MATHEMATICAL ASSESSMENT OF EPHAPTIC INTERACTION AND THE RECORDING OF TRANSMEMBRANE POTENTIAL Shifts

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A theoretical analysis is given of ephaptic interaction between nerve cells. The larger cells must be more exposed to ephaptic effects. Intracellular studies of transmembrane potential shifts induced by ephaptic action show that the position of the reference electrode is very important. The efficiency of ephaptic interaction is proportional to the specific impedance of the nerve tissue.

KEY WORDS: nerve cells; ephaptic interaction.

Ephaptic interaction between nerve cells is the name given to the influence of currents generated by neurons on the excitability of neighboring neurons. Since ephaptic interaction takes place by the direct shift of potential on the membrane by currents of external origin as regards the neuron concerned, and not synaptically, the latent period of this interaction must theoretically be equal to zero. A latent period of almost zero for ephaptic interaction has been found, for example, in the work of Rosenthal et al. [7]. In addition, currents of external origin differ in their effects on the excitability of diametrically opposite regions of the neuron membrane: that part of the cell membrane through which the electric current enters the cell is hyperpolarized, whereas the opposite part of the membrane, through which the current leaves the neuron, is depolarized. If, therefore, a region with increased excitability exists in a neuron, the same external electric field may produce different effects on the excitability of the neuron depending on its orientation [8, 9].

In this paper the dependence of the transmembrane potential change (ΔVₜ) as a result of ephaptic action on the density of the external current, the dimensions of the cell, and the specific impedance of the external medium is deduced. Some theoretical aspects of the recording of ΔVₜ are also examined.

METHODS OF CALCULATING AND DISCUSSION OF THE RESULTS

To simplify the calculation of the value of ΔVₜ it was considered that the cell is spherical and that the electrolyte surrounding it is infinitely large. It was also assumed that before the spherical cell was placed in the electrolyte, the latter had a uniform current field with density J₀. With this model of ephaptic interaction the following expression can be obtained for the value of the transmembrane potential change (ΔVₜ) in relation to the level of the resting potential:

\[ ΔV_m = -\frac{3}{4} J_0 \rho_0 \cdot D \cdot \cos θ, \]  

where ρ₀ is the specific resistance of the medium surrounding the cell, D the diameter of the cell, and θ the angle between the direction and the radius drawn from the center of the cell (Fig. 1).

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Fig. 1. Model of nerve cell in homogeneous field of electric current: \( \mathbf{j}_0 \) vector of current density sufficiently far from the cell; \( \rho_0 \) specific resistance of surrounding electrolyte; \( D \) diameter of cell; \( \theta \) angle between direction of \( \mathbf{j}_0 \) and radius drawn from the center of the cell; \( L \) distance between equipotential lines on which points A and B lie.

Fig. 2. Nerve cell in field of current of ephaptic dipole. Shaded circles represent poles of dipole; 1 and 2) two symmetrical positions of nerve cell; numbers on isopotential curves are equal to values of potential on them in conventional units.

The calculations showed that the change in transmembrane potential (\( \Delta V_t \)) during ephaptic action is proportional to the size of the cell (\( D \)). This can be explained qualitatively as follows. A decrease in voltage between the points A and B (Fig. 1) must be equal to the potential difference between the equipotential lines on which these points lie. These equipotential curves can be taken as parallel a short distance from the cell, and the distance between them is \( L \). The potential difference sought between the points A and B is thus \( \mathbf{j}_0 \cdot \rho_0 \cdot L \). The voltage drop between A and B must be divided between three resistors connected in series (the resistance of the membrane for the inward current, the resistance of the intracellular medium, and the resistance of the membrane for the outward current). Since the first and third resistances are many times greater than the second, essentially the whole potential drop between A and B is divided half and half between the resistance of the membrane for the inward current and its resistance for the outward current. The expression \( \Delta V_t = \frac{1}{2} \mathbf{j}_0 \rho_0 L \) can thus be obtained for the magnitude of \( \Delta V_t \). Let us estimate \( L \). It is evident that \( L \) is greater than \( D \), but it is a value of the same order as \( D \). This follows from the general argument that the distortion of the field (i.e., the deviation of its equipotential curves) is a value of the same order as the size of the object as a result of which the distortion took place. Accordingly, \( L \) in the last expression for \( \Delta V_t \) can be replaced approximately by \( D \), and the resulting expression for \( \Delta V_t \) now has the form \( \Delta V_t = \frac{1}{2} \mathbf{j}_0 \rho_0 D \), from which it follows that \( \Delta V_t \) is proportional to \( D \).

The true value of \( \Delta V_t \), incidentally, can be measured when the potential difference is measured between the intracellular and extracellular electrodes, the last of which must be placed as near as possible to the membrane of the cell concerned. In that case the potential difference between the intracellular and extracellular electrodes will be equal to the sum of the resting potential and \( \Delta V_t \) of that part of the cell membrane that lies closest to the extracellular electrode. The potential drop in the intracellular medium between the point where the electrode is situated and the inner surface of the membrane is a negligibly small magnitude compared with \( \Delta V_t \).

To measure the value of \( \Delta V_t \), the position of the reference electrode thus becomes extremely important. If this electrode is sufficiently far, compared with the size of the current ephaptic dipole, from that dipole the reference electrode can be regarded as lying on the zero isopotential curve (Fig. 2). If, therefore, a sufficiently distant reference electrode is used the potential difference between the intracellular and reference electrodes will depend only on the position of the investigated cell in the field of potentials generated by the current ephaptic dipole. The same potential difference (but differing in resting potential) could be recorded from the active electrode after the cell had been removed but the active electrode was left in its old position. The potential difference recorded by this distant reference electrode can even change its sign, whereas the ephaptic influence on the cell (proportional to the potential gradient) may remain unchanged (see positions 1 and 2 of the cell in Fig. 2).