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The Energy Involved in the Electric Change in Muscle and Nerve.

By A. V. HILL, F.R.S.

(Received April 8, 1921.)

Considerable electromotive forces are produced by the activity of excited muscles or nerves—up to three or four hundredths of a volt—and it was conceivable that an appreciable amount of energy might be involved in the currents set up in the tissue by them. This paper contains an examination of the question.

In fig. 1 is shown a nerve fibre, on which rest electrodes (not shown) connected to an electrometer or galvanometer. Along the outside of the fibre is travelling, from right to left, a wave of negative potential, with velocity a cm. per second, having at any point distant x cm. along the nerve, and at time t seconds, a value y volts, as recorded on the electrometer, and shown (after the appropriate analysis) in the lower curve of the figure. We are not concerned here with the cause of this electromotive change, nor with what happens inside the fibre, but only with the physical results of it in an external circuit.

In consequence of the differences of potential existing along the length of the nerve, currents tend to flow, as shown by the full arrows and the strength of the current flowing at any moment between two neighbouring points, is

proportional to the difference of potential between them. Thus the current in the external circuit at any point at any given moment is directly proportional to the slope at that point of the curve giving the E.M.F. of the

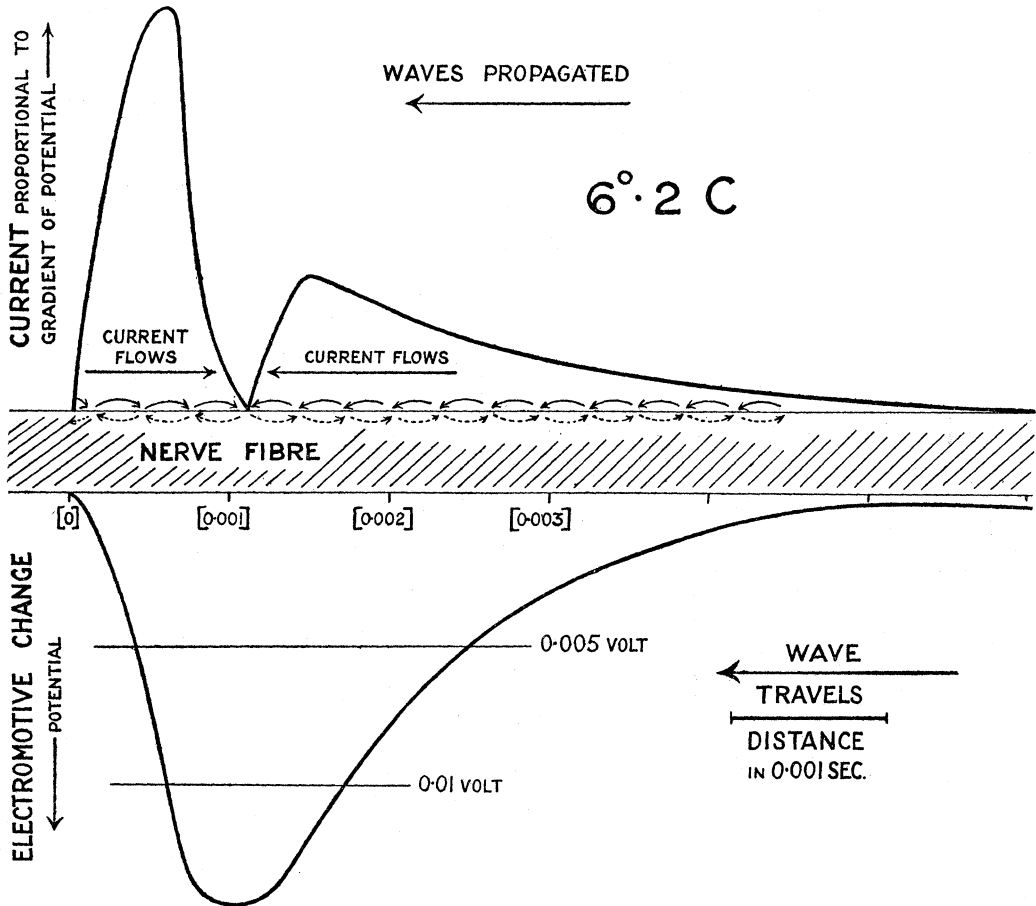


FIG. 1.—Sciatic nerve fibre, at 6.2° C., showing observed monophasic electric response (lower curve) moving from right to left with velocity about 10 metres per second, and consequent current distribution in nerve (upper curves). Black curved arrows show flow of current outside fibre: dotted curved arrows show conjectured flow inside fibre. The numbers in square brackets below the fibre represent times (in seconds) since the front of the wave passed the corresponding points.

electric change, and is represented graphically by the upper curve of the figure.

This current distribution should be regarded as sweeping along the nerve to the left with velocity a . It is probable that the currents observed on the outside of the fibre by experimental means return on the inside of the fibre, as shown by the dotted arrows of fig. 1, but, as the internal electrical

resistance is unknown, and as the distribution of the return currents is a matter more or less of speculation, it seems advisable to consider only the effect of the currents in the external circuit, where the E.M.F. and the resistance can be accurately observed. The energy of the currents, as calculated below, is less, therefore, than the true amount by the unknown quantity involved in the return currents inside the fibre.

The most natural assumption as to these return currents is that they are similar to the external currents observed, the E.M.F. being located somehow in the walls of the fibre; in that case the total amount of energy involved in the electric change is double the quantity calculated below.

Suppose that the wave of negative potential shown in the lower curve of the figure is represented by the equation

$$y = f(t - x/a),$$

the function f being given by the observed form of the electric response. Let R be the resistance per unit length of a tissue, as measured by direct experimental means. The potential at a point x being $(t - x/a)$ at a moment t , the potential at a neighbouring point $(x + \delta x)$ at the same moment will be $f\{t - (x + \delta x)/a\}$, so that the current running in the small element of length δx between them will be

$$\begin{aligned} C &= \frac{f\{t - (x + \delta x)/a\} - f(t - x/a)}{R\delta x} \\ &= \frac{f'(t - x/a)}{Ra}, \end{aligned}$$

where $f'(z)$ is the differential coefficient of $f(z)$ with respect to z . Hence the heat produced in this element of tissue in time t , being $R\delta x C^2 \delta t$ joules, is equal to

$$\frac{f'^2}{4 \cdot 18 Ra^2} \delta x \delta t \text{ calories.}$$

Integrating this with respect to x and t , in order to determine the total heat H produced in the whole length l of the tissue by the whole wave, we find

$$H = \frac{1}{4 \cdot 18 Ra^2} \int_{x=0}^{x=l} \int_{t=0}^{t=\infty} f'^2 dx dt.$$

Now it is obvious that if the wave be propagated unchanged the same amount of heat is liberated at each point of the tissue: hence the value of $\int_{t=0}^{t=\infty} f'^2 dt$ cannot depend upon x and must be equal to its value at any convenient point on the tissue, *e.g.*, at the electrode used in the experiments. Hence, from a curve relating electrical potential to time at one spot (as

observed in a monophasic response), we can calculate this integral numerically: suppose that its value is A : then the total heat becomes

$$\frac{1}{4.18 Ra^2} \int_0^l A dx = \frac{Al}{4.18 Ra^2} \text{ calories,}$$

or, per unit length, $\frac{A}{4.18 Ra^2}$ calories.

The value of R in this formula can be considerably decreased by immersing the muscle or nerve in a conducting fluid. I am informed, however, by Dr. E. D. Adrian that the potential difference of the action current as measured by an electrometer also depends very much on the amount of fluid adhering to the nerve, and that a large E.M.F. can be obtained only by using a fairly dry nerve; in fact, the external conducting fluid is acting as a short-circuit and lowering the E.M.F. between any two points on the tissue. It is probable therefore that no considerable increase in the production of heat will be caused by lowering the resistance between two points on the nerve by immersing it in a conducting fluid. We will consider only the case of a muscle or nerve in a reasonably dry condition.

Let us apply the formulæ deduced above to the case of the monophasic electric change of the frog's sartorius, as determined by Keith Lucas* for 8° C. and 18° C. The data are as follows:—

Secs.	8° C. volts.	18° C. volts.	Secs.	8° C. volts.	18° C. volts.
0.0050	0.0013	—	0.0094	0.0325	0.0144
0.0056	0.0032	0.0011	0.0100	0.0268	0.0107
0.0062	0.0089	0.0052	0.0106	0.0206	—
0.0069	0.0187	0.0156	0.0112	0.0140	0.0067
0.0075	0.0239	0.0213	0.0125	0.0070	0.0054
0.0081	0.0292	0.0251	0.0150	—	0.0048
0.0087	0.0322	0.0217			

These numbers have been plotted in curves and the values of A calculated. They are as follows:—

$$A_8 = 0.5, \quad A_{18} = 0.35.$$

The velocity of the wave may be taken to be roughly as follows in the two cases:—

$$A_8 = 140 \text{ cm./sec.}, \quad A_{18} = 220 \text{ cm./sec.}$$

These results are approximate only, as Keith Lucas does not give the exact distance apart of his electrodes in the case where he recorded the diphasic response. He states, however, that they were "as far apart as possible," and from his figure their distance cannot have been far from 2 cm. The time

* 'Journal of Physiol.,' vol. 39, p. 220 (1909).

relations of the diphasic response recorded by him then give the above velocities.

The resistance to an alternating current of a frog's sartorius muscle, after death, between electrodes placed directly upon it, is given by the following hitherto unpublished experiments, made by myself in 1913, at about 12° C., by the method described in a previous paper.*

(1)	No. of experiment	1	2	3	4	5
(2)	Distance between electrodes, centimetres ...	3·0	2·85	3·2	3·7	3·2
(3)	Mass of muscle between electrodes, grammes	0·183	0·147	0·205	0·241	0·207
(4)	Resistance between electrodes, ohms	13540	14860	12300	15910	12800
(5)	Resistance per centimetre, ohms	4510	5220	3850	4300	4000
(6)	Mass per centimetre, grammes	0·061	0·0515	0·064	0·065	0·065
(7)	(5) × (6)	275	270	247	280	259

The muscles being of different sizes, the conductivity should be proportional to the mass per centimetre, or, in other words, the resistance per centimetre multiplied by the mass per centimetre should be constant. That this is so is shown by the last row where this quantity is tabulated. We may assume therefore that a muscle 1 cm. long, weighing 1 gm., has a resistance of about 260 ohms at 12° C. Substituting this value with those preceding in the expression for the heat per unit length of muscle, viz., $H = A/4\cdot18 Ra^2$, we find

$$H_8 = \frac{0\cdot5}{4\cdot18 \times 260 \times 140^2} = 23\cdot4 \times 10^{-9} \text{ calories per gramme,}$$

$$H_{18} = \frac{0\cdot35}{4\cdot18 \times 260 \times 220^2} = 6\cdot6 \times 10^{-9} \text{ calories per gramme.}$$

The quantity of heat liberated in a muscle twitch is of the order of 3×10^{-3} calories per gramme, *a quantity more than one hundred thousand times as great as the larger of the quantities calculated above.* The amount of energy associated with the electric change in a muscle is negligible therefore when compared with that liberated in the subsequent contraction.

The same formulæ may be applied to the case of a nerve. Dr. E. D. Adrian has kindly provided me with a record of a monophasic response of a frog's sciatic nerve at 6·2° C., which is the curve shown in the lower half of fig. 1. Here the calculated value of A is 0·38 (compare this with the value 0·5 given above for the sartorius muscle at 8° C.), and the value of a was about 10 metres, i.e., 1000 cm. per second. Assuming that the specific electrical resistance of nerve is the same as that of muscle, an assumption which can cause no serious error, the value of the heat production at 6·2° C., per gramme of nerve, caused by the passage of a single electric change becomes,

$$H_6 = \frac{0\cdot38}{4\cdot18 \times 260 \times 1000^2} = 3\cdot5 \times 10^{-10} \text{ calories.}$$

* A. V. Hill, 'Journal of Physiol.,' vol. 46, p. 457 (1913).

This quantity lies between 1 and 2 per cent. of the value calculated for the sartorius muscle at 8° C.

The precise values deduced above are, of course, of no importance as they can be changed considerably by small alterations in the experimental conditions. The interest lies in their *order of size*, not in their exact values. Consider the case of a nerve. In a previous paper* the production of heat (if any) in the passage of a single impulse along a nerve was shown to be not greater than about 5×10^{-8} calories per gramme. This is more than 100 times as large as the heat liberated by the electric currents produced by the nerve. Now *the only known accompaniment of the nervous impulse is the electric change*, and it is of importance therefore to realise that this electric change involves in itself only a very small liberation of energy, corresponding to a rise of temperature of less than one thousand millionth of a degree, or to the amount of work required to lift the tissue through fifteen millionths of a millimetre. It is natural, therefore, that no direct method should be capable of determining the heat liberated in the passage of a nervous impulse.

The electric change however, is, in a way, a relatively large effect, being quite easily shown on a galvanometer or electrometer, and capable of directly exciting other tissues ("rheoscopic frog"). Presumably, therefore, it is energetic enough to account for the sudden and temporary change of permeability required to initiate the muscle twitch. The facts: (*a*) that apart from the electric change there is no known accompaniment of the nervous impulse; (*b*) that down to 5×10^{-8} calories per gramme no production of heat occurs in the passage of an impulse; (*c*) that the energy involved in the electric change itself is almost inconceivably small; and (*d*) that the electric change is nevertheless sufficient to stimulate other tissues; tend to confirm the belief either that the electric change *is* the nervous impulse, propagated in some manner at present unknown, or that it is the immediate consequence of some physico-chemical change propagated as a wave with a very small degradation of energy. Unlike the mechanical response of muscle, the electric response of muscle and nerve is accompanied by practically no liberation of energy.

Summary.

An expression is given for the heating effect, in a muscle or nerve, of the currents produced by the electric response accompanying the propagated impulse. In a muscle the heat produced is not more than one hundred thousandth part of the energy liberated in a twitch; in a nerve it is of the order of size of 3.5×10^{-10} calorie or 0.015 erg. per gramme. It is concluded from the smallness of these quantities that no appreciable provision of energy

* A. V. Hill, 'Journal of Physiol.', vol. 43, p. 433 (1912).

is required in the propagation of the electric response, and that the physico-chemical change producing the response is the only factor involved in the propagated nervous impulse.

My thanks are due to Dr. E. D. Adrian and to Mr. R. H. Fowler, both of Trinity College, Cambridge, to the former for experimental results and critical suggestions, to the latter for help in the mathematical treatment of the problem.

A Method of Analysing Galvanometer Records.

By W. HARTREE, M.A., and A. V. HILL, Sc.D., F.R.S.

[This paper is printed in Proceedings, Series A, vol. 99, p. 172 (No. A 697).]

CROONIAN LECTURE :—*Release of Function in the Nervous System.*

By HENRY HEAD, M.D., F.R.S.

(Received April 22,—Lecture delivered May 5, 1921.)

It is a common experience that the manifestations of nervous disease may comprise both loss of function and some positive outburst of excessive activity. Thus, in many cases of hemiplegia, the paralysed limbs tend to be more or less rigid and the reflexes are greatly increased. This spasticity, although due to a destructive lesion, was attributed to "irritation"; the morbid agent, or the conditions it produced in the nervous system, were supposed to have an "irritative" effect upon the tissues, and this was expressed in the positive signs and symptoms.

But more than fifty years ago, Hughlings Jackson [11]* laid down the rule that destructive lesions never cause positive effects, but induce a negative condition, which permits positive symptoms to appear. This he applied to all morbid expressions of nervous activity; but his most striking instance was the motor condition in organic hemiplegia. He showed that it depended on two factors. First, there was loss of voluntary power, especially in the fingers, the parts most directly under cortical control; this was the negative

* Numbers in square brackets refer to List of References at end.