Study of skin burns due to contact with cold mediums at extremely low temperature

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Although very important, the freezing burns caused by extremely low temperature have received few attentions up to now. In this study, a three-dimensional multi-layer bioheat transfer model is developed to predict the tissue damage following a freezing burn. This mathematical model is numerically solved using finite-difference method. The results indicate that the production of freezing burns is dependent on both the surface area exposed to cold medium and the duration of exposure to freezing. Further, a preliminary experiment is also conducted to validate the theoretical results. The experimental results qualitatively agree with the theoretical ones.

INTRODUCTION

The burn injury is one of the most commonly encountered types of trauma in both civilian and military communities. It is typically caused due to interaction with various high temperature sources, including exposure to flames, contact with a hot solid or liquid, inhalation of a hot vapor, exposure to harmful radiations, or electrical energy dissipation. With the widespread use of cold liquids and gases at extremely low temperature in many industries and scientific researches, the freezing injuries caused by these coolants become more and more common [1]. The pathophysiological mechanism of such injury suggests the treatment analogous to that of burns; customarily, it is also named as "burn". Although the thermal burns caused by high temperature have been intensively studied over the last half-century [2-4], the freezing burns caused by extremely low temperature receive few attentions besides several case reports described in the surgical literatures [1, 5, 6].

To better understand and accurately predict the tissue damage following a freezing burn, a three-dimensional multi-layer bioheat transfer model is developed in this study. In the model, multiple factors to respectively present the properties of the different layers of the biological tissues and solidification features due to freezing are considered. The model is solved by a finite-difference algorithm based on the effective heat capacity method. The extent of freezing burns is then determined from the numerical results. In order to validate the theoretical results, a preliminary experiment is also performed to illustrate the effect of freezing duration on the extent of burn damage.

THEORETICAL ANALYSIS

Mathematical model and numerical algorithm

It is reasonable to partition the biological tissue into three-layers (including the skin, fat and flesh layer respectively). In each layer, the thermal parameters are treated as constant however different from each other. The simplified three-layer geometry used for the analysis is shown as Fig. 1.

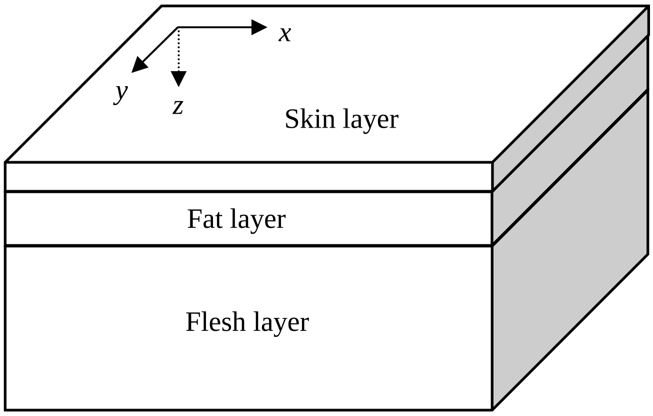


Figure 1 Simplified three-layer model of tissue (*z* denotes the tissue depth from the skin surface, and three layers are skin, fat and flesh layer respectively)

For brevity, the governing equations describing the phase change problem of biological tissue are not presented here. Readers can refer to [7] for more details. In order to avoid complex iteration at the front of phase change, the effective heat capacity method is applied in this study. A detailed development of the numerical algorithm for such phase change problem is similar to that for the freezing problem involved in cryosurgery (which has been developed in our previous work [7]). The derivation is not repeated here.

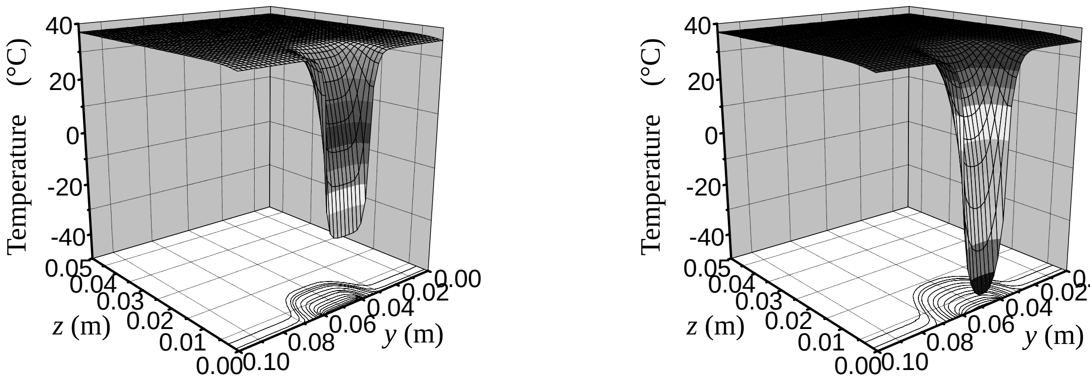
<u>Theoretical results and discussion</u>

In calculations, the typical thermal physical properties of tissue are applied as given in reference [7]. The thicknesses of skin and fat layers are respectively taken as 2 mm and 4 mm [8]. The tissue dimension parameters are taken as 0.1 m in x and y directions and 0.05 m in z directions. Considering that at the positions far from the center of the domain, the temperature field there is almost not affected by the center domain, the adiabatic conditions are assumed at the boundaries along x and y directions. The other boundary conditions are prescribed as follows:

$$-k\frac{\partial T}{\partial z} = h_f\left[T_f - T\right] \text{ at } z = 0; \qquad T = 37\ °\text{C at } z = 0.05\,\text{m} \tag{1}$$

For the area of skin surface contacted with the cold medium (liquid nitrogen assumed in this study), the convective parameters are taken as h_f=200 W/m^2·°C and T_f =-196 °C, respectively; and for the other area of skin surface, h_f=10 W/m^2·°C, T_f =20 °C. The area contacted with the cold medium is prescribed as a rectangular region located at the center of skin surface.

Figure 2 shows the temperature distributions at cross-section x=0.05 m, in which the size of skin surface contacted with cold medium is 2 cm×2 cm. Here, as is expected, the temperature distributions of tissues around the area contacted with cold medium are much lower than that of tissues far from this area. After the temperature distribution inside the tissue is given, the possible extent of the freezing burn can thus be determined by the freezing burn threshold of tissues. It had been proved that the value of the freezing burn threshold depends on many factors, and ranges from -2 °C to -70 °C [9]. The determination of practical value of the freezing burn threshold for a given tissue needs tremendous experimental works. In this study, the freezing burn threshold is taken as the solidification point of tissues for simplicity. Figure 3 gives the fronts of freezing burn threshold at cross-section x=0.05 m, which are determined by the isotherms at solidification point of tissues. The results indicate that the extent of freezing burns is dependent on both the surface area exposed to cold medium and the duration of exposure to freezing. The extent and severity of the freezing burn is important in medical treatment, and its determination will guide the clinician to apply a specific skin grafting. Unfortunately, due to the complex mechanisms for freezing damage, it is hard to establish a quantitative model similar to that for high-temperature thermal burns to evaluate the severity of freezing burn (namely the degree of freezing damage). Such important issue needs tremendous researches in future.



(a) t=60s (b) t=120s

Figure 2 Temperature distributions at cross-section x=0.05 m

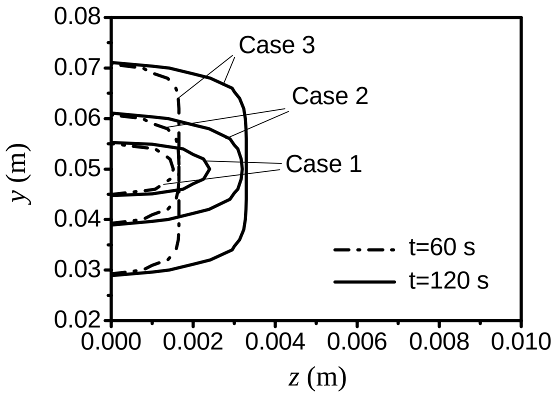
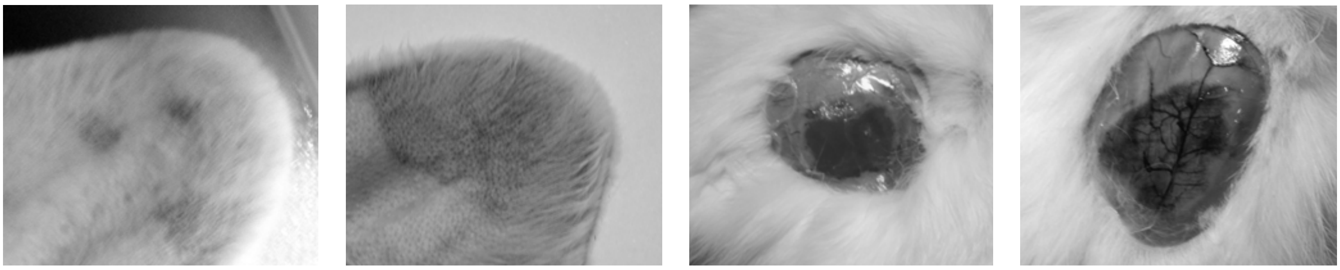


Figure 3 The fronts of freezing burn threshold at cross-section x=0.05 m. Cases 1, 2 and 3 respectively present 1cm×1cm, 2cm×2cm and 4cm×4cm skin surface contacted with cold medium

PRELIMINARY EXPERIMENTS ON FREEZING BURNS

Considering that the physiological response to freezing burns involves complicated and coupled reactions which are not well understood up to now, a preliminary experiment is also conducted. In the experiment, dehaired rabbit under anesthesia is burned by liquid nitrogen under different conditions, and the corresponding freezing damage degrees are respectively examined after 72 hours postburn.

Figure 4 shows the photograph of rabbit’s ear and thigh 72 hours after the corresponding freezing burn. During dealing with the photographs, the scaling for the four photos is taken as identical as possible. Comparing these photos, it is clear that the extents of the freezing burns for the cases presented in Figs. 4(a) and 4(c) are much less than that presented in Figs. 4(b) and 4(d). So it can be concluded that the experimental results qualitatively agree well with the theoretical ones presented above. It needs to be pointed out that the present experiment only demonstrated qualitatively the effect of freezing duration on the extent of burn damage. Further researches along this direction are needed in the near future.



(a) (b) (c) (d)

Figure 4 Photographs 72 hours after the freezing burn: (a) - (d) respectively present the cases of contact with liquid nitrogen 5, 15, 30, 60 seconds, in which (a) and (b) are photographs for rabbit ear, (c) and (d) for rabbit thigh

CONCLUSIONS

This study develops a three-dimensional multi-layer bioheat transfer model for predicting the tissue damage following a freezing burn. The theoretical results indicate that the extent of freezing burns is dependent on both the surface area exposed to cold medium and the duration of exposure to freezing. A preliminary experiment qualitatively agrees with the theoretical prediction. It concludes that the theoretical analysis presented in this article can be applied to quantitatively predict the extent of skin burns resulted by cold mediums at extremely low temperature.

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