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THERMOPHYSICAL MODELS FOR EVALUATION OF THE ACTIVITY OF THE FUNCTIONING KIDNEY BY MEANS OF INFRARED THERMOGRAPHY

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Methods of biothermal modeling and analysis are used to determine the possibility of evaluation of the thermophysical parameters of the functioning kidney using infrared thermography. It is shown that the induced local heating from the outside enlarges the information content of medical thermography. It is shown that the main factor that determines thermographic visualization diagnostics is connected with the bloodflow. An analysis makes it possible to interpret thermographic situations for the kidney in the normal state and in the case of its particular pathology.

Introduction. Modern devices and recent developments in diagnostic visualization in the field of medical introscopy use the response of the living organism or its organs to multiple natural and artificial fields of various physical nature acting from the outside [1]. Evaluation of the physical parameters of these fields in connection with the measure of their safety for the human organism is a pressing problem [2]. Therefore, particular emphasis is placed upon visualization methods that are based on investigation of the natural radiation of a human and do not require an additional ray load [3]. These advantages are inherent in thermographic systems [4], in particular, infrared (IR) systems, whose production range is being diversified and expanded [5, 6]. Meanwhile, numerical processing of sequences of IR thermograms is in the development stage, and diagnostic methods have not been substantiated and are virtually unrealized in the clinic [7].

The development of thermophysical models of particular organs working in various physiological regimes is of particular importance. It is necessary to investigate the possibilities of methods of IR thermography and their accuracy and to reveal diagnostically reliable situations. Despite the considerable number of works on IR thermography [7, 8], its models have been scarcedly considered [9]; however, in recent years they have received increasing attention. But even in most modern works [10] the authors neglect bloodflow, which in a number of investigations [11] is considered an indicator of the physiological status of the functioning organ.

The kidneys are a part of the system that maintains the temperature homeostasis of the organism [12]. Inasmuch as the heat production of the kidney is extremely high [13], thermographic information on this organ should have a high information content. It is assumed that heat generation in the kidney takes place mainly as a result of metabolic processes. It appears that its bloodflow is proportional to the metabolism level [14]. Moreover, investigation of heat transfer processes in the kidney under normal conditions and in the case of pathology is complicated by the fact that metabolic processes in various tissues of the organ differ substantially both qualitively and quantitatively [5, 15]. This results in nonuniformity of the temperature field within the organ. It is stated [9, 13] that merely the calculation of these nonuniformities is at present an important physiological and mathematical problem.

For the reasons outlined above, we made an attempt to develop and analyze thermophysical models of the kidney under various physiological conditions with and without pathology.

Mathematical Statement of the Problem. Let us consider a model of a stationary regime of kidney functioning with regard for the effect of bloodflow and the process of production of metabolic heat in the heat transfer process in the kidney. The objective of this modeling is clarification of the conditions under which representation of various regimes of this organ is possible using methods of IR thermography.

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For simplicity, we present a spatial geometric model of the kidney as a rectangular parallelepiped with one of its side planes projected onto the corresponding skin surface. Taking into account the complex thermal energy regime of kidney tissue, we will consider the kidney a multisubstance organ each substance of which is characterized by its own power of generation of metabolic heat and bloodflow. In what follows we will consider kidney tissue as plane plates of finite thickness which can be produced by sectioning the parallelepiped in planes perpendicular to its base. Due to substantial morphological and functional differences in the cortical, medullary, and surface substances of the kidney [5, 15], a three-substance model of the organ is analyzed in the article. For the geometry chosen, these layers are adjacent flat plates with thicknesses a, b, and c equal to the thicknesses of the corresponding layers.

For calculation of thermal regimes we make use of the classical phenomenological biothermal equation [11, 15], which takes into account regularities of heat transfer in biological tissue associated with the bloodflow and the generation of metabolic heat. This equation has been repeatedly criticized in the literature [12], and the criticism is significant. However, an important advantage of the classical biothermal equation is that it is simpler than the probably more accurate recently published models [16, 17]. This equation contains a smaller number of parameters characterizing properties of biological tissue. Just this circumstanse it makes it possible to reveal more clearly the physical essence of the phenomena under consideration.

We resrtict ourselves to a one-dimensional model of the biological heat transfer processes being analyzed. Then the classical biothermal equation in dimensionless variables can be presented as follows:

$$\frac{\partial \Theta}{\partial \tau} = \frac{\partial^2 \Theta}{\partial \xi^2} - \beta^2 \Theta - \beta^2 Q , \tag{1}$$

$$\xi \in [0; 1], \quad \tau \in [0; +\infty) .$$

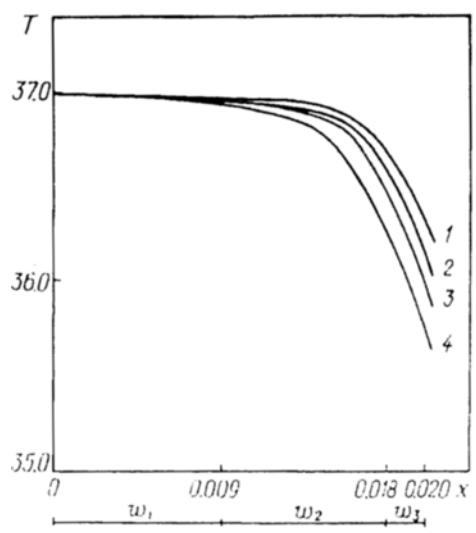
Let us consider the effect of factors that determine the thermal regime of the functioning kidney on the possibility of IR-thermographic visualization of these situations on its surface under conditions of their adequate description by Eq. (1). It is known that the result of measurement by this method is a thermogram that is a two-dimensional map of the temperature distribution over the surface of the body. It is evident that the one-dimensional model chosen here makes it possible to make a qualitative estimate of the character of the IR image from the numerical value of the local skin temperature ($T_s = T(1)$). We choose the origin on the boundary of the renal pelvis and the medullary substance. In the chosen model we neglect the thermophysical properties of the skin and tissue adjacent to the kidney. Therefore, the model appears to be not quite adequate for biophysical concepts on the temperature field of the human body recorded by IR devices. However, in estimates of the energy balance it should be taken into account that the skin layer is extremely thin. Therefore, skin bloodflow is likely to affect negligibly the skin temperature. Experimentally, this can be substantiated by fixing the absence of changes in the thermogram in the case of a bleeding scratch (created, e.g., by a finger nail), which points to an increase in bloodflow [11]. Allowance for subcutaneous tissue can contribute substantially to the interpretation of IR thermography effects depending on the thickness of the subcutaneous fat and the fatty membrane of the kidney [17], but this is not taken into account in the present work. This, most likely, does not limit the practical value of the model, since the viability of a kidney stored for transplantation can be successfully monitored by IR thermography [5, 18], whose possibilities in this case are by no means exhausted.

Thus, we will seek the temperature distribution in the chosen kidney model under the following boundary conditions:

$$\left.\frac{\partial \Theta}{\partial \xi}\right|_{\xi=0} = 0 , \quad \tau \in [0; +\infty) ; \tag{2}$$

$$k \left.\frac{\partial \Theta}{\partial \xi}\right|_{\xi=1} = \mathrm{Bi}\,(1 - \Theta)|_{\xi=1} , \tag{3}$$

$$\tau \in [0; +\infty) .$$



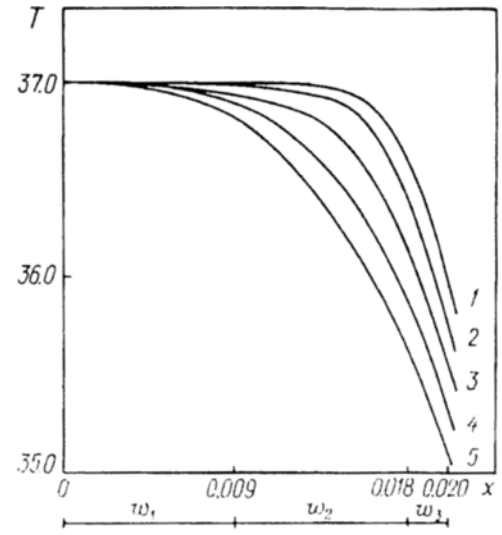


Fig. 1. Temperature distribution in renal tissue at h = 14 W/m$^2 \cdot$°C, Q_0^i = 0.17 W/kg ($i = \overline{1,3}$ and various blood perfusion rates w_i (ml/g·min), $i = \overline{1,3}$ in the normal state and in the case of pathology: 1) 2.00, 2.00, 2.00 (constant bloodflow); 2) 0.4, 2.0, 1.0 (normal blood perfusion); 3) 0.32, 1.60, 0.80 (ischemia); 4) 2.00, 1.20, 0.40 (acute tubular necrosis). T, °C; x, m.

Fig. 2. Temperature distribution in renal tissue for various blood perfusion rates in the medullary substance at h = 14 W/m$^2 \cdot$°C, Q_0^i = 0.17 W/kg ($i = \overline{1,3}$), w_1 = 2.00 ml/g·min, w_3 = 0.32 ml/g·min and the values of w_2 (ml/g·min): 1) 4.00; 2) 2.00; 3) 0.80; 4) 0.40; 5, 0.20.

Boundary condition (2) determines the natural condition of adiabaticity on the boundary between the renal pelvis and the medullary substance, and (3) determines the convective heat exchange with the external medium according to the Newton law. The latter is characterized by the total heat transfer coefficient h [19]. The initial temperature distribution is assumed to be given.

From the viewpoint of practical diagnostics it is important to find out to which extent the values of $\beta(\xi)$ and $Q(\xi)$ (depending on the bloodflow in various kidney tissues) provide reliable monitoring of their changes in terms of the quantities T_s measured by IR thermographs.

Let us consider the problem stated for stationary conditions. We assume that the parameters Q_0 and w vary discretely.

The problem for the three-substance kidney model is reduced to the following system of equations with boundary conditions

$$\frac{d^2\Theta_i}{d\xi^2} - \beta_i^2\Theta_i = \beta_i^2 Q_i, \quad \xi \in [\xi_i, \xi_{i+1}], \quad i = \overline{1,3}; \tag{4}$$

$$\left.\frac{d\Theta_1}{d\xi}\right|_{\xi=0} = 0, \tag{5}$$

$$\Theta_i|_{\xi=\xi_i} = \Theta_{i+1}|_{\xi=\xi_i}, \quad i = 2, 3; \tag{6}$$

$$k_i \left.\frac{\partial\Theta_i}{\partial\xi}\right|_{\xi=\xi_i} = k_{i+1} \left.\frac{\partial\Theta_{i+1}}{\partial\xi}\right|_{\xi=\xi_i}, \quad i = 2, 3; \tag{7}$$

$$k_3 \left.\frac{\partial\Theta_3}{\partial\xi}\right|_{\xi=1} = \mathrm{Bi}\,(1 - \Theta)|_{\xi=1}. \tag{8}$$

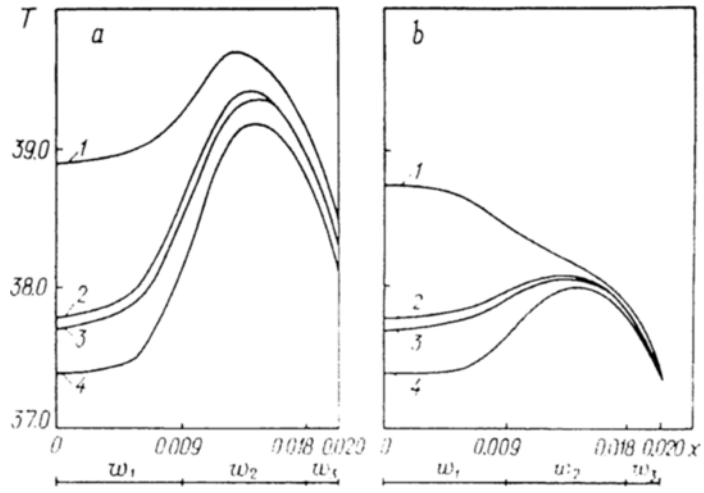


Fig. 3. Temperature distribution in renal tissue in the case of forced heating at various blood perfusion rates in the cortical substance at $h = 279$ W/m$^2 \cdot$°C, $w_3 = 0.32$ ml/g·min, $Q_0^i = 100$ W/kg ($i = \overline{1,3}$), bloodflow in the medullary substance $w_2 = 0.40$ ml/g·min (a) and $w_2 = 1.20$ ml/g·min for various values of w_1 (ml/g·min): 1) 0.80; 2) 1.80; 3) 2.00; 4) 4.00.

Let us consider a kidney for which the thicknesses of the cortical, medullary, and surface substances $a = b = 0.009$ m, and $c = 0.002$ m, respectively. The thermophysical parameters of the renal tissues and blood are as follows [9, 15, 18]: $c = c_b = 1480$ J/kg·°C, $\rho = \rho_b = 1000$ kg/m^3. In addition, we used the following data: $k = 0.627$ W/m·°C, $T_a = 37$°C, and $T_\infty = 20$°C.

Results and Discussion. We obtained numerical solutions of the problem (4)-(8). Graphical representations of some of them are presented in Figs. 1-3.

The corresponding values of bloodflow in the cortical, medullary, and surface substances were taken into account in various bloodflow regimes in the normal state and in the case of pathology [15, 18]. Changes in T_s (Fig. 1) in these cases vary from 0.2 to 0.6°C, i.e., within the limits of the resolution of IR thermographs. Therefore, we can state that in the case of the renal pathologies specified, their diagnosis by means of static thermography is possible.

It appears that at fixed Q_0^i ($i = \overline{1,3}$) corresponding to processes of generation of metabolic heat in biological tissue and w_i ($i = \overline{1,3}$), variations in w_2 within as little as one order of magnitude can lead to an increase in T_s by $\Delta T_s = 0.4$°C (Fig. 2).

With an increase in the intensity of convective heat transfer at the tissue–environment interface, the corresponding temperatures T_s increase, reaching $\Delta T_s \approx 1.1$°C at $h = 72$ W/m$^2 \cdot$°C. It is evident that theoretically obtained values ΔT_s in these cases indicate possibilities of revealing by means of IR thermography anomalies in the physiological regimes of the kidney connected with changes in bloodflow in the medullary substance alone. The approach developed in this work and the clear possibility of obtaining analytical expressions make it possible to propose and calculate thermal criteria for identification of particular disorders as functions of h with controlled heat exchange.

However, diagnosis of pathological states in the cortical substance associated with the bloodflow within the substance seems to be questionable, since the registered ΔT_s values are beyond the resolution limits of high-speed IR thermographic devices.

It was found that the temperature distribution over the kidney cross-section depends only slightly on the values of the metabolic heat (Q_0^i ($i = \overline{1,3}$) is of the order of 10^3 W/m^3 [18]) generated in the organ. Inasmuch as the classical biothermal equation obviously does not take into account the interaction between heat generation and bloodflow, the conclusion obtained should be treated with caution.

Consideration in (4) of Q_0^i ($i = \overline{1,3}$) instead of Q_i as the power of a source of forced heating of biological tissue from outside (e.g., by active thermography [5, 20], local hyperthermy, and thermotherapy [16], etc.) is of

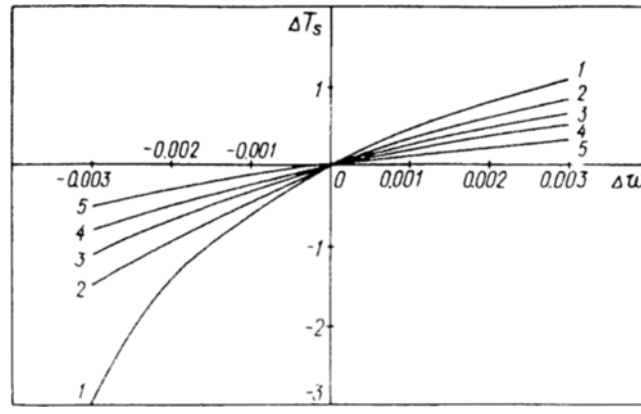


Fig. 4. Dependence of changes of the steady-state temperature ΔT_s on fixed changes in bloodflow in the single-substance model at h = 279 W/m$^2 \cdot$°C, Q_0 = 0.17 W/kg, and various values of w (ml/g·min): 1) 0.20; 2) 0.30; 3) 0.40; 4) 0.50; 5) 0.80. Δw, sec^{-1}

practical interest. The latter is connected with the important but still unsolved problem of noninvasive measurement of temperature distributions and their monitoring in the biological tissue of the kidney or other organ by means of, e.g., IR visualization under conditions of controlled heating used as therapy.

Figure 3 illustrates the temperature distribution in renal tissue under conditions of forced heating. In the calculations we assumed that an external source of heat was present that provided, in order to simplify the calculations and reveal biophysical regularities, a uniform heat production power in all renal tissue. It is important (Fig. 3a) that under conditions of forced local heating a change inthe physiological regime, e.g., bloodflow, in the cortical substance of the kidney can be reliably detected by methods of IR thermography (cf. Fig. 3b). However, it should be noted that the results obtained are consequences of the analysis of models based on the classical biothermal equation and do not take into account processes of thermoregulation of the organism. Under conditions of local consideration, the correctness of the classical biological heat trasfer equation can be demonstrated in a number of cases [16].

Thus, we have shown that the use of external heating increases the information content of IR thermography data on thermal processes in biotissues. In practice, this fact substantiates the new method of active IR thermography [5, 20].

In this connection it is of definite interest to determine possible changes in temperature T_s^{st} as a function of fixed changes in bloodflow (Δw) and the power of the source of metabolic heat (ΔQ_0) at preset values of w_{st} and Q_{st} characterizing the steady-state thermophysical regime of kidney operation with dimensionless temperature Θ_{st}. This problem is in some sense a limiting case of dynamic thermography, since it reveals temperature distributions in renal tissue at $t, \tau \to +\infty$.

For a single-substance model the stationary problem is reduced to solution of (1)-(3) with

$$\Theta = \Theta(\xi, \beta, Q) = \Theta_{st}(\xi) + \Delta\Theta(\xi, \beta, Q), \quad \xi \in [0; 1];$$

$$\beta^2 = \beta^2(\Delta\beta) = (\beta_{st} + \Delta\beta)^2, \quad Q = Q(\Delta Q) = Q_{st} + \Delta Q.$$

We found an analytical solution of this problem; from this solution, we obtained the following expression for the temperature change ΔT:

$$\Delta T = \Delta T(\xi, \beta, Q) = T(\xi, \beta, Q) - T_{st}(\xi, \beta_{st}, Q_{st}) = \left[\frac{\operatorname{ch}\beta_{st}\xi}{\beta_{st}\operatorname{sh}\beta_{st} + \mathrm{Bi}\operatorname{ch}\beta_{st}} - \frac{\operatorname{ch}\beta\xi}{\beta\operatorname{sh}\beta + \mathrm{Bi}\operatorname{ch}\beta}\right] \times$$

$$\times (1 + Q)(T_a - T_\infty)\,\mathrm{Bi}, \quad \xi \in [0; 1]. \tag{9}$$

Several calculations for ΔT_s (9) at ξ = 1 are presented in Fig. 4. They demonstrate the possibility of determination of values of a new steady-state temperature detected and resolved by IR thermographs in the dynamic regime for particular parameters of the model.

Thus, the theoretical analysis carried out in the paper makes it possible (on a somewhat limited scale) to investigate the possibilities of diagnostic IR visualization in determination of regimes of nonstationary bloodflow in renal tissue in hyperthermy and thermotherapy. The results obtained show the fundamental validity of applications of IR thermography methods in the diagnosis of physiological states of the kidney.

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NOTATION

T, T_a, and T_∞, temperatures of tissue, arterial blood, and environment, respectively; c and c_b, specific heat of renal tissue and blood, respectively; k, specific thermal conductivity of tissue; ρ and ρ_b, densities of tissue and blood, respectively; w, blood perfusion rate; Q_0, power of heat source in tissue ensuring its temperature regime under normal conditions, in the case of pathology [9], and with forced heating from the outside in hyperthermy and regulated thermal therapy [16]; Bi = hL/k, dimensionless Biot number; T_s, surface temperature; $\Theta = \Theta(\xi, \tau) = (T_a - T)/(T_a - T_\infty)$; $\xi = x/L$; $L = a + b + c$; $\tau = kt/L^2\rho c$; $\beta^2 = \beta^2(\xi) = L^2 c_b \rho_b \rho w(\xi)/k$; $Q = Q(\xi, \tau) = Q_0(\xi, \tau)\rho/\beta^2 k(T_a - T_\infty)$; $\xi_1 = 0$, $\xi_2 = a/L$; $\xi_3 = (a + b)/L$; $\xi_4 = 1$; $\Theta_{st}(\xi) = \Theta(\xi, \beta_{st}, Q_{st})$; $\xi \in [0; 1]$; $\Delta\beta = \Delta\beta(\Delta w) = L\rho\sqrt{c/k}\,(\sqrt{w_{st} + \Delta w} - \sqrt{w_{st}})$.

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