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# THE MEMBRANE RESISTANCE OF A NON-MEDULLATED NERVE FIBRE

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Eight years ago, Cole & Curtis (1939) showed that the membrane resistance of the squid giant axon underwent a transient decrease during the passage of a nervous impulse. At about the same time Cole & Hodgkin (1939) obtained an approximate measurement of the membrane resistance in a resting axon. A comparison of the two sets of measurements showed that the membrane resistance at the height of activity was only about one-fortieth of that in the resting nerve. The large size of the resistance change suggests that other phases of nervous activity might be illuminated by measurements of membrane resistance. It would, for instance, be interesting to know what happens to the resistance during the refractory period or to discover how it is affected by ions and other chemical agents known to affect nervous activity. The second of these problems has been the main subject of my research, and the present paper contains an account of experiments which form an essential preliminary to this work. Previous determinations of membrane resistance have been made on the squid giant axon (Cole & Hodgkin, 1939; Cole & Baker, 1941*b*) and on the large axons of the lobster (Hodgkin & Rushton, 1946). Neither of these preparations is entirely suitable for a prolonged investigation, since the experimental animals are difficult to obtain and the axons must be dissected with great care before accurate measurements can be made. An attempt was therefore made to use the isolated axons of the shore crab *Carcinus maenas* (Hodgkin, 1938). These animals can be obtained throughout the year, and clean axons can be isolated from them without great difficulty. The membrane resistance of an isolated axon is so high that it can be measured with fair accuracy in spite of the small fibre diameter. The axon possesses the further advantage that its membrane resistance remains reasonably constant over a considerable period of time. Before starting to examine the effect of ions upon the membrane resistance it was necessary to settle two preliminary questions. First: what is the approximate value of the membrane resistance

in a normal axon? Second: what is the largest current which can safely be used for measurement without causing the membrane resistance to depart from its resting value? This paper attempts to answer these two questions and gives some additional information about other physical constants in *Carcinus* axons.

The method of estimating the membrane resistance is based upon that developed by Hodgkin & Rushton (1946) and depends upon the following principles. When a voltage is applied to a nerve fibre some of the current spreads along the fibre forming a local circuit in the extrapolar region. The distance over which this local circuit spreads in the steady state determines the spatial distribution of the extrapolar potential (electrotonus) and depends upon the resistances of nerve membrane, axis cylinder and external fluid. According to theory the potential should decline exponentially with distance and should fall to $1/e$ in a characteristic length which is related to the resistive constants in the following way:

$$\lambda = \sqrt{\frac{r_4}{r_1 + r_2}}. \tag{1}$$

$\lambda$ is the characteristic distance or space constant, $r_1$ and $r_2$ are the resistances per unit length of the external fluid and axis cylinder respectively and $r_4$ is the resistance $\times$ unit length of the nerve membrane. The meaning of $r_1$ and $r_2$ is easily understood, but the dimensions and significance of $r_4$ may need further clarification. Suppose that the potential difference across the nerve membrane can be changed by a certain voltage over 1 unit length of nerve and that everywhere else the membrane potential has its normal resting value. Then the total current which flows across the membrane will be equal to the change in voltage divided by $r_4$. $r_4$ is expressed as a resistance $\times$ unit length because the total current which flows across the membrane increases with the length of nerve exposed to the applied voltage. $r_2$ and $r_4$ are fundamental constants for any particular axon, but their magnitudes depend upon the axon diameter. In comparing the properties of different axons it is therefore best to use the basic constants $R_2$ and $R_4$. $R_2$ is the resistance which would be observed if electrodes 1 cm. square could be placed on either side of a centimetre cube of axoplasm. $R_4$ is the resistance across 1 sq.cm. of membrane. In a cylindrical cell the two sets of constants are related in the following way:

$$R_2 = r_2 \pi a^2, \tag{2}$$

$$R_4 = r_4 2\pi a, \tag{3}$$

where $a$ is the radius of the axon.

The determination of $\lambda$ is the first step in estimating membrane resistance, but it must be followed by measurements of $r_1$ and $r_2$. The next stage consists in a measurement of the longitudinal resistance of the nerve under conditions which ensure that all the current is flowing parallel to the nerve membrane.

The resistance measured in this way is often called $m$ and is defined by the relation

$$m = \frac{r_1 r_2}{r_1 + r_2}. \tag{4}$$

It may be determined by observing the potential gradient which exists between two electrodes separated by a large distance.

A third measurement must then be made in order to determine the relative magnitude of $r_1$ and $r_2$. No very satisfactory way of finding the ratio $r_2/r_1$ has been developed, but a reasonable estimate can be obtained by measuring the difference between the potential at a point where current is led into the nerve and a distant part of the extrapolar region. A necessary condition for measurement is that the anode and cathode of the applied current should be remote from one another. The voltage of the anode or cathode will be called $V_A$ and is related to the applied current $I$ in the following way:

$$\frac{V_A}{I} = \frac{m\lambda r_1}{2r_2}. \tag{5}$$

There are now three equations (1, 4 and 5) from which the three unknowns $r_1$, $r_2$ and $r_4$ can be determined.

When the membrane resistance has been measured it is a fairly simple matter to obtain the membrane capacity and this has been done in the present research. The membrane time constant is determined from the rate at which the extrapolar potential rises when current is applied and the membrane capacity obtained by the relation

$$C_m = \tau_m / R_4, \tag{6}$$

where $C_m$ is the membrane capacity per sq.cm. and $\tau_m$ is the membrane time constant.

## METHOD

Five or six axons with a diameter of 25–35 $\mu$. were isolated from one of the walking legs of *Carcinus maenas* by a method which has been described previously. Loose strands of connective tissue were detached from the axons with fine needles or knives. The cleanest and most uniform axon was mounted on the electrode assembly and raised into aerated paraffin oil. This method of recording gave satisfactory results, since axons were found to be capable of transmitting a large number of impulses and of surviving for 12–30 hr. Measurements were always made on excitable axons.

The electrodes consisted of glass tubes containing sea water and silver wires which had been coated electrolytically with chloride. One end of the tube was drawn into a capillary and terminated in a fine agar wick. The wick was made by allowing agar to solidify around a 60 $\mu$. hair and had a thickness of about 100 $\mu$. at the tip.

Electrical changes were recorded through cathode followers and a balanced d.c. amplifier similar to that described by Hodgkin & Rushton (1946). No grid leaks were employed and care was taken to ensure that stray leakage paths had a resistance greater than about $10^9$ $\Omega$. Rectangular pulses of current were applied to the nerve by an electronic circuit capable of producing pulses of variable width, amplitude and sign. One terminal of the pulse generator was earthed and was connected to electrodes $A$ or $C$ (Fig. 1). The other terminal was connected to the forceps $F'$ through

an 0·5 μF. condenser and a resistance of 100 MΩ. The forceps behaved like a polarizable electrode, but the resulting polarization did not alter the form of the applied current since its effect was swamped by the series resistance of 100 MΩ. The current through the nerve was determined by inserting a monitoring resistance of 0·280 MΩ. and measuring the voltage across it. Reference should be made to a former paper (Hodgkin & Rushton, 1946) for a more detailed account of the circuit arrangements.

The absolute standard of resistance was a set of wire-wound resistors calibrated by the National Physical Laboratory, while the 50-cycle mains was used as the absolute standard of time.

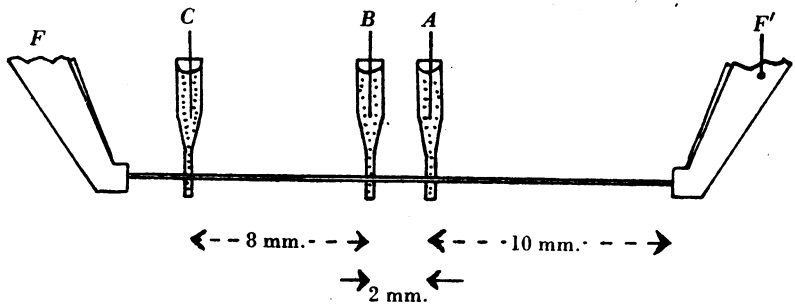


Fig. 1. Diagram of electrode arrangement. *A*, *B*, *C* are non-polarizable electrodes, and *F*, *F'* are metal forceps used for holding the axon.

## PART 1

### EXPERIMENTAL PROCEDURE

In previous measurements (Hodgkin & Rushton, 1946) the constants $\lambda$ and $m$ were determined from a number of observations made with a movable electrode. This was done partly in order to obtain the greatest possible accuracy and partly in order to check the validity of the theoretical equations. In the present work a simpler but less accurate method was employed. The nerve was arranged on the three agar wick electrodes shown in Fig. 1 and the distance between electrodes *A* and *B* carefully measured with a binocular microscope and an eyepiece micrometer. At the same time the effective thickness of each electrode was noted. The reason for using fixed electrodes was that the axons were subsequently needed for another investigation and I wished to avoid the technical difficulties associated with a movable electrode. The value of the space constant $\lambda$ was obtained from the ratio of the membrane potentials at *A* and *B* when a weak positive current was applied between *A* and *F'*. The potential difference recorded between *B* and *C* (hereinafter called $V_B$) was directly proportional to the membrane potential at *B*. The potential recorded between *A* and *C* was spuriously increased by the voltage drop across the ohmic resistance of the agar wick and had to be corrected before a comparison with $V_B$ could be made. Fortunately, the correction amounted to only about 5 % of $V_A$ and an accurate evaluation was therefore unnecessary. An approximate estimate of the electrode resistance was obtained by dipping

the tip of the electrode into a large volume of sea water to a depth such that the oil-sea water interface coincided with the point where the axon normally made contact with the wick. The potential drop across the electrode was calculated from the current and the electrode resistance. The value so obtained was subtracted from the recorded potential difference and the resulting voltage ($V_A$) used for comparison with $V_B$. $\lambda$ was determined by means of the equation

$$\lambda = l/\log_e(V_A/V_B), \tag{7}$$

where the length $l$ was taken as the distance between the left-hand edges of electrodes $A$ and $B$ (Fig. 1). Some error was introduced by the fact that the electrodes were not infinitesimal, as assumed in the theory, but had a width of about 0·2 mm. However, this error should not have been large, since $\lambda$ was about 2 mm. and the ratio of internal to external resistances was about 1·6.

The ratio $V_A/I$ (eq. (5)) was determined by inserting a monitoring resistance of 0·280 MΩ. in series with electrode $A$ and comparing $V_A$ with the voltage drop across this resistance.

The parallel resistance of axis cylinder and external fluid ($m$) was determined by connecting the amplifier leads to electrodes $A$ and $B$, and the pulse generating leads to $C$ and $F'$. A comparison of the voltage recorded in this way with the voltage across the monitoring resistance gave the parallel resistance of axis cylinder and external fluid over the length $AB$. In calculating $m$ this length was taken as the distance between the adjacent edges of the two electrodes.

At the end of each experiment the axon diameter was determined by microscopic observation. On the majority of occasions a binocular microscope with a magnification of 60 was employed. In certain cases these measurements were checked by observations with a $\frac{1}{8}$ in. water-immersion objective and an overall magnification of 800. On a number of occasions the axon diameter varied by as much as $\pm 20$ %, and this variation must be regarded as one of the principal sources of error. But no serious systematic error seems to have been introduced, since the results obtained on uniform axons were of the same general order as those obtained on irregular ones.

The membrane time constant $\tau_m$ was usually measured by analysing a photographic record of the potential obtained at the polarizing electrode ($V_A$). According to theory (Hodgkin & Rushton, 1946) the curve so obtained should have the form

$$(V_A)_t = (V_A)_{t=\infty} \operatorname{erf}[\sqrt{(t/\tau_m)}] \tag{8}$$

for the make of current, where $t$ is time.

Time constants obtained in this way are usually slightly longer than the true membrane time constant since the electrode is not infinitesimal as assumed by theory. A better method, which was used in one experiment, is to determine $\tau_m$ from the voltage ($V_B$) recorded at some distance from the

polarizing electrode. In this case the more complicated equation derived by Hodgkin & Rushton must be employed, viz.

$$(V_B)_{\substack{t \\ X}} = (V_B)_{\substack{t=\infty \\ X=0}} \tfrac{1}{2}\{e^{-X}\,[1-\mathrm{erf}\,(X/2\sqrt{T}-\sqrt{T})]-e^{X}\,[1-\mathrm{erf}\,(X/2\sqrt{T}+\sqrt{T})]\}, \tag{9}$$

where $X = l/\lambda,\ T = t/\tau_m$.

Equation (8) can be applied very simply to the experimental results. A check is first made to ensure that the rise of potential agrees reasonably with the theoretical curve. The time constant is then taken as the time when the potential rises to 0·843 of its final amplitude.

## RESULTS

The quantitative data obtained are summarized in Table 1. The measurements on which these results are based were obtained from experiments which were primarily directed towards another end. The data are therefore not as accurate as they might be and should eventually be replaced by more precise figures. But the results almost certainly give a correct order of magnitude for the physical constants in isolated *Carcinus* axons.

The average membrane resistance is about three times that found in the 70 $\mu$. axons of *Homarus* and about ten times greater than that in the squid axon. The high values of membrane resistance encountered in the present work suggests that the density or mobility of the ions in the surface membrane must be extraordinarily low. The thickness of the surface membrane in *Carcinus* axons is likely to be of the same order as that in the mammalian red cell, since the membrane capacities are similar. According to Waugh & Schmitt (1940) the thickness of the lipoid layer in the red cell envelope is about 100 A. A layer of sea water 100 A. thick would have a resistance of only $2 \times 10^{-5}\,\Omega.\,\mathrm{cm.}^2$ so that the product of ionic mobility and ionic density in an $8000\,\Omega.\,\mathrm{cm.}^2$ membrane must be about $\frac{1}{4} \times 10^{-8}$ of that in sea water. There is nothing to show whether the high resistance of the cell membrane is primarily due to a low ionic density or to a low ionic mobility. A plausible compromise is to suppose that both are depressed to an equal extent. In this case the area of membrane containing one ion can be shown to be about $(\frac{1}{18}\,\mu.)^2$. This calculation suggests that the membrane must be a formidable ionic barrier. It also indicates that calculations about ionic movements in the membrane must be based on rather different premises from those used in dealing with the bulk phase of a solution.

Table 1 shows that the ratio of internal to external resistances is about 1·58. The action potential recorded from *Carcinus* axons averages about 45 mV. (cf. Hodgkin, 1938) so that the membrane action potential would be $45\,\mathrm{mV.} \times (1+1{\cdot}58) = 116\,\mathrm{mV.}$ This figure is of the same order as Hodgkin & Rushton's (1946) estimate for *Homarus* axon and as the direct measurements of Curtis & Cole (1942) or Hodgkin & Huxley (1939, 1945) on *Loligo* axons.

TABLE 1. Electrical constants in *Carcinus* axons

| Axon diameter ($\mu$.) | $\lambda$ (mm.) | $\tau_m$ (msec.) | $r_2/r_1$ | $R_2$ ($\Omega$. cm.) | $R_4$ ($\Omega$. cm.$^2$) | $C_m$ ($\mu$F. cm.$^{-2}$) |
|---|---|---|---|---|---|---|
| 33·9 | 2·04 | 5·96 | 1·34 | 98·9 | 8490 | 0·702 |
| 35·6 | 2·82 | — | 1·52 | 88·4 | 13050 | — |
| (34·8 | 2·46 | 8·17 | 1·55 | 80·6 | 9190 | 0·889 |
| (34·8 | 2·28 | 8·73 | 1·47 | 84·7 | 8500 | 1·027 |
| (30·5 | 1·64 | — | 1·58 | 70·9 | 4080 | — |
| (30·5 | 1·35 | 4·60 | 1·15 | 67·1 | 3000 | 1·531 |
| [27·8 | 1·66 | 4·40 | 1·75 | 93·8 | 5830 | 0·754 |
| [27·8 | 0·89 | 4·15 | 1·59 | 109·3 | 2050 | 2·025 |
| (30·9 | 2·67 | 9·75 | 2·20 | 115·8 | 15600 | 0·625 |
| (30·9 | 1·68 | 8·60 | 1·75 | 111·5 | 6420 | 1·340 |
| 32·2 | 2·34 | — | 1·44 | 69·2 | 7970 | — |
| Average | | | | | | |
| 31·8 | 1·98 | 6·79 | 1·58 | 90·0 | 7653 | 1·112 |

Square brackets indicate that the two sets of measurements were made on the same nerve fibre; curved brackets that they were made on the same stretch of the same nerve fibre. An interval of several hours elapsed between the two sets of measurements. Data obtained over period April to August 1946. Temperature 15–18° C.

Another interesting conclusion can be drawn from Table 1. According to mathematical theories, such as those of Offner, Weinberg & Young (1940), the velocity of propagation should decrease by the factor $\sqrt{r_2/(r_1+r_2)}$ when the axon is removed from a large volume of sea water in which $r_2 \gg r_1$ and immersed in oil in which $r_2$ is comparable to $r_1$. The basis of Offner, Weinberg & Young's calculation may be regarded as speculative, but it can be shown that the square-root law is completely general and makes no assumptions about the membrane beyond the fact that it is capable of transmitting an impulse by local circuit action at constant velocity (unpublished calculations). In *Carcinus* axons the ratio (velocity in sea water/velocity in oil) was found to have a mean value of 1·27 and the standard deviation of the mean of sixteen observations was 0·018 (Hodgkin, 1939). Table 1 indicates that the quantity $\sqrt{(r_1+r_2)/r_2}$ has a mean of 1·28 and a standard deviation of the mean of 0·012 (eleven observations). There is therefore a close agreement between the quantitative predictions of the local circuit theory and the results of two quite different sets of observations. As Offner *et al.* (1940) have pointed out, Cole & Hodgkin's (1939) data are also in reasonable agreement with Hodgkin's (1939) measurement of the conduction velocity change in *Loligo* axons.

The individual values for the axoplasm resistivity must be regarded with some suspicion, since they were each based on a single measurement and not on a set of points (cf. Hodgkin & Rushton, 1946). The calculated values were also subject to the errors introduced by non-uniformity of axon diameter and by the assumption of infinitesimal electrode width. But the average result obtained is not very different from that found in other animal cells which are known to have a resistivity several times greater than that of the external medium.

Table 1 indicates that the membrane resistance decreased and the capacity increased when successive measurements were made on the same axon. The decrease in membrane resistance has been observed before (Cole & Hodgkin, 1939; Hodgkin & Rushton, 1946) and is probably due to some kind of progressive deterioration of the surface membrane. The increase in membrane capacity was not observed by Hodgkin & Rushton and cannot be regarded as established by the three experiments given in Table 1.

## PART 2

The values for membrane resistance shown in Table 1 were obtained with anodic currents with strengths of the order of 1–2 × threshold. The experiments to be described in this section were made in order to discover whether such currents had any disturbing influence upon the membrane resistance. In other words, their object was to find the range of current over which the nerve membrane obeys Ohm's law.

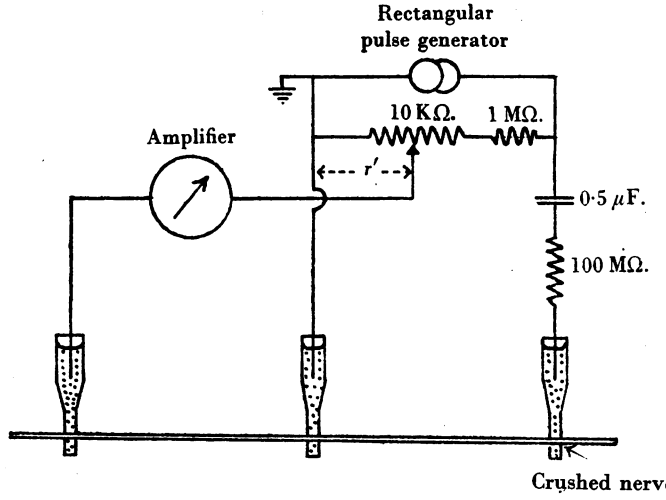


Fig. 2. Diagram of circuit used for measuring effect of current on membrane resistance.

The axon was arranged in the manner shown by Fig. 2, and rectangular waves of current with a duration of about 200 msec. were applied from the pulse generator. When the potentiometer slider was moved to the extreme left ($r'=0$) the potential recorded was that given by the sum of the membrane potential and the small potential resulting from the ohmic resistance of the electrode. The steady potential which was established after about 10 msec. could be neutralized by moving the potentiometer slider to the right. Balance was achieved when $R_4=k_1(k_2r'-\Delta)^2$. In this equation $\Delta$ is the electrode resistance, while $k_1$ and $k_2$ are factors which do not depend upon membrane resistance and so do not vary with current. It was therefore possible to study

the effect of current on membrane resistance by determining the balance position for different strengths of current. A typical experiment is illustrated by Fig. 3, in which relative membrane resistance is plotted against current. The results show that the membrane resistance was nearly constant over a wide range of anodic currents, but appeared to increase markedly when the current was cathodic and approached threshold. In this particular experiment there was also a small increase of resistance on the anodic side, but it is clear that any strength of current up to about three times threshold may be employed without introducing serious error.

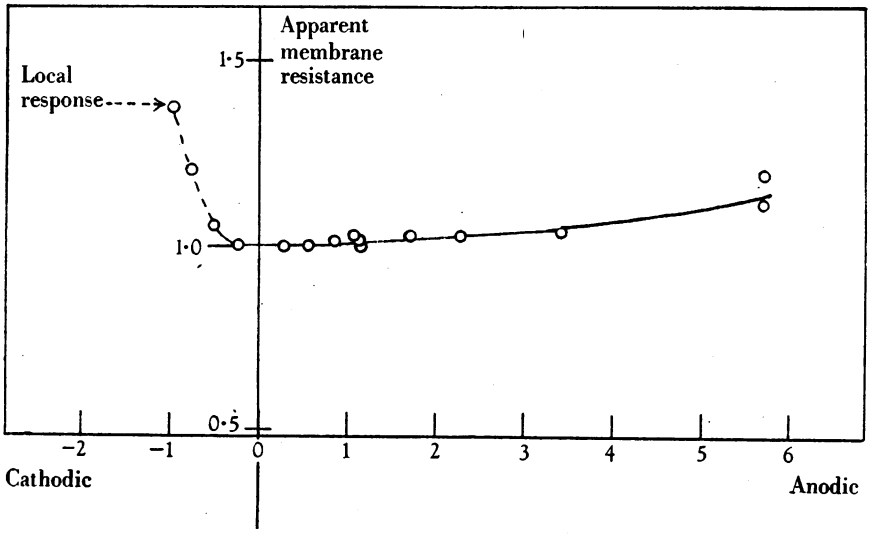


Fig. 3. Ordinate: apparent value of membrane resistance. 1 unit≒8000 Ω. cm.$^2$ Abscissa: current through axon in units such that −1 = threshold current (rheobase). 1 unit ≡1·30 × 10$^{-8}$ amp. through axon≡*c.* 1·14 × 10$^{-6}$ amp.cm.$^{-2}$ membrane current density under electrode.

The apparent increase of resistance on the cathodic side seems to conflict with Cole & Baker's (1941*a*) observation that the membrane resistance decreases under the cathode. The contradiction can be resolved in the following way. The increase in resistance observed with a just subthreshold current was definitely due to a local response. Instead of rising to a steady maximum the membrane potential showed a prolonged but definite hump (cf. Hodgkin & Rushton, 1946, fig. 15). The flat maximum of this hump was balanced in a bridge so giving the value of 1·4 shown in Fig. 3. At 0·5 threshold there was no definite hump and the potential appeared to rise to a steady maximum. But there was complete continuity between the two sets of curves, and it is not difficult to believe that a 0·5 threshold current evoked a very slight but sustained response which added to the passive electrotonic potential and appeared to increase the membrane resistance. Cole & Baker (1941*a*)

determined the membrane resistance change with transverse electrodes and alternating current of frequency about 5 kcyc./sec. Under these conditions a resistance decrease might be expected, since the steady e.m.f. changes associated with subthreshold activity would not affect the a.c. bridge measurements, and the only change observable would be the actual decrease in resistance associated with subthreshold activity.

Cole & Curtis (1941) studied the membrane voltage-current relation with direct current applied to impaled axons and again found a decrease in resistance when strong cathodic currents were employed. But this experiment was made under very different conditions from mine. In the first place the small size of the membrane action potential (< 50 mV.) and the extremely

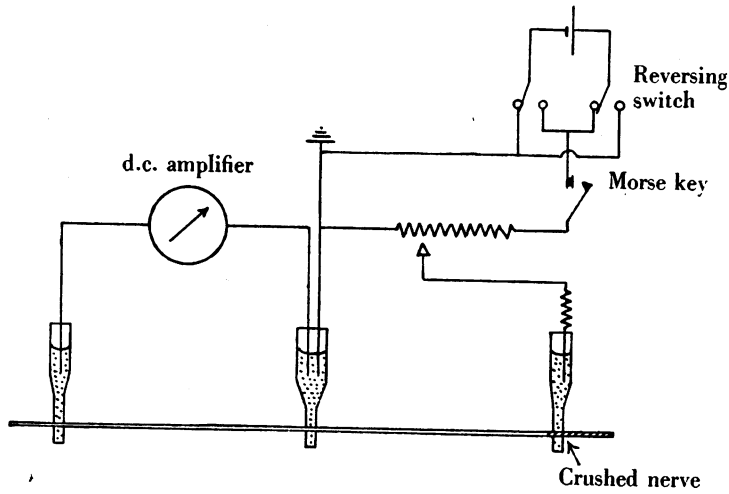


Fig. 4. Arrangement for determining current-voltage relation with currents of long duration. The electrodes are of the silver chloride-agar-wick type.

low membrane resistance (23 Ω. cm.$^2$) suggest that the measurements were made on nerve which had been depolarized by proximity to the point where the micro-needle punctured the axon. Furthermore, the actual membrane current densities used by Cole & Curtis were about 300 times greater than those employed in my experiments, so that no physical comparison of the two results can really be made. The effect observed by Cole & Curtis can be seen in *Carcinus* axons when the current is increased beyond the point at which impulses arise and is left on for a long time. In this case a prolonged discharge of impulses occurs, but the membrane potential eventually attains a steady level which bears the same kind of relation to current as that found by Cole & Curtis. This point is illustrated by an experiment in which the voltage-current relation was determined with a wide range of currents lasting several seconds. A double electrode was employed in order to remove any possibility of electrode

polarization, and electronic complications were avoided by using a simple circuit operated by a morse key (Fig. 4). The results are shown in Fig. 5; curve 1 indicates the steady voltage finally attained, while curve 2 shows the

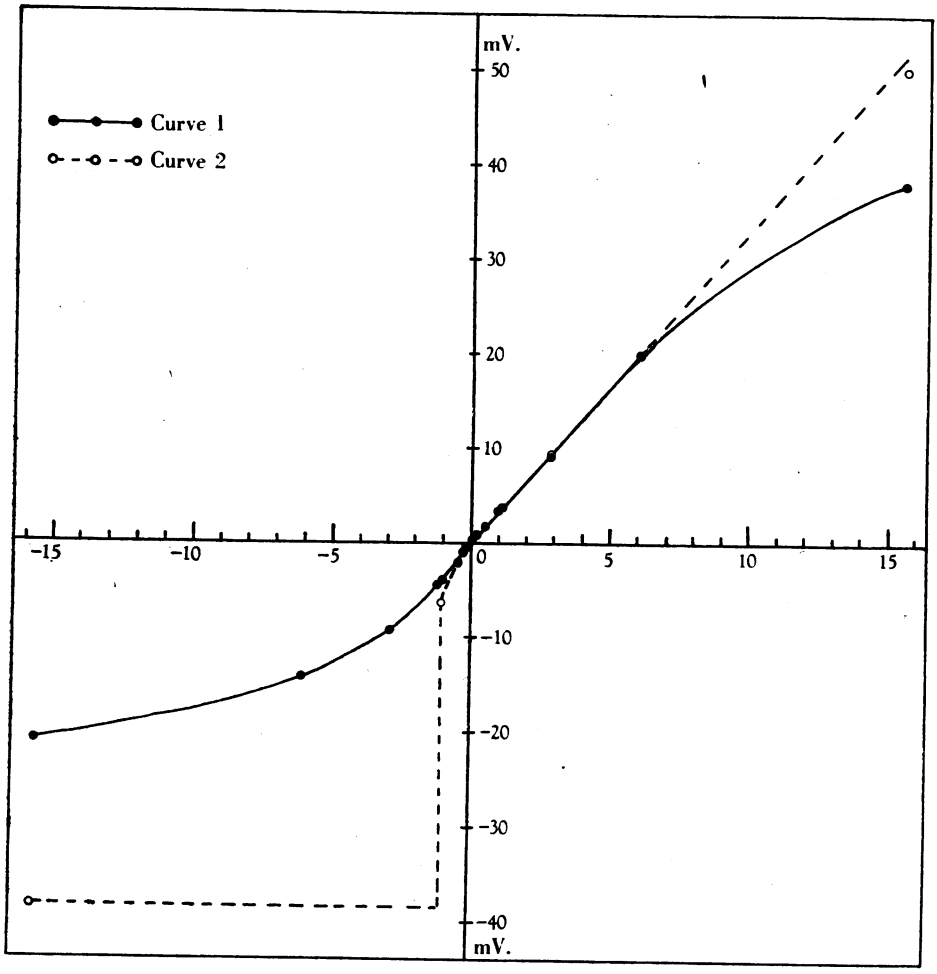


Fig. 5. Ordinate: change in potential produced by current. Curve 1 steady deflexion; curve 2 extreme deflexion. Abscissa: current through axon expressed in units such that $-1$ = threshold. 1 unit $\fallingdotseq 0{\cdot}866 \times 10^{-8}$ amp. $\fallingdotseq 1{\cdot}52 \times 10^{-6}$ amp.cm.$^{-2}$ membrane current density under electrode (rough estimate only).

extreme voltage evoked by each current. On the anodic side the nerve behaved in a relatively simple manner. The voltage was proportional to current over most of the range, and the potential time curves rose to their maximum without overshoot. The absence of overshoot is indicated by the coincidence of curves 1 and 2 and by the typical record of Fig. 6*d*. The slight increase

in resistance shown in Fig. 3 was either absent or not revealed by the relatively insensitive method of measurement. With a very strong anodic current, the potential was not maintained but declined from its original maximum. One way of explaining this effect would be to assume that the membrane was temporarily damaged by the large voltage across it. This hypothesis received support from the fact that anodic pulses of this magnitude were followed by a long burst of impulses (Fig. 6*e*). The results were more complicated when

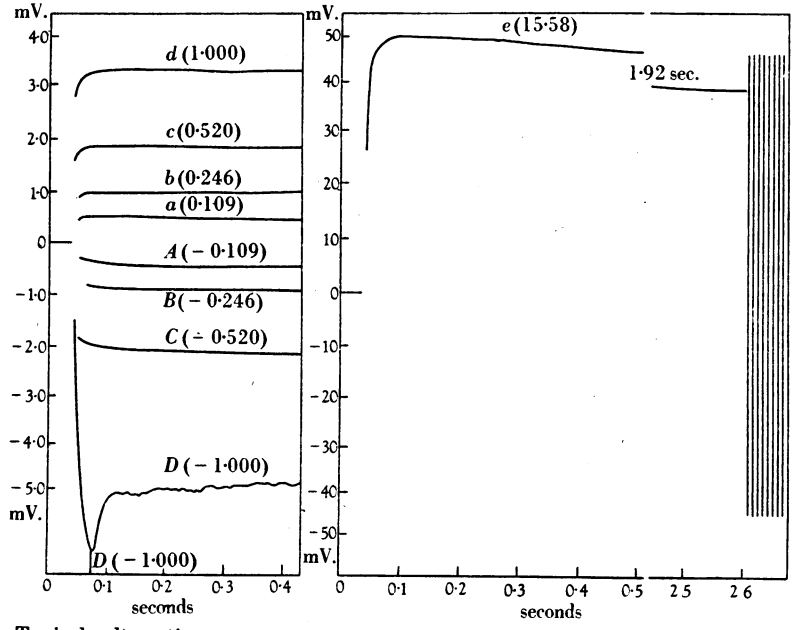


Fig. 6. Typical voltage-time curves used in plotting Fig. 5. Current strengths given in units such that $-1$ = threshold. In *e* the action potentials which follow the break of current are shown diagrammatically.

cathodic currents were employed. With very weak currents the voltage was proportional to current and no overshoot occurred. Just below threshold a prolonged local response was produced. Since this showed a definite hump the curves for extreme and steady potential diverged. The divergence was greatly accentuated at threshold because curve 1 then fell to the extreme level determined by the action potential while curve 2 started to bend in the opposite direction. Currents appreciably greater than threshold evoked a long train of impulses and a steady potential was not attained for several seconds. But the steady potential, which was eventually produced, followed the same general type of curve as that described by Cole & Curtis (1941). When the current was strong and cathodic the voltage-current gradient was clearly much less than that obtained with weak or anodic currents, and this effect may be interpreted as a decrease in membrane resistance.

Some of the voltage-time curves used in this experiment are shown in Fig. 6. In *a*, *b*, *c*, *d*, *A* and *B* the membrane behaved like a linear circuit element containing only resistance and capacity. In *C* there was no overshoot, but the slight difference between anodic and cathodic curves suggests the presence of subthreshold activity. *D* shows a 'humped' local response with a duration of about 50 msec. The fact that the cathodic potential exceeded the corresponding anodic potential throughout the entire period of current flow suggests that the axon was maintained in a state of subthreshold activity after the end of the humped local response.

The complicated effects shown in Figs. 3, 5 and 6 are not claimed to be a fundamental property of all excitable membranes. Nor is it certain that they represent the behaviour of *Carcinus* axons over a wide range of experimental conditions. But one quite definite fact emerges from experiments of this type. Namely, that accurate measurements of membrane resistance in *Carcinus* can only be obtained when the current is anodic or less than about one-third threshold. This fact was not clearly recognized in the past, and neglect of it may have introduced occasional errors. Cole & Hodgkin (1939) used both cathodic and anodic currents in their determination of the resistance-length curve in squid axons. But the strength of current employed was only one-tenth threshold and should therefore have given satisfactory results. Hodgkin & Rushton (1946) used cathodic currents of strength 0·4 to 0·5 threshold so that some of their results may have been complicated by traces of local activity. But the errors introduced in this way could not have been large, since the determination of $\lambda$ was based on measurements which extended far into the extrapolar region where the membrane current was much less than one-third threshold. In the present work cathodic currents were never employed and the anodic currents used were too weak to have any appreciable effect on the membrane resistance.

## SUMMARY

1. The electrical constants of isolated axons from *Carcinus maenas* were measured with pulses of direct current and longitudinal electrodes.

2. The electrical resistance of the nerve membrane varied between 2000 and 16,000 $\Omega$. cm.$^2$ in excitable axons and had an average value of about 8000 $\Omega$. cm.$^2$

3. The average capacity of the surface membrane was 1·1 $\mu$F. cm.$^{-2}$

4. The specific resistance of the axoplasm was found to be about 90 $\Omega$. cm. (4 times sea water).

5. The ratio of internal to external resistance per unit length was approximately 1·6.

6. The nerve membrane was found to obey Ohm's law over a wide range of anodic currents, but showed marked deviations with relatively weak cathodic currents.

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