Journal of Engineering Physics and Thermophysics, Vol. 78, No. 1, 2005

SIMULATION OF HEATING OF BIOLOGICAL TISSUES IN THE PROCESS OF ULTRAHIGH-FREQUENCY THERAPY

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UDC 536.2:532/533

A physicomathematical model of the temperature distribution over the surface and the bulk of a biological object (human palm) exposed to an ultrahigh-frequency electric field (40.68 MHz) for therapeutic purposes is presented. Various approaches to studying the propagation of laser radiation and radio-frequency electromagnetic waves in biological tissues are considered. The temperature distributions in various biotissues, obtained by numerical solution of the nonstationary heat problem, are presented.

Natural and artificial physical factors are of great importance in the treatment and rehabilitation of patients with various diseases. Prominent among the modern methods of physiotherapy are methods of high-frequency electrotherapy, including methods of ultrahigh-frequency (UHF) therapy involving the action of the electric component of an electromagnetic field of frequency 10–300 MHz on an organism.

UHF therapy exerts an action on an organism mainly due to the current arising in its tissues and media exposed to an electric field. Physiological and medical effects arise as a result of the interaction of high-frequency electric oscillations with electrically charged particles in these tissues. The energy of a UHF electric field absorbed by biotissues is expended in the ionic conduction, dielectric losses, and resonance effects. Complex physicochemical processes occurring under a UHF electric field manifest themselves as endogenic heat that is generated as a result of the conversion of a portion of the electric energy into heat energy.

Traditionally, the dosimetry of UHF therapy was done by the heat sensations of the patient. Depending on these sensations, the following prescriptions were set: a non thermal action (the output power of stationary apparatus is 15–20 W), a weak thermal action (50–70 W), a thermal action (70–100 W), a strong thermal action (100–150 W) [1]. Control and prediction of the thermal parameters of biotissues exposed to a UHF electric field can serve as the basis for estimating the efficiency of the UHF therapy. The temperature is a criterion of the thermal state of tissues. Contact temperature-sensitive elements disturb the initial quasistationary temperature distribution; therefore, remote methods of determining the temperature in human tissues, based, e.g., on recording of the intrinsic infrared radiation of a human body (infrared thermography), are more suitable from the standpoint of both the correctness of measurements and the comfort of the patient. However, these methods allow one to measure only the temperature on the surface of tissues. At an admissible temperature of the skin, deep tissues (e.g., muscles) can be significantly overheated, and this overheating cannot be controlled by remote methods. This problem can be solved to a certain extent by physicomathematical simulation of the temperature distribution over the surface and the bulk of a biological object, which makes it possible to predict the effects of therapeutic procedures, performed by different methods with the use of different radiation doses, on different biological objects. Such data will allow one to determine the optimum conditions for conducting physiotherapeutic procedures. However, the thermal processes in biotissues are strongly dependent on functions of the nervous, cardiovascular, and thermal regulation systems and therefore are very difficult to simulate; because of this, actual processes occurring in an organism subjected to an external radiation action cannot be exactly determined by this method.

The thermal processes in biological objects are simulated differently in the case where these objects are exposed to radio-frequency waves and in the case where they are exposed to laser radiation. The thermal processes occurring in the latter case have been given much attention; however, we only know of a few works devoted to

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simulation of the energy and temperature distribution in human tissues exposed to meter waves [2–4]. In the present work, we propose a physicomathematical model for determining the dynamics of change in the temperature of biotissues of a human palm exposed to a UHF electric field (of frequency 40.68 MHz).

Formulation of the Problem. *Mathematical formulation of the problem.* H. H. Pennes was the first to investigate the heat exchange in a living perfusion tissue [5]. The thermal processes in various biological tissues are described using the phenomenological equation of thermal balance that defines the interaction of a volume of a biotissue with the surrounding medium:

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_i \frac{\partial T_i}{\partial x}\right) - q_{\mathrm{b}i} + q_{\mathrm{m}i} + q_{\mathrm{r}i} \, , \tag{1}$$

where $T = T(x, t)$. It follows from Eq. (1) that, to maintain the heat balance, the energy generated in any region of a tissue as a result of the metabolism processes or any external action is transferred to the neighboring regions of the tissue due to heat conduction or convection or is accumulated in this region of the tissue, with the result that its temperature changes. It would serve no purpose to use a multidimensional approximation in this case since the geometric model proposed describes the actual structure of an object only schematically. The model based on the biological-heat equation is approximate since this problem itself cannot be uniquely formulated because of the complexity of the processes of heat transfer in a living organism and, therefore, the indicated equation simplifies their description. Since blood vessels differ largely in architectonics and size, it is impossible to estimate the contribution of individual vessels, except for large arteries and veins, to the process of heat transfer. In the present work, the circulatory system is assumed to be a continuum, i.e., the heat exchange between blood and tissue is considered only at the capillary-net level, and it is assumed that the heat exchange between arteries and arterioles and between venules and veins proceeds under adiabatic conditions. The perfusion is assumed to be isotropic throughout the biotissue volume considered.

There are also other mathematical models of thermal processes in a biological object [6–8], which allow one to estimate the self-regulation of the temperature of the microvascular bed and the contribution of large blood vessels to the heat exchange between blood and tissue. Comparison of our model with these models have shown that the Pennes equation (1) defines the thermal state of biological tissues adequately, even though it involves a lesser number of parameters characterizing an object as compared with other equations.

The heat transferred by a convective blood stream is defined as

$$q_{\mathrm{b}i} = \rho_i w_i c_{\mathrm{b}} \, (T_i - T_{\mathrm{a}}) \, . \tag{2}$$

The temperature of the arterial blood is assumed to be equal to 35.8$^{\mathrm{o}}$C [2].

The heat formed due to the metabolism processes is determined by the temperature of a biotissue:

$$q_{\mathrm{m}i} = \rho_i q_{\mathrm{m,o}i} \, 1.07^{\frac{(T_i - T_{\mathrm{o}})}{0.5}} \, . \tag{3}$$

The energy of an external source absorbed by biotissues is mainly responsible for the biological effects arising in them. A thermoselective effect can be obtained in a biological object on exposure of it to a UHF electric field since different tissues are heated, depending on their electric parameters, differently. Low-conduction tissues absorb a larger portion of the UHF radiation energy than liquid media (blood, lymph, cerebrospinal liquid). Therefore, in the case of UHF therapy, the maximum portion of energy is absorbed in the skin and in the nerve, connective, adipose, and osseous tissues, with the result that the maximum amount of heat is generated in these tissues. The amount of heat generated increases with increase in the frequency and strength of the electric field and is determined by the biophysical properties of the tissues and, primarily, by their permittivity and electrical conduction.

Radio-frequency waves propagate rectilinearly, much like light rays. Therefore, the spatial distribution of the UHF radiation energy adsorbed in a biological tissue can be described using the Bouguer law

$$q_{\mathrm{r}i} = A_i Q_{\mathrm{o}} \exp\left(- A_i x\right) . \tag{4}$$

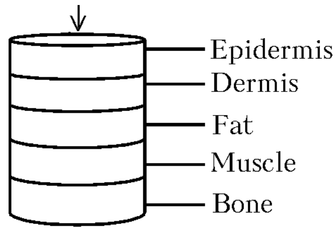


Fig. 1. Schematic representation of the object studied (to its middle compartment).

The absorption coefficient at a definite wavelength is related to the depth of penetration of radiation into a biotissue as

$$A_i = \frac{1}{2\delta_i} . \tag{5}$$

Note that the scattering of radio-frequency electromagnetic waves in a biological medium can be disregarded (in contrast to laser radiation) [9].

The initial temperature distribution is obtained from Eq. (1) if the blood stream does not change with time and the surface temperature is known:

$$T(x, 0) = T_{s0} \quad \text{at} \quad x = 0 , \quad x = h . \tag{6}$$

For the nonstationary problem, the boundary conditions are as follows:

$$-\lambda \frac{dT_1(x, t)}{dx} = \alpha (T_e - T_1(x, t)) \quad \text{at} \quad x = 0 , \quad x = h , \tag{7}$$

where the subscript 1 is related to the epidermis. Equation (7) defines the heat transferred from the skin surface to the environment as a result of the radiative heat exchange. In the case of UHF therapy, the velocity of the air near the skin surface can be assumed to be zero; therefore, the convective heat exchange between the skin and the environment can be disregarded. The evaporation of moisture from the skin surface can also be disregarded. It is assumed that the temperatures at the inner boundaries of the layers correspond to the heat flows.

The first-order conditions are usually used in problems on interaction of laser radiation with a biotissue. Under these conditions, the homeostasis temperature is established at a certain depth of the biotissue. However, such a formulation is incorrect in the case considered, since the UHF radiation penetrates throughout the bioobject studied, i.e., all the tissues accumulate energy; therefore, it is necessary to take into account the change in their temperature at each instant of time.

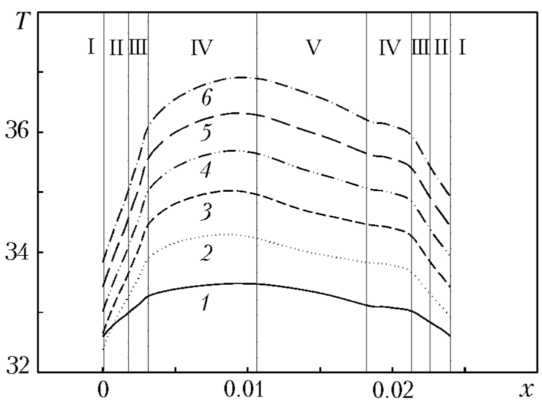
Geometric Formulation of the Problem. Properties of an Object. A UHF electric field is supplied to the organism of a patient with the use of two condenser electrodes. The UHF electric field, due to its high penetrability, penetrates to all the tissues positioned in the electrode spacing. In the UHF-therapy procedures, the air gap between the electrodes and the surface of the object comprises several centimeters, which provides a uniform distribution of heat between the surface and the deep tissues.

In the present work, we simulated the action of a UHF electric field on a human palm, which represents an inhomogeneous medium. When the thermal processes in biotissues are simulated, the object studied is conventionally divided into layers, each of which has its own structure. A human palm is represented in the form of a cylinder consisting of homogeneous layers corresponding to biotissues of different types (Fig. 1): epidermis, dermis, adipose hypodermic tissue, muscle, bone, muscle, adipose hypodermic tissue, dermis, epidermis.

To eliminate the edge effect, we will assume that the radius of the model cylinder is smaller than the radius of the electrodes (5 cm). The thickness of the layers was determined in accordance with the actual sizes of the object irradiated and the cross-section anatomy atlas [10]. Each layer is characterized by its own isotropic biophysical properties (see Table 1) [11–13].

TABLE 1. Biophysical Characteristics of Biotissues

Biotissue	Density, 10^3 kg/m^3	Specific heat capacity, 10^3 J/(kg·K)	Heat conduction, W/(m·K)	Basal temperature, ^{o}C
Epidermis	1.6	3.7	0.266	35.06
Dermis	1.0	3.2	0.498	35.06
Fat	0.85	2.512	0.171	35.36
Muscle	1.05	3.768	0.628	35.71
Bone	1.5	1.591	0.116	35.74



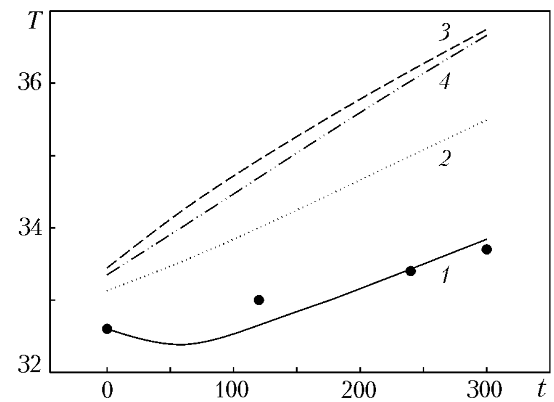


Fig. 2. Temperature of biotissues of a human palm exposed to a UHF electric field (40.68 MHz) prior to the action (1) and after 1 min (2), 2 min (3), 3 min (4), 4 min (5), and 5 min (6) of the action [I) epidermis, II) dermis, III) fat, IV) muscle, V) bone]. T, ^{o}C; x, m.

Fig. 3. Kinetics of heating different biotissues of a human palm (points denote experimental values obtained for the skin) under the action of a UHF electric field (40.68 MHz): 1) epidermis; 2) fat; 3) muscle; 4) bone). T, ^{o}C; t, sec.

Since the object of investigation is a living biotissue and blood is not a separate compartment in the model considered, the characteristics of biotissues taken from the literature are true primarily for vascularized tissues. The heat capacity of blood $c_b = 3.645 \cdot 10^3$ J/(kg·K) [11]. The values of the basal metabolism and of the perfusion were taken from [14]. The velocity of blood stream is different for different biotissues; however, we disregard small changes in this velocity in the prehyperthermal state [15, 16]. The coefficients of absorption of UHF radiation in different biotissues were determined by the data of [17]. The power of the acting radiation was 100 W.

Results and Discussion. The physicomathematical model (1)–(7) proposed is realized with the use of the finite-difference method. Figure 2 presents temperature distributions at the initial instant of time (stationary temperature distribution over the depth of the object) and in the process of action of a UHF electric field on a human palm (solution of the nonstationary thermal problem). Experimental investigations have shown that different effects arise in different regions at one and the same UHF-radiation power. Therefore, the physicomathematical model should take into account the structure of a concrete region of the body exposed to the field. Since both the surface and deep tissues are heated uniformly, an increase in the duration of the procedure can increase the temperature of the deep tissues to the critical value even when the intensity of the action remains unchanged. The energy of an external source is intensively absorbed in the skin and in the connective, osseous, and adipose tissues [17]. The curves shown in Fig. 3 reflect changes in the thermal state of all the layers of the object considered. It is seen that the temperature of the muscular and osseous tissues increases markedly (to 3.5^{o}C), and the temperature of the skin surface increases by 1.2^{o}C in the course of 5 min of the procedure.

The data of numerical simulation show that the skin temperature somewhat decreases for the first two minutes of the procedure. The experimental data point to the tendency toward increasing temperature throughout the action time; however, these data were obtained two seconds apart [18] and therefore, they do not reflect the actual kinetics of change in the temperature in this time interval. It should be noted that the calculation curve (Fig. 3, curve 1) corresponds to the epidermis in which a blood stream is absent, while the experimental values of the skin temperature additionally account for the temperature state of the lower-lying tissues supplied with blood.

CONCLUSIONS

1. Clearly the physicomathematical model proposed for determining the temperature distribution over the surface and the bulk of a biological object (human palm) exposed to a UHF electric field (40.68 MHz) in therapeutic purposes does not exactly describe the effects arising in this object under such an action; however, the data obtained point to the advisability of pursuing research in this direction.

2. The temperature distributions presented were obtained for different biotissues by numerical solution of stationary and nonstationary heat problems. It has been established that the temperature both on the surface of a biological object and in its bulk increase under the action of a UHF electric field. Deep tissues are heated more strongly in this case, which allows us to recommend the use of the above-described procedure for heating muscular and osseous tissues in therapeutic purposes.

3. The calculation data obtained agree with the corresponding experimental data. Conceivably the changes that arise in the skin blood stream as a result of small changes in the skin temperature should be taken into account when the above-mentioned processes are simulated.

NOTATION

A, absorption coefficient, 1/m; c, specific heat capacity of a biotissue, J/(kg·K); c_b, specific heat capacity of blood, J/(kg·K); h, thickness of the object, m; q_b, q_m, and q_r, heat generated in a unit volume of a biotissue due to the perfusion, metabolism, and external-radiation action, W/m^3; $q_{m,o}$, heat generated due to the basal metabolism, W/kg; Q_o, incident radiation power density, W/m^2; t, time, sec; T, temperature of a biotissue, K; T_a, temperature of the arterial blood, K; T_e, ambient temperature, K; T_o, temperature of a tissue under the basal conditions, K; T_{s0}, temperature of the skin surface at the initial instant of time, K; w, perfusion, 1/sec; x, depth (Cartesian coordinate), m; α, coefficient of heat transfer from the surface of the skin to the environment (air), W/(m^2·K); δ, depth of penetration of radiation into a biotissue, m; λ, heat conduction of a biotissue, W/(m·K); ρ, density of a biotissue, kg/m^3. Subscripts: a, arterial; b, blood; e, environment; i, number of the layer corresponding to a given tissue; m, metabolism; o, basal conditions; r, external radiation; s, skin; 0, initial conditions.

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