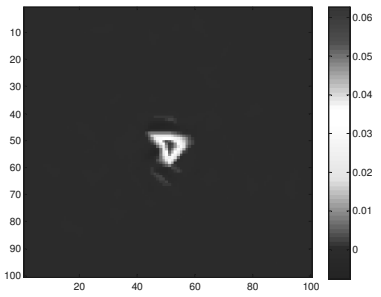

Fig.5. Temperature distribution image of tumor on the breast surface when there is 10 mA current stimulation at 800 kHz, color bar indicates the temperature difference (°C)

IV. CONCLUSION

In this study, 3 dimensional woman breast was modeled including malignant tissue, and thermal images of an electrically stimulated breast were obtained. The closer the tumor tissue to the surface, the higher the performance improvements can be acquired with the current application. Moreover, different temperature distributions were obtained for the same object by changing the frequency of the stimulation current. In the study, electrodes were assumed to be stable. If the places of electrodes are changed with respect to the location of the tumor tissue, more improvements in the performance can be achieved.

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