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RHEOLOGICAL FACTOR IN THE THERMAL PROBLEM OF SHF-HYPERTHERMIA TREATMENT. 1. HOMOGENEOUS TISSUE

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Influence of blood flow and external cooling intensities on the temperature field in a homogeneous tissue under local SHF hyperthermia is considered.

As is known [1], hyperthermia treatments of tumors are most effective when the tissue is heated to 42-45°C (therapeutic range). Such conditions may be provided by changing the power of an SHF radiation source. For this, it is necessary to match its value with the thermophysical characteristics of the tissue to be heated (thermal conductivity λ, specific heat c_b, density ρ), the abundance of heat sinks due to blood flow (perfusion f), and the external heat transfer of the body to the surrounding medium (Bi).

In this case perfusion, viz., blood flow rate per unit time per 100 g of tissue, is the governing factor. As experiments show [2], perfusion in different live tissues may change within wide limits (by more than an order of magnitude). A rigorous description of changes in blood flow intensity under heating conditions is impossible without a correct account for the rheological factor and hemodynamic characteristics of the microcirculation system.

We approximately evaluate the influence of the enumerated factors on the temperature field in a tissue in the steady state. For the sake of simplicity, we use a one-dimensional biothermal equation [1]. Let an electromagnetic field heat a homogeneous tissue layer. Its external surface (skin) is cooled by a liquid having a temperature T_s and a heat transfer coefficient α, with a homestasis temperature T_0 given at depth L (Fig. 1):

$$\lambda \frac{d^2T}{dl^2} + q_R - q_b + q_m = 0\,, \quad -\lambda \frac{dT}{dl}\Big|_{l=0} = \alpha\,(T_s - T)\,, \quad T\Big|_{l=L} = T_0\,. \tag{1}$$

The power density of internal heat sources produced in the tissue by SHF radiation may be described by the equation for a plane electromagnetic wave [3]:

$$q_R = \rho s P \exp\,(a\,(l - d))\exp\,(by^2/(l + c))\,. \tag{2}$$

We consider only heat sources generated by an SHF antenna along its axis ($y = 0$). The density of hemodynamic heat sinks is determined from the convective condition

$$q_b = w_b\, c_b\,(T - T_0)\,, \tag{3}$$

where $w_b = f\rho_b\,\rho$ is the mass velocity of blood flow.

The metabolic heat release in the tissue subjected to intense SHF hyperthermia may be neglected [4].

Having reduced Eq. (1) to a dimensionless form, we arrive at the system

$$\Theta'' - B^2\Theta + R\exp\,(aLx) = 0\,, \quad \Theta'|_{x=0} = Bi\,(1 + \Theta|_{x=0})\,, \quad \Theta|_{x=1} = 0\,, \tag{4}$$

where

$$x = \frac{l}{L}\,; \quad Bi = \frac{\alpha L}{\lambda}\,; \quad \Theta = \frac{T - T_0}{T_0 - T_s}\,; \quad B^2 = \frac{w_b\, c_b\, L^2}{\lambda}\,; \quad R = \frac{\rho s P L^2 \exp\,(-ad)}{\lambda\,(T_0 - T_s)}\,. \tag{5}$$

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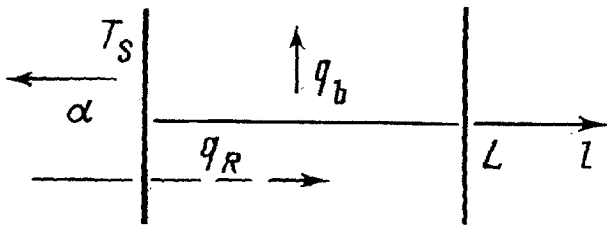

Fig. 1. Scheme for solving the biothermal problem.

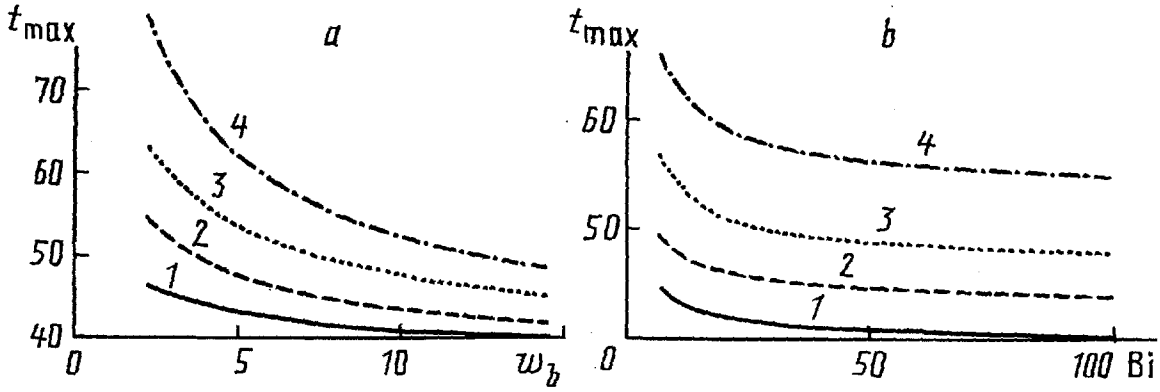

Fig. 2. Maximum heating of homogeneous tissue at different mass velocities of blood flow (a) (Bi = 12, Il = 0) and skin cooling intensities (b) (w = 5 kg/(m^3·sec), Il = 0): 1) λ = 0.8 W/(m·K), P = 15 W; 2) 0.4 and 15; 3) 0.8 and 30; 4) 0.4 and 30. t_{max}, °C; w_b, kg/(m^3·sec).

The general solution of the problem is as follows:

for $B \neq |aL|$

$$\Theta = C \exp(-Bx) + D \exp(Bx) + E \exp(aLx), \tag{6}$$

where

$$E = \frac{R}{B^2 - (aL)^2};$$

$$C = -\frac{[\mathrm{Bi}(1+E) - EaL]\exp(B) + E(B - \mathrm{Bi})\exp(aL)}{(B + \mathrm{Bi})\exp(B) + (B - \mathrm{Bi})\exp(-B)};$$

$$D = \frac{[\mathrm{Bi}(1+E) - EaL]\exp(-B) - E(B + \mathrm{Bi})\exp(aL)}{(B + \mathrm{Bi})\exp(B) + (B - \mathrm{Bi})\exp(-B)};$$

for $B = |aL|$

$$\Theta = C \exp(-Bx) + D \exp(Bx) + E(1 - 2x)\exp(Bx), \tag{7}$$

where

$$E = \frac{R}{4B^2};$$

$$C = -\frac{[\mathrm{Bi}(1+E) - EB]\exp(B) + E(B + \mathrm{Bi})\exp(B)}{(B + \mathrm{Bi})\exp(B) + (B - \mathrm{Bi})\exp(-B)};$$

$$D = \frac{[\mathrm{Bi}(1+E) - EB]\exp(-B) + E(B + \mathrm{Bi})\exp(B)}{(B + \mathrm{Bi})\exp(B) + (B - \mathrm{Bi})\exp(-B)}.$$

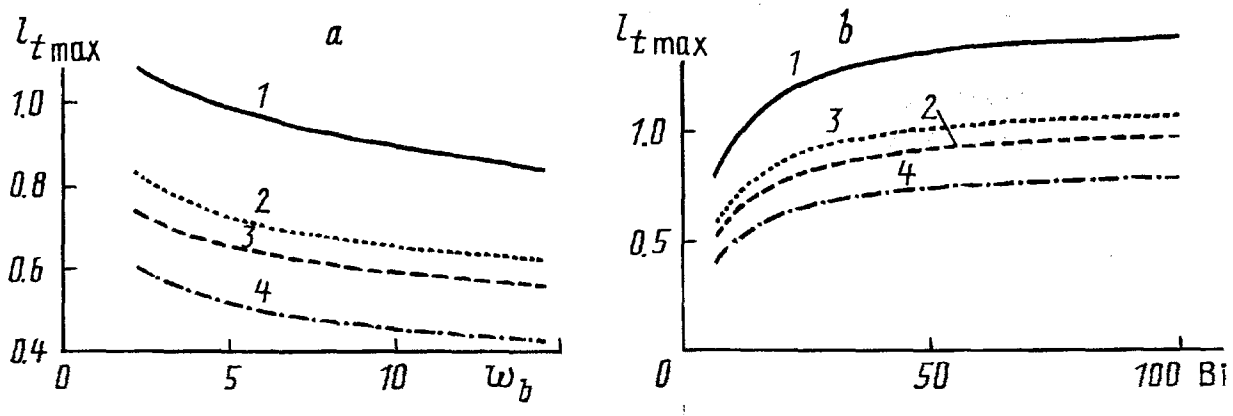

Fig. 3. Localization depth of maximum heating of homogeneous tissue at different mass velocities of blood flow (a) (Bi = 12, Il = 0) and skin cooling intensities (b) (w_b = 5 kg/(m^3·sec), Il = 0). Designations are the same as in Fig. 2. $l_{t_{max}}$, cm.

Since an analogous problem is considered in [3, 4], to compare the results we take the same values of the thermophysical parameters, namely, λ = 0.4, 0.8 W/(m·K); w_b = 5.0, 9.0 kg/(m^3·sec); P = 15, 30 W; c_b = 3640 J/(kg·K); $\rho_b = \rho$ = 1050 kg/m^3.

Figures 2, 3 show maximum tissue temperatures T_{max} and depths of their localization as a function of the mass velocity of blood flow and skin cooling (Biot number) for different combinations of thermal conductivity λ (W/(m·K)) and power P (W). Note that T_{max} at w_b < 5 kg/(m^3·sec) and λ = 0.4 W/(m·K) increases abruptly. Dangerous temperatures (exceeding 48°C) are localized in a near-surface layer of the tissue and are attained even at small Bi numbers. With an increase of the Bi number from 7 to 50, one may expect a substantial decrease of T_{max}, by 5-10 deg. In the interval 42-45°C, i.e., in the therapeutic temperature range, we have determined the required optimal values of the emitter power and cooling rate Bi. To sum up, by increasing the heat removal from the skin we may rather effectively "deepen" an extremum on the temperature profile, thus displacing it toward the tumour middle. The same effect may be achieved by reducing the tissue perfusion.

NOTATION

λ, thermal conductivity of the tissue; c_b, specific heat of blood; ρ, tissue density; ρ_b, blood density; (If, perfusion; w, mass velocity of the blood flow; T_s, temperature of the skin cooling liquid; T_0, homeostasis temperature (37°C); α, skin-to-environment heat transfer coefficient; Bi, Biot number; s, a, b, c, d, antenna parameters; P, power of the SHF emitter; T, tissue tempearture; l, depth; L, thickness of the heated tissue layer; Θ, dimensionless temperature; x, relative depth; q, power density of internal heat sources generated by the shf emitter in the tissue; q_b, power density of hemodynamic heat sinks; Il, Il'yushin parameter.

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