

Early Detection of Breast Cancer using Thermal Texture Maps

Hairong Qi, Phani Teja Kuruganti, Zhongqi Liu

Abstract—This paper focuses on the discussion of using thermal infrared imaging (TIR) in early detection of breast cancer. We use the term thermal texture maps to represent the images captured from TIR imaging. Even though the heat emanating onto the surface from the cancerous tissue can be successfully modeled using the Pennes bio-heat equation, the complexity of the boundary conditions associated with the biological body makes it impractical to solve the inverse problem. This paper presents a new method for analyzing a thermal system based on an analogy to electrical circuit theory; referred to as thermal-electric analog. We demonstrate how the analog can be used to estimate the depth of the heat source, and furthermore, help understand the metabolic activities undergoing within the human body. The method has been used in early breast cancer detection and has achieved high sensitivity. Several breast cancer study cases are given to show the effectiveness of the method. On-going clinical study results are provided as well.

I. Introduction

Temperature is a long established indicator of health. The Greek physician, Hippocrates, wrote in 400 B.C. that “In whatever part of the body excess of heat or cold is felt, the disease is there to be discovered.” The ancient Greeks immersed the body in wet mud and the area that dried more quickly, indicating a warmer region, was considered the diseased tissue [4], [10]. Before Galileo invented thermoscope, the ancient Egyptians used fingers as scanners to monitor the surface temperature of the human body [10]. Modern development of the temperature measurement has been in the area of thermal infrared (TIR) imaging which does not need body contact. Based on FDA’s definition, TIR imaging measures the heat emanating from the heat source transported by radiation.

Infrared (IR) radiation occupies the region on the electromagnetic spectrum between visible and microwaves. All objects in the universe emit radiations in the IR region as a function of their temperature. As an object gets hotter, it gives off more intense infrared radiation, and it radiates at a shorter wavelength [3]. Human eye cannot detect IR rays, but they can be detected using the thermal infrared cameras and detectors.

TIR imaging has been applied to a wide spectra of applications, ranging from the military, industrial engineering, to modern medicine. It is non-invasive and nondestructive, which makes it a valuable tool to assist diagnosis. 1)Electrical and Computer Engineering Department, University of Tennessee, Knoxville, TN 37996, USA, Email: hqi,teja@utk.edu

2)Bioyear Group, Inc. 10618 Rockley Rd., Houston, TX 77099 Email: ubyg@bioyear.net

This paper focuses on the discussion of using TIR imaging in early detection of breast cancer. We use the term thermal texture maps to represent the images captured from TIR imaging. The application of IR imaging in breast cancer study starts as early as 1961 when Williams and Handley first published their results in the Lancet [7]. However, “the ill-conceived and poorly controlled introduction of IR imaging into the Breast Cancer Detection Demonstration Projects (BCDDP)” 30 years ago has led to its early demise [5]. IR-based diagnosis was criticized to generate a higher false-positive rate than mammogram, and thus was not recommended as a

standard modality for breast cancer detection. We argue that one of the major problems existed in the early study of IR imaging is the prevalence of some superficial understanding of the generation of IR images. Conclusions such as “the resulting IR image contains only a small amount of information as compared to the mammogram, so that the reading of the IR image is a substantially simpler task [11]” shows severe misinterpretation of the thermogram.

Infrared imaging is a physiological test that measures the physiology of the blood flow and behavior of the nervous system by means of precise temperature measurement. Unlike imaging techniques such as X-ray radiology and CT that primarily provide information on the anatomical structures, IR imaging provides functional information not easily measured by other methods [3]. Thus correct use of IR images requires in-depth physiological knowledge for its effective interpretation.

All objects at temperature above absolute zero emit electromagnetic radiation spontaneously, called the natural thermal radiation [3]. The heat emanating on to the surface from the cancerous tissue and the surrounding blood flow can be quantified using the Pennes [9] bioheat equation [8]. This equation includes the heat transfer due to conduction through the tissue, the volumetric metabolic heat generation of the tissue, and the volumetric blood perfusion rate whose strength is considered to be the arterio-venous temperature difference. The equation is given as:

$$k\Delta^2 T - c_b w_b (T - T_a) + q_m = 0 \quad (1)$$

where k is conductivity, q_m is volumetric metabolic rate of the tissue, $c_b w_b$ is the product of the specific heat capacity, the mass flow rate of blood per unit volume of tissue T is the unknown tissue temperature, and T_a is the arterial temperature.

In theory, given the heat emanating from the surface of the body measured by IR imaging, by solving the inverse heat transfer problem, we can obtain the heat pattern of various internal elements of the body. Different methods of solving the bio-heat transfer equation have been presented in literature [1], [2]. Although it is possible to calculate the thermal radiation from a thermal body by thermodynamics, the complexity of the boundary conditions associated with the biological body makes this approach impractical.

This paper presents a new method for analyzing a thermal system based on an analogy to electrical circuit theory; referred to as thermal-electric analog. We demonstrate how the analog can be used to estimate the depth of the heat source, and furthermore, help understand the metabolic activities undergoing within the human body. The method has been used in early breast cancer detection and has achieved high sensitivity. Several breast cancer study cases are given to show the effectiveness of the method. On-going clinical study results are provided as well.

II. The Thermal-Electric Analog

As the living cells within a biological body are constantly undergoing metabolic activities, the biochemical and the physical metabolic processes generate heat. Thus the amount of radiation on the surface of the human body can reflect its metabolic rate. The theory underlying conventional thermographic techniques as applied to cancer is that the change of the pulse distribution around a cancerous area and the rate of metabolism are greater than the general tissue, resulting in a higher temperature at the skin surface [6].

Even though the temperature of the skin surface can be measured, if the relationship between the surface temperature and the emissions from inside of the body cannot be established, the application of TIR imaging technique is still limited. Pennes' bio-heat equation models the process

of heat transfer but has its limits in practice. Thus, a new method that does not require a direct solution to the inverse heat transfer problem, the thermal-electric analog, comes into light.

Figure 1 illustrates the analogy between thermodynamics systems and the electrical circuit, where the heat source S inside the human body can be simulated as a battery with voltage U_S , the heat loss inside the heat source can be simulated as the heat loss on a resistor R_S . The temperature

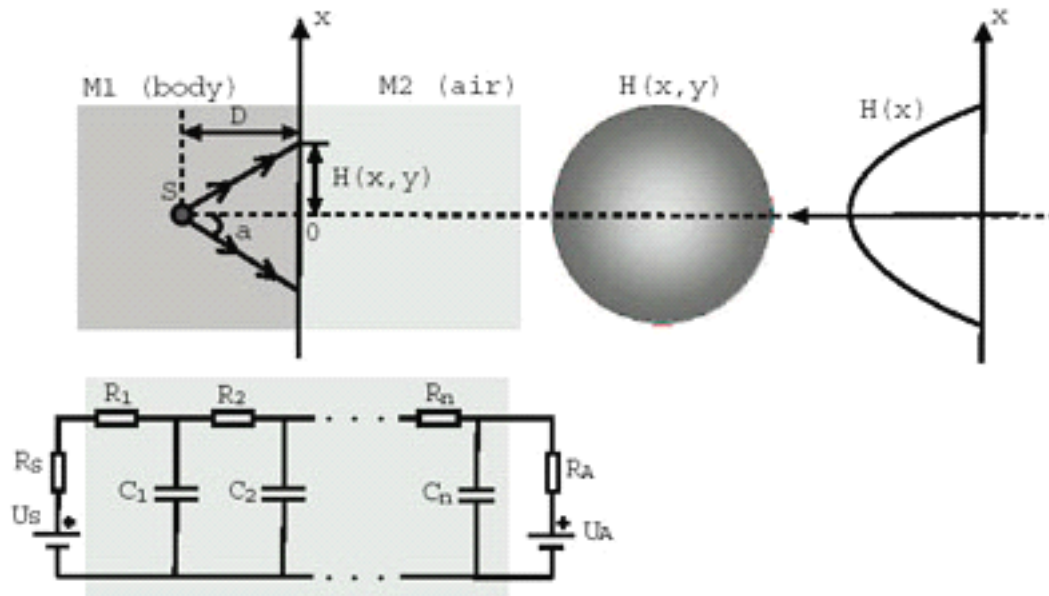


Fig. 1. The thermal-electric analog.

of the heat source can then correspond to the voltage of the battery, and the heat current to the circuit current. Similarly, we can map the heat source in the air (outside the human body) as U_A , and the heat loss as R_A . The set of R_i 's and C_i 's correspond to the unit heat resistance and heat capacity along each radiation line. The circuit in Fig. 1 only shows the analogy for one radiation line. In the study of breast cancer, it is reasonable to assume that the medium between the heat source (S) and the surface is homogeneous. Therefore, the radiation pattern sensed by the IR camera at the surface should have a distribution like Gaussian as shown in Fig. 1. The surface temperature $H(x)$ corresponds to the output voltage can then be calculated by Eq. 2.

$$H(x) = U_S - \frac{\sum_{i=1}^n R_i}{R_S + R_A + \sum_{i=1}^n R_i} \times (U_S - U_A) \quad (2)$$

and

$$n = \lfloor \frac{D}{R_0 \cos a} \rfloor$$

where a represents the largest integer less than a , n is the number of resistors used in the circuit, D is the depth of the heat source, and R_0 is the unit heat loss in a certain medium (or the heat resistance rate). Different parts of human body have different heat resistance rate, as shown in Table I.

body parts	heat resistance rate
fatty tissue	0.1 — 0.15 ⁰ C/cm
muscle	0.2 ⁰ C/cm
bone	0.3 — 0.6 ⁰ C/cm

TABLE I

Heat resistance rate of different body parts.

The thermal-electric analog provides a convenient way to estimate the depth of the heat source.

A. Estimation of the Depth of the Heat Source

The depth estimation is based on the assumption that we can use Gaussian to model the distribution of the surface temperature. Half power point is a useful property of Gaussian distribution. The property says that the half power point divides the area enclosed by the Gaussian into equally half. If we slice the Gaussian from top to bottom at a fixed interval as shown in Fig. 2, the increment of the radius in the horizontal direction would not have dramatic change until the half power point is crossed. From Fig. 2, we can see that the relative increment of the radius between the first slice and the second slice is 34 pixels, and 40 pixels between the second slice and the third slice, but 116 pixels between the third slice and the fourth slice. Therefore, the half power point is at the position of the third slice.

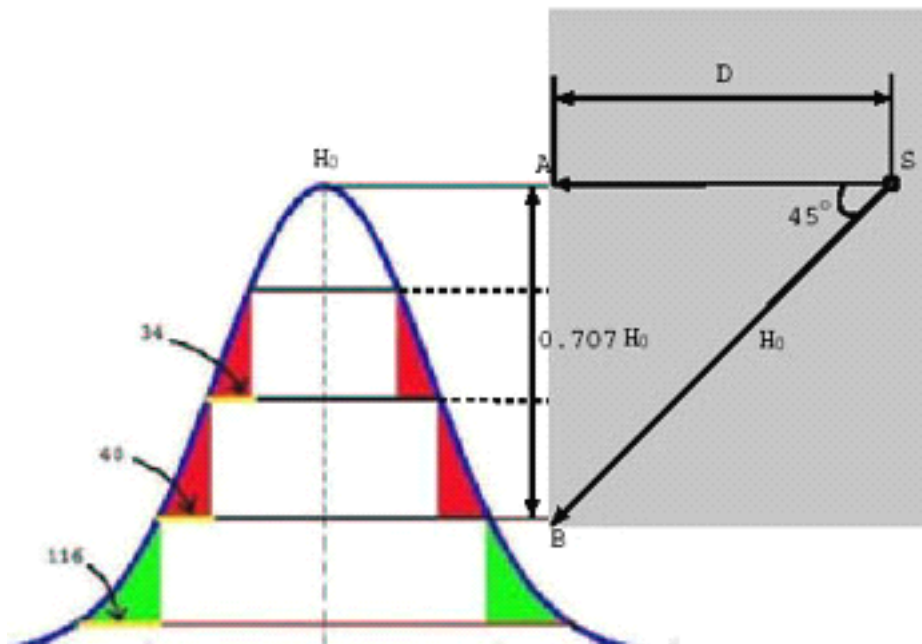


Fig. 2. Illustration of half power point of Gaussian and the depth of the heat source.

Suppose the temperature of the heat source is H_0 . In the right triangle formed by SAB, the hypotenuse (SB) is equal to H_0 and the sides (SA = AB) should be equal to $0.707H_0$. The horizontal side (SA) is the depth of the heat source, and the vertical side (AB) is the temperature drop between the maximum value of the Gaussian and the half power point. In another work, if we can find the half power point, we can find the depth of the heat source. Each slice of the Gaussian curve corresponds to a temperature deduction of 0.1 degree. For the application of breast cancer detection, based on the heat resistance rate of fat tissues, the 0.1 degree temperature drop

corresponds to a distance of 1cm. Therefore, by slicing (decreasing) the surface temperature at a certain degree per step, we can find the half power point with the accuracy at the level of centimeter.

III. Experimental Results and Analysis

A. Simulation Results

Figure 3 shows a synthetic example of how slicing works. The image is taken from a piece of pork fat. An electric bulb is lit and inserted at the center of the pork fat as a heat source such that we can control the location of the heat source. The pseudo color-map is also shown in the figure. “White” represents the highest temperature and “black” represents the lowest temperature. First of all, an appropriate temperature needs to be found such that white pixels at the center of the pork fat will show up in the next slice. In this example, this appropriate temperature is 20.50o. Each following slicing process decreases the highest temperature in the color-map by 0.1 degree (e.g. the threshold is lowered by 0.1 degree), such that more white pixels can appear. If we come to a point where the increment of the white pixel is dramatic, the half power point is the slice before it. In the example, the fourth slice generates much more white pixels than the previous three slices. The depth of the bulb is 3cm, which is the same as the ground truth. Note that the increment of the white pixel is measured by the increment of the radius of the white cluster.

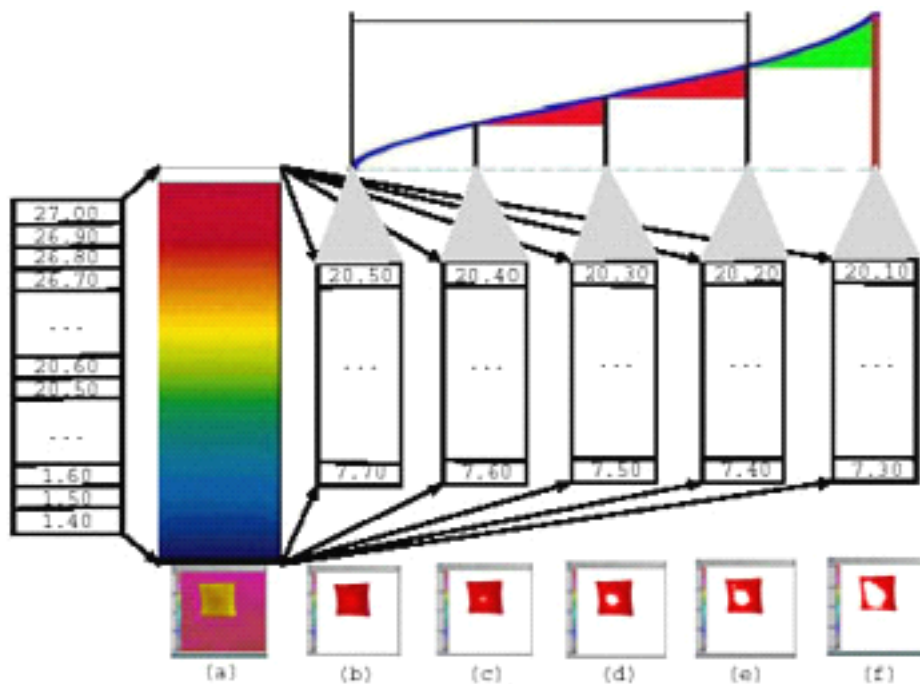


Fig. 3. Simulation of slicing operation on pork fat.

B. Patient Data Analysis

Besides measuring the depth of the heat source, slicing can also reveal the growth pattern of the white pixels. Different tissues have different growth patterns. By observing this pattern, different tissues can be distinguished as well. For example, the pixels of lymph nodes and tumors should grow in a circular pattern, while the growth pattern of blood vessel is along the direction of the blood vessel.

A diagnosis protocol has been designed for early breast cancer detection. Six steps are involved in this protocol: . Step 1: Growth pattern of lymph nodes in the armpits

. Step 2: Size of the abnormal area

- . Step 3: Appearance of the abnormal area
- . Step 4: Vascular pattern
- . Step 5: Nipples and areola pattern
- . Step 6: Dynamic diagnosis with outside agents (antibiotic, etc.)

Take the .rst step as an example, if the lymph nodes in the armpits reveal one heat source with a depth less than 2cm, one abnormal sign (+) will be recorded; if two heat sources appear with a depth less than 2cm and a bilateral temperature di.ference greater than 0.2 degree, then two abnormal signs (++) will be recorded, etc.

Figure 4 shows a patient with lobular carcinoma in the left breast. From slicing, we observe the following abnormal signs:

1. 2cm tumor surrounded by 4 blood vessels (+++);
2. White pixels surround the nipple in 3 slices (+++);
3. Nipple bilateral temperature di.ference is 0.8 degree (+).

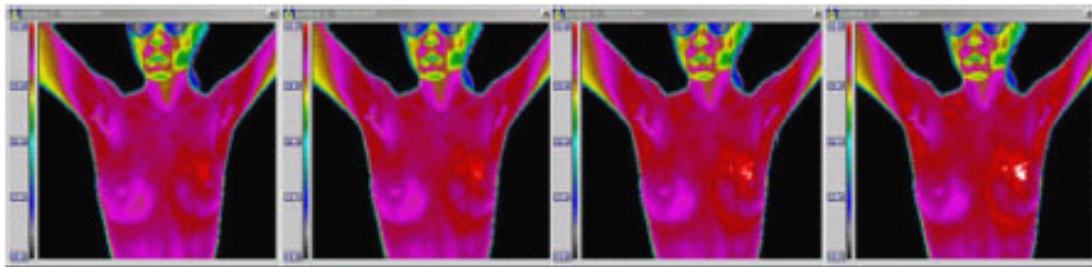


Fig. 4. Slicing of patient with lobular carcinoma in the left breast.

Figure 5 shows a patient diagnosed to have ductal carcinoma in her left breast. From slicing, we observe the following abnormal signs:

1. Lymph node bilateral temperature di.ference is 0.8 (++++);
2. The tumor is 2cm from the surface (++);
3. The tumor is surrounded by .ve blood vessels (+++);
4. It takes less than three slices to have the white pixels surround the nipple (++).

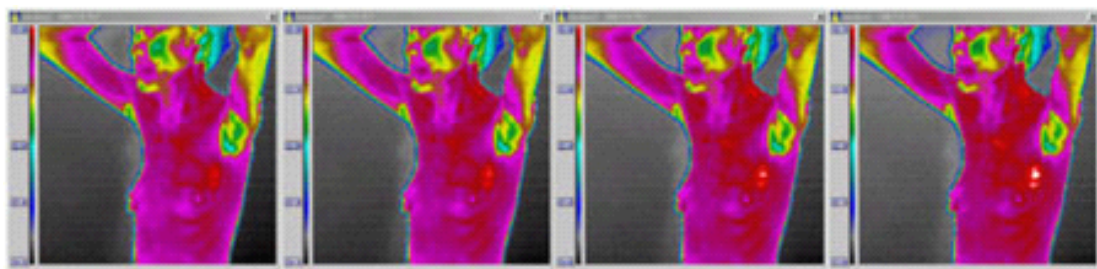


Fig. 5. Slicing of patient with ductal carcinoma in the left breast.

IV. Summary

Slicing is not a new technique. Radiologists have been using slicing to observe IR images all the time. The innovations of this paper lie in the fact that it .rst reveals the relationship between the pattern in each slice with the metabolic activities within a patient's body. Using thermal-electric analog and half power point to estimate the depth of tumor is just one way to reveal this relationship. This technique and the resulting apparatus have been patented [6]. We refer to the

system as Bioyear system or the TMI system. Clinical study has shown increased sensitivity and specificity. The concept has been validated in China for several applications, including breast cancer detection, ovarian cancer detection. About 400,000 patients were scanned using the Bioyear system in .ve years. Among them, 50,000 patients did breast scan. There are 103 breast cancer cases detected by TMI were proved by biopsy. Among these 103 cases, 92 cases also went through mammography. Mammography missed 6 out of these 92 cases. 2 of the missed tumor size is 2mm. The concept is also in the process of validation in US/Canada, including the Ville Marie Breast Cancer Center in Canada (TMI's diagnosis agrees with Center's diagnosis on 198 cases out of 200 testing images), Elliott Mastology Center at Baton Rouge, LA, and NIH (Kaposi Sarcoma / Angiogenesis).

The system is also used for ovarian cancer detection. Of the 77 cases studied, the error rate of IR is 6% compared to the error rate of ultrasound or CT scan which ranges from 3% to 5% where body contact is needed and is painful.

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