

IDENTIFICATION OF SKIN LESIONS FROM THE TRANSIENT THERMAL RESPONSE USING INFRARED IMAGING TECHNIQUE

M. Pirtini Cetingul, C. Herman

Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD, USA
{mpirtini,cherman}@jhu.edu

ABSTRACT

Increased availability of thermal imaging cameras has led to an interest in the application of infrared imaging techniques to the detection and identification of subsurface structures. We study the use of the transient thermal response of skin layers to determine to which extent surface temperature distribution reflects the properties of subsurface structures, such as lesions. A numerical model using the finite element method is described to obtain this response, which enables us to draw conclusions regarding the size, depth and nature of subsurface structures. This work validates the idea of examining the transient thermal response and using thermal imaging as a solution for lesion identification. A sensitivity study of surface temperature distribution to variations of thermophysical properties, blood perfusion rate, and thicknesses of skin layers is performed. It is observed that variations in these parameters have minimal effects on surface temperature distribution.

Index Terms— Infrared imaging, Transient thermal response, Skin lesions

1. INTRODUCTION

The infrared imaging technique has been quite successful in measuring physical properties in single or multi-layer systems, as it is documented particularly in the manufacturing applications by Honner et al. [11], building services by Datcu et al. [4], polygraph by Pavlidis and Levine [17], military applications by Deans et al. [5], contact problems by Sakagami et al. [19], geological applications by Yoshimori et al. [23] and biological tissue by Head and Elliot [9], Jones and Plassmann [12] and Otsuka et al. [16]. Recent improvements in infrared sensor and computer technology led to the resurgence of the infrared imaging in medicine. The technique has many advantages such as being noninvasive and relatively less expensive than MRI or ultrasound, whereas its main drawback is the need of knowing surface emissivity to obtain quantitative results.

A considerable amount of work has been done on the general problem of layered samples with fixed thermal properties subjected to external heating and cooling. Li et al. [14], Hierl et al. [10] showed that sudden heating or cooling of a surface is used to enhance the detection capability of buried objects by thermal infrared imaging. To the authors' knowledge, Gustafsson et al. [8] presented the first work that analytically calculated the skin temperature distribution due to subcutaneous heat production in a spherical heat source. From a medical perspective, any disease can be associated with an alteration of the thermal distribution of human body. This principle motivated Xianwu et al. [22], Buzug et

al. [2] and Mital and Scott [15] to detect the abnormalities such as breast cancer and skin cancer.

This paper aims at developing an infrared imaging based model to estimate the location, size, and nature of skin lesions as well as subsurface lesions. We use a simplified model to obtain physiological information and detect lesions close to the skin surface, with the possibility of applying this model to other diseases. Many of the parameters used in the model, such as thermophysical properties, dimensions and locations of lesions relative to the skin surface vary widely. First, the model is used to investigate the importance of the aforementioned parameters for surface temperature distribution. Next, the time evolution of the infrared signal is analyzed after a cold stress is applied to human skin. In the modeling step, a constant temperature boundary condition applied to the skin surface yields cooling, and a natural convective boundary condition allows the tissue to return to the steady state. By considering both the steady state and transient results, information about the size and depth of masses within the skin layers is recovered.

2. THEORY

Stenn [20] represented the skin as a complex inhomogeneous medium. It consists of three main layers from the surface: epidermis, dermis and subcutaneous fat. Human skin can be modeled, by Pennes [18], using the bioheat equation, which is a modified ordinary transient heat conduction equation given by:

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + \rho_b C_b w_b (T_b - T) + Q_{met} \quad (1)$$

where ρ is the tissue density, C is the heat capacity of the tissue, T is the local tissue temperature, k is the thermal conductivity of the tissue, ρ_b is the blood density, C_b is the heat capacity of the blood, T_b is the arterial blood temperature, w_b is the blood perfusion rate per unit volume and Q_{met} is the metabolic heat generation per unit volume. The term on the left-hand side of the equation is the rate of change of thermal energy contained in a unit volume. The three terms on the right-hand side represent the rate at which thermal energy enters or leaves the unit volume by conduction, perfusion and metabolic heat generation respectively. For our simplified numerical model, metabolic heat generation is taken as zero. Skin tissue is modeled as a semi-infinite homogeneous medium. Femlab, commercial software by Comsol [3], uses finite element method to solve the coupled differential equations for the three skin layers.

The thermophysical properties of the skin vary widely throughout the body and from subject to subject. Torvi and Dale

[21] carried out a literature survey to determine the range of variation of the thermophysical properties. Their results relevant for our study are shown in Table 1. The blood perfusion rates in Table 1 correspond to the normal blood perfusion rate and twice that value. In addition, we investigate the variation in thicknesses h of the skin layers.

Table 1. Properties of skin layers

	Epidermis	Dermis	Fat Layer
h (mm)	0.08-0.1	2-4	8-10
C (J/kgK)	3578-3600	3200-3400	2288-3060
k (W/mK)	0.21-0.26	0.37-0.52	0.16-0.21
ρ (kg/m ³)	1200	1200	1000
w_b (1000/s)	0	6-12.5	6-12.5

Figure 1 is a representative model of skin tissue with a lesion embedded into the epidermal and dermal layers. Based on the study by Elder [7], which considers lesions as generally symmetric structures, a 2D axisymmetric model is formed, as shown in Figure 1(b). The lesion is represented by a circular region with a constant temperature boundary condition prescribed along its perimeter. To create semi-infinite tissue layers, the model is simply made large enough in the lateral direction to deem the thermal effects of the lesion negligible at the side boundary of the model.

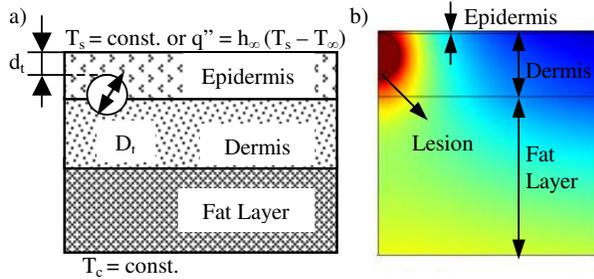


Figure 1. (a) Sketch of skin layers, lesion geometry, initial and boundary conditions, (b) Geometry for the computational model

Skin lesions are modeled as 0.5, 1.5, and 4 mm in diameter, and spheres are located starting in the epidermis at 0.02, 0.04, and 0.06 mm depth below the surface. The lesions are considered to be 0.5, 1.5, and 3 degrees warmer than the core body temperature based on study by Lawson [13] and Deng and Liu [6]. Thermal conductivity of a skin lesion was found to be approximately 89% that of water by Ahuja et al. [1]. Assuming a standard core body temperature of $T_c = 310.15$ K and a specific heat and density approximately comparable to the properties of water, we obtain the following skin lesion properties: $k_l = 0.558$ W/m K; $C_l = 3852$ J/kg K; $\rho_l = 1030$ kg/m³.

The problem is first solved for the steady state situation. The surface is exposed to natural convection, which is a boundary condition described by equation $q'' = h_{\infty}(T_s - T_{\infty})$ with a heat transfer coefficient of $h_{\infty} = 20$ W/m² K and ambient temperature of $T_{\infty} = 294.15$ K. This solution serves as the initial condition to study the effects of cooling. To achieve cooling, a surface temperature boundary condition of $T_s = 273.15$ K is applied to the surface. The skin is cooled for duration of 120 s. After this step, the constant temperature boundary condition is removed, and the surface is again exposed to natural convection. The skin is then allowed to return to its original temperature, which is called the recovery process. It takes approximately 1500 s for the skin to

reach its original steady state condition. The sizes, depths and temperatures of the lesion, each having three different values, are tested to evaluate the changes of the surface temperature distribution as a function of the lesion parameters. In addition, the effects of varying the values of specific heat, thermal conductivity, blood perfusion rate and thicknesses of the skin layers on surface temperature are investigated as a part of the sensitivity study. Each parameter is tested at its extreme values for a single layer, while keeping those values for the remaining layers constant. The resulting surface temperature distributions are compared and the maximum temperature difference after the skin reaches its steady state is used as a measure of the sensitivity.

3. RESULTS

The results of the sensitivity study for each parameter are summarized in Table 2. As the variations in these thermophysical properties are minimal over the individual layers, variations in temperature are found to be very small as well. The results of varying the blood perfusion rate and the thicknesses are outlined in Table 3. It is observed that the perfusion rate and the thicknesses have little effect on surface temperature distribution.

Table 2. Maximum temperature differences for variation thermophysical properties

	C (J/kgK)	Max. ΔT	k (W/mK)	Max. ΔT
Epidermis	3578-3600	0.01	0.21-0.26	0.04
Dermis	3200-3400	0.02	0.37-0.52	0.3
Fat Layer	2288-3060	0.2	0.16-0.21	0.2

Table 3. Maximum temperature differences for the blood perfusion rate and thickness variation

	w_b (1000/s)	Max. ΔT	h (mm)	Max. ΔT
Epidermis	0	0	0.08-0.1	0.02
Dermis	6-12.5	0.5	2-4	0.2
Fat Layer	6-12.5	0.6	8-10	0.2

Figure 2 displays the 2D temperature distribution in a skin cross-section with a 0.5 mm diameter lesion present. The first two temperature distributions present the steady state with the natural convection boundary condition and two minutes after the cooling stress is applied, respectively. After the cooling stress is removed, the temperature distribution is displayed at different recovery times. It is observed that the skin temperature reaches steady state after approximately 25 minutes.

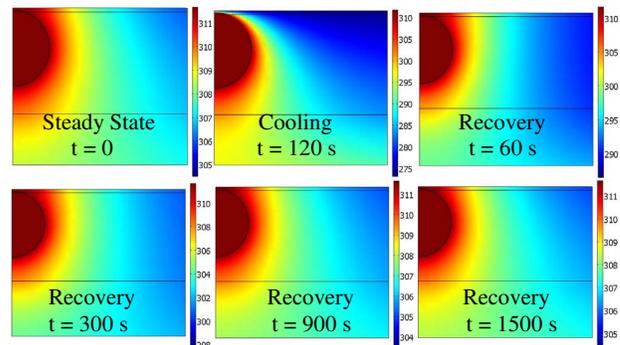


Figure 2. Sequence of images displaying the temperature fields in a skin cross-section for steady state, cooling and recovery conditions

Figure 3 shows the surface temperature profiles during the recovery phase for different lesion depths, sizes. Each line represents a particular recovery time. The plots illustrate the speed at which natural convection heats the skin. The largest temperature changes occur in the first few minutes after the cooling is removed. The temperature profiles also indicate that lesion size is of greater influence than lesion depth, and size affects both peak temperature and width of the region affected by the lesion.

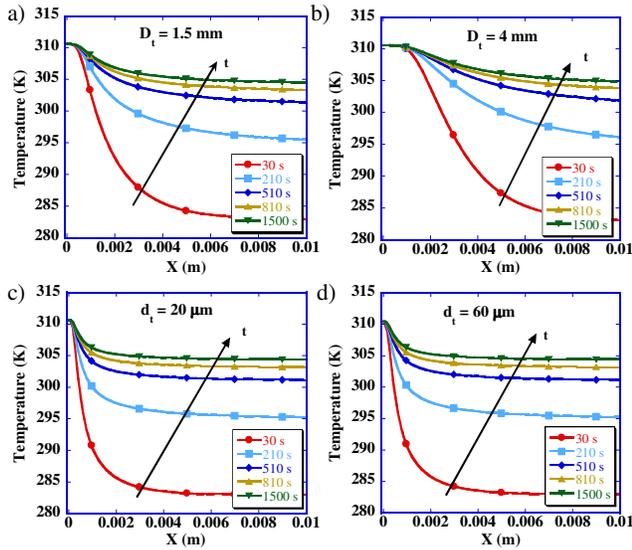


Figure 3. Surface temperature profiles for lesion diameters D_t (a) 1.5 mm, (b) 4 mm, for lesion depths d_t (c) 20 μm , (d) 60 μm

Figure 4(a) shows the transient response of the skin surface temperature at location 1 mm away from the lesion axis. The lesion is at a depth of 20 μm during the recovery process and results are shown for three different lesion diameters. Within the first 10 seconds after removing the cooling stress, the temperature converges rapidly to the initial steady state value for the 4 mm diameter lesion, while the temperatures for the 0.5 and 1.5 mm diameter lesions take longer time to reach steady state values. Figure 4(b) shows the transient response of the skin surface temperature at location 10 mm away from the axis of 4 mm diameter lesion during the heating process for three lesion depths. Depths appear to make only a slight difference in the transient response of the surface temperature.

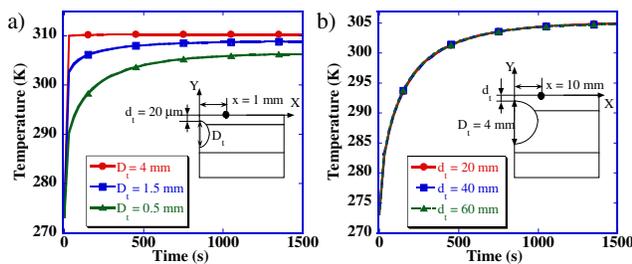


Fig. 4. The transient response of the skin surface temperature; (a) $x = 1 \text{ mm}$, $d_t = 20 \mu\text{m}$, (b) $x = 10 \text{ mm}$, $D_t = 4 \text{ mm}$

The standard deviation is the root mean square deviation of values from their arithmetic mean. The standard deviation along the surface temperature profile is related to the width of the region affected by the lesion. Figure 5 displays the transient response of standard deviation of the surface temperature profile for different depths and sizes. The results show that depth makes little difference in the width of the region affected by the lesion; however, standard deviation at any point in time during the heating process yields valuable information about the size of the lesion.

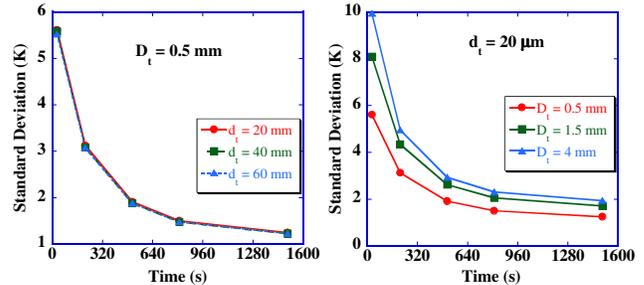


Figure 5. The transient response of standard deviation from the mean temperature of the surface temperature profile for different depths and sizes

4. CONCLUSIONS

Infrared imaging is a reliable, inexpensive and noninvasive technique that has been used to obtain physiological parameters in human tissue. The skin layers subjected to cooling are tested using numerical modeling to see the effects of variations in thermophysical properties, blood perfusion rate and thicknesses of skin layers on surface temperature distribution. It is found that the variations in these parameters have little effect on surface temperature distribution. By selecting the duration of cooling stress, the internal temperature of the skin changes, and this change can be felt at different depths. When the cooling stress is removed, the transient response yields valuable information pertaining to size and depth of any abnormalities within the skin. The results of the numerical studies using the Femlab software provide visual identification of the lesion depth and size based on surface temperature. This work explores the possibilities and limitations of this combined experimental and modeling approach. The surface temperature distribution obtained in this way is expected to be consistent with the patterns recorded by the infrared camera.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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