OPTIMIZATION OF LOCAL THERMOCOAGULATION AS APPLIED TO STEREOTAXIC NEUROSURGERY

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Several fundamentally different methods of local destruction of living tissue have been developed and are being used for surgical intervention on the deep formations of the human brain [1]. Procedures using heat, especially the method of thermocoagulation, have been shown to satsify most fully the demands of modern stereotaxic neurosurgery [2-4].

Unfortunately no reference can be found in the literature of stereotaxic thermodestruction to the search for optimal operating conditions for thermocoagulation. The absence of any theoretical recommendations relating to the choice of temperature and time of destruction is undoubtedly a handicap to the more extensive practical use of this effective method.

This paper gives the results of a model study of thermocoagulation, with an attempt to define optimal regimes aimed at securing minimal damage to the tissue adjacent to the focus of destruction, i.e., obtaining as sharp a boundary as possible between the completely coagulated region of the pathological focus and surrounding healthy tissue. From the thematic point of view this paper is a continuation of the work begun by Filippov, et al. and published in this journal [5].

To construct a mathematical model of local thermocoagulation of brain tissue, the results of previous investigations can be used [6], and the equation for thermal conductivity for this tissue can be written in the form:

$$\lambda\left(\frac{\partial^2\vartheta}{dr^2}+\frac{2}{r}\cdot\frac{\partial\vartheta}{\partial r}\right)-V_{\mathrm{bl}}(\vartheta,t)\cdot c_{\mathrm{bl}}\cdot\vartheta=\rho\cdot c\cdot\frac{\partial\vartheta}{\partial t},$$

where λ is the coefficient of thermal conductivity of the tissue; ϑ the excess temperature of coagulation relative to the body temperature ($\vartheta = T-37$); t the time, r the distance from the axis of the heat probe to the point examined; c_{bl} the specific heat of blood; c the specific heat of the tissue; ρ the density of the tissue; V_{bl} an index of the intensity of the blood flow.

The initial and boundary conditions are set by the equation:

$$\begin{gathered}\vartheta(r,t)|_{t=0}=0,\\ \vartheta(r,t)|_{r=r_0}=\vartheta_0(t),\\ \vartheta(r,t)|_{r=\infty}=0.\end{gathered}$$

The tips of the heat probes as a rule are shaped like a short cylinder. The equation connecting the temperature of the active surface of the probe $\vartheta_0(t)$ with the temperature of the heater $\vartheta_{00}(t)$, for a heating period of ($0<t\leq t_{\mathrm{heat}}$) is in the form:

$$\vartheta_0(t)=\vartheta_{00}(t)-\frac{q_{00}(t)}{\sigma_g},$$

and for the period of cooling ($t > t_{\mathrm{heat}}$):

$$\frac{\partial\vartheta_{00}(t)}{\partial t}=\frac{[\vartheta_0(t)-\vartheta_{00}(t)]\cdot\sigma_g}{\sigma_c},$$

where $q_{00}(t)$ is the density of the heat flow created by the electric heater; σ_g the heat capacity of the probe per unit active area; σ_c the thermal conductivity of the probe per unit active area.

All parameters of the medium and probe, except the index of intensity of the blood flow V_{bl}, are taken to be constant.

Cessation of the blood flow in the focus of coagulation is allowed for by a gradual change in the value of V_{bl}:

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$$V_{bl} = \begin{cases} \text{const} > 0, & \Omega < 1, \\ 0, & \Omega \geq 1, \end{cases}$$

where the integral index of injury to the living tissue $\Omega = \Omega(r, t, T)$ characterizes the state of the tissue in the process of thermocoagulation. According to its definition [7], the medium is considered to be completely damaged if $\Omega \geq 1$, and partly damaged is $0.53 \leq \Omega < 1$. If $\Omega < 0.53$, the medium remains undamaged (Fig. 1).

The criterion of optimization of the destruction regime providing for minimal injury to the tissue adjacent to the focus of destruction can be expressed as a minimization problem:

$$\delta = r|_{\Omega = 0.53} - r|_{\Omega = 1} = \min.$$

On the basis of the analytical description a mathematical model of the thermocoagulation process was built on the ÉMU-10 analog computer. The following parameters of brain tissue were used: coefficient of thermal conductivity of the gray matter of the brain 0.565 W/(m · K), the density of the brain tissue $1.05 \cdot 10^3$ kg/m^3, the specific heat of the tissue and blood $3.77 \cdot 10^3$ J/(kg · K), and the index of intensity of the blood flow (specific perfusion) in the gray matter of the brain 10 kg/m^3 · sec. As the parameters of the probe, values of the thermal parameters of the cannula of the Term-TGU thermodestructor [8], with an active tip measuring 2 mm (bore) × 7 mm, were used in the model. The parameters σ_c and σ_g for this cannula were determined experimentally and are as follows:

$$\sigma_c = 1{,}48 \cdot 10^3 \frac{\text{J}}{\text{K} \cdot \text{M}^2}, \quad \sigma_g = 2{,}68 \cdot 10^3 \frac{\text{W}}{\text{K} \cdot \text{M}^2}.$$

It was found by varying the radius of the equivalent spherical electrodes r_0 that best agreement between the calculated and experimental temperature fields is obtained in the side region of the active tip when r = 1.7 mm and in the end region when $r_{0z} = 1.1$ mm.

The mathematical model was verified by experimental investigations on a passive physical analog of brain tissue, consisting of egg albumin, and by experimental morphological investigations on the brain of experimental animals. Comparison of simulated temperature fields (for the case of a passive biological medium, $V_{bl} = 0$) and of fields recorded in egg albumin showed very slight discrepancy between the data (≤ 1°C). Comparison of the linear dimensions of the focus of injury predicted by the model with injuries actually produced in egg albumin and in the rabbit brain also showed good agreement between thermocoagulation in the model and the real process (the error in the first case $\leq \pm 0.15$ mm and in the second case $\leq \pm 0.20$ mm).

The optimization problem expressed above was solved by the ÉMU-10 computer by the consecutive approximation method. As classes of controlling factors, among which the optimal was sought, the following were chosen (Fig. 2): continuous regimes of constant temperatures of coagulation (T(A)), regimes of linearly rising temperature (B), regimes of a linearly falling temperature (C), interrupted (cyclic) regimes with the temperature constant within each cycle (F), and linear combinations of the first three regimes (D and E).

In view of the considerable thermal inertia of the medium to be coagulated, it appeared worthwhile studying more complex forms of controlling factor.

The results of an investigation of different regimes of destruction which correspond to the types of factors listed above are given in Table 1. For a more correct comparison of the results of the tests, the controlling factors were chosen so that foci of injury of about equal size were created (the volume of affected tissue was 90-110 mm^3, corresponding to an effective diameter of destruction of 5-6 mm). In this case it is more convenient to compare, not the absolute values of the thickness of the zone of incomplete necrosis δ, but the relative values:

$$\delta\% = \frac{\delta}{r_* - r_0} \cdot 100\%,$$

where r_* represents the radius of the zone of complete necrosis.

The investigations showed that variations of regimes do not very greatly affect the thickness of the region of incomplete necrosis, and for that reason definite deviations from the optimal regime of destruction can be regarded as noncritical. The most valuable regimes for stereotaxic neurosurgery may prove to be interrupted and continuous regimes with a constant moderate coagulation temperature, which gives an optimal size of the zone of incomplete necrosis and, at the same time, are simple from the practical point of view. To create foci of injury of average size, regimes with a coagulation temperature of 77-87°C may also be recommended.

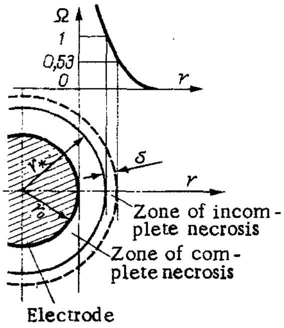

Fig. 1. Explanation of criterion of optimality of destruction.

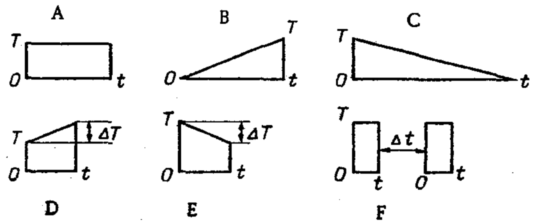

Fig. 2. Types of factors tested when seeking optimal regimes of thermocoagulation.

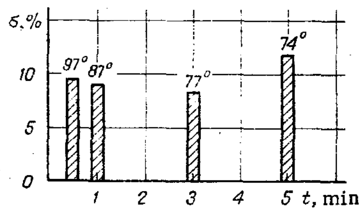

Fig. 3. Dependence of thickness of zone of incomplete necrosis on time and temperature (°C) of continuous coagulation regime.

TABLE 1. Optimal Parameters of Destruction Regimes

Parameters	Regimes						
	A	B	C	D	E	F	
T, °C	77	87	87	77	97	87	77
ΔT, °C	—	—	—	20	20	—	—
t, c	180	225	340	45	60	47	115
Δt, c	—	—	—	—	—	193	125
δ %	8,2	10,0	8,4	10,8	9,2	8,3	8,3

Legend: regimes A-F are described in the text.

Low-temperature regimes of thermocoagulation, with a long action time, and rising temperature regimes, which increase the thickness of the incompletely destroyed zone by 20-30%, were found to be unsatisfactory.

The search for optimal parameters of constant temperature regimes revealed an extremum at mean temperatures of coagulation (Fig. 3). At lower temperatures (with a correspondingly increased duration of action) the dimensions of the zone of incomplete necrosis are increased. The use of high temperatures for short times also leads to an increase in the thickness of the zone of incomplete recrosis.

The presence of the extremum at average coagulation temperatures can be explained, in the writers' view, as follows. On the one hand, the use of low coagulation temperatures leads to a decrease in the temperature gradient $\left|\frac{dT}{dr}\right|$, which naturally widens the zone of incomplete necrosis δ. On the other hand, at excessively high coagulation temperatures the final formation of the focus takes place to a large extent after the heating has ceased, while the electrode is cooling down, when the value of the gradient $\left|\frac{dT}{dr}\right|$ is decreasing. Under real conditions of destruction an increase in the parameter δ at high coagulation temperatures may also be facilitated by dehydration of the coagulant close to the electrode, the effect of which was not taken into account in the model.

CONCLUSIONS

1. Interrupted and continuous regimes with an average coagulation temperature, which give small zones of incomplete necrosis and which are simple when applied in practice, may be of practical importance in stereotaxic neurosurgery. To produce foci of destruction of average size (with a volume of destroyed tissue of 90-110 mm^3) regimes with a coagulation temperature of 77-87°C can also be recommended.

The use of low-temperature regimes with a long coagulation time and the use of short regimes with a high temperature, both of which increase the size of the zone of incomplete necrosis by 20-30%, was found to be unsatisfactory.

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