IDENTIFICATION OF SUBSURFACE STRUCTURES FROM THE TRANSIENT THERMAL RESPONSE AND SURFACE TEMPERATURE MEASUREMENTS

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Abstract

Infrared imaging techniques offer an opportunity for detecting and identifying subsurface structures. The principle of these techniques is based on the fact that, when a surface is heated or cooled, identifiable temperature contours develop on it due to the variation in the thermal properties of the subsurface structure. These contours are characterized by the structure’s size, depth, and its thermal properties. In this paper, the transient thermal response of skin layers is analyzed to match the surface temperature distribution with the properties of subsurface structure, such as a lesion. Numerical simulations based on using an appropriate finite element model are preformed to obtain these responses and draw conclusions regarding the size, position 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 presented in the paper. It is observed that variations in these parameters have minimal effects on surface temperature distribution.

Nomenclature

Subscripts

\( w_b \) blood perfusion rate (1/s)
\( Q_{\text{met}} \) metabolic heat generation (W/m³)
\( d \) depth (m)

Subscripts

\( b \) blood
\( s \) surface
\( \infty \) ambient
\( t \) tumor
\( c \) core

1 Introduction

Infrared imaging techniques have been applied to measure physical properties in single or multilayer systems; particularly in the manufacturing applications by Honner et al. (2004), building services by Datcu et al. (2005), military applications by Deans et al. (2006), contact problems by Sakagami et al. (2000) and biological tissue by Head and Elliot (2002), Jones and Plassmann (2002) and Otsuka et al. (2002). Recent improvements in infrared sensor and computer technology resulted in a resurgence of interest in infrared imaging in medicine. The technique has many advantages such as being noninvasive and relatively less expensive than MRI or ultrasound.

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. (1995), Hierl et al. (1997) showed that sudden heating or cooling of a surface enhances the detection capability of buried objects by thermal infrared imaging. Gustafsson et al. (1975) analytically calculated the skin

1 This work has been funded by NSF (Grant No.0651981).
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. Lesions are accompanied by local temperature changes, which are a result of the changes in metabolic activity of the diseased tissue. This principle motivated Xianwu et al. (2004), Buzug et al. (2006) and Mital and Scott (2007) to detect the abnormalities such as breast cancer and skin cancer.

This paper is focused on developing an infrared imaging based model to estimate the location, size, and nature of skin lesions as well as other subsurface lesions. A simplified model is presented to obtain physiological information and detect lesions close to the skin surface, with the possibility of applying this model to other diseases or situations arising in engineering or nature. Many of the parameters, which are used in the model, such as thermophysical properties, dimensions and location of lesions relative to the skin surface, vary widely. First, the importance of these parameters for surface temperature distribution is investigated. Next, the time evolution of the infrared signal is analyzed after a cold stress is applied to human skin. In the modeling effort, 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. The information about the size and depth of masses within the skin layers is recovered by considering both the steady state and transient results.

2 Theory

Stenn (1988) represented the skin as a complex inhomogeneous medium consisting of three layers from the surface: epidermis, dermis and subcutaneous fat. The most common model for simulating the thermal behavior in living tissue is the bioheat transfer equation by Pennes (1948), which is a modified ordinary transient heat conduction equation, given by:

\[
\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + \rho_b C_b w_b (T_b - T) + Q_{\text{met}},
\]

where \(w_b\) is the blood perfusion rate, \(T\) is the local tissue temperature, \(T_b\) is the arterial blood temperature, and \(Q_{\text{met}}\) 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. On the right-hand side the three terms represent the rate at which thermal energy enters or leaves the unit volume by conduction, perfusion and metabolic heat generation, respectively. Metabolic heat generation is taken as zero in our problem to simplify the numerical model. Skin tissue is modeled as a semi-infinite homogeneous medium using Femlab, commercial software by Comsol (2006). Based on the finite element method, the coupled differential equations for the three skin layers are solved.

The thermophysical properties of the skin vary widely throughout the body and from subject to subject. A literature survey was carried out by Torvi and Dale (1994) to determine the range of variation of the values of the thermophysical properties. 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, the variations in thicknesses of the skin layers are investigated.

<table>
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<th>Table 1: Properties of skin layers</th>
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<td>Thickness (m)</td>
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<td>Epidermis</td>
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<tr>
<td>Dermis</td>
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<tr>
<td>Subcutaneous fat</td>
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Figure 1 is a representative model of skin tissue with a lesion of conical shape embedded into the epidermal and dermal layers. Based on the study by Elder (1999), which considers lesions as generally symmetric structures, a 2D axisymmetric model is formed, a cross-section of it shown in Figure 1b. A triangular region represents the lesion 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 and into the depth to deem the thermal effects of the lesion negligible at the side boundary of the model.

Skin lesions are modeled as cones, 0.5, 1.5, and 4 mm in width and height to study the influence of lesion size on the thermal response, and they are located starting in the epidermis at 0.02, 0.04, and 0.06 mm depth below the surface to evaluate the influence of depth. The lesions are considered to be 0.5, 1.5, and 3 degrees warmer than the core body temperature to evaluate the influence of lesion temperature based on study by Lawson (1956) and Deng and Liu (2004). The thermal conductivity of a skin lesion was found to be approximately 89% that of water by Ahuja et al. (1978). 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:

$$k_t = 0.558 \text{ W/mK}; \quad C_t = 3852 \text{ J/kg K}; \quad \rho_t = 1030 \text{ kg/m}^3.$$

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/m$^2$K, corresponding to natural convection in ambient air, 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 boundary condition of $T_s = 273.15$ K is applied to the surface. The skin is cooled for duration of 120 s. After two minutes, 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 influences of the sizes, depths and temperatures of the lesion are tested to evaluate the changes of the surface temperature distribution as a function of the lesion parameters. In addition, the effects of varying 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 absolute 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 the investigated thermophysical properties are minimal over the individual layers, the variations in temperature are found to be very small as well. The results of varying the blood perfusion rate and the thicknesses are summarized in Table 3. It is shown here that the perfusion rate and the thicknesses have little effect on surface temperature distribution.

<table>
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<th>Table 2: Maximum absolute temperature differences for variation thermophysical properties</th>
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<td>Specific Heat (J/kgK)</td>
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<td>Epidermis</td>
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<tr>
<td>Dermis</td>
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<td>Subcutaneous fat</td>
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<th>Table 3: Maximum absolute temperature differences for the blood perfusion rate and thickness variation</th>
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<tr>
<td>Blood perfusion rate (1/s)</td>
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<td>Epidermis</td>
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<td>Dermis</td>
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<td>Subcutaneous fat</td>
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Figure 2 displays the 2D temperature distribution in a skin cross-section with a 4 mm width and 1.5 mm height lesion present. The temperature distributions in Figure 2a and 2b display the steady state. Figure 2a for ambient conditions with the natural convection at the boundary surface and Figure 2b two minutes after the cooling stress is applied, respectively. After the cooling stress is removed, the temperature distribution is displayed at different recovery times in Figure 2c-f. It is observed that the skin temperature reaches initial steady state after approximately 25 minutes.

Figure 2: Sequence of images displaying the temperature fields in a skin cross-section with a lesion for steady state, cooling and recovery conditions
Surface temperature profiles during the recovery phase for different lesion depths and sizes are shown in Figure 3. 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, especially lesion width, is of greater influence in the surface temperature distribution than lesion depth. Lesion size affects both peak temperature and width of the region affected by the lesion. Lesion width, depth and height are identified in Figure 1a.

Figure 3: Surface temperature profiles for lesion width $W_t$ (a) 1.5 mm, (b) 4 mm, for lesion height $H_t$ (c) 0.5 mm, (d) 1.4 mm, for lesion depths $d_t$ (e) 20 $\mu$m, (f) 60 $\mu$m
Figure 4a shows the transient response of the skin surface temperature at a location 1 mm away from the lesion axis. The lesion is at a depth of 20 µm, temperature profiles are displayed during the recovery process and results are shown for three different lesion widths. Within the first 10 seconds after removing the cooling stress, the temperature converges rapidly to the initial steady state value for the 4 mm width lesion, while the temperatures for the 0.5 and 1.5 mm width lesions take longer time to reach steady state values. Figure 4b shows the transient response of the skin surface temperature at location 1 mm away from the axis of 1.5 mm width lesion during the recovery process for three lesion heights. The response for different heights does not show significant impact compared to the influence of widths. Figure 4c shows the transient response of the skin surface temperature at the same location from the axis of a 1.5 mm width and 1.5 mm height lesion during the recovery process for three lesion depths. Depths appear to have only a slight influence on the transient response of the surface temperature.

We use the standard deviation, the root mean square deviation of values from their arithmetic mean, to characterize the thermal response of the skin with a lesion present. The standard deviation of 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 of lesions. The results show that depth of the lesion makes little difference in the width of the region on the surface, viewed in terms of the surface temperature distribution, affected by the lesion; however, standard deviation at any point in time during the recovery process yields...
valuable information about the width of the lesion. The surface temperature distributions are most sensitive to lesion width, moderately sensitive to lesion height and insensitive to lesion depth.

Figure 5: Standard deviation of the transient temperature from the mean temperature of the surface temperature profile for different lesion depths and sizes at $t = 1500$ s

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 in the presence of a lesion. It is found that the variations in these parameters have little effect on surface temperature distribution. By selecting the duration of cooling stress, the 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 underneath the skin surface. The results of the numerical studies using the Femlab software allow visual identification of the lesion depth and size based on computed surface temperature profiles. Future work is focusing on experimental modeling of subsurface skin lesions and the identification of their characteristic features by comparing experimental data obtained using infrared imaging with data (similar to data reported in this paper) obtained using numerical models. 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.
6 References

Comsol Multiphysics, 2006, Version 3.2b, Comsol Inc.