THE ELECTRICAL FIELD WHICH A TRANSMITTING NERVE FIBER PRODUCES IN THE FLUID MEDIUM

by

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Action currents of the myelinated nerve fiber have been shown to leave and enter the fiber mainly through the nodes of Ranvier (TASAKI AND TAKEUCHI[1, 2]). It is therefore expected that, if one lead the electric responses of an excised single nerve fiber with a micro-electrode, the magnitude of the response would show a maximum at each node of Ranvier of the fiber. A rough estimation of its magnitude indicates, however, that under ordinary experimental conditions the observed potential should be approximately equal to the noise level of the amplifier.

It is well known that a source of current in a volume conductor produces an electrical field described by the formula $V = is/4\pi R$, where V is the potential at the distance R from the source of the current i, and s the specific resistance of the fluid conductor. In the large motor nerve fiber of the toad or the frog, the current from an individual node of Ranvier is of the order of 10^{-9} ampere and the specific resistance of Ringer's fluid is approximately 10^2 ohm·cm. Introducing these values into the equation above, one finds that in the immediate neighbourhood of a node ($R = 10^{-3}$ cm) the observed potential should be approximately 10^{-5} volt.

A very practical way of increasing the magnitude of the observed potential is to lay the fiber in a thin layer of Ringer on a glass plate. Under such circumstances, the potential V at the distance R from the source of the strength i is given by the formula

$$V = \frac{-is}{2\pi d} \log R + \text{constant},$$

where d denotes the thickness of the conducting layer. If the thickness is reduced to below 0.1 mm, therefore, potentials of appreciable magnitudes are expected to appear in the space around a node of Ranvier.

The purpose of this paper is to present the results of experiments done to test these predictions. The effect of leakage of the action current through the myelin sheath upon the electrical field about a travelling impulse is discussed in this connection.

METHOD

All the experiments described in this paper were carried out on the large motor

References p. 342.

nerve fiber innervating the gastrocnemius muscle of the toad (TASAKI[3]). In most cases, fibers with relatively long, regular internodal intervals were selected for the experiment.

The single fiber preparation was first floated in a large amount of Ringer's fluid in a Petri dish. Beneath the operated region of the preparation was introduced a thick glass plate (6 × 12 mm² and 5 mm high), and then paraffin oil was poured into the dish. Next, the Ringer's fluid under the layer of paraffin oil was withdrawn with a pipette until the level of the Ringer in the dish became lower than the surface of the glass platform. By this procedure, it was easy to reduce the thickness of the layer of Ringer on the glass platform to below 100 microns.

The micro-electrode consisted of a steel needle sharpened to a point of about 5 microns in diameter. As only the tip of the electrode was brought into contact with the conducting medium, insulation of the body of the needle was not necessary. The needle was held at an angle and was brought towards the fiber by means of a micro-manipulator. When the tip of the needle crossed the oil-Ringer interface, deformation of the boundary could be observed very clearly under a low power microscope. The micro-electrode was led to the input of the amplifier and the mass of Ringer's fluid in the dish was grounded.

With the proximal nerve trunk of the preparation placed on the glass platform, action potentials from the nerve trunk were found to be so large as to be disturbing. Therefore, care was taken to keep the unoperated portion of the nerve proximal to the operated region in the large pool of Ringer around the platform.

In the early stage of this investigation, the fluid in the dish consisted of one part of normal Ringer mixed with two to three parts of a 8 per cent cane-sugar solution. It has been shown by YAMAGIWA[4] that an isotonic sugar solution augments the action potential from a single nerve fiber, and we have seen that this is actually due to an increase of electric resistance of the medium through which the current developed by the fiber flows (unpublished). But, all the records reproduced in this paper were obtained from fibers kept in normal Ringer.

RESULTS

When the sheet of the fluid on the glass platform became sufficiently thin, it was always possible to record distinct action potentials with the micro-electrode dipped in the fluid around the nerve fiber. The fiber under observation was brought into action by induction shocks sent into the proximal portion of the preparation. When the micro-electrode was brought close to one of the nodes of Ranvier of the fiber, the amplitude of the observed action potential showed in all cases a distinct maximum; there was no exception to this rule.

The configuration of the observed action potential was always diphasic, the needle electrode being positive to the ground electrode in the first phase. With the micro-electrode kept in the immediate neighbourhood of a node of Ranvier of the fiber, the start of the second, negative phase was found to be particularly sharp.

Records furnished in Fig. 1 were obtained from a nerve fiber with relatively long internodal intervals (longer than 2 mm). Only one node of Ranvier was exposed in the middle of the operated region, and this region was laid, together with the distal unoperated portion of the nerve, on the glass platform. Records of action potentials were taken at a number of points around the node. Nerve impulses were elicited by induction

References p. 342.

shocks of 110 per cent of the threshold strength applied at a point 45 mm from the operated region.

As can be seen in the figure, the action potential led directly from the node is characterized by its large, but short, downward deflection in the second phase. At the node, the second downward deflection was always larger than the first upward deflection, the former corresponding to 120 to 200 per cent of the latter. This sharp second deflection

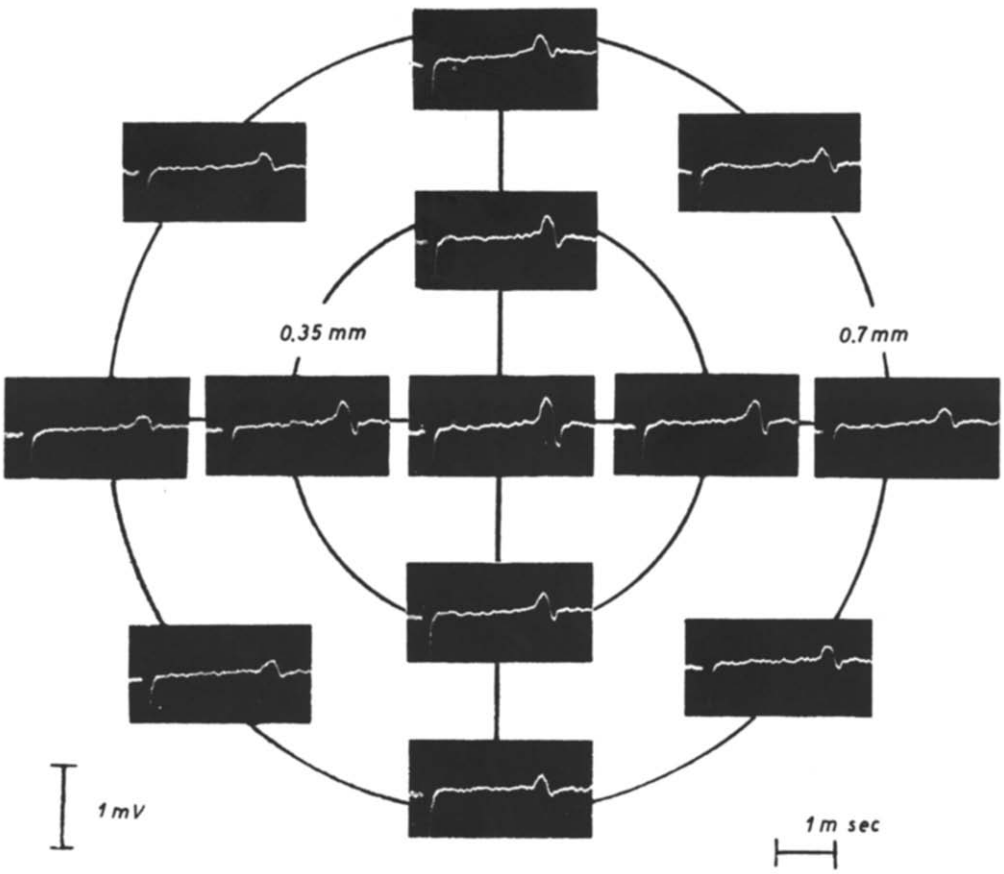

Fig. 1. Records of action potentials taken with a microelectrode placed at various positions around a node of Ranvier. The vertical line represents the nerve fiber and the center of the two concentric circles the node of Ranvier. The impulse is travelling downwards. Five records on the vertical line were taken with the needle electrode along the fiber and slightly to one side. Other nodes of Ranvier of the fiber were not exposed in the operated region of the preparation. The ground electrode was placed at a large distance away from the fiber. The conduction distance was about 45 mm, and the room temperature was 20° C.

reduced its magnitude very rapidly as the micro-electrode was moved away from the node, either along or sidewise from the fiber. The magnitude of the first deflection was also found to decrease as the distance from the node; but the change in this positive phase of the action potential was less marked than that in the second, negative phase.

In preparations with several nodes of Ranvier exposed in the operated region of the preparation, the decrease in the amplitude of the observed action potential as the

References p. 342.

distance from a node was in general less marked than in the example of Fig. 1. At the point half-way between two neighbouring nodes (along the fiber and slightly to on one side), the action potential had a slow, slightly diphasic configuration, its amplitude being generally smaller than a half of that recorded at the node (see the upper record in Fig. 2, right).

When an accurate measurement of the time interval from the induction shock to the appearance of the action potential was desired, we always employed shock strengths of double the threshold. Records in Fig. 2 were obtained from a preparation with 3 nodes of Ranvier exposed in the operated region. In order to make it easy to compare the conduction times for the responses taken from these three nodes, two micro-electrodes were used, one being held close to one node and the other electrode to another node. A record was first taken of the potential difference between the ground electrode and one

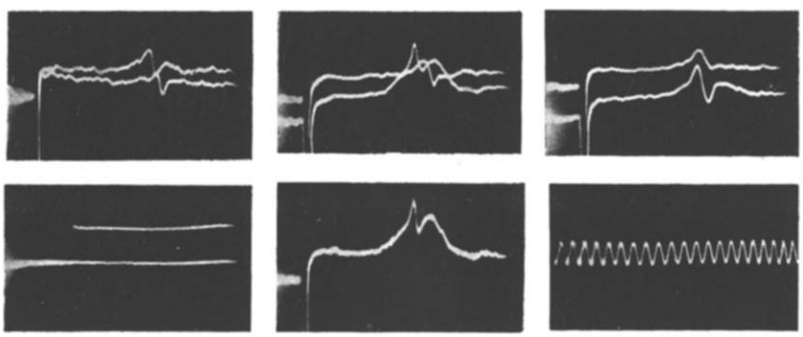

Fig. 2. Action potentials taken with micro-electrodes at three different nodes of Ranvier of a nerve fiber. The record on the left was taken with one micro-electrode E_1 placed close to the middle node N_1 and the other micro-electrode E_2 near the distal node N_2. Two successive sweeps of the electron beam were photographed on the same film. The ground electrode was placed away from the fiber. The upper record in the middle column was taken with E_1 fixed close to the proximal node N_0 and E_2 near the distal node N_2. Below is shown a record obtained by superimposition of two figures on the screen of the Braun tube in two successive sweeps; potentials were led with one needle electrode placed close to N_0; the base line was distorted by the action potential from the nerve trunk. The upper curve in the record on the right was taken with E_1 placed at a point half-way between N_1 and N_2 and E_2 close to N_1. The conduction distance was 45 mm, the rectangular pulse 0.4 mV, time marker 5000 per sec, temperature 20° C.

of the micro-electrodes, and then, switching the amplifier input from that needle electrode over to the other, another action potential record was taken on the same photographic film.

It was demonstrated by this method that there is, as is expected, a difference of the order of 0.1 msec. in the conduction times determined at two neighbouring nodes. The lower photograph in the middle column of Fig. 2 was obtained by superimposing two action potential records from one and the same node in two successive sweeps. As the micro-electrode was placed on the proximal node N_0 and the shock strength was well above the threshold, the action potential arising from the proximal nerve trunk distorted the base line appreciably. But, the perfect congruity of the two records indicates undoubtedly that our method of comparing the conduction times by superimposition of two records works very satisfactorily.

At a point half-way between two neighbouring nodes, the observed action potential showed a very slow configuration (see Fig. 2, right). It was therefore slightly difficult

References p. 342.

to compare the shock-response interval for such a record with that for a record taken at a node. It seemed, however, safe to conclude that, so far as the first, positive phase of the action potential is concerned, the record taken at a point half-way between two neighbouring nodes N_1 and N_2 shows approximately the same conduction time as that taken at the proximal node N_1.

INTERPRETATION OF THE RESULTS

Physiological bases for interpreting the action potential records obtained with a micro-electrode are furnished by an observation reported previously by TASAKI AND TAKEUCHI[1] (Fig. 8). It was demonstrated by the method of the bridge-insulator that, when an impulse travels along a nerve fiber, nodes of Ranvier of the fiber are traversed by a current having a diphasic configuration. In Fig. 3 are reproduced action current records obtained by the old method.

In the diagram of Fig. 3, the arrow in the circle labelled G_1 shows a current recording system, an amplifier with low input resistance in conjunction with a Braun tube, connected between the node of Ranvier N_0 and N_1. When the action current of the fiber was to be recorded with G_1, the proximal electrode (the one on the right in the figure) was grounded. The current which traverses the node N_1 in the middle could be recorded with the galvanometer G_2; in that case the middle electrode was led to the input of the amplifier. In obtaining the records reproduced in Fig. 3, a photograph was taken at one position of the amplifier and then the input of the amplifier was switched over to another position and another photograph was taken on the same film.

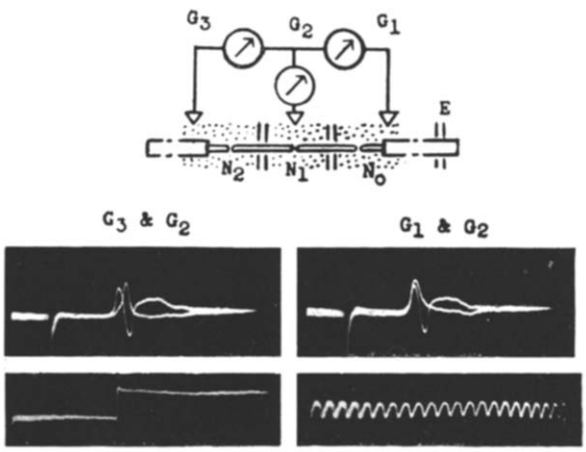

Fig. 3. Left: A record of action current of a nerve fiber taken with the current recording system G_3 superposed on another record taken with G_2. Right: Records taken with G_1 and with G_2. The conduction distance was 27 mm. The width of the middle pool was 1.5 mm, and the length of the desiccated regions was 0.2 mm. Temperature, 24° C; calibration, 2×10^{-9} ampere; time, 5000/sec. Note that addition of the curve recorded with G_2 to that recorded with G_3 gives, as is expected, a curve having the same configuration as the record taken with G_1.

As has been fully discussed in the previous paper, the diphasic action current recorded with G_2 is caused by transmission of an impulse across the node N_1. When the node N_0 is brought into action by an impulse arriving at this node, the node N_1 begins to be traversed by a very strong outwardly directed current. Then, when N_1 is also thrown into action by this current, the current between N_0 and N_1 ceases immediately, but the current flowing now between N_1 and N_2 passes through N_1 in the opposite direction. This inwardly directed current ceases at the moment when the distal node N_2 is further brought into action.

The simplest explanation of the action potential records obtained with a micro-

References p. 342.

electrode is bases on the consideration of the nervous transmission figured out above. If we assume the myelin sheath to be a perfect insulator, the electric field produced by a nerve fiber carrying an impulse can roughly be represented by that generated by a source and a sink of equal strength located at a distance of about 2 mm. As the impulse proceeds along the fiber, the position of the source and sink must be considered to shift at the rate of an internodal distance per internodal conduction time.

If such a source and a sink are placed in a sheet of conducting medium, it is clear that the potential V at the distance R_1 and R_2 respectively from the source and the sink is given by the formula

$$V = \frac{is}{2\pi d} \log \frac{R_2}{R_1}.$$

It is therefore expected that the potential at any point in the field varies step by step as the impulse is conveyed from one node to the next. At the point half-way between two neighbouring nodes, the temporal change in the relative magnitude of potential is expected to be expressed by the following series:

$$\ldots, \log \frac{7}{5}, \log \frac{5}{3}, \log \frac{3}{1}, \log \frac{1}{1}, \log \frac{1}{3}, \log \frac{3}{5}, \log \frac{5}{7}, \ldots$$

This indicates that, as the impulse approaches the site of the micro-electrode, the observed potential should increase gradually and then change to negative values when the impulse passes beyond the region of the lead electrode.

In an entirely analogous manner, the potential at the immediate neighbourhood of a node is inferred to change its magnitude according to the series

$$\ldots, \log \frac{3}{2}, \log \frac{2}{1}, \log \frac{100}{1}, \log \frac{1}{100}, \log \frac{1}{2}, \log \frac{2}{3}, \log \frac{3}{4}, \ldots$$

At the moment when the impulse passes across the node under consideration, the ratio R_2/R_1 is considered to rise at once up to about 100 and then fall immediately to about 1/100. The shift of the position of the source and the sink is considered to be discontinuous, or „saltatory"; but the change in the amplitude of the action potential is smoothed by the capacitive property of the myelin sheath.

It is evident that the very simple consideration stated above serves to roughly explain the experimental results described in the preceding section. In the experiment in which the micro-electrode is moved around a node of Ranvier (as in the case of Fig. 1), the amplitude of the action potential is considered to vary as the logarithm of R/c, R being the distance between the micro-electrode and the node and c the internodal distance; this agrees roughly with the observed data. At the point half-way between two neighbouring nodes, the action potential is expected to show a slow, diphasic configuration; and this is also consistent with the actual observation.

The main fault of the simple explanation stated above lies in its failure to interpret the difference in the configuration of action potential in its positive and negative phases. As can be seen in all the records in Figs. 1 and 2, the first, positive phase of the action potential is longer in duration and smaller in amplitude than the second, negative phase. And this fact is considered to be fully accounted for if we take the leakage of the action current through the myelin sheath into consideration.

References p. 342.

TASAKI AND TAKEUCHI[2] have previously recorded the currents which traverse the myelinated portion of a nerve fiber when an impulse travels along the fiber. In Fig. 4 are reproduced a couple of records obtained by the method described previously. The fact that the current led through the myelin sheath is directed outwards has been interpreted as indicating that there is, during transmission, no change in the electro-motive force in the surface layer of the axis-cylinder covered with the myelin sheath.

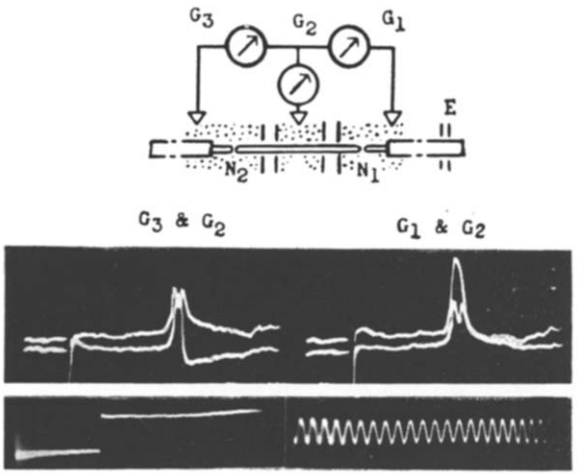

Fig. 4. Left: Records taken with G_3 and with G_2. Right: Records taken with G_1 and G_2. The portion of the nerve fiber in the middle pool was 1.1 mm. The conduction distance was 45 mm, the desiccated regions were 0.15 mm in length, the distance between N_1 and N_2 was 2.05 mm, 21° C. Calibration, 2×10^{-9} ampere; time, 5000/sec.

When the nerve fiber is floating in the fluid medium, the portion of the myelin sheath traversed by an outwardly directed current behaves like a linearly distributed source in the medium. As the amount of current leaving the fiber at any moment must be equal to the amount entering the fiber at that moment (because there is no source of any sign in the medium), it follows that the current entering the node acting as the punctiform sink in the above-stated consideration is stronger than that leaving the node acting as the point-source. It is thus very reasonable that at the immediate neighbourhood of a node the observed action potential has a greater amplitude in the negative phase than in the positive phase.

Judging from the duration of the current flowing through the myelin sheath, it is clear that the sink in the fluid medium is surrounded by the linearly distributed source stated above, while the point-source travels ahead of the line-source. This brings about an asymmetry in the field of potential in the medium, and this asymmetry is considered to be such as to serve to curtail the negative phase of the action potential.

DISCUSSION

Quite recently, HUXLEY AND STÄMPFLI (1948) published a clear demonstration of the saltatory character of the nervous transmission in the myelinated nerve fiber. The experimental conditions under which they recorded the action current of a single nerve fiber are considered to be similar to those of the experiment of Fig. 4 in this paper. They have further demonstrated by shifting the position of the insulated region of the nerve fiber further that the size of the electric response increases periodically as a node of Ranvier crosses the insulator. This finding is undoubtedly to be interpreted as due to the leakage of the action current through the myelin sheath (see the difference in the action current records taken with G_1 and G_3 in Fig. 4).

According to a recent edition of HOWELL'S text-book of physiology, LORENTE DE NÓ

References p. 342.

carried out a thorough investigation on the electrical field produced by a whole nerve carrying a volley of impulse. As the field of potential set up by a whole nerve is considered to be given by summation of potentials arising from impulses in individual fibers, it should be possible to reconstruct equipotential contours of a nerve volley from the data obtained with single fibers. In doing so, however, we have to take the weak, long components of the action current into consideration, which have been neglected in the explanation of the field of a small dimension.

SUMMARY

The electrical field produced by a nerve fiber carrying an impulse in a thin layer of Ringer was determined with a steel micro-electrode placed at various points in the field. It was observed that, as the electrode approaches a node of Ranvier of the fiber, the observed action potential reaches a maximum. The action potential recorded with the micro-electrode placed close to a node was diphasic, the second, negative phase being greater in amplitude and shorter in duration than the first, positive phase. Between two neighbouring nodes the observed action potential showed a slow diphasic configuration. All these experimental results were interpreted in terms of distribution of source and sink of electric current along the fiber.

RÉSUMÉ

Nous avons déterminé le champ électrique produit par une fibre nerveuse portant un influx dans une couche mince de Ringer à l'aide d'une micro-électrode placée en divers points du champ. Nous avons pu constater que le potentiel d'action atteint un maximum lorsque l'électrode s'approche d'un nœud de Ranvier de la fibre. Le potentiel d'action enregistré avec la micro-électrode placée près d'un nœud était diphasique, la seconde phase, qui est négative, montrant une amplitude plus grande et une durée plus courte que la première phase qui, elle, est positive. Entre deux nœuds voisins le potentiel d'action observé consistait en deux phases lentes. Nous avons interprété tous ces resultats en termes d'une source et d'une perte de courant électrique se propageant le long de la fibre.

ZUSAMMENFASSUNG

Das elektrische Feld, das eine Nervenfaser, welche eine Erregung erhalten hat, in einer dünnen Schichte Ringerlösung hervorruft, wurde mit Hilfe einer Mikroelektrode aus Stahl bestimmt, die an verschiedene Stellen des Feldes gesetzt wurde. Wenn die Elektrode sich einem Ranvier-Knoten der Nervenfaser nähert, so beobachtet man, dass das Aktionspotential ein Maximum erreicht. Das mit der Mikroelektrode in der Nähe eines Knotens aufgenommene Aktionspotential zeigte zwei Phasen, wovon die zweite, negative eine grössere Amplitude und kürzere Dauer hatte als die erste, positive. Zwischen zwei benachbarten Knoten hatte das Aktionspotential eine langsame Zweiphasen-Konfiguration. All diese Versuchsergebnisse wurden unter Zugrundelegung der Verteilung einer elektrischen Stromquelle und einer Stromsenke entlang der Nervenfaser interpretiert.

REFERENCES

[1] I. TASAKI AND T. TAKEUCHI, *Pflüger's Arch.*, 244 (1941) 696.
[2] I. TASAKI AND T. TAKEUCHI, *Pflüger's Arch.*, 245 (1942) 464.
[3] I. TASAKI, *Am. J. Physiol.*, 125 (1939) 367.
[4] K. YAMAGIWA, *J. Physiol.*, 84 (1935) 83.
[5] A. F. HUXLEY AND R. STÄMPFLI, *Helv. Physiol. Acta*, 6 (1948) C22.
[6] R. LORENTE DE NÓ, in *Howell's Textbook of Physiology*, edited (1946) by J. F. FULTON, p. 16.

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