VERIFICATION OF THE THERMAL CONTACT BETWEEN PROBE AND TISSUE IN CRYOSURGICAL OPERATIONS

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The study confirms that the temperature-dependent variation of the thermal conductivity of biological media must be taken into account in determining the temperature profiles in cryogenic interventions.

The problems involved in the thermal contact between biological tissue and a cryosurgical probe are important in planning and performing cryosurgical operations. If there is any thermal resistance to the heat flux between the tissue and the probe, this is equivalent to a reduction of the cold-producing power of the cryogenic instrument, which often means that the required low temperatures cannot be achieved and the cryointervention conditions are not fulfilled. The occurrence of such thermal resistances may be due to various mechanisms, and the resistance itself may occur randomly and take on arbitrary values (cf., for example, [1, 2]). It is also known that cold can have a so-called adhesive effect [3, 4], in which the tissue freezes to the tip of the cryogenic instrument if the temperature T_A when the two are in contact is in or above the range from −80 to −85°C; when the temperature is lower, the two do not freeze to each other. The absence of such cold adhesion is manifested in the fact that the temperature field of the medium in equivalent experiments [5] is not single-valued, a fact which may also be attributable to the presence of an uncontrolled thermal resistance on the probe-tissue interface. From the mathematical point of view, this constitutes a case in which the boundary conditions in the model and the experiment are not the same. Thus, it is imortant to find cooling conditions under which, inter alia, there is good thermal contact, i.e., the surface temperature of the cryogenic instrument is the same as that of the biological tissue with which it comes into contact.

While the temperature of the working tip of the cryogenic instrument can be measured in a fairly simple manner by means of a thermocouple soldered to it, the temperature of the biological tissue layer touching the probe cannot be measured directly because of the large gradients of the temperature field in this area [5]. Therefore the desired temperature is usually calculated by extrapolating the temperature profile measured by thermocouples far from the surface fo the cyogenic instrument. We shall consider the determination of the quality of the thermal contact along the profile of the stationary temperature field T in the frozen zone, in which we may disregard the heat exchange with the circulatory system and the metabolic heat generation, so that the following equation holds [6]:

$$\operatorname{div}(k \operatorname{grad} T) = 0. \tag{1}$$

Suppose that the temperature field has been established in a homogeneous semiinfinite model medium around a cryosurgical applicator of radius a (Fig. 1) with ideal thermal contact. (Other variants of the geometry of the problem (cf., for example, [6]) can be considered in an analogous manner.) In real experiments we may disregard the heat exchange between the model medium and the environment and assume that

$$T = T_A \quad \text{on} \quad S_1, \tag{2a}$$

$$\partial T/\partial \mathbf{n} = 0 \quad \text{on} \quad S_2. \tag{2b}$$

The second boundary condition is usually taken to be the condition that the temperature of the medium at infinity is constant: T_∞ = const > T_F. But when we pass to a coordinate system based on an oblate ellipsoid of revolution [7], Eq. (1) becomes one-dimensional in the coordinate σ, where

$$\frac{x^2 + y^2}{1 + \sigma^2} + \frac{z^2}{\sigma^2} = a^2, \tag{3}$$

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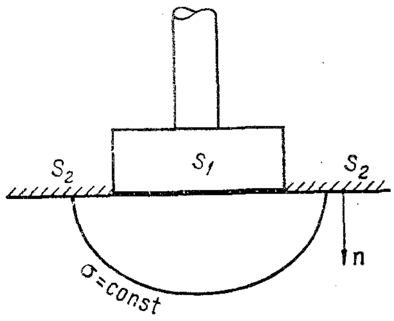

Fig. 1. Geometry of the problem.

and takes the form

$$\frac{\partial}{\partial\sigma}\left(k(1+\sigma^2)\frac{\partial T}{\partial\sigma}\right)=0. \tag{4}$$

One boundary value for (4) is a direct consequence of (2a):

$$T(\sigma=0)=T_A, \tag{5a}$$

and the second can conveniently be chosen to be the following:

$$T(\sigma=\sigma_F)=T_F. \tag{5b}$$

Suppose that the temperature field, in accordance with the method used in [5], is measured with thermocouples whose working junctions are on the boundary between the medium being frozen and the external medium, i.e., in the region S_2. The temperature profile will in this case be a function of the radial coordinate r, measured from the center of the applicator along S_2 and related to σ, in accordance with (3), by the equation ($r^2 = x^2 + y^2$, $z = 0$):

$$r^2=a^2(1+\sigma^2). \tag{6}$$

When k = const, the boundary-value problem (4), (5) is easily solvable, and the temperature distribution over the surface of the medium near the cryogenic instrument for $a < r < r_F$ takes the form

$$T(r)=(T_F-T_A)\frac{\arccos a/r}{\arccos a/r_F}+T_A. \tag{7}$$

The variation of the thermal conductivity k with temperature in Eq. (1) preserves the symmetry of the previous problem; however, it is not possible to obtain a simple analytic solution of (7). Therefore, in general, it will be impossible to use it for extrapolating the temperature fields to the entire freezing region. We shall estimate the error in the determination of the temperature in the region of contact with the cryoprobe in comparison with the real values if we disregard the functional relation k(T). We shall make the estimate by using the data of the experimental study [5]. The surface temperature profile was measured by means of the thermocouples placed at distances of approximately r = 4.7, 6.5, 9.0, 11.8, and 13.6 mm from the center of applicator of radius a = 3.5 mm, where the thermocouple at r = 13.6 mm coincided with the position of the front of the frozen zone (i.e., r_F = 13.6 mm) and the temperature of the applicator was T_A = 90°C. The model medium used was a 3% gelatin solution, "as the substance most often used for simulating soft tissue." Therefore, with a good degree of accuracy, we have T_F = 0°.

Owing to the lack of exact data, we assume that the thermal conductivity of such a medium in the freezing zone is equal to the thermal conductivity of ice at corresponding temperatures. In Fig. 2 the solid curve indicates the solution of Eq. (4) along the surface of the model medium for the following variation of the thermal conductivity as a function of temperature:

$$k(T)=2{,}1725-3{,}403\times10^{-3}T+9{,}085\times10^{-5}T^2. \tag{8}$$

The points on the solid curve correspond to the positions of the thermocouples. The dashed straight line, corresponding to Eq. (7), is drawn through these points by the method of least squares in such a way that one of its ends coincides exactly with the point whose coordinates are r = 13.6 mm and T = 0°. It is equivalent to the extrapolation of the temperature field of the biological tissue, formed according to the method of [5], and in the area of contact with the cryogenic instrument (r = 3.5 mm) it yielded a value of $T_A^* \approx -101$°C. Consequently the error was 11°C for a probe temperature T_A = −90°. At more negative temperatures on the cryogenic instrument, the difference would be even grater. At the same time, the maximum

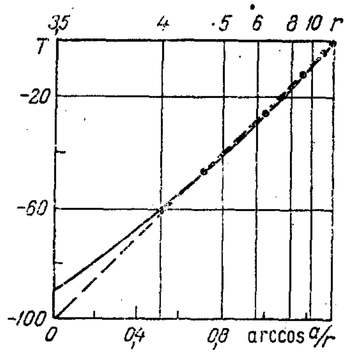

Fig. 2. Temperature profile of the frozen zone around a cryogenic applicator of radius a = 3.5 mm at temperature T_A= −90°C.

deviation of the points from the extrapolation line in Fig. 2 was approximately 0.6°C. Substantial deviations began at temperatures in the range below −50 to −60°C. This was the reason the experimental points in [5] were arranged along a straight line, since in that study the lowest temperature value measured with a thermocouple was approximately −40°C. The arrangement of the measuring thermocouples in the region of lower temperatures, i.e., closer to the applicator, appears to be unrealistic, since the nearest thermocouple (r = 4.7 mm), even though only 1.2 mm from its tip (a = 3.5 mm), shows a temperature which differs by 44°C.

It should also be noted that freezing of the cryogenic instrument to the biological tissue does not appear to be a sufficient condition for good thermal contact between them, even though the results in this case repeat the results of [5]. The temperature T_A^* = −101°C lies below the real value of T_A = −90°, whereas in [5], for T_A = −90°C the extrapolated value is $T_A^* \approx -72$°C, i.e., $T_A^* > T_A$. This trend might not be observed if k(T) were decreasing as the temperature decreases, although in our opinion this is not very probable.

Thus, in computing the temperature profiles in the frozen region for cryosurgical calculations, we must take account of the variation of the thermal conductivity of the frozen material as a function of temperature. At the same time, if the temperature on the cryogenic instruments does not go below about −45°C, the function k(T) may be disregarded.

NOTATION

a, radius of the working tip of the applicator, mm; k, thermal conductivity, W/(m·K); **n**, normal vector to the surface of the medium; r, radial coordinate, measured from the center of the applicator along the surface of the medium, mm; S_1, region of contact between the applicator and the model medium; S_2, surface of the medium on which the temperature distribution is measured; T, temperature, °C; T_A^*, extrapolated value of the temperature of the working tip of the applicator, °C; x, y, z, Cartesian coordinates of the points; σ, coordinate characterizing the position of the isotherm in the medium. The subscript F corresponds to the front of the frozen zone.

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