Numerical Simulation of the Cryosurgery Process Basing on Arm Layered Model with Major Blood Vessels

Chu-xiao XU1,*, Kui-ning LI1,2, Bin LIU1,2 and Yu-xiao YANG1
1School of Power Engineering Chongqing University, Chongqing, 400044
2Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Ministry of Education, Chongqing, 400044
*Corresponding author

Keywords: Cryosurgery, Bio-heat transfer, Blood perfusion rate, Phase change.

Abstract. Basing on the tissue structure of the human arm in regional anatomy, a new three-dimensional thermal model of the human arm with the major artery and veins was built. The arm model was divided into four layers due to the difference of physical parameters. Liquid nitrogen (76K) was chosen for the cold source. This paper described the specific heat and the coefficient of thermal conductivity as the linear function of temperature and set up the influence of dependent blood perfusion rate and metabolic heat generation on temperature and the major blood vessels flowing during the biological tissue heat transfer of the cryosurgical process. The finite element analysis method was used to study the thermal gradient field when cold sources are distributed in different coordinates and transient thermal field. This paper predicted the radius of ice sphere and phase boundaries during the freezing process in different location of the cryoprobes, and compared the results whether considering the dependence of temperature or not. The influence of the major blood vessels flowing for the arm tissue thermal gradient field was studied meanwhile.

Introduction

Cryogenics and cryobiology are a discipline that has gradually developed along with the development of biology, medicine, and cryogenic refrigeration technology [1]. It is an important application of bioheat transfer in medical field. The purpose of hypothermia therapy is to inactivate all tumor cells completely while minimizing the damage to normal healthy tissues around the tumor tissue. This is also the purpose of the optimal design of the cryogenic treatment process [2-3]. The evaluation of the effective treatment radius requires accurate prediction of the critical isothermal and the temperature distribution within the tissue [2].

In recent years, domestic and foreign scholars have made a lot of research on the experiments and simulations of cryosurgery. Copper et al. applied the quasi-steady state method to obtain analytical solutions for the one-dimensional temperature field of the lesion and its nearby tissues in cryosurgery, spherical coordinates and cylindrical coordinates [4-5]. Ji et al. used finite element method to simulate the two-dimensional phase transition of biological tissue in cryosurgery. Proving that the mathematical model and finite element method used in the cryosurgery can effectively simulate the phase transition of biological tissue [1]. Zhao Gang et al. established the temperature-dependent relationship between human blood perfusion rate and metabolic heat production in treatment areas, and proved the importance of considering the temperature nonlinearity of human blood perfusion rate and metabolic heat production[6]. In the research of heat transfer in the phase transition of biological tissues, the biological structure is mostly simplified as a two-dimensional model or a simple cylinder, and the change of thermo physical properties of tissues is not considered. The effect of blood perfusion rate on the heat transfer of biological tissues have been studied[7], but they did not take the existence of blood vessels into consideration. This simplification will make a big difference with the phase change process. Moreover, most of the experimental study of the freezing process of biological tissues stay in the ex vivo experimental stage due to the limitation of experimental conditions. In the simulation study of tissue temperature distributions during cryogenic surgery so far, it is extremely
rare to have a precise three-dimensional model of tissue considering both temperature dependence and major vessel structure. This paper establishes a layered human upper arm model based on the Pennes[8] bio-heat transfer equation and choose liquid nitrogen (76K) for the cold source[9]. The specific heat and the coefficient of thermal conductivity are described as the piecewise function of temperature in this work. In addition, relationship between the blood perfusion rate, metabolic heat production and temperature is set up. The major blood vessels flowing during the cryosurgical process is also considered. The temperature distributions are numerically simulated and the impact of the cold knife's freezing results in different situations is evaluated.

Physical Model

Bio-heat Transfer Equation

Pennes gave the biological heat transfer equation in 1948. It can be used to describe the heat transfer problem in the freezing process. The Pennes equation after considering the temperature effect is expressed as:

\[ \rho C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \rho_b C_b W_b(T)(T_b - T) Q_{\text{net}}(T) \] (1)

Where \( \rho \) is the tissue density (kg/m³); \( \rho_b \) is the blood density (kg/m³); \( C \) is the specific heat specific pressure (J/kg·K); \( t \) is the time (s); \( W_b \) is the blood perfusion rate (ml·s⁻¹·ml⁻¹), that is, the volumetric flow rate of blood in a unit volume of tissue; \( T_b \) is the blood temperature (K); \( T \) is the tissue temperature (K); \( C_b \) is the constant specific heat of blood (J/kg·K); \( Q_{\text{net}} \) is metabolic heat production (W/m³). In the formula, the heat sources in the second and third terms on the right side of the equation are recorded as \( Q \). Experimental results have shown that human blood perfusion and metabolic heat production have a significant effect on the tissue temperature field during cryotherapy [10]. Human blood perfusion and metabolic heat production are not constant, but are temperature dependent [11-12]. In most hypothermic phase-change heat transfer assays, blood perfusion rate and metabolic heat production are often ignored or defined as a constant. Although this assumption simplifies the calculation, it does not conform to the actual physiological conditions of the human body and can lead to large errors between the calculation results and the actual situation. Base on the physiological response of human tissues to cold conditions, taking the blood perfusion rate and metabolic heat production as functions of temperature makes numerical simulation more accurate.

Unlike common pure substances, the phase transition of human tissue after freezing does not occur at a fixed temperature. It occurs at a temperature range, undergoing three states of non-frozen zone, concomitant zone, and frozen zone. \( T_{ml} \) and \( T_{ms} \) represent the upper and lower limits of the phase transition temperature range, which are taken as -1°C and -8°C in this paper [13].

According to the theoretical relationship and experimental data [14-15] in the literatures, the metabolic heat production and blood perfusion temperature dependence used in this paper are as shown in (2) and (3):

\[ Q_{\text{net}}(T) = \begin{cases} Q_{\text{net,0}}(T - T_{ml})/(37 - T_{ml}), & T_{ml} \leq T \leq T_{cg} \\ 0, & T < T_{ml} \text{ or } T > T_{cg} \end{cases} \] (2)

\[ W_b(T) = \begin{cases} W_{b,0}(T - T_{ml})/T_{cr,\text{hypero}} - T_{ml}, & T_{ml} < T < T_{cr,\text{hypero}} \\ W_{b,0}, & T_{cr,\text{hypero}} \leq T \leq T_{cr,\text{hyper}} \\ W_b[T - (T_{cr,\text{hyper}} - T_{cr,\text{hypero}}) - T_{ml}]/T_{cr,\text{hypero}} - T_{ml}, & T_{cr,\text{hyper}} < T < T_{th} \\ W_b[T_{th} - (T_{cr,\text{hyper}} - T_{cr,\text{hypero}}) - T_{ml}]/T_{cr,\text{hypero}} - T_{ml}, & T_{th} \leq T \leq T_{cg} \\ 0, & T < T_{ml} \text{ or } T > T_{cg} \end{cases} \] (3)

Where \( W_{b,0} \) and \( Q_{\text{net,0}} \) are the blood perfusion rate and metabolic heat production when the tissue is at a normal body temperature of 37°C; \( T_{cr,\text{hyper}} \) and \( T_{cr,\text{hypero}} \) are chosen as 42.5 °C and 31.5 °C, which represent the high and low body temperature trigger the change of values of blood perfusion.
rate (ie, the critical temperature at which the blood perfusion rate response to temperature changes, at the temperature change between $T_{\text{cr,hyper}}$ and $T_{\text{cr,hypo}}$ does not cause the body's regulation, and the blood perfusion rate does not change); the body's ability to regulate is limited, and when the tissue is above a certain temperature, the blood perfusion rate will not continue to increase. $T_{\text{th}}$ is taken as 45 °C, which is the temperature corresponding to the maximum blood perfusion rate, $T_{\text{cg}}$ (taken as 60 °C) is the temperature at which the tissue begins to coagulate caused by high temperatures, at which time the biological tissue begins coagulation necrosis until it completely loses its activity.

In the process of biological transformation, with the change of temperature, there is a difference between the heat capacity and the thermal conductivity of the frozen zone and the non-frozen zone. This article assumes that $C$ and $k$ in the frozen zone and the non-frozen zone are constant in the respective zones. In the concomitant zone, the specific heat capacity and thermal conductivity are linearly changed [16], and the latent heat of phase change is converted into the equivalent heat capacity in the tissue heat capacity. The constructed equivalent heat capacity expression $C$ and the equivalent thermal conductivity expression $k$ are expressed as [17]:

$$C(T) = \begin{cases} C_s, & T < T_{ms} \\ \frac{L}{\Delta T} + C_s + \frac{C_1 - C_s}{\Delta T} (T - T_{ms}), & T_{ms} \leq T \leq T_{ml} \\ C_1, & T > T_{ml} \end{cases} \tag{4}$$

$$k(T) = \begin{cases} k_s, & T < T_{ms} \\ k_s + \frac{k_1 - k_s}{\Delta T} (T - T_{ms}), & T_{ms} \leq T \leq T_{ml} \\ k_1, & T > T_{ml} \end{cases} \tag{5}$$

Where $C_s$ and $C_1$ represent the heat capacity when the organization freezes and not freezes, $k_s$ and $k_1$ represent the thermal conductivity coefficient that the organization is frozen and non-freezing, $L$ is the latent heat of phase change.

Because of the complexity of heat transfer process of human tissues, the following basic assumptions are made in order to facilitate the calculation in this paper:

1. The volume of tissue does not change during freezing and the density is considered as a constant.
2. The thermal conductivity and the specific heat capacity remain constant in the frozen and non-frozen areas, only changing linearly in the concomitant area.
3. The diseased tissue to be removed has the same thermal properties as the surrounding normal tissue.

Geometric Model

During the cryosurgical process, a large part of heat is provided due to the high temperature blood flowing. When the target tissue is in a low temperature environment, a large temperature gradient tends to be formed in the tissue connected with the blood vessels. Therefore, for those tumor tissues containing large blood vessels or close to large blood vessels. If the existence of blood vessels is ignored and the influence of heat transfer in major vessels is not evaluated, the analysis of the internal temperature distributions may be caused a great error, leading to the operation to fail.

Therefore, to establish a reasonably improved human tissue heat transfer model is important for solving practical problems. In this paper, the human upper arm is selected as the research object, and a three-dimensional physical model close to the real structure of the upper arm is established. The main reasons of choosing the upper arm are:

1. Compared with other organizational structures, the shape of the upper arm structure are extremely similar to elliptical column, facilitating the geometrical simplification during modeling. The simplified results can match the actual situation better.
2. Many skin diseases often appear on the surface of the upper arm (such as blemishes, plaques, flat warts, etc.) and internal (such as fibrosarcoma, cavernous hemangioma, bone cyst, etc.). So modeling and simulating calculations of the upper arm are very useful and have guiding significance.
for optimizing the treatment of many diseases.

In this paper, the traditional two-dimensional geometric model is improved, and a three-dimensional model of the human arm model is established. The elliptical column is used as the arm geometry. Based on the complex comlocational structure of human tissue materials, the organization is stratified. From the inside out, it is divided into four layers: skin, fat, muscle, and bone. And select different parameters. Considering the influence of large blood vessels on tissue temperature distribution, three-dimensional structures of major blood vessels were introduced based on real human physiological structures. As shown in Fig. 2, the major blood vessels are divided into one arterial blood vessel and one branched venous blood vessel. The direction of the arrow is blood flow. Considering the structure of arteriovenous blood vessels provides a more accurate theoretical basis for cryosurgery.

The overall shape of the model is an elliptical column with height h=200mm, ellipse major axis a=49.5mm, minor axis b=45mm, skin thickness d1=2.6mm, fat thickness d2=5mm, muscle thickness d3=25.4mm, and the center is the bone structure. Artery radius ra = 1.8mm, two vein radius rv1 = 1.5mm, rv2 = 1.1mm.

As shown in Figure 3, the common contact cryogenic surgical methods are mainly divided into probe surface contact method and probe penetration method. Surface contact method is a method in which the freezing head is directly brought into contact with a diseased tissue located on the surface or applied with a slight pressure to perform freezing and cooling. The method of penetration is to destroy the cancer in the depths of the tissue. An elongated cryogenic head is used. Under anesthesia, the cutting head is inserted directly into the center of the lesion. Based on these two treatment methods, in order to deal with different pathological conditions of lesions in different locations and observe the effect of arteriovenous blood vessels on the temperature distribution. Distributing cold sources with a 2.5 mm radius in five different locations. As shown in Figure 3, they are arranged on the lateral skin surface, 10 mm from the lateral skin, 20mm from the lateral skin, on the medial skin surface and 10 mm from the medial skin. Replacing them with location 1 to location 5.
Each property of the physical parameters used in the model are taken as typical values[9], as shown in Table 2.

Table 2. The typical parameters of every layer of the human arm.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$C$ (J/kg·K)</th>
<th>$k$ (W/m·K)</th>
<th>$Q_{neu}$ (W/m$^3$)</th>
<th>$W_{p}$ (ml/s·ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>1085</td>
<td>3680</td>
<td>0.47</td>
<td>368</td>
<td>362</td>
</tr>
<tr>
<td>Fat</td>
<td>920</td>
<td>2300</td>
<td>0.21</td>
<td>368</td>
<td>77</td>
</tr>
<tr>
<td>Muscle</td>
<td>1085</td>
<td>3800</td>
<td>0.51</td>
<td>684</td>
<td>543</td>
</tr>
<tr>
<td>Bone</td>
<td>1357</td>
<td>1700</td>
<td>0.75</td>
<td>368</td>
<td>0</td>
</tr>
<tr>
<td>Blood</td>
<td>1059</td>
<td>3850</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Boundary Conditions**

1. The first type boundary condition is applied at the cold source, $T_c=76\text{K}$. Due to the vacuum insulation at the cold knife cylinder surface, the adiabatic boundary conditions are applied at the cold source cylinder surface.

2. The first type boundary condition is applied to the cross-sections of the arm. The skin cross-section temperature is 308K, the fat cross-section temperature is 309K, and the muscle and bone cross-section are 310K.

3. Convection heat transfer between the skin surface and the surrounding environment is set as the third type boundary condition, $h_r=4.2\text{W/(m}^2\text{·K)}$. Environment temperature is 300K.

4. The convective heat exchange between the blood and the surrounding muscle is set as the third type boundary condition. The arterial and venous blood inlet flow rates are 0.2 m/s and 0.08 m/s respectively, and the inlet temperature is 310K.

**Results and Discussion**

The temperature of the tissue tends to be stable after the cold source working enough time. In this paper, temperature nephograms in location1 are showed. Meanwhile, the figures of the radial direction and axial direction temperature distributions when the cold sources working in location1,
location 3 and location 4 are showed. Other simulation results are given by table formats. $T_0^*~T_5^*$ represent the results regarding the of blood perfusion rate and metabolic heat production as constants. In other words, the value of them is not influenced by the temperature. However, $T_0~T_5$ are the results concerning the dependence of blood perfusion rate and metabolic heat production on temperature.

The tissue is frozen at -8℃. As Fig. 4 shows, the frozen area is appeared as sphere. The freezing tissue with a temperature below -8℃ is called ice sphere. The ice sphere radius is an important parameter to measure the effect of cryogenic treatment.

---

**Figure 4.** The temperature nephogram of the location 1.

**Figure 5.** The temperature nephogram across x-axis and z-axis of location 1 during freezing.
Figure 6. The temperature nephogram across x-axis and z-axis of location 3 during freezing.

Figure 7. The temperature nephogram across x-axis and z-axis of location 5 during freezing.

Table 3. The radius of the ice sphere freezing at different locations.

<table>
<thead>
<tr>
<th>Cold source</th>
<th>( r'/\text{mm} )</th>
<th>( r'/\text{mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>radial</td>
<td>axial</td>
</tr>
<tr>
<td>location 1</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>location 2</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>location 3</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>location 4</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>location 5</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

From the above figures and table, it can be seen that the temperature gradient of the tissue is quite large and the isotherm is dense at the location close to the cold source. As the distance from the cold source increases, the temperature gradient gradually decreases. At the tissue phase interface (at a temperature of \(-1°C\)), the tissue begins to enter the concomitant zone, and the latent heat is continuously released at \(-1°C\) to \(-8°C\), making the temperature gradient of the tissue within this temperature range more gradual, and then there is an increase.

Regardless of the location of the cold source in the human arm tissue, whether or not the dependence of blood perfusion and metabolic heat production on temperature is considered will have a great impact on the estimation of the ice sphere radius. If the dependence of blood perfusion and metabolic heat production on temperature are ignored, the critical isotherm and the ice sphere radius will be underestimated.
By comparing locations 1, 2 and 3, it can be seen that when the cold source location moves 10 mm inward from the skin surface, the ice ball radius slightly increases, and when the inward movement 20 mm, the ice ball radius becomes significantly larger. This is because the cold source moves from the skin surface to the muscles, and the physical parameters of each layer of the human tissue are not the same. The skin surface is covered with rich capillaries, while the muscle is distributed with large vessels of the arteries and veins, making the blood perfusion rate of other muscle areas. The less than that of the skin. The heat generated by blood perfusion is also relatively lower, resulting in an expansion of the ice sphere radius. Although the movement of the cold source reduces the distance from the great vessels, the great vessels are located on the inner side of the arm. There is still some distance between the two, and the heat production has little effect on the radius of the ice sphere in the above two cases.

By comparing locations 1, 4 and 5, it is also known that as the cold source is arranged on the surface of the skin, the radius of the ice sphere located on the inner surface is smaller than the radius of the ice sphere on the outer surface. This is because this paper considers the major vessel structure of the arm. The arteriovenous blood vessels of the human arm are distributed on the inner side of the arm. The blood temperature in arteriovenous vessels is high and the flow rate is relatively large. Therefore, the influence of the heat production of large vessels on the temperature distribution cannot be ignored. The cold source locating on the inner surface of the arm, it is very close to the large blood vessels, and the convective heat exchange between the large blood vessels and the muscles makes the ice sphere radius decrease. Location 5 is the closest case from the major vessels, so the radius of the ice sphere is the smallest.

As can be seen from the axial charts of locations 4 and 5, there are two obvious temperature discontinuities near x = -0.03m. The existence of such a local temperature difference is due to the higher blood temperature in the arteriovenous blood vessels, however the temperature of the surrounding muscle tissue was affected by the cold source. Temperature discontinuities at locations 1, 2, and 3 were not obvious.

**Conclusions**

In this paper, based on the temperature dependence of blood perfusion rate and metabolic heat production in the cryosurgery temperature zone, the three-dimensional phase change physical model of human arm tissue containing major blood vessels is set up. By applying he finite element method to perform numerical simulation, the calculation results of the steady-state temperature field when the cold source acts on different parts of the tissue are obtained. Through above analysis and calculation, some conclusions are as follows:

1. The skin, fat, muscles, bones, and blood vessels in human tissues all have different physical parameters and heat production. The cold source working on different parts of the tissues, the temperature distribution within the tissues differs greatly. The treatment plan should be considered separately for different parts of the tumor during surgery.

2. After the freezing process reaches a steady state, the ice spheres in the tissue are nearly spherical or ellipsoidal, that is, the isotherms are on semicircular or elliptic arcs. When the cold source is in location 5, the ice ball radius is about 14mm. When the cold source is in location 5, the radius of the ice hockey is the smallest, about 14mm; when the cold source is in location 3, the radius of the cold source is the largest, 24mm in the radial direction and 30mm in the axial direction. Neglecting the temperature dependency of blood perfusion rate and metabolic heat production can lead to overestimation of tissue temperature during cryosurgery and the estimated ice ball radius is underestimated.

3. When the cold source location is far away from the major blood vessels, the blood flow in the vessels has little effect on the ice sphere radius. When the cold source location is close to the major blood vessels, its influence on the temperature distribution of the tissue and the ice sphere radius is quite obvious and cannot be ignored.
References


