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ORIGINAL PAPER

Thermal Shock Resistance of Skin Tissue

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Abstract Understanding the mechanisms of skin behavior under thermal shock is crucial for medical treatments. However, no reasonable criteria are available for the maximum thermal loadings that skin tissue can survive. To address this, in this paper we analyzed thermal and neural behaviors of skin tissue exposed to thermal loadings by introducing the thermal shock resistance (a parameter widely used for engineering materials) of skin for the first time. Skin thermal shock resistance was analyzed according to two distinct criteria: (1) maximum local temperature at epidermis-dermis (ED) interface defined as the thermal threshold of skin thermal pain; (2) maximum thermal damage at ED interface defined as the first degree burn where irreversible skin damage occurs. Numerical simulation was performed and the results show that the thermal shock resistance of skin tissue depends on the Biot number (which characterizes the features of thermal shock). These results indicate that skin thermal shock resistance can be used as an efficient tool to predict thermal damage (e.g., burn) and the corresponding pain level induced by noxious thermal loadings (e.g., clinical thermal treatments).

Keywords Skin tissue · Thermal shock resistance · Biot number · Numerical method

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Introduction

Human skin is often exposed to thermal shock, such as burning in daily life and heat therapy in clinics. The incidence of burn injuries in US is 120,856 cases per year [1]. More and more heat therapies (e.g., microwave [2, 3], radiofrequency [4, 5], and laser [6–8]) have been used to treat different diseases and injuries involving human skin tissue. The heating parameters of the applied thermal therapies (e.g., heating source, temperature, duration) are critical for the treatment results. For example, the choice of heat source, such as CO_2, Er:YAG, is critical to laser treatment, and the precise spatial and temporal control of thermal energy induced in target tissue is a main challenge for the success of the therapy. Therefore, the knowledge of skin behavior (e.g., thermal damage, thermal pain sensation) under thermal shock is crucial for improving the effects of these therapies.

Previous studies related to the thermal shock behavior of skin tissue mainly focus on skin thermal damage (i.e., burn). Pearse et al. [9, 10] studied the burn of pig skin induced by flash, which induced higher degree of thermal damage than contact induced burn. Torvi et al. [11] developed a finite element model about flash burn to forecast the thermal damage of skin tissue. Majchrzak et al. [12] analyzed the heat transfer in skin subjected to flash burn using numerical simulation. There are also studies investigating the relationship between skin thermophysical properties (e.g., thermal conductivity, specific heat capacity) and skin thermal damage [13, 14]. However, the effects of heating method on the thermal damage criteria of skin are not clear.

To analyze skin tissue exposed to thermal loadings, the parameter of thermal shock resistance was first introduced in this paper. Thermal shock resistance is a major issue in the selection of engineering ceramics for thermal applications, such as furnaces and engine parts [15]. A major problem in designing against thermal shock is the identification of appropriate material selection criteria in order to for selecting the most shock resistant material for a given application [15]. However, skin tissue is different from traditional engineering materials.

In the present study, thermal shock resistance of skin tissue was investigated from two different selection criteria: (1) maximum local temperature at epidermis-dermis (ED) interface equals the thermal threshold of skin thermal pain; (2) maximum thermal damage at ED interface equals the first degree burn where irreversible damage occurs. The damage-induced inflammation that may contribute to skin thermal pain was also considered. The temperature and thermal damage in the skin tissue were first analyzed for the full range of Biot number (Bi) using closed-form from our previous study [16]. Lower bound solutions were then obtained for the maximum thermal shock that the skin can sustain without catastrophic failure according to the proposed criteria.

Theoretical foundation

The one-dimensional (1D) heat transfer process in skin tissue can be described using Pennes equation, given as [17]:

$$\rho c\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} + \varpi_b\rho_b c_b(T_a - T) + q_{met} + q_{ext} \tag{1}$$

where ρ, c, k are the density, specific heat and thermal conductivity of skin tissue, respectively; ρ_b, c_b are the density and specific heat of blood, ϖ_b is the blood perfusion rate; T_a and T are the temperatures of blood and skin tissue; q_{met} is the metabolic heat generation in the skin tissue, and q_{ext} is the heat source due to other heating. The first term, $\rho c\ \partial T/\partial t = k\ \partial^2 T/\partial z^2$, represents the classical Fourier heat conduction theory; and the second term, $\omega_b\rho_b c_b(T_a - T)$, represents the heat taken away (as a heat sink for heating case) or added (as a heat source for cooling case) by blood perfusion.

The thickness of skin is denoted as H, with $z = -H/2$ at skin surface, Fig. 1. Initially, the skin is at a uniform temperature T_i. At time t=0, the skin surface is suddenly exposed to a convective medium of temperature T_∞ while its bottom surface is kept at the body core temperature T_c. The boundary conditions can be written as:

$$\begin{cases} -H\,\partial T/\partial z = Bi(T_\infty - T), z = -H/2 \\ T = T_c, z = H/2 \end{cases} \tag{2}$$

The non-dimensional heat transfer coefficient $Bi = hH/k$ is the Biot number for the skin tissue with the physical meaning of the ratio of heat transfer resistances inside of and at the surface of a body; k is the thermal conductivity of skin in the z-direction; h is the coefficient of heat transfer. Biot number in the present paper denotes the various heating sources and methods (Table 1), which plays an important role in the thermal shock resistance of skin tissue. For example, breeze is a case of natural condition which gives a Biot number in the range of 0.07–2 with a typical value of 1; while for contact heating such as cigarette scald, Biot number increase to infinite which means that all the heat from the heat source (e.g., cigarette) is taken away into the body.

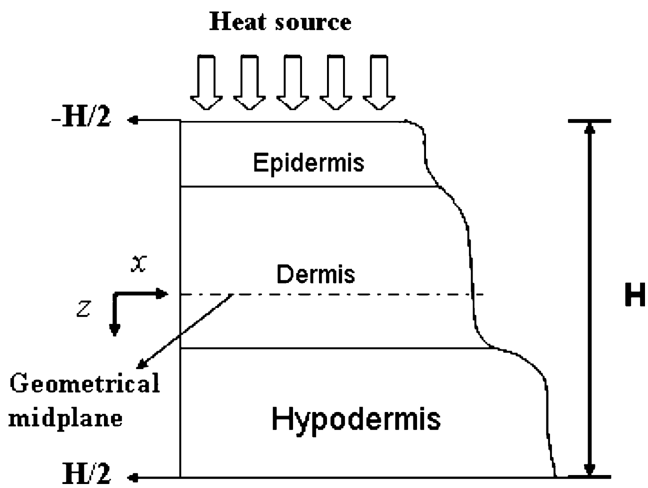

Fig. 1 Idealized multilayer skin model

Equation 1 can be solved with heat transfer boundary condition (2) by using the Green function method as reported in our earlier work [16, 18, 19], resulting in:

$$\overline{T} = \frac{T(z,t) - T_i}{(T_\infty - T_i)} = \alpha Bi \sum_{m=1}^{\infty} \left\{ \begin{matrix} \left\{ \frac{2\left(\beta_m^2 + Bi^2\right)}{\left(\beta_m^2 + Bi^2\right) + Bi} \sin\beta_m(1/2 - \overline{z}) \right\} \sin\beta_m \\ \frac{1}{\alpha\beta_m^2 + H^2\frac{\varpi_b\rho_b c_b}{pc}} \left(1 - e^{-\beta_n^2\overline{t} - \frac{\varpi_b\rho_b c_b}{pc}\left(\overline{t}H^2/\alpha\right)}\right) \end{matrix} \right\} \tag{3}$$

where $\alpha = k/\rho c$ is thermal diffusivity of skin tissue.

Results

Thermal shock resistance based on thermal damage

When skin tissue is suddenly exposed to a convective medium, the induced injury can be expressed in terms of the total damage function as [20]:

$$\Omega = \int_0^t A\exp(-E_a/RT)dt \tag{4}$$

In clinics, skin injuries are typically classified into three classes, i.e., epidermal damage (first degree), epidermal plus superficial dermal damage (second degree), and epidermal plus near-full to full dermal damage (third

Table 1 Typical value of *Bi* number for various medium

Convection mode		Biot number	Typical value	Example
Air	Natural convection	0.07–2	1	Breath
	Forced convection	2–7.5	4	Fan cooling
Oil	Natural convection	2–22	10	Oil scald
	Forced convection	5–150	40	Oil injection
Water	Natural convection	5–75	20	Central heating
	Forced convection	24–1125	180	Water cooling
	Boiling	60–2625	400	Boiling scald
	Condensation	120–1875	600	Condense scald
Contact	∞	∞	Cigarette scald	

degree) [21], which is consistent with the threshold of skin burn given by Henriques [22]. However, only the epidermis is capable of regenerating without any stigmata left. Therefore, a thermal damage-based criterion for heat shock is taken to be that thermal damage at the ED interface is considered as attaining the first degree (i.e., $\Omega=0.53$).

The effects of different Biot numbers on the skin thermal damage are shown in Fig. 2a. When skin surface is exposed to a heat medium of constant temperature, the degree of skin thermal damage and time needed for first damage to occur vary with Biot numbers (i.e., different heating sources). When Biot number is infinite (e.g., cigarette scald), it takes less time to get first degree damage at ED interface, while more time is needed when Biot number is equal to 10 (i.e., hot oil scald).

To check the effect of different heating media and methods on skin burn, the relationship between Biot number and time needed for first degree thermal damage is shown in Fig. 2b. Convective heat transfer coefficient and temperature of heating source are observed to have significant influences on the induced damage. Long time thermal convection to skin can also damage the skin even for medium at relatively low temperature, which is significant for predicting accurately the time of first degree damage in clinic. This may be the reason why the damage degree induced by hot oil is higher than that induced by hot water at the same temperature. It can be seen from Fig. 2b that the effects of different heating methods on skin thermal shock resistance are different. Contact burn (e.g., brand iron) can cause more serious skin damage than fluid burn (e.g., hot water of steam) under the same conditions.

Thermal shock resistance based on thermal pain sensation

Generally, pain can be classified as nociceptive pain, inflammatory pain and neuropathic pain [23]. The current study is focused on nociceptive pain induced by the activation or sensitization of nociceptors (the special receptor for pain sensation). For heat shock, when skin temperature rises above a critical value T_{thr} (~43°C [24]), an uncomfortable feeling or pain sensation will be induced. The pain intensity is defined here to be directly related to the T-cell output value. When the value exceeds the threshold of pain −55mV the induced electrical signal is transported to the next point. If the signal arrives at the cortex, it is considered as pain. In order to compare with

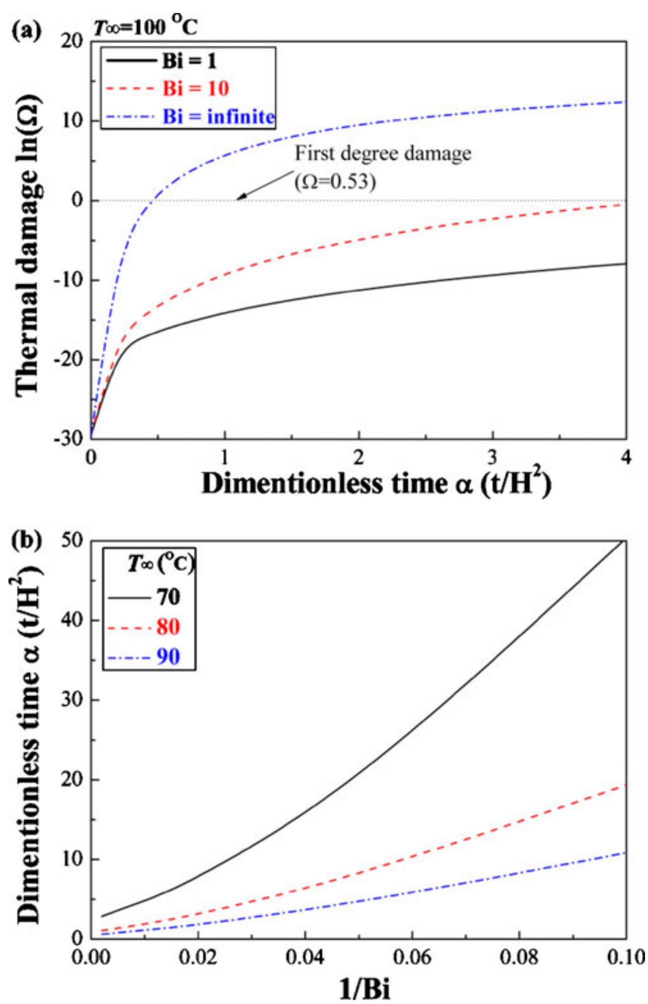

Fig. 2 (**a**) History of thermal damage and (**b**) occurrence time of first burn degree at Epidermis-Dermis interface for different Biot numbers

the results presented above, we examine the pain intensity assuming the position of nociceptor in skin at the ED-interface. We define here the pain intensity (PI) as PI= (VT−VTthreshold)/((VTmax−VTthreshold)) × 100.

According to the model of nociceptor transduction developed in our previous studies [25–27], we checked the thermal shock resistance of skin based on thermal pain sensation for different stimulus intensity considering thermal stress and thermal damage. The frequency response of nociceptor and pain intensity associated with different Biot numbers are shown in Fig. 3a–b, respectively. At the same stimulation, the response of receptor increases with increasing Biot number. That is, the heating media and methods have an important effect on the predicted level of skin thermal pain, which is consistent with that predicted based on thermal damage. According to the threshold defined before, it is found that the pain sensation happens much faster than the first burn degree damage. The response may be induced by the nerves, which directs human body to behave quickly before irreversible damage occurs. This

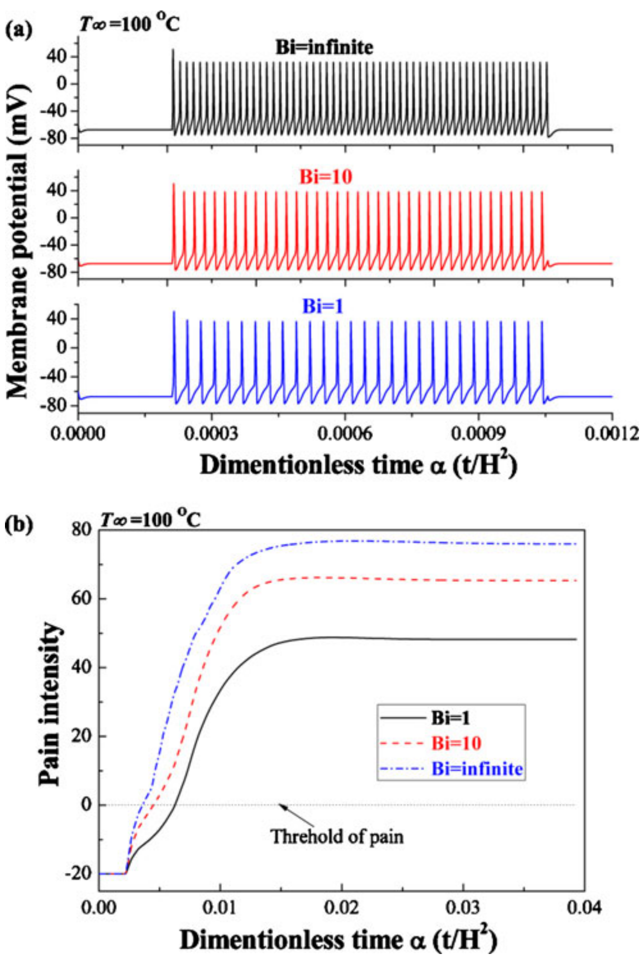

Fig. 3 Influence of Biot number on (**a**) frequency response of nociceptor and (**b**) pain intensity

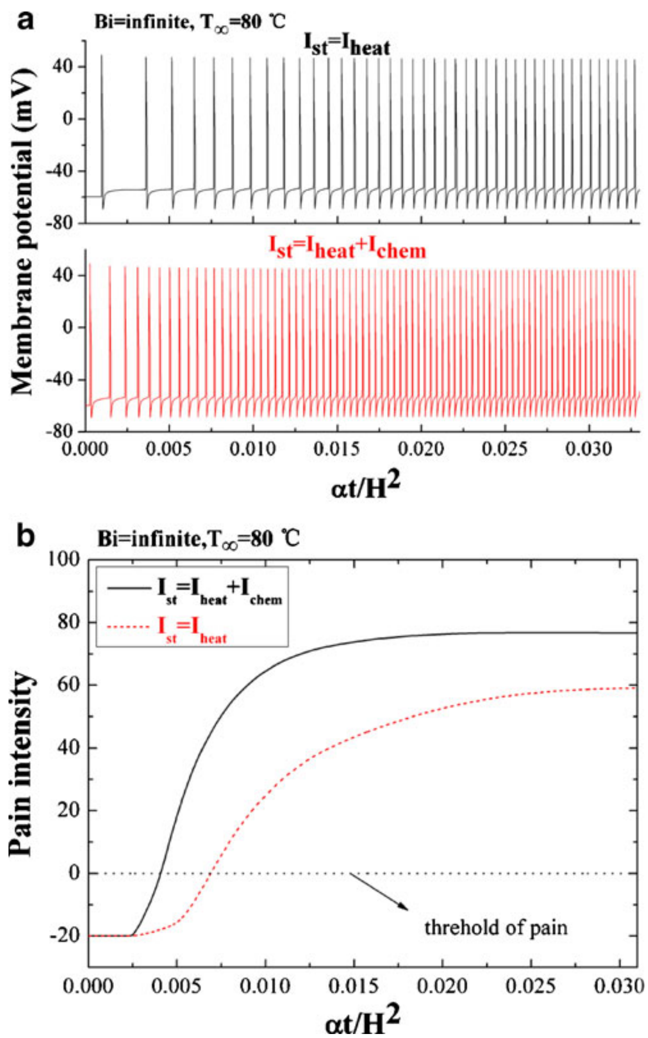

Fig. 4 Influence of thermal damage on (**a**) frequency and (**b**) pain intensity

physiological feature of human may be helpful for protecting human body in extreme thermal environment.

Comparison of two different criteria

The results based on both the selection criteria for skin thermal shock resistance suggest that the type of heating mode, the heat duration, the temperature and thermophysical properties of heating medium play important roles in skin burn process. Therefore, these parameters are crucial for the accurate estimation of thermal injury. It is also found that the thermal conductivity of skin tissue influences the burn degree, which may explain why some burn accidents occur when the patients use 40~50°C hot-water bag.

On the other hand, under thermal shock loading, the present results show that the thermal pain theory can be employed to predict the start time when thermal burn occurs, and can be used as a reference for forecasting the pain degree under heat treatment. Thermal stimulation, one of the three main causes of pain, has been widely used in the study of pain [28]. The difference between neural responses predicted with and without considering the effect of thermal damage on pain level is shown in Fig. 4a–b. It can be seen that the model predicts a higher frequency response and pain level when the influence of thermal damage is considered, which may explain why people still feel pain after removing heat source.

Conclusions

Thermal shocks (e.g., contact and convective heating) affect significantly the damage initiation time and damage degree of skin tissue. Therefore, they are important to estimate thermal injury. The multilayer heat transfer model based on Pennes' equation and thermal pain sensation for skin exposed to a convective medium (e.g., burn) was used to analyze the effect of different contact modes and heat media on skin thermal shock resistance. The model can be used to predict quantitatively the starting time for thermal damage for given heating mode, medium and heating duration. Thermal conductivity of skin tissue has also influence on the degree of thermal damage, which varies from person to person. To predict the occurrence of thermal burn, the thermal pain theory considering the influence of thermal damage is more accurate and can provide a reference for the degree of thermal pain in clinical thermal treatments.

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