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TEMPERATURE DISTRIBUTION WITH MICROWAVE HEATING FOR A TWO-LAYER MODEL OF A BIOLOGICAL OBJECT

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Increasing use is being made of a physiotherapeutic apparatus operating at 460 MHz, which gives better treatment than instruments working at 2375 MHz as regards deeper heating and a better temperature distribution as between the fat and muscle layers, without excessive heat stress on the fat. This has made it necessary to examine the temperature distribution produced by microwaves in a two-layer system of fat and muscle. There are various measurements [1-3] on the temperature distribution in such a two-layer system, but the problem has not been considered theoretically. A more complete conception of the temperature distribution may be obtained in relation to the intensity, exposure, and frequency via calculations on the effects for a model consisting of a fatty layer of finite thickness and a semi-infinite muscle layer. Figure 1 shows the model schematically.

It has been found [4] that there is a peaked distribution of the field and heat release when a two-layer model is exposed to a planar electromagnetic wave incident from the fat side; the dependence of the heat release on the coordinate is [2] defined by

$$Q(x) = Q_0 [exp(-2\alpha_f x) + p^2 exp 2\alpha_f x + 2p \cos(2\beta_f x + \varphi)],$$

where $Q_0 = 0{,}5\delta_f E_0$; E_0 is the strength of the electric field in the incident wave at the fat-muscle interface, α_f is the attenuation coefficient for the fat, p is the modulus of the δ_f is the conductivity of the fat medium, β_f is the phase constant reflection coefficient at the interface, φ is the phase coefficient for reflection, and The field strength and heat release decrease exponentially in the muscle medium. for the fatty layer.

If the thickness of the fatty layer does not exceed $\lambda_f/4$, where λ_f is the wavelength in the fat, the heat-release distribution can be considered roughly as linear (lines A_1B_1 and A_2B_2 in Fig. 1). Then the temperature distribution in the first (fat) medium is found by solving the following conduction equation:

$$\frac{\partial^2 T_1}{\partial x^2} - \frac{1}{\varkappa}\frac{\partial T_1}{\partial t} + \frac{A_0}{k}(a - bx) = 0, \tag{1}$$

where T_1 is the temperature in the fat, k is the thermal conductivity, and $\varkappa$ is the thermal diffusivity, while A_0, a, and d are parameters characterizing the heat release in the fat layer, which is assumed to be a linear function of the coordinate. We have the following boundary condition at the external boundary of the model:

$$\frac{\partial T_1}{\partial x} = hT_1 \quad \text{for } x = 0, \tag{2}$$

where h is the coefficient for heat transfer from the surface of the model. Also, $T_1 = 0$ for $t = 0$.

The equation of thermal conduction is as follows for a muscle medium:

$$\frac{\partial^2 T_2}{\partial x^2} - \frac{1}{\varkappa}\frac{\partial T_2}{\partial t} + \frac{Q_0}{k} exp(-2\alpha_m x) = 0, \tag{3}$$

where T_2 is the temperature in the muscle, Q_0 is the heat release at the interface, and α_m is the damping coefficient in the muscle. Equation (3) is solved also for zero initial conditions: $T(x) = 0$ for $t = 0$, while

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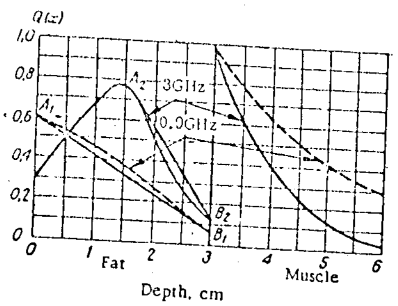

Fig. 1.

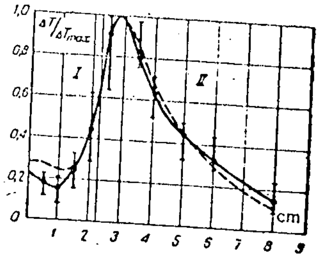

Fig. 2.

Fig. 1. Heat production Q(x) in a two-layer model on heating at 0.9 and 3 GHz with the unit taken as the heat release at the interface in muscle.

Fig. 2. Normalized temperature distribution in a two-layer model at 0.4 GHz (exposure 3 min). The vertical lines on the solid line show the limits of possible variation from data of [3]; the broken line is from calculation.

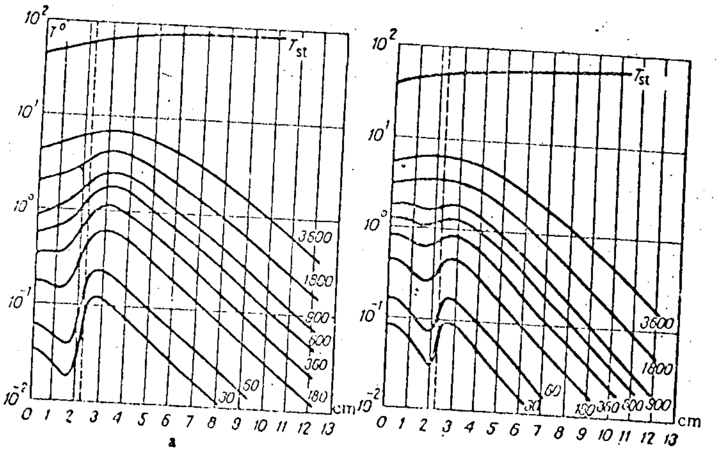

Fig. 3. Calculated temperature distributions on heating a two-layer model at: a) 0.4 GHz, b) 0.9 GHz. The numbers on the curves are the exposure times in sec, while T_{st} is the steady-state distribution. The ordinate is the temperature (degrees) referred to the electric field at the interface, while the abscissa is the depth (cm) from the outer surface.

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~~he~~ for the boundary conditions at the fat-muscle interface we have

$$T_1 = T_2 \text{ and } \frac{\partial T_1}{\partial x} = \frac{\partial T_2}{\partial x} \text{ for } x = d, \tag{4}$$

where d is the thickness of the fat layer, i.e., it is assumed that the thermophysical properties of the fat are the same as those of the muscle. Equations (1) and (3) have been solved by Laplace transformation [1]. Figure 2 shows the resulting temperature distribution for a fat layer 2.25 cm thick irradiated for 3 min at 0.4 GHz. This distribution is not monotonic, with a peak attained not at the external surface but within the muscle layer at a certain distance from the interface; the calculated curve agrees well with the results of Rush and Ott on temperature in two-layer tissue models with microwave heating. The calculated curve deviates somewhat from the experimental one because of inaccurate determination of the electrophysical parameters of the tissue model, especially for the fatty tissue, whose parameters are very variable [3].

We examined the dynamics of microwave heating by computer calculation of the temperature distributions for exposure times from 30 sec to 1 hr (I am indebted to Yu. P. D'yakov for much assistance with the computer calculations). Figure 3 shows curves calculated for 0.4 and 0.9 GHz; the frequency clearly has a pronounced effect on the curve shape: 1) the temperature at the surface of the model increases relative to the temperature peak in the muscle as the frequency is raised, which is due to increased electrical thickness of the fat layer and increase in the electrical field at the surface of the model; 2) the temperature peak approaches the fat-muscle interface as the frequency is raised; 3) the steepness of the curves for the temperature distribution in the muscle increases with the frequency, which is due to reduced penetration of the microwaves into this medium. Figure 3 indicates the time dependence of the temperature distribution. The temperature oscillations in the fatty layer tend to die out as time passes, especially at the higher frequencies.

The curves show that uniform heating of the fat requires longer exposure times and higher frequencies, while heating of the muscle without serious temperature stress on the fat requires lower frequencies and short exposures (up to 5 min). In applying these results to a real living biological object, one has to bear in mind the possible effects on the temperature distribution from the blood circulation, which carries off part of the heat; this has been neglected in these calculations.

CONCLUSIONS

1. Microwave heating of a two-layer model produces a peaked temperature distribution with its peak in the muscle, and the surface temperature cannot be used as an adequate indication of the thermal effects on the object.

2. Avoidance of thermal stress on the fat layer while heating the muscle requires the use of lower frequencies and shorter exposure times in physiotherapeutic procedures.

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