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Modeling of bioheat equation for skin and a preliminary study on a noninvasive diagnostic method for skin burn wounds

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ABSTRACT

Heat transfer in a unit three-dimensional skin tissue with an embedded vascular system of actual histology structure is computed in the present work. The tissue temperature and the blood temperatures in artery and vein vessels are solved with a multi-grid system. The mean temperature of the tissue over the cross-section of the unit skin area is evaluated. The resulting one-dimensional function is regarded as the temperature of healthy tissue (or injured skin but the blood perfusion is still normally working) for large area of skin in view of the symmetric and periodic structure of the paired artery–vein vessels in nature. A three-dimensional bioheat equation then is formulated by the superposition of the skin burn wound effect and the healthy skin temperature with and without thermal radiation exposure. When this bioheat equation is employed to simulate ADT process on burn wounds, the decaying factor of the skin surface temperature is found to be a sharply decreasing function of time in the self-cooling stage after a thermal radiation heating. Nevertheless, the boundary of non-healing (needing surgery) and healing regions in a large burn wound can be estimated by tracking the peak of the gradient of decaying factor within 30 s after the thermal radiation is turned off. Experimental studies on the full ADT procedure are needed to justify the assumptions in the present computation.

1. Introduction

The first attempt to quantitatively describe heat transfer in human tissue with blood flow effect was presented by Pennes [1]. He added a source term $\omega_b\rho_b(c_p)_b(1-k)(T_a-T)$ to the heat conduction equation for tissue temperature by considering heat transfer from blood to tissue, where T_a and T denote arterial blood and tissue temperatures, while ρ_b, $(c_p)_b$ and ω_b are density, specific heat and perfusion of blood, respectively. The equilibrium factor

$$k=\frac{T_v-T}{T_a-T} \quad (1)$$

is a prescribed constant in the range $0 \le k \le 1$ throughout the tissue. Pennes [1] assigned $k = 0$ by assuming thermal equilibrium between venous blood and tissue ($T_v = T$). This is the well-known Pennes equation.

The Pennes equation has gained widespread acceptance ever since it was published in 1948, although its validity has been seriously questioned in many applications [2,3]. One of the major problems is the countercurrent heat exchange taking place between artery and vein in paired artery–vein vessels. The net heat lost to the tissue from the vessel pairs was found to be the predominant mode of bioheat transfer for vessels of 50–200 μm in diameter [4–6]. This behavior has been confirmed by the numerical investigation for a branching

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countercurrent network [7,8]. To take this effect into account, some nonvascular models were proposed to improve the Pennes equation by altering the equilibrium factor such as the efficiency function [3] and the correction coefficient [6].

The artery and vein vessels in skin are typically paired. Their diameters are less than 200 μm in general [6]. Hence, the countercurrent heat exchange in the vessel pairs might be significant. Henriques and Moritz [9] were the pioneers in the study of skin burn. They found that a first degree burn occurs when the skin is maintained at a temperature above 44 °C. Since then, a few mathematical models of heat transfer in skin have been proposed for some thermal hazards including contact burn, scald burn, flash fire, and thermal radiation exposure [10–16]. The grades of skin burn wound are classified according to the severity of the injured skin. The burn wounds of grades I and IIa would heal spontaneously within 3 weeks of the burn, whereas both grades IIb and III need surgery. In clinical practice even an inexperienced doctor has no difficulty in distinguishing grades I and III burn wounds. However, differentiation between grade IIa and IIb is still problematic. Accurate prognosis is only 50–70% in clinical evaluation based on visual inspection [17].

To assess the burn wound grade more accurately, Renkielska et al. [18] developed a noninvasive diagnostic method termed as active dynamic thermography (ADT). They conducted an experiment on young domestic pigs (each weighted approximately 20 kg) in view of the high degree of functional and structural similarity of pig skin to human skin [19]. The wounds were inflicted by an aluminum rod which was applied to the skin at controlled temperature and time. One day after the burn the ADT experiment was performed with a short optical excitation (halogen lamps of 1000 W). The optical heating resulted in a surface temperature rise of about 2.5 °C followed by a self-cooling stage. The skin surface temperature was assumed to decrease exponentially with a *constant* time constant during the self-cooling stage. The time constant was calculated for each of the burn wounds, while the wound depth was determined by the method of histological analysis [20]. In this experiment, Renkielska et al. [18] found that burn wound having a time constant longer than 10.125 s would heal after 3 weeks of burn spontaneously, otherwise it would be unhealed.

It is noted that the thermo-physical properties of the skin tissue do not significantly change 24 h after the burn is inflicted [13,15,21]. Hence, the time constant variation from one skin burn wound to another that Renkielska et al. observed in their experiment [18] can be attributed to the disabled blood perfusion (or destruction of vascular system). Bejan and coworkers [22,23] seems to be the only investigator in the literature that computes heat transfer in 3D triple-layered skin embedded with artery and vein vasculature. However, their mathematical model does not properly reflect the structure of the actual vascular system in skin. In the present work, the heat transfer in a unit 3D skin tissue with an embedded vascular system of actual histology structure is computed. Based on the 3D numerical result, a simple bioheat equation is developed for healthy skin (or injured skin but the blood perfusion is still normally working). The effect of disabled blood perfusion is then taken into account for burned skin by a superposition technique. The bioheat equation then is employed to simulate the ADT process on burn wounds as in the experiment by Renkielska et al. [18]. A new parameter is proposed to estimate the boundary of non-healing and healing regions in burn wounds of large area from the different responses of the healthy and burned skins.

2. Three-dimensional vascular model

2.1. Governing equation

Skin consists of three layers, namely epidermis, dermis, and hypodermis. Fig. 1 shows a histological diagram [24] and a schematic vascular system [6–8] of human skin. The blood vessels (including artery and vein) beneath the muscle are known as primary vessels (see Fig. 1(b)). The blood circulates between the primary vessels and the cutaneous vessels by separate riser vessels. The blood enters the secondary artery in the bottom of the dermis with a temperature T_{a0} approximately the same as that in the primary artery. Next, the blood rises to the top of the dermis by the terminal artery, and then flows to the terminal vein through a capillary bed. Subsequently, the blood descends to the secondary vein by the terminal vein. The blood temperature in the secondary vein T_{v0} is slightly smaller than T_{a0}. There is no blood vessel in epidermis.

The counterparts of the secondary and terminal vessels illustrated in Fig. 1(b) are observable from the histological diagram [24] of human skin shown in Fig. 1(a). The secondary vessels are the major supplier of blood perfusion for the skin. Destruction of the secondary vessels would lead to the necrosis of the whole skin. Surgery is needed under this situation. It is noted that the secondary vessels are located in the bottom of the dermis layer (see Fig. 1(a)). Thus the differentiation of grades IIa and IIb for a burn wound should depend on the survival of the secondary vessels rather than merely consider the burn depth of the injured skin.

The terminal vessels are roughly 20–40 μm in diameter. They form a pair of countercurrent heat exchanger. The spacing between the terminal vessel pairs is the typical length of the capillary bed, 500–1000 μm. The typical diameter of the secondary vessels is 50–100 μm [6,7]. In the present study, diameter and spacing of the terminal vessels are assumed to be 30 and 750 μm, respectively, while the distance between the terminal artery and terminal vein is 30 μm (60 μm center-to-center). The diameter of the secondary vessels is 75 μm. The average thicknesses of the epidermis, the dermis, and the hypodermis are, respectively, 75, 1500, and 10,000 μm [15]. Fig. 2 shows a simple 3D model for a unit skin area that contains just one single pair of terminal artery and vein. The dimensionless coordinates (x, y, z) is normalized with the thickness of the dermis L = 1500 μm such that the dimensionless thicknesses of the hypodermis and the epidermis are $\beta = 6.667$ and $\delta = 0.05$, respectively. Due to symmetry, the computational domain $-b \le x \le b$, $0 \le y \le b$, $0 \le z \le 1 + \delta$ is employed, where $b = 0.25$. The radius of the secondary vessel is $c = 0.025$. All of the thermophysical properties in the tissue are assumed constant.

After imposing the assumptions and introducing the dimensionless transformation,