Journal of Engineering Physics and Thermophysics, Vol. 81, No. 6, 2008

HEMODYNAMICS AND HEAT TRANSFER IN CONTROLLED WHOLE-BODY HYPERTHERMIA: MODELING OF PROCESSES

N. V. Kinsht[a] **and D. N. Kinsht**[b]

UDC 519.68

The possibilities of describing structural couplings between the organs of a human being subjected to a treatment procedure of controlled whole-body hyperthermia at 43–44°C are considered. The requirements on a model that characterizes changes in the hemodynamics have been formulated, and the interrelations between the models of hemodynamics and heat transfer are shown. As an example of the implementation of the proposed approaches, a system of equations is given that describes heat exchange between an organism and a heat carrier, numerical simulation in the Matlab, toolbox Simulink medium is carried out, and the results of simulation are presented.

Introduction. At the present time the method of controlled whole body hyperthermia (CWBH) at 43–44°C is finding increasingly wider use in medicine. Many of the experimental investigations on animals and volunteers have demonstrated its high efficiency in treating oncologic diseases, a decrease in the toxicity of chemotherapy, correction of immunity, and therapeutic effect in the treatment of viral diseases, including AIDS [1–6].

The aim of the CWBH procedure in a pathological process consists of the heating of all organs and tissues of the organism to a given temperature and sustaining it for a time sufficient for inflicting irreparable damage to the defective cells. In doing so, one should see to it that healthy tissues are preserved and the viability of the organism is sustained. At the present time, this is achieved by various methods: heating of an organism by an electromagnetic SHF field, heating of blood outside the organism, and an immersion-convective method where in an organism is immersed in a bath with a hot heat carrier (usually hot water). We think that the most promising method is the last one, which does not need expensive equipment for heating, ensures a high rate of heating, and excludes local superheatings of skin above 46–47°C.

Wide use of CWBH with the body temperature above 43°C is difficult for a human being because of inefficiently controlled disorders of the hemodynamics: peripheral vasodilation and cardiac rhythm disturbance [7]. Upon a decrease in the diastolic pressure, the blood supply to the myocardium is appreciably impaired. This leads to a decrease in the cardiac output and to progressing hypotonia. Correspondingly, the blood flow decreases and, as a consequence, the heating of the affected tissues, which decreases the efficiency of hyperthermia.

Present-day pharmacology is capable of affecting various chains of hemodynamics. For the effective use of drugs it is necessary to be capable of predicting disturbances in the hemodynamics and providing the corresponding correction of disturbed functions by accurately analyzing the situation in real time.

Some authors emphasize the necessity of considering the problem on a system level, but in the models suggested the problem of predicting the hemodynamics parameters had not even been posed. There are various models of hemodynamics (stochastic descriptions, models with lumped parameters, with distributed parameters) that were directed at qualitative and quantitative interpretation of the phenomena of mass transfer in the vasculature [1, 8–10]. However, they do not allow one to predict, with sufficient accuracy, changes in the hemodynamics occurring in the course of CWBH, since they do not take into account the nonuniformity in the change of the peripheral resistance of vessels in various organs upon a nonuniform increase in the body temperature. Models are needed that could be analyzed numerically and that make it possible to follow the processes of substance and energy transfer. The results of a numeri-

[a]Institute of Automation and Control Processes, Far-East Branch of the Russian Academy of Sciences, 5 Radio Str., Vladivostok, 690041, Russia; [b]Novosibirsk Regional Hospital, Naukograd, Kol'tsovo, Novosibirsk District, 630559, Russia; email: kin2@nm.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 81, No. 6, pp. 1188–1197, November–December, 2008. Original article submitted March 9, 2006; revision submitted August 17, 2007.

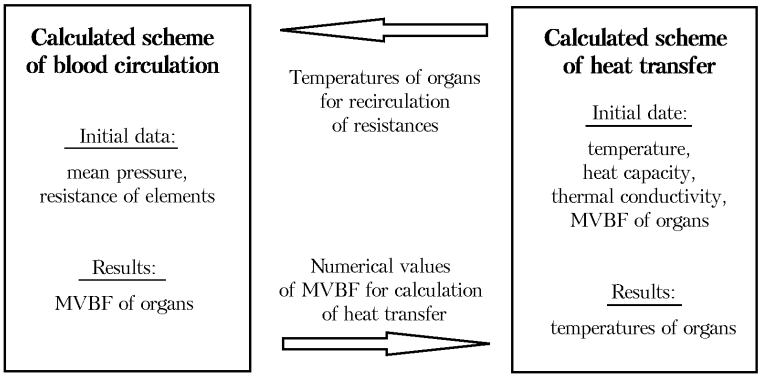

Fig. 1. Interrelationship between the models of blood circulation and heat transfer.

cal analysis can serve as more reliable and timely information for carrying out an analysis of the state of an organism subjected to CWBH [11].

Interrelationship between the Models of Blood Circulation and of Heat Transfer. In the present work the CWBH is considered as a physical process of heat and mass transfer, viz.,

1) heat is transferred in two ways: directly from the skin into organs and from the skin to organs via blood, with mixing of heated portions of blood from the venous sinuses of the skin with cooler fractions occurring in the venous channel and with the arterial blood transferring heat into organs;

2) heat transfer from the arterial blood into organs depends on the state of hemodynamics as a whole and the minute volume of blood flow (MVBF) in each organ;

3) changes in the temperature of organs lead to changes in the physical parameters of heart, vessels, and blood that in turn determine the hemodynamics.

The organs are heated up at a different rate, and in the process of heating they have different temperatures. The reason is the differences in the heat capacity of tissues, MVBF, and in the masses of the organs. For the problem posed to be solved, of interest are the temperature and MVBF of each organ.

The following requirements to be met by the model have been formulated:

1. The basic elements of the hemodynamic model (HDM) are individual organs that are characterized by the sole value of temperature and the sole value of MVBF through an organ. If different fragments of an organ have substantially different temperatures (e.g., heated and nonheated fragments of skin) or different blood supply (e.g., blood vessels with branches), then the corresponding fragments of these organs with the sole values of temperature and blood flow are considered to be the elements of the hemodynamic model.

2. The points of blood flow branching are considered to be the nodes of the hemodynamic model. Each node numbered i (i = 1, ..., q) is characterized by a potential, i.e., blood pressure p_i, and each branch numbered k (k = 1, ..., n) is characterized by the value of MVBF I_k.

3. The regimes of operation of the elements are considered from two points of view: the thermal regime of operation (heat transfer model, HTM) and the hemodynamic model, HDM. Actually two interrelated models of lower level are considered: the thermal regime of operation of the elements is characterized by their temperature and heat flux, whereas the hemodynamic regime is characterized by the average arterial pressure (AAP) (or by a drop in the arterial pressure) and by MVBF.

4. The couplings between the elements must be adequately described.

To analyze the processes occurring in the given model it seems most effective that the mathematical apparatus of the circuit theory be used. To formalize the problems posed, analogies are drawn between the elements of the model and electric elements. In the model of blood circulation an analog of electric voltage is the drop in hydrodynamic pressure on this element. An analog of electric current is the MVBF. In the simplest case, the heart can be considered as the source of arterial pressure (AP), if the latter is known exactly, or as the current source if MVBF is known. The resistance of a portion of a blood vessel is understood to refer to the ratio of the pressure drop to the blood flow. In the heat transfer model the analog of electric voltage is the temperature difference and that of electric current — the heat flux. The ratio of the heat flux between a pair of elements to the difference of their temperatures

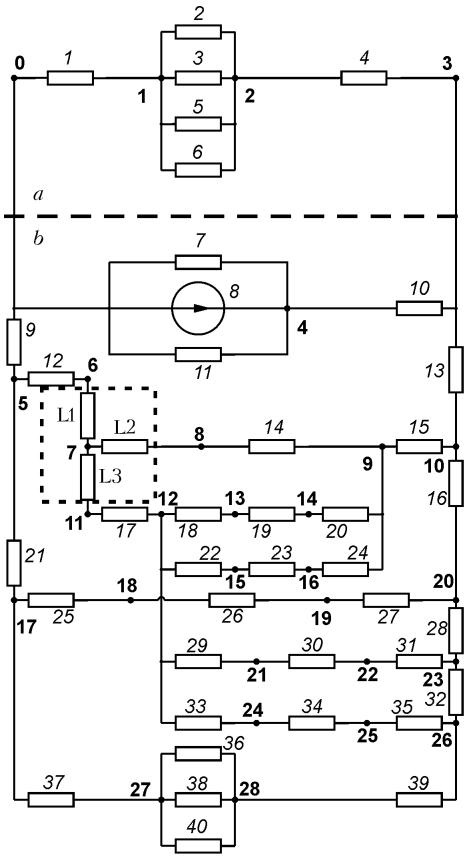

Fig. 2. Equivalent scheme of blood flow in CWBH (a) unheated part of the body not immersed into the heat carrier; b) heated part of the body, dashed lines show the portions of liver L1, L2, L3, with specific features of blood supply; bloodstream nodes 0–28 are in semi-bold type); elements of body: 1) upper hollow vein; 2, 3, 5) skin, muscles, and bones of unheated part of the body; 4) common carotid artery; 6) brain; 7) lungs; 8) heart; 9, 21) part of lower hollow vein; 10) aorta arc; 11) vessels of heart; 12) liver vein; 13, 16, 28, 32) parts of aorta; 14) liver artery; 15) maw trunk; 17) portal vein; 18) stomach vein; 19) stomach; 20) stomach artery; 22) spleen vein; 23) spleen; 24) spleen artery; 25) kidney veins; 26) kidneys; 27) kidney arteries; 29) upper mesentery artery; 33) lower mesentery vein; 34) large intestine; 35) lower mesentery artery; 36, 28, 40) skin, muscles, and bones of heated part of the body; 37, 39) veins and arteries of the heated part of the body.

represents thermal conductivity. In the model of heat transfer the heat capacities of elements are introduced. In the problem of predicting the disturbances in the hemodynamics in the course of CWBH the temperature-dependent non-linear resistive model should be used. The two models are coupled by the temperature of elements and by the blood velocity that determines the intensity of heat transfer (Fig. 1). The blood temperature is taken equal to the temperature of the corresponding organs.

Since the average times of changes in the temperature of organs are measured in minutes, all the parameters of the hemodynamics (MVBF, HR) must also be considered in this time scale. In general, the hemodynamics may be characterized by the parameters of fast processes (e.g., by the duration of a systole and sphygmogram parameters) and when required their averaged values can be used. This approach was used by other authors in modeling heat transfer in blood vessels [12].

An Equivalent Scheme of the Hemodynamic Model. The main regulator of the vascular resistance (also after a change in temperature) in organs are arterioles. To simplify the analysis, each element of the hemodynamic

TABLE 1. Description of the Connection of Elements (fragments)

Part of body	Element	No. of element	Node of beginning	Node of the end
Unheated	Skin 1	*2*	**2**	**1**
	Muscles 1	*3*	**2**	**1**
Heated	Heart	*8*	**0**	**4**
	Bones 2	*40*	**28**	**27**

model can be represented as one resistor. In describing the general structure of the model, we will use the simplified representation of the element, whereas when it is necessary to present more accurately its parameters that depend on temperature and other factors, we will use a detailed representation. Passive elements are characterized by the resistance R_k or conductivity $G_k = 1/R_k$ that relate the pressure drop and MVBF. It is evident that

$$I_k = (p_i - p_j)/R_k = (p_i - p_j)\, G_k\,, \quad k = 1, ..., n\,, \quad i, j = 1, ..., q\,,$$

where k is the number of the branch attached to a pair of nodes (i, j); p_i and p_j are the potentials (nodal pressures of blood) of the corresponding nodes.

In what follows we will also use matrix representation:

$$\mathbf{G} = \text{diag}\left\{G_k\right\}\,, \quad k = 1, ..., n\,.$$

We will give the complete scheme of the hemodynamic model with the main organs that participate in the blood circulation system of the organism (Fig. 2). Presented in the figure are 40 passive elements connected with the aid of $q = 28$ nodes. The liver is thrice attached to the blood system, L1–L3. It is assumed that the parameters of all elements are given and at least their dependences on temperature. A simple way of describing the connection of elements is presented in Table 1, which gives the name of the element, its number, and the numbers of the nodes to which it is connected.

To describe the algorithm of the mathematical analysis of the problem, the incidence matrix of $\mathbf{A} = \{a_{ik}\}$ (of size $(q-1) \times n$)) is used, the lines of which correspond to the nodes of the hemodynamic model (except one), whereas the columns corresponds to the branches (elements). Here, $a_{ik} = 0$, if the branch k is not connected with the node i, and $a_{ik} = 1$, if the branch k is connected to the node i by its beginning and $a_{ik} = -1$, if the branch k is connected to the node i by its end. In this case the description of the analysis of the hemodynamic problem is reduced to the matrix equation

$$\mathbf{AGA'P} = \mathbf{AJ}\,. \tag{1}$$

Here, $\mathbf{A}'$ is the transposed matrix $\mathbf{A}$; $\mathbf{P} = \text{col}\ \{p_1, ..., p_{(q-1)}\}$, $\mathbf{J} = \text{col}\ \{J_1, ..., J_{(q-1)}\}$, $J_8 \neq 0$, the remaining $J_i = 0$; $\mathbf{G} = \text{diag}\ \{G_k\}$, $k = 1, ..., n$.

Solution (1) for the sought vector $\mathbf{P}$ has the form

$$\mathbf{P} = (\mathbf{AGA'})^{-1}\,\mathbf{AJ}$$

and for the distribution of the blood flow $\mathbf{I} = \text{col}\ \{I_1, ..., I_n\}$ in the elements of the hemodynamic model we obtain the expression

$$\mathbf{I} = \mathbf{GA'P}\,.$$

Equivalent Scheme of the Model of Heat Transfer. The construction of an equivalent scheme of the heat-transfer model is methodically analogous to the previous ones, but it has been made somewhat more complex. While for the hemodynamic model it suffices to have a nonlinear algebraic (resistive) description, the heat transfer model is described by differential equations. The problem of the analysis of heat transfer is reduced to calculation of the temperature of elements. Here we have to apply the notion of the heat capacity of organs C_k and of heat fluxes Q_k to the organs. As a potential function the temperature of organs T_k ($k = 1, ..., n$) is used.

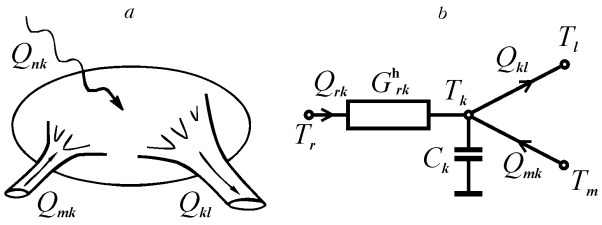

Fig. 3. Physical processes of heat transfer in each element (a) and the local scheme of replacement (b).

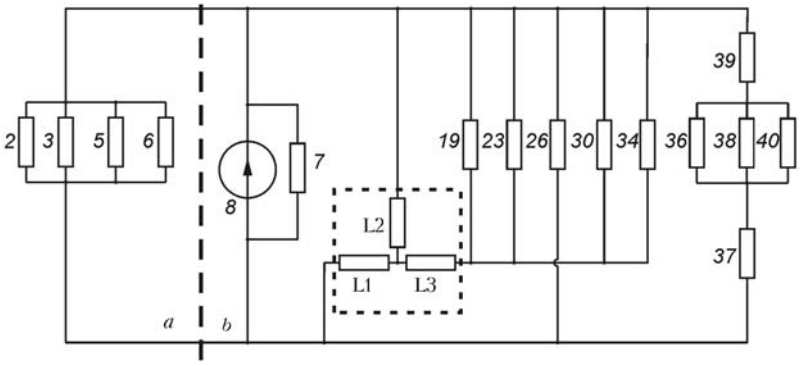

Fig. 4. Simplified scheme of blood circulation. Depicted are elements in direct thermal contact. Numbering of elements corresponds to the numbering in Fig. 2.

In the case of the immersion-convective method of hyperthermia there are three ways of heat exchange of a body with the environment: portions of the skin heated by a heat carrier, unheated portions of the skin with the surrounding air, and through breathing. A preliminary analysis shows that the first factor plays the most important role in the process of hyperthermia at a high rate of heating. The metabolic heat production can be neglected, since its level is several orders of magnitude lower than the quantity of heat transferred by the heat carrier to an organism. The physical processes of heat transfer in each element can be presented in the form depicted in Fig. 3a and in the form of the corresponding local scheme of substitution in Fig. 3b.

Corresponding to the nodes of the heat-transfer model are the points (organs) characterized by a certain temperature. Moreover, the surrounding medium-heat carrier that serves as a heat source with the known temperature will be added as an individual node. The ways of heat transfer are the branches of the heat-transfer model. This requires information on the MVBF of the element and on the area of the thermal contract of the element with neighboring elements. The equation of heat balance in the node k will be written in the form

$$C_k dT_k/dt = G^{h}_{rk}(T_r - T_k) + Q_{mk} - Q_{kl}\,. \tag{2}$$

Here $G^{h}_{rk} = \alpha_{rk}S_{rk}$; $Q_{mk} = c_b I_k T_m$; $Q_{kl} = c_b I_k T_k$. Relation (2) can be written as

$$C_k dT_k/dt = -(\alpha_{rk}S_{rk} + c_b I_k)\,T_k + \alpha_{rk}S_{rk}T_r + c_b I_k T_m\,.$$

It is evident that the terms of the type $(c_b I_k)$ and $(\alpha_{rk}S_{rk})$ formally represent thermal conductivities (they are based on different mechanisms of heat transfer), and in what follows we will use the generalized designation G^{h}_{rk}. We will write Eq. (2) in matrix form:

$$\mathbf{C}d\mathbf{T}/dt = \mathbf{G}^{h}\mathbf{T} + \mathbf{J}^{h}\,. \tag{3}$$

Here $\mathbf{T}$ = col $\{T_1, ..., T_n\}$; $\mathbf{C}$ = diag $\{C_k\}$, $k = 1, ..., n$; $\mathbf{G}^{h} = \mathbf{G}^{h}(\mathbf{I}) = \{G^{h}_{rk}(I_k)\}$; $\mathbf{J}^{h}$ = col $\{J_1, ..., J_n\}$. The differential equation (3) should be supplemented with the initial condition, i.e., the values of the temperatures of organs at $t = 0$.

TABLE 2. Structure of the Matrix of the Thermal Contact of Organs (the numbering of elements corresponds to the numbering in Fig. 2)

Element	No. of element	No. of element																
		2	3	5	6	7	8	L1–L3	19	23	26	30	34	36	37	38	39	40
		Unheated part																
Skin 1	2	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0
Muscles 1	3	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0
Bones 1	5	1	1	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0
Brain	6	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0
		Heated part																
Lungs	7	0	0	0	0	1	1	1	1	0	0	0	0	0	1	1	1	1
Heart	8	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	1	0
Liver	L1–L3	0	0	0	0	1	0	1	1	0	0	1	0	0	1	0	1	0
Stomach	19	0	0	0	0	1	1	1	1	1	0	1	0	0	1	0	1	0
Spleen	23	0	0	0	0	0	0	0	1	1	0	1	0	0	1	1	1	0
Kidneys	26	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0
Small intestine and blind gut (cecum)	30	0	0	0	0	0	0	1	1	1	1	1	1	0	1	1	1	1
Large intestine	34	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1
Skin 2	36	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0
Veins	37	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
Muscles 2	38	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1
Arteries	39	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
Bones 2	40	0	0	0	0	1	0	0	0	0	0	1	1	0	1	1	1	1

Note. 0 means the absence of direct thermal contact of elements; 1, direct thermal contact.

In the context of constructing the model of heating of an organism in the course of hyperthermia it would be logical that the models of blood circulation and of heat transfer could have the same elements [13]. Therefore it makes sense that in the given problem a simplified scheme of blood circulation be used (Fig. 4), in which the elements of the scheme of blood circulation that have a direct thermal contact are shown.

The structure of the matrix of direct thermal contact of organs is presented in Table 2. The numbers of elements are given vertically and horizontally.

Organization of the Process of Computations. Based on relations (1) and (3), it is possible to organize the iteration process of computations. On the one hand, the parameters of the hemodynamic model depend on the temperature of organs and, on the other hand, the parameters of the heat transfer model depend on the distribution of MVBF. A specialist that carries out the procedure of hyperthermia must be aware of the predicted values of MVBF and of arterial pressure. The models obtained allow one to introduce, into the process of calculation, real values of temperature, arterial pressure, and of other parameters measured in the process of hyperthermia and to correct the model in real time.

Here only basic (structural) couplings between variable quantities have been illustrated. To obtain a correct solution of the problems posed it is necessary to have information on a large quantity of parameters of each patient. Part of these parameters (mass, volume, blood flow in various organs) can be measured during preliminary anthropometric, tomographic, and ultrasonic investigations. One can also use experimentally observed trends in the blood flow in organs during hyperthermia [7].

An Example of Implementation of the Proposed Approaches. Numerical simulation of the heating of an organism subjected to hyperthermia is carried out. Not rejecting the above-stated principles, here we use the simplest model of blood circulation and heat transfer. The model took into account the change in the blood flow in the heated portion of skin on change in its temperature [14].

Let us isolate several fragments of the body: heated skin 1, internal organs 2, subcutaneous fat 3, bones 4, and unheated skin 5. We assume that the total mass of blood m_b and mass velocity of the blood flow v are given. Each of these fragments (k = 1, ..., 5) is characterized by the following parameters: m_k, c_k, and general heat capacity

$C_k = m_k c_k$, a_k, b_k, T_k. The specific heat of fragments 1, 2, 5 and of blood can be considered identical and equal to c = 3600 J/(kg·deg) [8].

Heat transfer from the skin to organs is made in two ways: through the subcutaneous fat and with the heated blood flow.

We will consider a more simplified system having united fragments 2–5 into one equivalent fragment and assign the number 6 to it. Then

$$b_6 = 1 - b_1 , \quad a_6 = 1 - a_1 .$$

The temperature of the arterial blood is

$$T_a = b_1 T_1 + (1 - b_1)\, T_6 . \tag{4}$$

The heated skin together with the blood contained in it receive heat from the heat carrier and spends it on raising their own temperature, heating the blood, and on contact heat transfer to organs through the subcutaneous fat:

$$\frac{dT_1}{dt} = \frac{(T_0 - T_1)\, S_{1h} G_0 - b_1 vc\, (T_1 - T_a) - (T_1 - T_6)\, S_{1h} G_1}{c\, (m_1 + a_1 m_b)}$$

or with account for (4)

$$\frac{dT_1}{dt} = \frac{(T_0 - T_1)\, S_{1h} G_0 - (1 - b_1)\, b_1 vc\, (T_1 - T_6) - (T_1 - T_6)\, S_{1h} G_1}{c\, (m_1 + a_1 m_b)} , \tag{5}$$

where $c(m_1 + a_1 m_b)$ is the total heat capacity of the heated skin together with the blood associated with it.

Fragment 6 together with the blood contained in it will heat up while receiving heat from the skin through the subcutaneous fat and with the arterial blood:

$$\frac{dT_6}{dt} = \frac{(1 - b_1)\, (T_6 - T_a)\, vc + (T_1 - T_6)\, S_{1h} G_1}{c\, (m_6 + (1 - a_1)\, m_b)}$$

or subject to (4)

$$\frac{dT_6}{dt} = \frac{(1 - b_1)\, b_1 vc\, (T_1 - T_6) + (T_1 - T_6)\, S_{1h} G_1}{c\, (m_6 + (1 - a_1)\, m_b)} , \tag{6}$$

where $c[m_6 + (1 - a_1)m_b]$ is the total heat capacity of the body without the mass of the skin and the blood associated with it.

We complement the system of equations (5), (6) by:

1) the coupling of the mass velocity of the blood flow v with the shock volume of heart V in terms of the heart rate F:

$$v = FV ; \tag{7}$$

2) the coupling of the shock volume of heart with the heart rate [15]:

$$V(F) = 1.7 \cdot 10^{-3} F - 7.1 \cdot 10^{-2} ; \tag{8}$$

3) the dependence of the filling of skin with blood a_1 on temperature T_1; the changes described in [16] will be described by the expression

$$a_1 (T_1) = 8.3 \cdot 10^{-3} T_1 - 2.5 ; \tag{9}$$

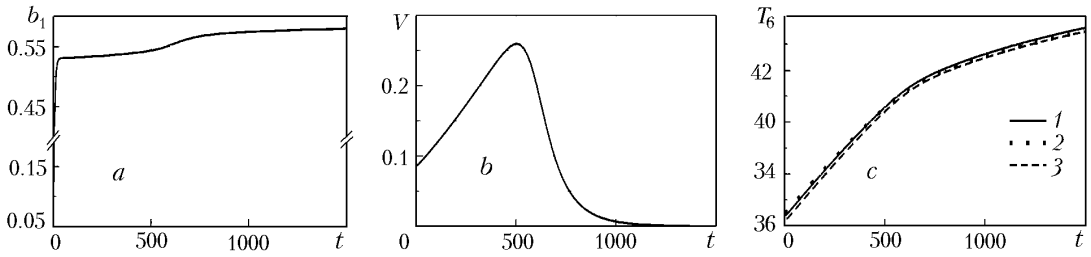

Fig. 5. Results of numerical simulation in the Matlab, toolbox Simulink medium; a) predicted changes of skin blood flow in the course of the CWBH procedure; b) predicted volume of blood circulation during the procedure of CWBH; c) temperature of the body in the course of the procedure of controlled whole-body hyperthermia; 1) calculated values; 2) temperature in nasal passage; 3) temperature in the middle third of gullet.

4) the dependence of the blood flow b_1 in the skin on temperature T_1, whereas the trends described in [17] will be expressed as

$$b_1 (T_1) = 4.5 \cdot 10^{-3} T_1 - 1.47 ; \tag{10}$$

5) the coupling of the heart rate F with the temperature T_6, since from a course in general physiology it is known that on an increase in the body temperature by a degree the heart rate increases by 10 beats per minute:

$$F (T_6) = F (T_{60}) + 10 (T_6 - T_{60}) ; \tag{11}$$

6) the following empirical relation to describe the drop in the volume ejections V at extreme values of F:

$$V (F) = \frac{V (F_0) F}{1 + \exp ((F - 130)/3)} ; \tag{12}$$

7) the well-known dependence of the skin area S_1 on the mass of the body M and its height L:

$$S_1 = (LM)^{-1/2}/60 . \tag{13}$$

Since the thermal conductivity of water is equal to 0.6 W·deg^{-1}·m^{-1}, and the skin thickness is equal to ~1 mm, G_0 is equal to 1200 W·deg^{-1}. The thermal conductivity of the fat is 0.12–0.15 W·deg^{-1}·m^{-1}, and the thickness of the subcutaneous fat may vary significantly; therefore we assume that G_1 is equal to 150 W·deg^{-1}.

To estimate the validity of the model and refine the parameters of the system of equations (4)–(13) presented numerical simulation was carried out in the Matlab, toolbox Simulink medium. The following parameters were assigned: the mass of the body M, its height L, the initial temperature T_6, the temperature of the skin T_1, the initial heart rate F of a particular patient V., 48 years old, before the CWBH procedure. The results of simulation are presented in Fig. 5. Changes of the skin blood flow b_1 during the CWBH procedure described in the present model by Eq. (10) are presented in Fig. 5a and the dynamics of the predicted volume of blood circulation is depicted in Fig. 5b. It is seen that the volume of blood circulation for the time of the procedure of CWBH undergoes great changes. It may quite be that the changes in b_1 and MVBF are the main reasons for the disturbance of the hemodynamics at elevated temperatures of the body. To verify these assumptions, information on the laws governing changes in the peripheral resistance of other organs with changes in temperature is required.

The results of the computational dynamics of the body temperature are presented in Fig. 5c. For comparison, the figure also presents real values of temperatures measured in the middle third part of the gullet and in the nasal passage of the same patient during the CWBH procedure. As is seen from the figure, the calculated results are close to those measured.

Conclusions. The approaches presented allow one to construct numerical models of the hemodynamics and heat transfer during CWBH. The model of heat transfer adequately reflects the processes of heating up of an organism in the case of controlled whole-body hyperthermia by the immersion-convective method and may serve as a basis for calculation of the distribution of heat inside an organism. For this purpose, it is necessary to have data on changes in the blood flow in various organs with temperature.

The realization of the above-described principles in full measure is limited at the present time by the possibilities of obtaining rather reliable numerical values of the model parameters. It seems promising to use the possibilities of refining the parameters of the model (heat capacity and thermal conductivity of organs, dynamics of blood flow in organs) directly at the initial stages of heating up and during stable hemodynamics. To determine the coefficients that allow one to carry out reliable numerical calculations one can use the principles and methods of the theory of diagnostics of electric circuits [18]. As the body temperature increases above 42°C, the use of the parameters obtained will make it possible to predict and present disturbances in hemodynamics, to calculate the temperatures of the organs, and thus to raise the efficiency and safety of hyperthermia.

NOTATION

A, matrix of the incidences of the hemodynamic model; a_i, coefficient of filling with blood of the ith fragment; it characterizes the fraction of the mass of the blood that fills the given fragment ($\sum a_i = 1$); b_i, coefficient of blood supply to the ith fragment; it characterizes the fraction of the mass of the blood that flows through this fragment per unit time ($\sum b_i = 1$); **C**, matrix of heat capacities of elements of size $n \times n$, J/deg; C_i, total heat capacity of the ith fragment or organ, J/deg; C_k, total heat capacity of the kth element, J/deg; c, specific heat, J/(kg·deg); c_b, heat capacity of blood, J/(kg·deg); c_i, specific heat of the ith fragment, J/(kg·deg); F, heart rate, sec^{-1}, min^{-1}; F_0, initial heart rate, sec^{-1}, min^{-1}; **G**, matrix of the conductivities of the hemodynamic model, m^3/(sec·Pa); G_k, conductivity of the branch k of the hemodynamic model, J/(sec·deg); G_0, thermal conductivity of the heat carrier–skin interface, J/(sec·deg); G_1, thermal conductivity of the skin–subcutaneous fat interface, J/(sec·deg); $\mathbf{G}^h$, matrix of nodal thermal conductivities of size $n \times n$, J/(sec·deg); G^h_{rk}, heat conduction between elements r and k, J/(sec·deg); **I**, vector of the distribution of blood currents, m^3/sec, liters/min; i, j, number of the node in the hemodynamic model; I_k, value of MVBF of branch k, m^3/sec, liters/min; **J**, matrix-column of nodal flows of blood, m^3/sec, liters/min; $\mathbf{J}^h$, matrix-column of nodal heat sources, W; k, l, m, r, number of the organ of the heat transfer model; L, height, cm; L1, L2, L3, different portions of blood supply to liver; M, mass of a body, kg; m_b, mass of blood, kg; m_i, mass of fragment i, kg; n, number of elements of the hemodynamic model; **P**, matrix-column of nodal pressures of blood, Pa; p_i, blood pressure in the node i, Pa; q, number of nodes of the hemodynamic model; Q_k, heat flux to the organ k, W; Q_{kl}, quantity of heat carried away from the element k with venous blood, W; Q_{mk}, quantity of heat brought to the element k from element m with arterial blood, W; Q_{nk}, quantity of heat brought to element k from element n in contact heat transfer, W; R_k, resistance of branch k of the hemodynamic model, sec·Pa/m^3; S_1, surface area of skin, m^2; S_{1h}, surface area of heated skin, m^2; S_{rk}, area of thermal contact between organs r and k, m^2; t, time, sec; **T**, matrix-column of the temperatures of elements, deg; T_1, temperature of heated skin, deg; T_a, temperature of arterial blood, deg; T_i, temperature of fragment i, deg; T_k, T_k, T_m, T_r, temperature of elements numbered k, l, m, and r, respectively, deg; v, bulk velocity of blood flow, kg/sec; V, shock volume of heart, m^3, liter; α_{rk}, coefficient of heat transfer between organs r and k, W·m/sec. Subscripts: a, artery; b, blood; h, heat; 0, initial value; 10, initial value of the first fragment; 60, initial value of the sixth fragment.

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