XLII. THE SPECIFIC ELECTRICAL RESISTANCE OF FROG'S MUSCLE.

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IN a large number of experiments carried out at various temperatures during the past two years we have found incidentally the electrical resistance of a frog's sartorius muscle after death to a single phase alternating current of about 90 periods per sec., and of a strength of the order of 1 milliampere. The results are so numerous and, when expressed in terms of the specific resistance of muscle, relatively so consistent, that we thought it advisable to collect them together and to put them on record. The observations were made during the "calibration" of a muscle, killed by chloroform vapour and resting in air or oxygen on a thermopile, by the method described in our recent paper [1920]. It should be noted that the resistances are to a relatively high current and that, in the case of a muscle, Ohm's law is not exactly obeyed: indeed we have found that a 50 % increase in the current leads to about a 10 % decrease in the resistance: consequently the resistance to a different current will be different. The cause of this failure of Ohm's law is presumably some hindrance to free diffusion, either at the electrodes (platinum wires in very good contact with the muscle) or more probably at membranes in the muscle substance. The quantity observed was the resistance of a pair of sartorius muscles in parallel between two electrodes at distance l (about $2\frac{1}{2}$ cm.) apart. It is clear that the resistance of a given mass m of a muscle of uniform cross-section A is directly proportional to its length l and inversely proportional to A . But $m = slA$ where s is the specific gravity of muscle, so that putting $A = m/sl$ the resistance is directly proportional to l and also to sl/m , i.e. altogether to sl^2/m . Thus we may put

$$R = ksl^2/m$$

where k is the specific resistance of muscle. Thus to find k we use the formula

$$k = Rm/sl^2.$$

The value of s was found directly by weighing a frog's muscle suspended in

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0.7 % NaCl solution, and had the value 1.057, say 1.06, at 10°, and with this value of s the value of k is calculated from the results of each experiment for the following table.

Table I. *Values of the specific resistance $k = Rm/sl^2$: a is the value of the current used, in milliamps.: s is put equal to 1.06.*

0°			5°			10°			15°			20°		
Mth	k	a	Mth	k	a	Mth	k	a	Mth	k	a	Mth	k	a
May	278	0.8	May	212	1.1	May	220	1.1	May	168	1.1	May	141	1.4
July	275	1.0	May	242	0.9	July	217	1.2	May	194	1.4	May	138	1.4
Oct.	293	1.0	May	214	0.8	July	184	1.1	May	179	1.3	May	164	1.2
Oct.	265	1.2	July	212	1.0	Aug.	217	0.9	June	190	0.8	July	143	1.6
Dec.	307	1.1	July	206	0.8	Nov.	192	1.4	July	158	1.4	July	148	1.5
Jan.	261	0.9	Oct.	209	1.1	Nov.	221	1.3	July	163	1.4			
Jan.	299	0.9	Dec.	230	1.1	Nov.	217	1.7	July	166	1.1	Mean	147	1.4
Feb.	320	1.1	Nov.	258	1.2				July	160	1.2			
Feb.	292	1.1				Mean	210	1.25	July	179	1.3			
Feb.	300	0.9	Mean	233	1.0				Nov.	183	2.0			
Feb.	317	0.8							Nov.	189	1.8			
Feb.	269	1.0							Nov.	162	1.8			
									Dec.	179	1.5			
Mean	290	1.0							Mean	175	1.4			

In the experiments recorded here it happened in general that the currents used at the higher temperature were greater than those used at the lower—owing to the greater resistance in the latter case. In the neighbourhood of 1 milliampere a 50 % increase in the current makes about 10 % decrease in the resistance, so that it is advisable to apply a small correction to reduce the resistances to a uniform basis of 1 milliampere. Corrected in this way the mean values given above become: 0°, 290; 5°, 223; 10°, 220; 15°, 189; 20°, 159. It is usual to employ conductivities, rather than resistances, in dealing with solutions, and the corresponding specific conductivities are: 0°, 344×10^{-5} ; 5°, 448×10^{-5} ; 10°, 454×10^{-5} ; 15°, 529×10^{-5} ; 20°, 628×10^{-5} . These quantities are plotted as circles in the figure, and the relation between conductivity and temperature is given by the solid curve (calculated as described below).

In order to compare the muscle with a solution of NaCl the broken curve in the figure is plotted to show the relation between the conductivity (at 18°) and the strength of the solution. The data were obtained from Landolt and Börnstein's tables. At 18° the specific conductivity of the muscle is 580×10^{-5} , which corresponds to that of a NaCl solution of strength 0.36 %. The muscle is in osmotic equilibrium with 0.7 % NaCl, and it is striking that the specific conductivity of the muscle is only half that of the NaCl solution with which it is in osmotic equilibrium. This lowering of the conductivity would seem to be due to the hindrance afforded to the passage of a current by the membranes and surfaces of the tissue.

The effect of temperature on the conductivity of a muscle is similar to its

effect on the conductivity of a NaCl solution. In Landolt and Börnstein's tables the conductivity of a 0.29 % NaCl solution is expressed by the formula:

$$K_t = K_{18} [1 + c(t - 18) + c'(t - 18)^2]$$

where K_t is the specific conductivity at $t^\circ \text{C.}$, and c and c' are constants having the values, $c = 224 \times 10^{-4}$, $c' = 79 \times 10^{-6}$; the constants c and c' change only slightly with concentration, so the above formula may be taken as applying

Fig. 1. (Solid Curve.) Temperature of Muscle.
(Broken Curve.) Strength of NaCl solution at 18°C.

equally to a 0.36 % solution. Putting $K_{18} = 580 \times 10^{-5}$, the value of K_t can be calculated from the above formula. In the following table the calculated values K of the specific conductivity of 0.36 % NaCl solution are compared with the observed values K' of the conductivity of the frog's muscle.

Temperature °C.	0	5	10	15	20
$K \times 10^5$	360	419	478	542	606
$K' \times 10^5$	344	448	454	529	628

In the figure the solid curve is drawn from the calculated values K in this table. It is seen that the agreement is good, that the effect of temperature is the same on the muscle and on the salt solution, and that *at all temperatures the specific conductivity of the muscle is the same as that of a 0.36 % NaCl solution*. If the electrical resistance of the muscle were made up of two distinct parts, (1) the resistance of a 0.7 % NaCl solution and (2) the *separate* resistance of colloidal structures or membranes, it might be expected that the conductivity of the muscle would be influenced by temperature in a manner different from that of a salt solution. The fact that this is not so suggests that the conductivity of a muscle is lower than that of the corresponding salt solution simply because the membranes and structures of the muscle hinder the diffusion of the ions of NaCl under a potential gradient.

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REFERENCE.

Hartree and Hill (1920). *J. Physiol.* 54, 84.