## NOTATION

$x$ and $\tau$, spatial and time coordinate, respectively; $\tau_m$, observation time; $T(x, \tau)$, temperature field; h, depth of thermocouple mounting; $q(\tau)$, thermal flux density supplied to the boundary of the body; a, thermal diffusivity coefficient; and $\lambda$, thermal conductivity coefficient.

## LITERATURE CITED


1. O. M. Alifanov, Identification of Heat Exchange Processes of Aircraft [in Russian], Moscow (1979).
2. A. N. Tikhonov and V. Ya. Arsenin, Methods of Solving Incorrect Problems [in Russian], Moscow (1979).
3. M. V. Kulakov and B. I. Makarov, Temperature Variations of Solid Surfaces [in Russian], Moscow (1979).
4. Yu. V. Polezhaev and F. B. Yurevich, Thermal Protection [in Russian], Moscow (1976).
5. N. V. Diligenskii and S. L. Balakovskii, Inverse Problems and Identification of Heat Exchange Processes (Proceedings) [in Russian], Ufa (1984).
6. A. V. Lykov, Theory of Thermal Conductivity [in Russian], Moscow (1967).


# AN INVESTIGATION OF HEAT EXCHANGE IN THE HUMAN ORGANISM ON EXPOSURE TO INTERNAL HEAT


G. N. Dul'nev, M. M. Korotkevich,
E. V. Maistrakh, and A. V. Sigalov



UDC 536.2



The thermal field of a person exposed to artificial heat is investigated. A variation in the blood flow as the temperature inside the body increases is calculated by solving the inverse problem of heat conductivity.


A disturbance of physiological processes in the human organism is often followed by changes in the thermal regime of the body; therefore, characteristics of the thermal field of the body can be used as indices of the physiological state in the diagnosis of disease and in the course of treatment [1]. At present, thermovisual (thermographic) methods of diagnosis based on variations of the thermal field of the skin in the presence of pathologic foci in the internal organs [2] are getting wide recognition.

Thermographical investigations in medicine are basically characterized by a symptomatic approach: a diagnosis is made on the basis of a subjective interpretation of a purely visual picture of a thermographical image. Biophysical mechanisms of the formation of a thermal field on the surface of the body for the majority of pathologic violations in the internal organs have still not yet been studied. For example, one of the most important issues of a thermovisual diagnosis still remains unclear: What is the cause of the change in the temperature of the skin in one or other case, a thermal flow penetrating through the "shell" from the internal organs or reflective changes in the blood flow and heat generated in the surface tissues [1]?

In order to find objective criteria and to define areas for suitable application of thermographical methods of diagnosis, theoretical and experimental investigations of the processes of heat exchange in the human organism are conducted. In [3, 4], a mathematical model is proposed, which allows one to calculate the thermal field of the skin, given the values of heat productivity and blood flow in different organs and tissues of the body. However, quantitative information about thermophysical properties of tissues, about the distribution of sources of heat, and the consumption of blood in the internal organs and tissues of the "shell" for normal and pathological cases is specified with a great error. This is due both to the individual spread of parameters and to reflective reactions, in-


Leningrad Institute of Precision Mechanics and Optics.


Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 4, pp. 654-659, April, 1987. Original article submitted December 20, 1985.




0022-0841/87/5204-0478$12.50

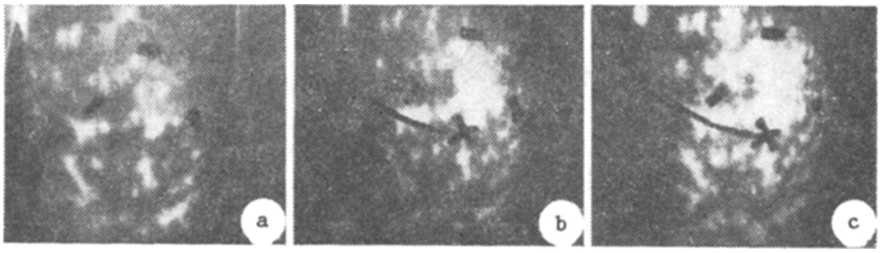

Fig. 1. Thermograms of the frontal abdominal wall: a) before the study; b) at $\tau$ = 20 min; c) at $\tau$ = 40 min.

vestigated insufficiently. Uncertainty in specification of the source information does not allow one to obtain reliable results concerning changes in the thermal field for different pathologic processes by means of a mathematical simulation only [4].

To verify adequacy between mathematical models and identification of their parameters, the necessity arises for conducting experimental investigations of thermal field with given heat effects. However, possibilities for a physical simulation of thermal effects in the internal organs as well as the measurement of temperatures, heat flows, and rate of blood flow in the tissues of the body are limited by various types of difficulties. We know only one similar experimental investigation [5], in which an internal pathological focus was simulated by administering a certain volume of water into the stomach, through a probe; however, a theoretical analysis of the results of that wok has not yet been performed.

The purpose of this work is to investigate quatitatively the mechanism of formation of a thermal field of the skin as the temperature in the internal organs is elevated. This problem was solved by means of a physical simulation of thermal effects in the stomach and a comparison between the thermal fields obtained in experiments and calculated according to a mathematical model.

In order to create controlled heat effects, an apparatus has been developed which allows one to maintain the temperature in the region of the stomach at a given level or to vary it with time [6]. The apparatus consists of a stomach probe with an elastic container through which water is pumped along flexible pipes. The level of the temperature of water in the circuit is specified by using a liquid thermostatic regulator. The flow of water into the probe and out of it is regulated by flowmeters. The temperature of water is measured in the container and at the outlet of the probe.

Investigations in the form of a functionally diagnostic probe were conducted in the following way. After the container was introduced into the stomach, the temperature of the water in it was elevated from 37 to 43°C and was maintained at this level for 40-50 min. In the process, the temperature of the skin in the zone of projection of the stomach was measured by a thermocouple; in addition, a "Rubin-2" thermal imager registered a thermal image of the frontal abdominal wall (Fig. 1). A series of observations on 11 subjects was conducted [6], and in all cases a considerable elevation of the temperature of the skin (from 1.6 to 2.9°K) was observed in the zone of projection of the stomach (Fig. 2).

For a quantitative description of the processes of heat transfer, it is necessary to know thicknesses of the layers of a "shell" of the body, i.e., skin, subcutaneous fatty tissue, muscle layer. These parameters can differ considerably for different people. That is why, as the above-described observations were conducted, individual measurements of the thicknesses of the layers of the "shell" were envisaged for all the subjects. The measurements were conducted by E. N. Kondrat'ev by the method of ultrasonic echolocation [7].

An observed elevation of the temperature of the skin can be due both to a conductive heat transfer through the tissues from the region of the stomach towards the surface of the body and also to a reflective enlargement of the cutaneous blood flow in the zone of projection of the stomach. To analyze the mechanism of formation of the thermal field of the skin, a mathematical simulation of the frontal abdominal wall was conducted, for given thermal effects on its inner surface.

An analysis of mathematical models describing heat exchange in a human was conducted in [3]. In [4], an application of different models is considered (one-dimensional and three-dimensional, single-layer and multilayer) for calculating the thermal field of the "shell,"

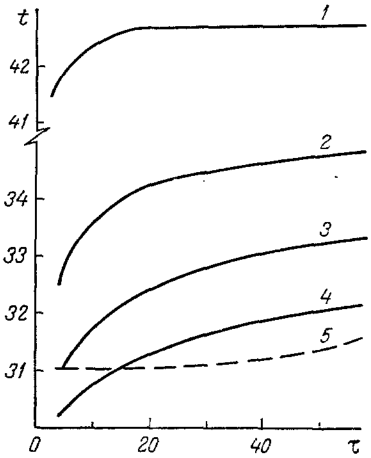


Fig. 2

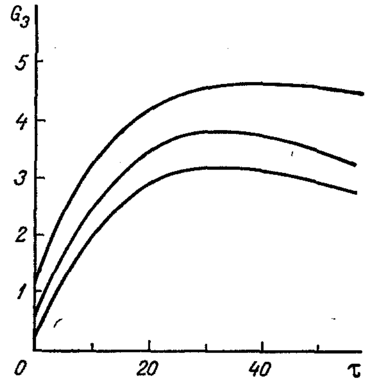


Fig. 3

Fig. 2. Variation in the temperature of liquid in stomach (1), variation in the temperature of the skin during a functional diagnosis for three subjects (2, 3, 4) and a calculated variation in the temperature of the skin at a constant rate of flow of blood (5). t, °C; τ, min.

Fig. 3. Specific flow rate of the skin blood flow versus time found by solving the inverse problem.

given local internal thermal effects. In this case, a heated region on the inner surface has dimensions ≈ 7 cm, while the thickness of the "shell" is 3-3.4 cm; therefore, on the basis of results from [4], a one-dimensional model is chosen, which takes into consideration the inhomogeneous structure of the "shell."

The thermal field in each of the layers is described by the equation

$$(c\rho)_i \frac{\partial t_i}{\partial \tau} = \lambda_i \frac{\partial^2 t_i}{\partial x^2} + q_{vi} + G_i c_{\mathrm{bl}} (t_{\mathrm{a}i} - t_i), \quad i = 1, 2, 3. \tag{1}$$

Here, when describing heat exchange in tissues with blood, we assume that the incoming blood with temperature $t_{ai}$ after having passed through a capillary network assumes the local temperature of the tissue $t_i(x, \tau)$, while heat exchange with arteries and veins is not taken into account.

On the boundaries of the layers, the following conditions of coupling are specified:

$$\lambda_i \frac{\partial t_i}{\partial x}\bigg|_{l_i} = \lambda_{i+1} \frac{\partial t_{i+1}}{\partial x}\bigg|_{l_i}, \quad t_i(l_i, \tau) = t_{i+1}(l_i, \tau), \quad i = 1, 2. \tag{2}$$

On the surface of the body ($x = \ell_3$), heat exchange with the medium is described by a boundary condition of the third kind

$$\left[\lambda_3 \frac{\partial t_3}{\partial x} + \alpha (t - t_{\mathrm{m}})\right]_{x=l_3} = -q_{\mathrm{E}}. \tag{3}$$

On the inner side of the surface of the "shell" ($x = 0$), the following change in temperature, known from the experiment, is specified:

$$t_1|_{x=0} = t_{\mathrm{in}}(\tau). \tag{4}$$

As an initial distribution, a steady thermal field is assumed, corresponding to the initial value of the temperature on the inner surface $t_{in}(0) = 37°C$.

Problem (1)-(4) was solved numerically, using an implicit difference scheme; a grid was adopted as a uniform one within the boundaries of each layer of the tissue.

Thicknesses of the layers of muscles, fat, and skin were measured individually for each subject. The values of the thermophysical properties of tissues $\lambda_i$, $(c\rho)_i$, volume densities of internal sources $q_{vi}$, specific mass flow rate of blood in muscles $G_1$ and in fat $G_2$ were determined from data from [8, 9].

From published data [8-10], the values of the specific mass flow rate of blood $G_3$ in the skin may vary during thermal regulation by more than an order of magnitude: from 0.3 to 3 kg/(sec·m³). A change in the rate of the skin blood flow leads to a considerable change in the temperature on the surface of the body $t_s = t_3|_{x=\ell_3}$.

Given a mathematical model (1)-(4) and experimental data, it is possible to state the problem of the rate of flow of blood $G_3(\tau)$ in the skin according to the variation in the temperature $t_s^e(\tau)$ on the surface of the body. In this case, an additional condition is defined on the boundary $x = \ell_3$:

$$t_3|_{x=l_3} = t_s^e(\tau), \tag{5}$$

and the rate of flow of blood in the skin $G_3(\tau)$, entering Eq. (1), is the desired function of time.

Such a statement leads to the inverse problem for thermal conduction in coefficients. In this work, a method for solving the inverse problem in an extremal formulation is used [11]. We seek a function $G_3(\tau)$, minimizing a functional f, represented as the root mean square deviation of calculated $t_s^c(\tau)$ and experimental $t_s^e(\tau)$ values of the temperature of the surface:

$$f = \frac{1}{N} \sum_{n=0}^{N} [t_s^c(\tau_n) - t_s^e(\tau_n)]^2 \to \min. \tag{6}$$

A change in the flow rate $G_3(\tau)$ is represented as the piecewise-linear function

$$G_3(\tau) = G_3^{m-1} + (G_3^m - G_3^{m-1}) \frac{\tau - \tau_{m-1}}{\tau_m - \tau_{m-1}}, \quad m = 1, \ldots, M, \tag{7}$$

and the flow rates $G_3^m$ at the moments of time $\tau_m$ (m = 0, ..., M) are to be defined from condition (6).

Thus, the inverse problem is reduced to the problem of parametric optimization. Optimization was performed by the method of quickest descent [11]. Minimization of f in the direction of the gradient was performed by the method of the "golden section." The goal function f and its gradient were calculated by solving numerically the problem (1)-(4).

When seeking an initial distribution of the temperature t(x, 0), flow rate $G_3(0)$ was selected from the condition of agreement between the calculated and experimental temperatures of the surface: $t_3(\ell_3, 0) = t_s^e(0)$. This value of flow rate was used as an initial point in solving the problem of optimization. Iterations in the method of quickest descent were terminated upon reaching a specified level of error f:

$$f \leqslant \sigma^2, \tag{8}$$

where σ is a specified value of error in the determination of the temperature.

Calculations were conducted under the following conditions: the number of points of a three-dimensional grid, 15; pitch in time, 30 sec; 8 values of the flow rate $G_3^m$ were determined at the moments of time $\tau_m$ = 0, 5, 10, 15, 20, 30, 40, 60 min; comparison between the calculated and experimental temperatures in (6) was conducted at the same moments of time. The value of the root mean square deviation σ was specified to be equal to 0.08°K and was reached after 3-4 iterations. As a result of solving the inverse problem, calculated values of temperatures $t_s^c(\tau_m)$ differ from experimental values $t_s^e(\tau_m)$ by not more than 0.15°K. We did not observe an instability of the solution with the chosen parameters of the difference scheme and under condition of termination of iterations.

According to the method given above, the variation in the rate of flow of blood $G_3(\tau)$ was calculated for all the subjects. Results for three cases are given in Fig. 3, from which it is seen that during the investigation, the flow rate of blood increases 4-12 times as compared with the value $G_3(0)$ before the beginning of the observation.

Calculations of a nonstationary thermal field for constant flow rate $G_3(\tau) = G_3(0)$ = const show that in this case the temperature on the surface of the skin increases much slower and by a smaller value as compared with the experimental results obtained. In Fig. 2, the experimental variation in temperature $t_s^e(\tau)$ and the result of calculation $t_s^c(\tau)$ are compared for a constant flow rate, equal to the initial value. In the experiments, the temperature of the skin increased by 1.6-2.9°K, and the increase in temperature of the skin did not exceed 0.5°K for a constant flow rate during 60 min.

For the mathematical simulation carried out, certain initial information is specified with a considerable error; first of all, this is true for the temperature of blood $t_{a3}$, entering the skin, the flow rate of blood in muscles $G_1$, and the power of sources $q_{V1}$ and $q_{V3}$. Calculations conducted for the perturbed initial data (dispersion of parameters was specified from the published data have shown that the absolute values of the flow rates $G_3(\tau)$, determined in solving the inverse problem, can change by almost a factor of two, but the behavior of the dependences, given in Fig. 3, is retained.

In this manner, a theoretical analysis shows that an increase in the temperature of the skin, observed in the investigations, is related, to a greater extent, to a local increase in the intensity of the skin blood flow than to the direct transfer of the heat flow from a heated region of the stomach. The values of the specific flow rate of blood, obtained from the solution of the inverse problem, are in good agreement with the published data [8-10] concerning possible ranges of the blood flow rate with thermal regulation.

A local increase in the intensity of the blood flow in the skin in the zone of projection of a heated internal organ can be explained by the reflective expansion of the vessels due to an internal heat effect. This effect should be taken into account in a mathematical simulation of the processes of formation of a thermal field of the skin under pathological changes in heat exchange of internal organs.

## NOTATION

$t_i$, $t_{ai}$, temperature of the tissue and arterial blood in the i-th layer; $t_{in}$, $t_s$, temperatures on the inner surface of the "shell" and on the surface of the body; $\lambda$, $c\rho$, thermal conductivity and volumetric heat capacity of tissues; $q_V$, volumetric density of internal sources; G, mass flow rate of the capillary blood flow per unit volume of the tissue; $c_{bl}$, specific heat capacity of blood; $\alpha$, coefficient of heat transfer in the medium; $q_E$, density of the heat flux dissipated by evaporation on the surface of the body; $t_m$, temperature of the medium. Indices: 1) muscles; 2) fat; 3) skin; c) calculation; e) experiment; in) internal; s) surface.

## LITERATURE CITED


1. E. V. Maistrakh, Clinical Pathophysiology of Thermal and Energy Metabolism of Man [in Russian], Leningrad (1983), pp. 3-13.
2. "Thermovisual medical equipment and practice of its application," in: Digest of Papers of the All-Union Conference TeMP-82, Leningrad, October 26-30, 1982, Leningrad (1982).
3. G. N. Dul'nev, M. M. Korotkevich, N. V. Pilipenko, and A. V. Sigalov, Inzh.-Fiz. Zh., 46, No. 1, 150-160 (1984).
4. G. N. Dul'nev, M. M. Korotkevich, E. V. Maistrakh, et al., Clinical Pathophysiology of Thermal and Energy Metabolism of Man [in Russian], Leningrad (1983), pp. 38-43.
5. V. F. Sukharev, M. A. Nikulin, and A. I. Chagin, Thermovision in Medicine, Leningrad (1984), pp. 230-232.
6. M. M. Korotkevich and E. N. Kondrat'ev, "Thermovisual medical equipment and practice of its application," in: Digest of Papers of the III All-Union Conference, Leningrad (1985), pp. 117-119.
7. E. N. Kondrat'ev and L. A. Eremeeva, Clinical Pathophysiology of Thermal and Energy Metabolism of Man [in Russian], Leningrad (1983), pp. 56-58.
8. P. A. Hancok, Comput. Biol. Med., 10, No. 1, 1-10 (1980).
9. G. R. Gordon, R. B. Roemer, and S. M. Horvath, IEEE Trans. Biomed. Eng., 23, No. 6, 434-444 (1976).
10. E. V. Maistrakh, Pathologic Physiology of Cooling of Man [in Russian], Leningrad (1975).
11. O. M. Alifanov, The Identification of Processes of Heat Exchange in Aircraft: Introduction to the Theory of Inverse Problems of Heat Exchange [in Russian], Moscow (1979).