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The Model of the Myocardium in the MSC Sinda System

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Abstract: The model for the physical system of myocardium and coronary vessels are realized on basis RC-thermal network in the MSC Sinda system for the heat transfer model, which allows you to explore the process of hypo- and hyperthermia with cardiopulmonary bypass.

Keywords: Thermogram Myocardium, Model, Temperature Distribution, MSC Sinda

1. Introduction

The purpose of the studies are to expansion of available information about protection of the myocardium and the state of its vascular layer using heat transfer model based on the pericardial temperature propagation in circumstances of CPB [1]. The purpose is to create the discrete model for the physical system of myocardium and coronary vessels which is realized on basis RC-thermal network in the MSC Sinda system for the heat transfer model to 2D-layer myocardium and 3D-structure of the coronary vessels. The numerical model of heat transfer allows to estimate the parameters of temperature propagation and temperature gradients at the surface of the myocardium at the time of registration of thermal images of the heart. To solve the differential equation of heat conduction in the MSC Sinda thermal system used the network method (TNM - Thermal Network Method) [2].

The discrete physical models of myocardial and coronary vascular system allow to studying the inhomogeneity of temperature field in the myocardium and thereby identify areas of ischemia in the heart. Application of model of heat exchange provided stationary convection laminar flow across the border surface of blood and myocardium gives the numerical description of the processes of heat transfer at the boundary between the myocardium and coronary vessels.

At the extracorporeal cardiopulmonary bypass (CPB) the heat transfer occurs by the heat exchange between the blood and the water in the heat exchanger device of cardiopulmonary bypass (DCB) and to the heat exchange between the blood and the body of the patient's. In the present physical model the system myocardium-coronary vessels consists of 2D-layer infarction and 3D-structures of the coronary vessels, which are located within the bulk layer. It allows to estimate the parameters of temperature propagation and temperature gradients at the surface of the myocardium at the time of registration of thermal images of the heart.

2. The Convective Heat Transfer in the Coronary Vessels and the Surface Myocardium

Simultaneously with the heat transfer in the myocardium during the hypo- and hyperthermia of heart are also involved of heat dissipation, which defines the heat exchange between the myocardium and the environment layer in contact with it – the structure of the coronary vessels. The heat irradiation in accordance with the law of Newton-Richman is proportional to the temperature gradient between the myocardium and coronary vessels [3, 4]:

$$div(\vec{q}_R) = \alpha(T_{heat} - T_{liq}), \qquad (1)$$

where α – the heat transfer coefficient,

T_{heart} – the surface temperature of the myocardium,

T_{liq} – the coolant temperature (perfusion fluid), which is introduced into coronary vessels,

If the value of thermal conduction coefficient is constant, then the heat transfer in the myocardium is defined as:

$$div(\vec{q}_c) = -\lambda_p (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}), \quad (2)$$

where λ_p – the coefficient of the myocardial thermal conductivity,

x, y, z – the space coordinates.

To determine the temperature field in the MSC Sinda system used the differential equation of thermal conductivity obtained using the generalized heat equation:

$$\rho C_p \frac{\partial T}{\partial t} = -div(\vec{q}) + q_v, \quad (3)$$

where C_p – the specific heat capacity of the myocardium,

$\vec{q} = \vec{q}_c + \vec{q}_R$ – the rate of temperature change per unit myocardial volume,

q_v – the distribution density of the structures of the coronary vessels in the myocardium.

Thus, in general the differential equation considering heat conductivity of the convective flow in the myocardium becomes the form:

$$\begin{cases} \rho C_p \frac{\partial T}{\partial t} + div(\rho \vec{u} \frac{\partial T}{\partial t}) = -div(\vec{q}_c) - div(\vec{q}_R), \\ \frac{\partial \rho}{\partial t} + div(\rho \vec{u}) = 0. \end{cases} \quad (4)$$

The convective heat transfer between the moving blood in the coronary vessels and the surface myocardium the heat transfer is performed with an intensity which is characterized by the heat transfer coefficient:

$$\alpha = \frac{\lambda_p}{l} N_u, \quad (5)$$

где λ_p – the coefficient of the myocardial thermal conductivity,

l – the thickness of the myocardial wall,

N_u – Nusselt number, which characterizes the similarity of the processes of heat transfer at the boundary between the myocardium and coronary vessels.

For laminar blood flow in the system of artificial circulatory the Nusselt number can be expressed as the equation [5]:

$$N_u = 0{,}15 R_e^{0{,}33} \cdot P_\Gamma^{0{,}43} \cdot G_\Gamma^{0{,}1} \cdot \left[\frac{P_\Gamma}{P_{\Gamma,st}} \right]^{0{,}5} \cdot E_l, \quad (6)$$

where $R_e = \frac{v_{liq} \cdot l \cdot \rho_{liq}}{\mu_{liq}}$ – Reynolds number, which characterizes the ratio of inertial forces and friction for the viscous flow,

$P_\Gamma = \frac{C_{liq} \cdot \mu_{liq}}{\lambda_p}$ – Prandtl number that characterizes the physical and chemical properties of the coolant - blood,

$G_\Gamma = \frac{l^3 g \beta_{liq} \Delta T}{\nu_{liq}}$ – Grashof number that characterizes the blood flow in the system in idle mode,

$\nu_{liq} = \frac{\mu_{liq}}{\rho_{liq}}$ – the kinematic viscosity of blood,

λ_{pc} – the thermal conductivity of the wall of myocardium and coronary vessels,

ρ_{liq} – the blood density,

c_{liq} – the specific heat capacity of the blood,

β_{liq} – the thermal expansion coefficient of the coolant,

v_{liq} – the blood flow velocity,

E_l – the tabular factor, which depends on the value of the Reynolds number R_e,

g – the acceleration of gravity,

$\Delta T = T_{heart} - T_{liq}$ – the temperature difference between the wall of the myocardium and blood in the coronary vessels.

3. The Discrete Model of the Heat Equation of Myocardial

To solve the differential equation of heat conduction in the MSC Sinda thermal system used the network method (TNM - Thermal Network Method) [6], in which system of heat equations is presented in the form of cellular-centered nodes and resistances between the nodes using the finite difference method (Figure 1).

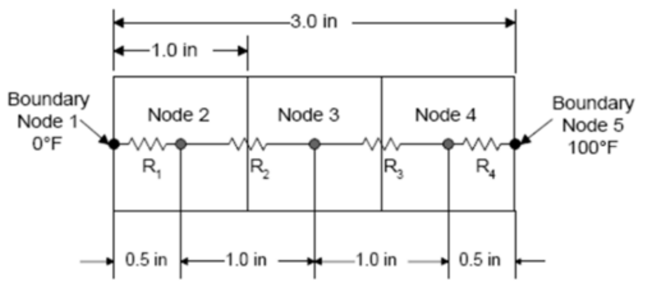

Figure 1. *The discrete model of the RC-thermal network.*

Application of the TNM to the heat equation yields the following discrete form of equation:

$$\frac{\partial T_i}{\partial t} \approx \frac{1}{(mC_p)_i} \left[\sum_{j=1}^{N} C_{i,j}(T_j - T_i) + \sum_{j=1}^{N} R(T_j^4 - T_i^4) \right] + \frac{q_i}{(mC_p)_i}, \quad i = 1, ..., N, \quad (7)$$

where $(mC_p)_i$ – the junction capacitance at node i,

N – the total number of diffuse network nodes,

$R_{i,j}$ – the thermal radiation from the resistance between the nodes i and j,

$C_{i,j}$ – the capacity of linear conductor between nodes i and j,

q_i – the distributed of heat sources in the myocardium.

In the model the heat radiation from the resistance between the nodes i and j is a member $R_{i,j}$ which defines a heat transfer from the material - blood and coronary vessels. Discrete formula has the form:

$$R_{i,j} = \sigma S_i^n \cdot f_{i,j} \tag{8}$$

where σ – Stefan-Boltzmann constant,

S_i^n – the radiant heat irradiation area,

$f_{i,j}$ – the heat factor of the heat radiation, which can be considered the same for constant surgical field with cardiopulmonary bypass.

In the model the linear conductor capacitance between nodes i and j represents a member $C_{i,j}$ that defines the heat transfers to the material – the myocardium and blood. Its discrete formula has the form:

$$C_{i,j} = \frac{\lambda_{i,j} \cdot S_i^n}{h_{i,j}}, \tag{9}$$

where $\lambda_{i,j}$ – the effective thermal conductivity between nodes i and j,

S_i^n – the area of heat conduction between nodes i and j,

$h_{i,j}$ – the distance between the nodes i and j.

Since most of the heat conductors in a system of myocardial-blood cannot be considered as homogeneous, the calculation of their values $R_{i,j}$ and $C_{i,j}$ requires to use in the model of thermal resistance. In the MSC Sinda system for solve the heat equation is used the modified scheme Dyufort-Frenkel [7]. According to this scheme, the heat conduction equation for the system of myocardial-blood has the form:

$$\left[1+\frac{\Delta t G_{i,j}}{(mC_p)_i}\right]T_i^{\tau+1} = T_i^{\tau} + \sum_{j=1}^{N}\frac{\Delta t \cdot G_{i,j}}{(mC_p)_i}T_i^{\tau} - \sum_{j=1}^{N}\frac{\Delta t \cdot G_{i,j}}{(mC_p)_i}T_i^{\tau-1} + \frac{\Delta t q_i}{(mC_p)_i}, \tag{10}$$

where N – the total number of diffusion nodes,

i, j – the nodes of thermal RC-network,

$\tau - 1$ – the previous time of calculation,

$\tau + 1$ – next (current) one time of calculation,

q_i – the heat source node i,

$G_{i,j} = C_{i,j} + R_{i,j}(T_i^2 + T_j^2)(T_i + T_j)$ – the overall conductivity between nodes i and j.

4. Model Local Fragment of the Myocardium in the MSC Sinda System

In constructing the model of myocardial in the MSC Sinda system the implemented thermal contact between three-dimensional bodies – the myocardium, coronary arteries, a liquid cooling of heart. The model of heat exchange for the local area of the myocardium is built for two conditions of heat transfer: heat conduction and free convection for the myocardial area, which is depleted of the coronary vessels and the myocardial region with double the density distribution of the coronary vessels in the myocardium, relative to the case of depleted distribution.

The heat transfer coefficient under free convection between three-dimensional objects – the myocardium and coronary vessels corresponds to the natural model of convection laminar flow across the surface with the characteristic length L:

$$h = \frac{\lambda_{heart-liq}}{L} \cdot N_u, \tag{11}$$

where $N_u^{\frac{1}{2}} = 0,825 + \frac{0,387 R_a^{\frac{1}{6}}}{\left[1+\left(\frac{0,492}{P_r}\right)^{\frac{9}{16}}\right]^{\frac{5}{27}}}$ – the Nusselt number,

$R_a = G_r \cdot P_r$ – the Rayleigh number ($0,1 < R_a < 10^{12}$).

For the laminar flow of blood in the blood vessels, these values $G_\Gamma \cdot P_\Gamma$ in the range $1 \cdot 10^3 < G_\Gamma P_\Gamma < 5 \cdot 10^2$.

A substantial increase of the wall thickness of the myocardium leads to an increase in the thermal resistance to zone of the atherosclerotic damage wall of the heart muscle. The equation of the heat balance for during the heat exchange between the inner and outer walls of the myocardium has the form:

$$Q_{heart} = Q'_{heart} \text{ or } \alpha_{heart} \cdot (T_{\text{int}} - T_{ext}) \cdot \Delta t = m_{heart} \cdot c_{heart}(T_1 - T_2), \tag{12}$$

where Δt – the duration of the process hyperthermia of the heart, s,

T_{int}, T_{ext} – the temperature of the inner and outer surfaces of the myocardium, K.

From this equation the coefficient cooling of the myocardium in a unit interval of time Δt is equal to:

$$r = \frac{\alpha_{heart}}{m_{heart} \cdot c_{heart}} = \frac{T_1 - T_2}{T_{\text{int}} - T_{ext}}, \tag{13}$$

Accordingly, the change in thermal resistance of the myocardium can be expressed in terms of the temperature of the inner wall T_{int}, which is cooled by the blood flowing from the heart-lung machine. And the outer wall temperature T_{ext}, are controlled by the thermal imager:

$$R_q = \frac{1}{m_{heart} \cdot c_{heart}}\left(\frac{T_{\text{int}} - T_{ext}}{T_1 - T_2}\right), \tag{14}$$

Or relative to end-diastolic volume of the myocardium:

$$R_q = \frac{1}{\rho_{heart} \cdot c_{heart} \cdot V_D}\left(\frac{T_{\text{int}} - T_{ext}}{T_1 - T_2}\right), \tag{15}$$

where T_1 и T_2 – the initial and final temperatures of hypothermia of the heart, which must be achieved by use the machine of an artificial heart-lung.

The thermal resistance R_q and the coefficient cooling r of the myocardium can be estimated based on a model of heat exchange in the local myocardial site which is implemented in the modelling system MSC Patran and MSC Sinda 2012.

Implementation of the model of heat exchange in the MSC Sinda system for infarction cooling process gives on the final process step in establishing the heat balance the temperature difference at the boundary between the myocardium and coronary vessels not more than $0.5\,°C$. However, in the areas of the myocardium that are removed from the coronary vessels the temperature difference exceeds $1.0\,°C$. The example of numerical heat transfer model, which employs the heat convection between ice cube and the surface of the myocardium, is shown in Figure 2.

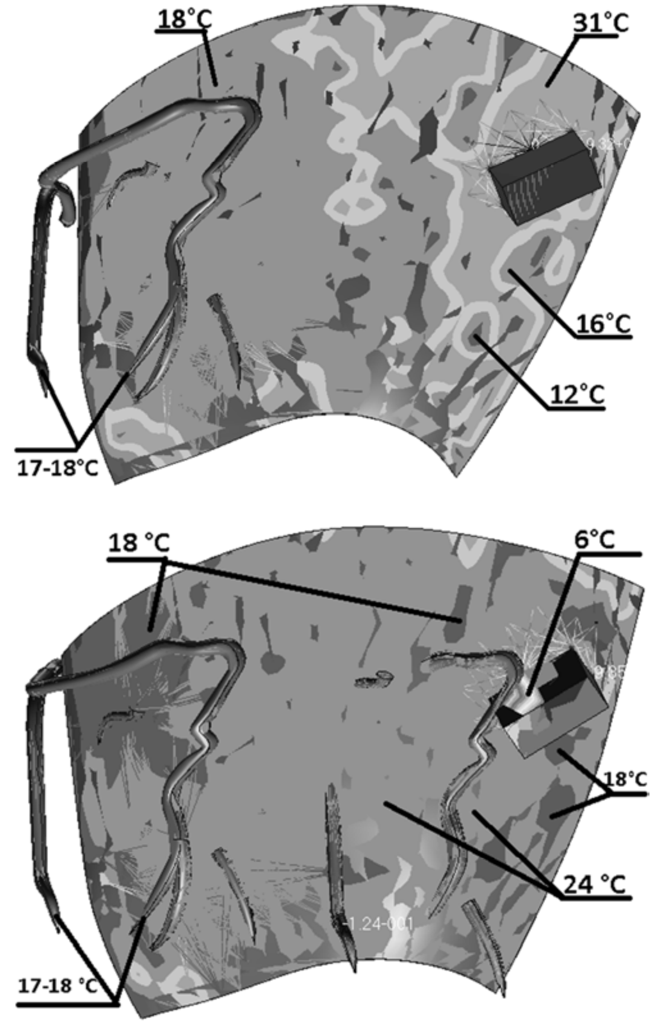

Figure 2. *The distribution of temperatures on the surface of the myocardium, which is further cooled of ice at a temperature* $T_{liq} \approx 1°C$.

From the analysis of the temperature distribution on the surface of the myocardium can be seen that a large temperature gradient $\Delta T_1 > \Delta T_2$ at the surface of the myocardium, which is depleted of coronary vessels, is caused by insufficient heat exchange between the blood and the myocardium. It is obvious that the lack of heat exchange between the three-dimensional objects in the model – the myocardium and coronary vessels is associated with a decrease in area of the critical section of the myocardium S_{heart} which has contact with the coronary vessels that filled with blood.

To ensure the temperature gradient between the perfusate (blood in the circuit of cardiopulmonary bypass) and the patient's body no more than $7°C$ the venous blood warmed with minimum speed $0,2°C/min$, which caused lengthy process hyperthermia more than 55 minutes. The maximum temperature gradient between values, which are recorded by thermal imager on the surface myocardium and in the esophagus of the patient was $6°C$ for 25 minutes process of warming the heart. And, in the final stage of hyperthermia under artificial circulation is leveling body temperature and heart and, consequently, reducing the temperature gradient $0,5°C$ to the value that corresponds to the accuracy of non-invasive temperature measurement using the thermal imager Flir i7.

Comparative analysis of the temperature distribution in the 2D-model on the surface of the myocardium for processes of hypo- and hyperthermia shows that in areas of ischemia observed a significant increase in the temperature gradient between local areas with a high temperature at cooling of the heart and lower temperature at warming the heart. The lowest temperature gradient at the surface infarction observed in areas saturated coronary vessels through which is carried drainage blood.

Application of model of heat exchange for problem of cooling of myocardium with the use of heat exchangers [8 - 10] provided stationary convection laminar flow across the border surface of blood-myocardium gives the value of convection coefficient, respectively, $h_1 \approx 4,70\frac{W}{m^2 \cdot K}$ and $h_1 \approx 4,70\frac{W}{m^2 \cdot K}$ in establishing the heat balance. These values the coefficients of convection correspond to the inner surface temperature – for coronary vessels $\Delta T_{\text{int}} \approx 5°C$, and the external surface temperature – for not cooled myocardium $\Delta T_{ext} \approx 35°C$.

5. Conclusion

Thus, a discrete 3D-model of heat transfer in the layer structure of the myocardium and coronary vessels allows us to investigate the process of hypo- and hyperthermia with cardiopulmonary bypass. The simulation results also make it possible to perform an analysis of the temperature distribution on the surface of the myocardium provided free convection of heat between the layers. The numerical heat transfer model in MSC Sinda for the myocardium takes into account real specific heat of human heart, the initial temperature distribution and free convection mechanism in the myocardium, and also allows to calculate the rate of cooling of the myocardium and to determine the presence of ischemic lesions on the surface of the myocardium.

Comparisons of the model with real thermograms of heart show that this method can provide additional important information regarding temperature and vascular uniformity of layer myocardium. Besides, temperature gradient on the surface of the myocardium before and after cooling of the heart is stable indicator which probably can be used as a diagnostic criterion in determining ischemic areas on the surface of the myocardium.

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