

**THE ALL-OR-NOTHING RESPONSE OF SENSORY  
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I. THE RELATIONS BETWEEN STIMULUS AND IMPULSE  
IN SENSORY NERVE FIBRES.

IN the motor nerve fibres of the frog's sciatic the disturbance which constitutes the impulse appears to obey the all-or-nothing rule. The size or intensity of the disturbance at any point does not depend on the strength of the stimulus which has given rise to it, or on the state of the fibre through which it has passed, but only on the local conditions at the point at which it is measured. If these remain constant, the intensity of the disturbance is invariable provided that it occurs at all, and any gradation in the response of the effector organ is brought about by gradation in the number of nerve fibres in action or in the frequency of the impulses in them. The proof of this statement is derived from several converging lines of evidence(1), but hitherto this evidence has related almost exclusively to the motor nerve fibres of the frog. The present research was undertaken to find out whether the all-or-nothing relation

holds good for afferent fibres as well as for efferent, and incidentally to investigate the relation in mammalian nerves, since it is in mammalian preparations that the most interesting questions in this connection have arisen.

The extreme range of gradation of certain sensations and certain reflex responses makes it difficult, at first sight, to believe that sensory fibres do not differ from motor fibres in possessing some means of varying their response apart from changes in frequency. It is unlikely that the conduction processes can differ radically in the two kinds of nerve fibre, but although the all-or-nothing reaction is the normal reaction of the motor fibre, yet it is not the only reaction of which the fibre is capable, and under artificial conditions it is easily brought into a state in which the intensity of the impulse is variable. It seemed possible to us that this state of affairs might be the normal condition of the sensory nerve fibre. The state referred to is that in which conduction takes place with a decrement, so that the impulse becomes smaller and smaller, or less and less able to travel, as it passes along; it can be produced in the frog's sciatic by treatment with narcotics, lack of oxygen, deprivation of ions in the perfusing fluid, etc. When the fibre conducts in this way, the size of the impulse at a given point does not depend on local conditions only, since it will be greater or smaller according as the impulse has travelled a short or a long distance in the affected region. This gradual dying out of the impulse seems to occur normally in certain rudimentary types of conducting tissue, *e.g.* the nerve net of the sea anemone<sup>(2)</sup>, the pseudopodia of *Diffugia*<sup>(3)</sup>, etc. In the vertebrate motor nerve fibre the mechanism of conduction has become more efficient and the impulse is normally conducted without any change in size, although adverse conditions cause a reversion to the less perfect form of reaction. It is therefore quite possible that conduction with a decrement may be a normal event in fibres which are sensory and not motor in function, and if so we need not reckon with the all-or-nothing reaction in explaining the gradation of reflex activity.

But although decremental conduction means that the size of the impulse depends on the distance it has travelled, it does not follow that it depends also on the strength of the stimulus which sets it up, for the setting up of an impulse may involve different processes from those concerned in its propagation from one section to the next. In the primitive nerve network, however, the size of the impulse does appear to vary with the stimulus, and there is evidence that medullated nerve fibres react in the same way when a decrement is produced artificially.

If this evidence can be accepted it is clear that we have a possible explanation of grading in the sensory nerve fibres.

As the experiments bearing on this point did not seem to us altogether conclusive we have tried to determine how far the size of the impulse can be made to vary with that of the stimulus in a fibre which conducts with a decrement, and we have then examined various mammalian nerve trunks and reflex preparations to see how far this will account for the grading in a reflex arc.

*Response to stimuli in a region of decrement.* It has been shown in the frog's nerve-muscle preparation that when an impulse set up on the proximal side of a narcotised region fails to reach the muscle, it fails for all strengths of stimulus, *i.e.* an increase in the stimulus does not increase the capacity of the impulse to pass through the region of decrement. Thus the size of impulse which can be set up in a normal nerve is independent of the strength of stimulus. But Lodholtz(4) and Rehorn(5) have shown that if the stimuli are applied within the decremental region there is a stage of narcosis in which the strength of stimulus required to set up an impulse which will pass to the muscle is greater and greater the longer the distance which the impulse must travel in the region. Since the local excitability must be the same throughout, it appears to follow that the impulse set up by a weak stimulus can only travel a short distance without extinction, whereas that set up by a strong stimulus can travel further. Thus if an impulse is set up in a region of decrement the initial size seems to depend on the strength of the stimulus. Whether this conclusion is valid or not depends on whether the stronger stimuli are accurately localised. A strong stimulus might succeed where a weak one fails, because it could spread down the nerve and start the impulse from a point nearer the muscle. As the evidence on this point did not seem to be conclusive, we have repeated the experiment, with certain modifications, taking special precautions against current spread.

The frog's sciatic gastrocnemius preparation was set up in a chamber shown diagrammatically in Fig. 1, so that the nerve passed through three chambers 9.5 mm. in diameter, through which an alcohol solution could be passed. The nerve could be stimulated at the slots *A* or *B* by sending a current through the fluid from one chamber to the next; in the later experiments a third partition at *A'* gave a third point of stimulation. With electrodes of this form the danger of current spread is very slight. The stimuli used were single break shocks from a coreless induction coil. The primary circuit could be made or broken by the

release of a spring key in which an amalgamated copper point dipped into a pool of mercury, or by the opening of one of the knock-down keys of a Lucas pendulum. The strength of stimulus was controlled by varying the resistance in the primary circuit, the coil distance remaining fixed, and the stimulus is said to be of unit strength when the resistance in the primary is 500 ohms, 10 units when the resistance is 50 ohms, etc.

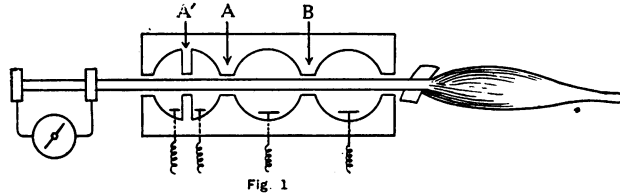


Fig. 1

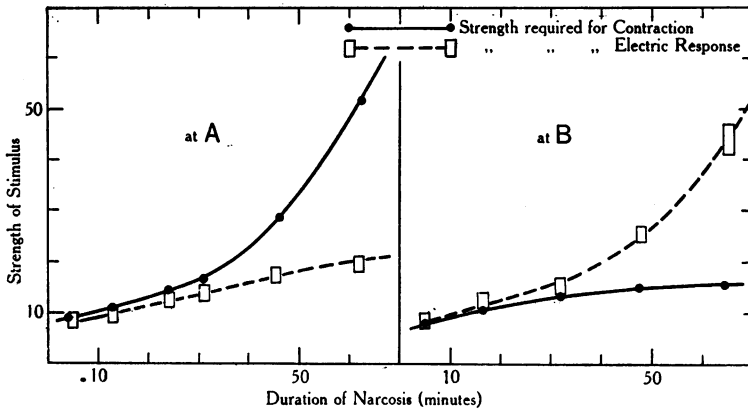


Fig. 2

Fig. 1. Arrangement of narcotising chamber.

Fig. 2. Strength of stimulus required at different stages of narcosis.

The distal end of the nerve was left in connection with the muscle and the arrival of an impulse at this end was shown by the muscular contraction. The proximal end lay on two non-polarisable electrodes connected with a string galvanometer, so that the arrival of the impulse at this end could be detected by a movement of the string. This was sometimes determined by observing its magnified image, but in all significant observations during narcosis photographic records were taken on cinematograph film. As the monophasic response causes a more visible excursion of the string than the diphasic, the nerve was crushed in the neighbourhood of the proximal lead.

When the stimulus is at *A* the impulse will have to pass through

10 mm. of narcotised nerve before reaching the galvanometer leads, and through 20 mm. before reaching the muscle. When the stimulus is at *B* these distances will be reversed. Six experiments on different preparations were made, and each showed a stage during narcosis in which a weak stimulus at *A* caused an electric response but not muscle contraction, and a weak stimulus at *B* caused a contraction but not an electric response, whereas a strong stimulus at *A* or *B* caused both electric response and contraction. Thus a stronger stimulus was required to make the impulse travel 20 mm. than to make it travel 10 mm.; in other words the distance travelled by the impulse varies with the strength of the stimulus. The results of a typical experiment are shown in Fig. 2. It will be seen that after 70 minutes perfusion with alcohol a much stronger stimulus was needed when the impulse had to pass 20 mm. of narcotised nerve and this increase applies to impulses travelling in either direction.

It remains to consider whether the effects of the stronger current are due to its spreading out and setting up an impulse at a distant point. Tests with a nerve damaged by crushing locally showed that a hundred-fold increase of current was needed to make the stimulus spread from one slot to the next. Now in two experiments the nerve was stimulated at *A'* as well as at *A* and *B* (Fig. 1). In one of these a stage was reached at which the strength needed to give a contraction was 81 units at *A'*, and 54 at *A*, whilst that for an electric response was only 2.5 units at either point. If these differences are due to current spread we must suppose that the stimuli from *A'* and *A* both spread down the nerve to the same point (since both are just adequate). But they cannot do this unless the stimulus at *A'* is 100 times as large as that at *A*, whereas in reality it is only 1.5 times as large. The other experiment gave a similar result.

We may conclude that the strong currents are effective, not because they spread down the nerve, but because they set up larger impulses, and there is therefore no doubt that in the late stages of narcosis the size of the impulse varies with the strength of the stimulus which gives rise to it. This conclusion confirms that of Lodholtz and of Rehorn.

*The amount of grading in different stages of narcosis.* In the preceding section we have only considered the later stages of narcosis where the decrement in unit length is large. On theoretical grounds it might appear that the degree of decrement should make no difference to the relation between stimulus and initial size of impulse, since the slightest decrement implies that the nerve no longer reacts on the all-or-nothing principle.

There is, however, abundant evidence that wide variations in the initial size of the impulse cannot be produced by altering the strength of the stimulus unless the degree of narcosis is considerable. Thus Lucas found that the threshold stimulus in a lightly narcotised area of the frog's sciatic was the same throughout the area (6), although there was no doubt that the nerve was conducting with a decrement. The same point is shown in Fig. 2 where the thresholds rise equally for the first 30 minutes of the narcosis. During this period there was no doubt that the nerve was conducting with a decrement, for it was found that a small impulse set up during the relative refractory phase was able to pass through 10 mm. of the affected nerve but not through 20 mm.

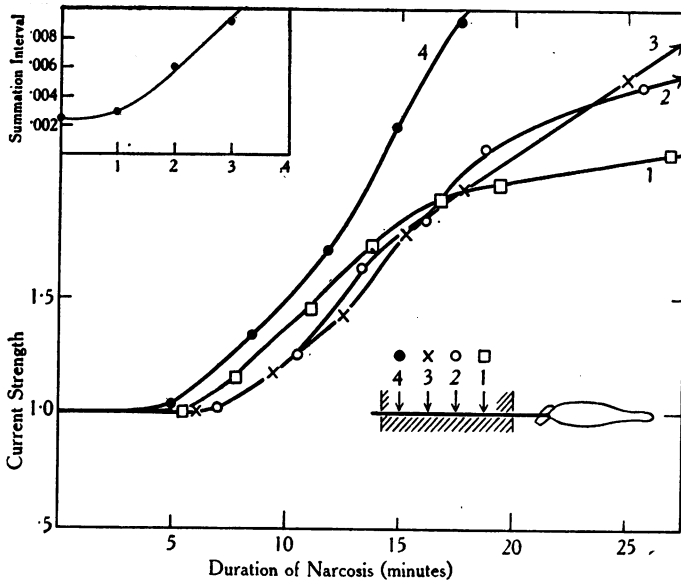


Fig. 3. Rise of threshold during early stages of narcosis.

The progress of events in the earlier stages of narcosis is shown more clearly in Fig. 3, which records an experiment on the frog's sciatic in which the strength required for contraction is measured at four points in a narcotised region. For the first 15 minutes the current strength rises equally at all four points, but later on this state is gradually transformed into one in which the increase in threshold varies with the distance which the impulse must travel in the narcotised area. The small inset in the figure gives the least interval for muscular summation at each electrode 15 minutes after narcosis began. This increases as the distance from the

muscle is increased (cf. Lucas, *loc. cit.*) and there is therefore little doubt of the existence of a decrement in conduction before there is any sign of divergence of the thresholds.

What is the relation between strength of stimulus and initial size of impulse in this early stage of narcosis? Evidently a stimulus of the threshold strength sets up an impulse large enough to travel the maximum distance in the narcotised region without extinction, and a stimulus weaker than this sets up no impulse at all—for if it did, it would be effective at the more distal electrodes. Thus there must be a lower limit to the initial size of the impulse in the early stages of narcosis. Above this lower limit an increase in the stimulus may well cause an increased impulse, although this is merely an inference from what happens at a later stage of narcosis. At a later stage the limiting size becomes smaller and the range of variation correspondingly greater.

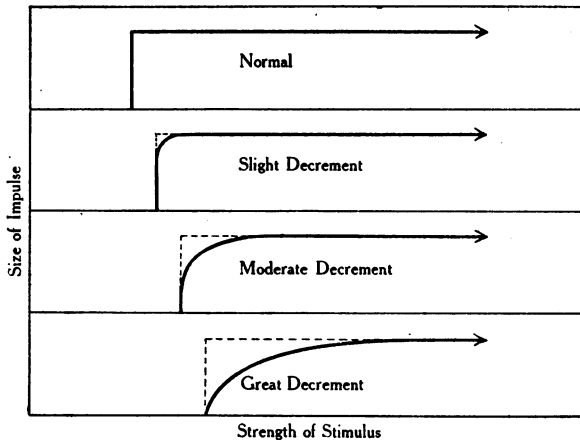


Fig. 4. Probable relation between stimulus and initial size of impulse in different stages of narcosis.

We may therefore represent, by the diagram in Fig. 4, the relation between the strength of stimulus and the initial size of the impulse set up in a region of decrement. This shows that in the normal nerve no variation in the size of the impulse is possible: when there is a slight decrement in conduction through unit length, as in the early stages of narcosis, the threshold stimulus sets up an impulse slightly smaller than the normal and an increase in the stimulus will increase the initial size of the impulse until it reaches an upper limit equal to that in the normal fibre. If the decrement in unit length is greater, the threshold stimulus sets up a smaller impulse and there is a greater possibility of gradation.

The threshold strength in the figure is represented as increasing as the decrement increases, since this would occur if the decrement was produced by narcosis. The form of the sloping part of the curve is entirely conjectural.

The conclusions embodied in this diagram seem to us to be of considerable interest to the theory of nervous conduction, but for the present we are concerned only with their bearing on the question of gradation in sensory nerve fibres. From this point of view the most important deduction is that there can be very little grading in the initial size of the impulse unless the fibre is in such a state that the impulse suffers a considerable decrement in travelling through unit length. It should be a simple matter therefore to discover whether there is normally such a degree of decrement in the sensory fibres as would admit of an appreciable variation in the initial size of the impulse set up by a single stimulus.

*Extent of decrement in mammalian sensory fibres.* We have used two methods to detect the presence of a decrement in conduction in sensory nerve fibres, and both of these depend on the use of a mammalian nerve removed from the body and set up in a moist chamber. The internal saphenous of the cat is a suitable nerve since it contains no motor fibres and there is no difficulty in obtaining a length of 6–7 cm. from an animal of average size. A certain amount of caution, however, is needed in interpreting the results obtained from surviving mammalian nerves, particularly in regard to decremental conduction. The conditions of survival have been worked out by one of us<sup>1</sup>, and it has been found that the nerve is in the most favourable state if it is dissected out with the least possible amount of traction, preserved from contact with damaged tissues and removed from the body not later than a few minutes after the death of the animal. A nerve prepared in this way will often continue to give an electric response for several hours, but in spite of careful dissection some nerves refuse to conduct at all in these conditions, and at best the nerve is in less favourable surroundings than it was in the body. Thus we might often expect to find a decrement in conduction in the surviving nerve though none was present before. On the other hand it is extremely unlikely that the nerve will conduct better out of the body than in it, so that if we find that the isolated nerve conducts without decrement we may be fairly certain that there was none before its removal.

The first method we have used consists in measuring the size of the

<sup>1</sup> A. F. An account of this work will appear shortly in the *American Journal of Physiology*.



electric response called up by an impulse which has travelled (*a*) a short, and (*b*) a long distance from its point of origin. If any reduction is found, we may safely infer that the "propagated disturbance" has been conducted with a decrement. The nerve was set up in a moist chamber at room temperature and connected with stimulating electrodes and non-polarisable leads to the string galvanometer. As the number of fibres

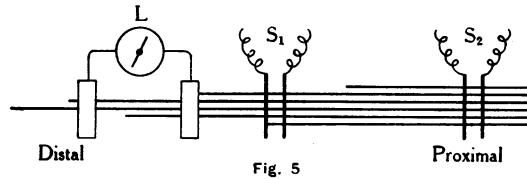


Fig. 5. Arrangement of electrodes on internal saphenous nerve.

in the trunk increases in passing towards the central nervous system, the distal end of the nerve was placed on the galvanometer leads (*L*, Fig. 5) and the stimulating electrodes were arranged nearer the proximal end at  $S_1$  and  $S_2$ . With this arrangement the number of fibres under the galvanometer leads is constant and all of them will be brought into play by a stimulus whether it falls at  $S_1$  or  $S_2$ . The experiment consisted in photographing the monophasic response to stimuli sent in alternately at  $S_1$  and  $S_2$ . The strength of stimulus was so adjusted that a maximal response was given at either point, and the direction of the current was repeatedly reversed so that any artefact due to it could be distinguished from the true electric response. It was found that the threshold stimulus was much the same at either  $S_1$  or  $S_2$ , and that the maximal response was given by a stimulus about three times as strong as the threshold.

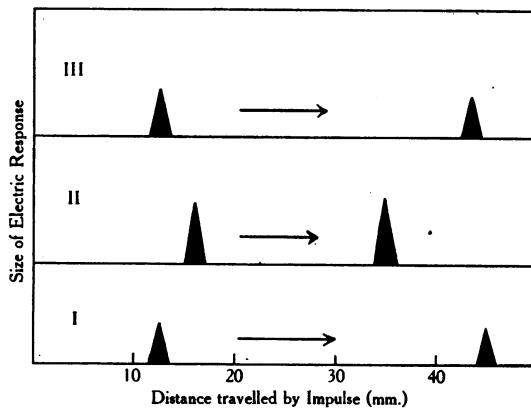


Fig. 6. Size of electric response after transmission through different lengths.

Three experiments were made on the internal saphenous and their results are shown in Fig. 6, which relates the size of the electric response to the distance which the impulse has travelled down the nerve. The size of the response is obtained by measuring the photographic records with a comparator and taking the average value for a series of responses. The figure shows that if there is any decrement at all it must be very small. A survey of all the measurements does appear to show that the response due to a stimulus at  $S_2$  is slightly smaller than that from  $S_1$ , but the difference is within the limits of experimental error. If we may accept the conclusions stated in the last section as applying to mammalian nerve fibre, it is clear that there could be very little grading in the initial size of the impulse unless the decrement in unit length was much greater than that shown in these experiments.

The second, and more delicate method of detecting a decrement in conduction is to produce impulses of very small intensity by stimulating during the period of recovery from a previous impulse and to see how far these can travel without extinction. With the arrangement shown in Fig. 5, if there is any decrement we should find that the small impulse set up in the early stages of recovery at  $S_2$  would fail to reach  $L$ , although an impulse of equal size starting at  $S_1$  would be successful. It would follow that the least interval between stimuli required to produce a double electric response at  $L$  would be greater when the stimulation is at  $S_2$  than at  $S_1$ , because the second impulse must be initially larger if it starts from  $S_2$ , and it must therefore be set up at a later stage of recovery.

To find the interval necessary for a double electric response the nerve was stimulated alternately at  $S_1$  and  $S_2$  with groups of two stimuli separated by gradually diminishing intervals. The stimuli were delivered by a Lucas pendulum breaking the circuits of two induction coils, and the resulting electric responses were photographed with the string galvanometer. The first series of exposures was developed whilst the experiment was still in progress and an inspection of the film gave a rough idea of the critical interval; the exact value could then be determined by more careful exploration.

Fig. 7 records the intervals measured in three experiments. Those marked I and II are taken from the same nerves as Experiments I and II in Fig. 6. The size of the rectangle shows the limits of accuracy of measurement in each determination. In the lowest line, Exp. I, it will be seen that there is no appreciable difference in the interval necessary at the two points, although the impulses have to travel nearly four times

the distance when they start from the further pair of electrodes. In Exp. II the interval is slightly longer at the greater distance so that in

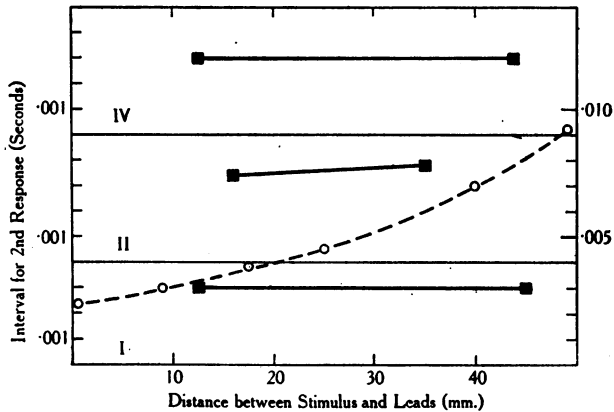


Fig. 7. Intervals required to give a double electric response.

this nerve the impulse probably undergoes a small decrement in conduction. In Exp. IV there is no difference. This experiment differs from the others in that the stimulus was applied to the lower end of the nerve and the response led off from the central end so that the impulses were passing in the direction of their natural flow in the body. The dotted line in Fig. 7 is taken from an entirely different source to show the way in which the interval should change if the decrement in unit length was considerable. It shows the intervals required to give a summated contraction in the frog's gastrocnemius when the stimuli are sent in at different points along a narcotised portion of the sciatic nerve. In this case the interval rises rapidly with increase of distance, although the decrement was not great enough to extinguish a full-sized impulse in 40 mm.

It will be seen that both lines of experiment lead to the same conclusion. In a mammalian sensory nerve the impulse undergoes at most a very slight decrement in conduction through unit length and often none that can be detected at all, and this in spite of the fact that it is exposed to conditions which might well produce decremental conduction. It is indeed surprising that this was not met with more often, seeing that a good many nerves failed to conduct at all when they were set up in the chamber, but it is probable that the decremental state in a medullated fibre is essentially unstable and that the nerve deteriorates rapidly as soon as it has set in. At any rate it is clear that under normal conditions

the sensory nerve fibre agrees with the motor nerve fibre in that the impulse travels down it with little or no reduction in intensity.

*The all-or-nothing reaction in sensory fibres.* If the sensory fibre of a mammal does not differ fundamentally from the motor fibre of a frog, the conclusion arrived at in the last section means that little or no grading is possible in the initial size of the impulse. The point may be tested directly, however, by a method like that employed for the motor nerve (see p. 303). Stimuli of different strengths are applied to the proximal end of a nerve and the impulses set up are allowed to travel into a narcotised area. If there is any grading in the initial size of impulse there should be a stage in the narcosis in which the impulse set up by a weak stimulus is extinguished in the affected area whilst that set up by a strong stimulus can still pass through. For the sensory nerve the electric response must be used instead of the muscular contraction to show the failure or success of the impulse in passing the decremental region.\*

The internal saphenous nerve was set up in a moist chamber, the central region, 35 mm. in length, passing through a trough which could be filled with 5-6 p.c. alcohol solution (Fig. 8). The stimulating electrodes were placed on the proximal end of the nerve and the electric responses led off from the peripheral end, this end being crushed to give a monophasic response. The experiment consisted in determining what strength of stimulus was needed to give (*a*) a minimal, and (*b*) a maximal electric response at different stages in the narcosis until the failure of conduction was complete. This could only be done by photographing the responses to a series of stimuli of different strengths covering a range wide enough to include the threshold and the maximal strength. The series was repeated at frequent intervals during the narcosis and a complete experiment would involve as many as 150 photographs on a strip of film 30-40 feet long.

The results of two such experiments are shown in Figs. 9 and 10. The strengths of stimulus are expressed on the same scale as in Fig. 2, *i.e.* a coreless coil is used at a fixed coil distance and the stimulus is said to be of unit strength when the resistance in the primary is 500 ohms, two units when the resistance is 250 ohms, etc. The limits of accuracy in the measurement of the threshold, etc. are shown by the small rectangles: the black triangles rising from the base line mark the height of the maximal electric response at different stages in the narcosis.

The two figures agree very closely with those obtained from the motor nerve fibres of the frog (7). As the electric response becomes smaller, the

strength required for a minimal response remains constant or rises, and that required for a maximal response falls. These changes are readily

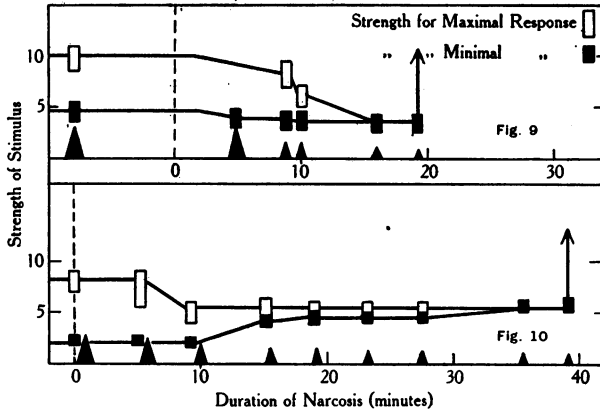
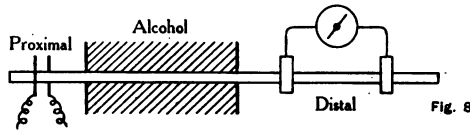


Fig. 8. Arrangement of electrodes, etc.

Fig. 9. Strength of stimulus needed for maximal and minimal electric response during final stage of narcosis.

Fig. 10. As Fig. 9.

explained by the early failure of some of the fibres, which may happen to be either the most excitable or the least excitable in the nerve. But the important point concerns the strength of stimulus which is effective just before the complete failure of conduction. In Fig. 9 this is no greater than the original threshold value. Thus the stimulus which remains effective until complete failure is one which was originally only just strong enough to produce any effect at all, so that the impulse which it sets up can withstand just as great a decrement as the impulse set up by a stimulus many times as strong. This can only mean that the size of the impulse does not depend at all on the strength of the stimulus. In Fig. 10 the final strength is greater than the original threshold value, but smaller than that originally required to give a maximal response. If we assume an all-or-nothing relation between stimulus and impulse in each fibre the result is very easily explained, for it means no more than the failure of the most excitable and the least excitable fibres before those of intermediate excitability. If we suppose that the size of the

impulse in each fibre varies with the stimulus we might account for the rise in the threshold strength as due to the failure of small impulses set up by weak stimuli, but we have still to explain the fall in the strength required for a maximal response. If this fall is due to the early failure of certain fibres (and no other explanation seems possible) we must admit that the rise in the threshold strength may be due to the same cause. There is therefore no positive evidence in favour of any gradation in the size of the impulse and very strong evidence against it.

Evidence of a slightly different kind is given in Fig. 11, which is plotted from the same experiment as that shown in Fig. 10. Fig. 11 shows

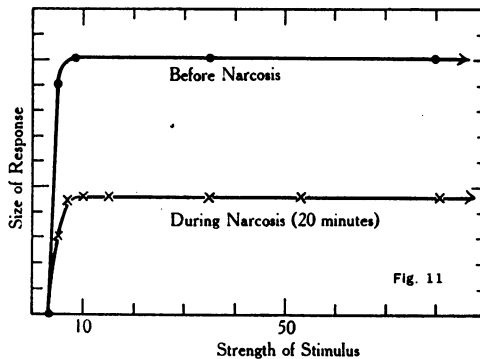


Fig. 11. Strength of stimulus and size of electric response before and during narcosis.

the relation between the size of the electric response and the strength of the stimulus before and during narcosis. It will be seen that the response is considerably reduced by the narcosis and that it cannot be restored to its former value by any increase in the strength of the stimulus.

Results of the type shown in Figs. 10 and 11 were found in all the other nerves which were examined. These were three internal saphenous nerves (two from cats and one from a rabbit) and two sciatic nerves, included to show any possible difference between sensory and mixed nerve trunks. As a rule the narcosis was repeated several times with each nerve, the alcohol being replaced by Ringer's fluid as soon as conduction was suspended. In no case was there evidence of a stage in narcosis in which the impulse was better conducted when the stimulus was increased in strength.

It must be admitted that this evidence does not show that an increase in the strength of the stimulus has no effect whatever on the size of the impulse, but it does show that there can only be a small range of

strengths which cause any variation. In Fig. 9 just before the failure of conduction a stimulus of 4.5 units gives an impulse of maximal size, whereas one of 3 units is not strong enough to set up any impulse at all. In Fig. 10 the possible range within which variation may occur is greater, since the original threshold is 2 and the final strength 6, although it is highly probable that the threshold strength has increased in the course of narcosis owing to the failure of some of the fibres. In the other experiments on the internal saphenous the limiting strengths were 2.5-4.5, 2-4.5 and 5.5-6.5. There is no evidence that variation does occur between these extremes, but the possibility has not been disproved as the method of experiment does not admit of greater accuracy.

Another possibility which cannot be tested is that the nerve may contain a few fibres which give a graded response but are not numerous enough to have any observable effect on the response of the entire nerve trunk. For the majority of fibres, however, we may conclude that the range of strength of stimulus which may possibly give rise to gradation in the initial size of the impulse is so narrow that such gradation could be of little value in the working of the central nervous system, and it could not possibly account for the wide range of response in the reflex arc.

## II. GRADATION IN THE REFLEX RESPONSE.

*Effects of supramaximal stimuli.* We come back to the difficulty with which we were faced at the beginning—*i.e.* how to account for graded reflexes without grading of impulses in each fibre. There are, of course, two methods of grading which involve no difficulty, (*a*) by the number of fibres involved, and (*b*) by the frequency of impulses set up by continuous or repeated stimulation. But it is well known that there is a wide range of reflex response to single stimuli as well. Sherrington and Sassa<sup>(8)</sup> have shown extensive gradation in the case of the flexion reflex in response to single shocks, all of which were of such strength that when applied to a motor nerve they provoked maximal contractions in the muscle. If one could judge from this response to motor nerve stimulation, it would be inferred that at all the strengths of stimulus under consideration every fibre in the nerve was being excited, and it would seem altogether probable that this would be the case whether the nerve was motor or sensory. If then the stimuli, which in Sherrington's experiments produced reflex responses of graded magnitudes, were all supramaximal, wherein could their differences in strength avail to produce differences in response?

The same question has been raised by Forbes and Gregg<sup>(9)</sup>, and

an answer proposed which was suggested by the records of action currents set up in a nerve by powerful stimuli. Apparently a single break shock of great strength was able in many cases to set up two successive nerve impulses, appearing in the galvanometric record as two distinct action currents. Garten<sup>(10)</sup> has published similar action current records and has interpreted them in the same way. Experimenting with the mammalian sensory nerve (saphenous) we have obtained many records of double responses to strong break shocks. The most striking series is that reproduced in Fig. 12 (p. 321) from the saphenous nerve of a rabbit. Such repetitive discharge of impulses provides a possible mechanism for grading the reflex effect in response to graded single shocks whose strength is greater than is required to excite every fibre in the nerve.

Sherrington's recent work<sup>(11)</sup> has brought to light several new facts of great interest which are, at first sight, rather difficult to reconcile with this suggestion. He has measured the magnitude and duration of mechanical responses to both reflex and motor nerve stimulation, and found with the latter a well defined maximal value of the muscular twitch which, as the strength of induction shocks increased, was not exceeded except in the case of extremely powerful shocks with which a "supra-maximal" response was obtained. When the same muscle, however, was reflexly excited by single shocks the increase in height of contraction appeared to be more gradual, and continued to increase till it was greater than the maximal simple twitch of muscle, this greater value being obtained with a strength of stimulus considerably less than the powerful shock required to produce a "supra-maximal" response in the case of motor nerve stimulation. Added to the increase in the height of contraction was an increase in duration in the case of the reflex which did not appear in the case of motor nerve stimulation.

It appeared to us that an analysis of the electrical response of the muscle and of the afferent side of the arc might help to interpret these results. We have therefore measured the electrical and mechanical response of a muscle stimulated both reflexly and by way of its motor nerve by break shocks of different strength, and we have measured also the electric response of the afferent nerve to the same stimuli.

*Response of different components of the reflex arc. Method.* The following procedure was carried out in three experiments. A cat was anaesthetised and the spinal cord transected at about the level of the last thoracic vertebra. Decerebration was then performed at the level of the anterior colliculi by the guillotine method. The popliteal nerve



was severed in the popliteal space and stimulating electrodes were applied to the central end. The tendon of the tibialis anticus muscle on the same side was attached to a thread leading to a muscle lever which threw a shadow on the film used to record the electrical responses. A spring torsion level of high periodicity was used, but unfortunately its records showed considerable oscillations owing to the great distance between the animal and the lever and to the weight and extensibility of the thread joining them. Two windows were cut in the skin over the tibialis anticus muscle and non-polarisable electrodes connected with the galvanometer were applied at these points. Contact was made and secured by means of twine soaked in Ringer's solution, imbedded at one end in a tube of gelatine and Ringer's solution, and at the other end tied to the surface of the muscle by means of a suture passing through the fascia. A series of records was then made of the action current of the muscle together with the contraction simultaneously recorded on the film. Single break shocks were used except in a few experiments in which both make and break shocks were used in rapid sequence. A rest of several seconds was allowed before each stimulus, in order to avoid the modifying effect on the centre of a stimulus having occurred within less than a second (12). The strength of break shocks was varied from the threshold to 100 or 200 times this value. After the complete series of reflex responses had been recorded the motor nerve was cut at the hip and stimulating electrodes were applied to it. Then the responses of the muscle, both mechanical and electrical, to a similar series of stimuli thus applied to the motor nerve (peroneal) were obtained. Finally, the afferent nerve was removed to a moist chamber with the stimulating electrodes as originally applied still in place: it was connected with the galvanometer, and its action currents in response to a similar graded series of stimuli were recorded. (In one experiment the afferent nerve had become damaged and no action currents were obtainable.) In the third animal the whole procedure was repeated on the other side, except the recording of the action currents of the afferent nerve.

The strength of the break shocks was measured in the way given on p. 304, the coil distance being kept constant and the resistance of the primary circuit noted. When, however, extremely strong stimuli were desired, the coil distance was decreased from its standard value, the resulting increase of the strength of stimulus being determined afterwards by the threshold method of v. Fleischl, as described by Martin (13).

*Results.* The results of the four experiments (counting the left side of the third animal as a separate experiment) were all concordant in

their main features. They agreed with Sherrington's experiments in showing that as the stimuli are progressively increased in strength there is a more constant and sustained maximal value of contraction in the case of stimulation through the motor nerve than in reflex stimulation. In this respect measurements of the galvanometric excursions indicating the action currents agreed with the measurements of mechanical contraction. On the other hand, when the strength of stimuli in terms of the units here employed are plotted quantitatively as abscissæ, and mechanical contractions (or action currents) as ordinates, the difference between the curves in the cases of reflex and motor nerve stimulation become relatively slight. In Figs. 13 A and 14 A are shown curves plotted in this way from our experiments.

The curves relating strength of stimulus and action current agree

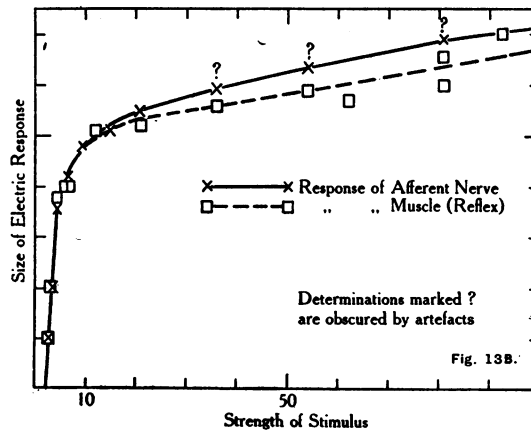
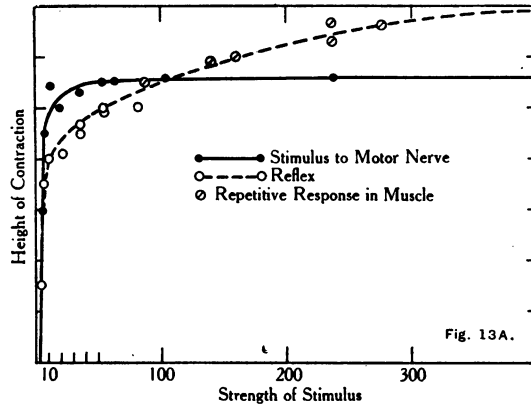


Fig. 13 A and B. Grading of response in flexion reflex (tibialis anticus).

so closely with that for contraction that they are not shown in the figure, but it is notable that in general the size of action current in the case of motor nerve stimulation exceeds that in the case of reflex stimulation, more than the corresponding contraction exceeds the reflex contraction. This may be explained by the fact that the duration of the action current is far briefer than that of the contraction, and consequently the action currents of the individual fibres overlap less when, as in the reflex, they fail to occur simultaneously. The diminution of the galvanometric excursion, due to lack of synchronism, would be especially marked with diphasic action currents, for the second phase in some fibres would tend to neutralise the first phase in others, but we found that it was still present after the response had been made monophasic. The action current of the muscle in maximal response to motor nerve stimulation was so large in some experiments that the shadow of the string left the film. In most experiments a second series of records was made with the string much tighter and therefore able to record maximal responses on the film. Thus, we obtained enough records to show that as far as magnitude of response was concerned, the mechanical contraction sufficed to yield all necessary data for plotting curves. The chief value of the galvanometer record was in showing when double response occurred in either afferent nerve or muscle.

It will be seen that in the case of motor nerve stimulation when the break shock has attained a value of from 5 to 15 units<sup>1</sup> (see above) the size of muscular response ceases to increase, the curve thereafter presenting a well sustained "plateau." In the case of reflex stimulation the curve of muscle response, electrical or mechanical, presents a similar plateau, but not beginning till the stimulus is from 10 to 40 units, and not so well sustained as with motor nerve stimulation. The bend in the curve is not so sharp, and the response continues to increase slightly as the stimuli increase, even after the curve has become nearly flat. Only in the first of the three preparations did the reflex response of the muscle ever become greater than the maximal twitch (Fig. 13), and this was so only in the case of the mechanical response; the reflex electrical response remained throughout much smaller than that of the maximal twitch.

Turning to the action currents of the afferent nerve subsequently obtained in response to a similar series of stimuli (Figs. 13 B, 14 B), they

<sup>1</sup> As nearly as we can judge by comparing our series of experiments with those of Forbes and Gregg, the unit here used is about two or two and a half times as large as the Z unit: see A. Forbes, *Amer. Journ. Physiol.* 56, p. 288. 1921.

yield when plotted, the same sort of curve as those for the muscle, and the "plateau" is reached more nearly at the strength of stimulus at

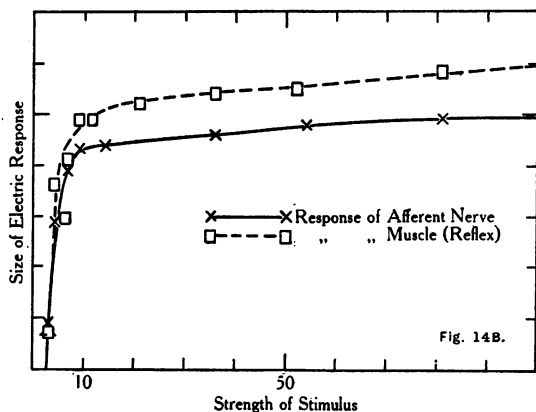
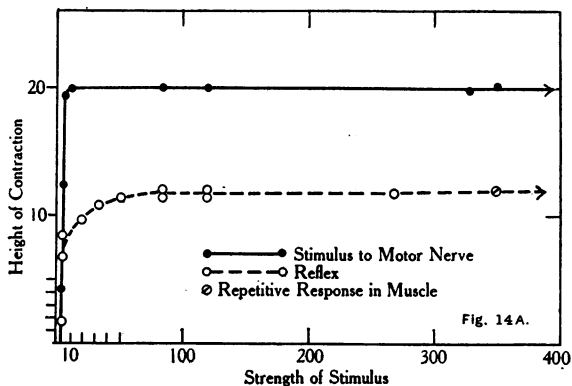


Fig. 14 A and B. Grading of response in flexion reflex (*tibialis anticus*).

which it is reached in the case of the reflex than in the case of motor nerve stimulation. It is impossible to trace the curve as far in the case of the afferent nerve action current as in the others, for with strong stimuli the excursion of the string is augmented by the electrical artefact, which distorts the measurements.

Clearly in the case of motor nerve stimulation, the beginning of the "plateau" signifies the attainment of the strength of stimulus required to excite all the motor fibres in the nerve. In the case of the reflex response the near approach to a plateau presumably depends similarly on excitation of nearly all the afferent fibres, and of all the afferent fibres if the curve becomes truly horizontal (as in Fig. 14 A). In the case of the action current of the afferent nerve itself a true plateau would un-

doubtedly signify excitation of all fibres, afferent and efferent alike. The much more rapid attainment of the plateau when the motor nerve is stimulated is no doubt due in part to the different sizes of the popliteal (afferent) and peroneal (motor) nerves and the consequent difference in the concentration of the stimulating current but it must also be due to a greater variability in the thresholds of sensory fibres, for the difference was still present (though reduced) when the slender internal saphenous nerve was used as afferent instead of the large popliteal.

The gradual increase in reflex response with large increase in strength of stimulus after the plateau has been reached and presumably the stimulus has become adequate for all afferent fibres, now calls for consideration. Is this gradation such as might be explained by compound stimulation (*i.e.* repetitive response) in the afferent nerve?

Examination of the electrical records reveals evidence of repetitive response in the case of the strongest stimuli both in the afferent nerve and in the muscle reflexly excited. In the experiment shown in Fig. 14, this evidence only appeared clearly with the strongest stimuli used, 350 units. Examples of it are shown in Fig. 15 (C and D), in which the continuance

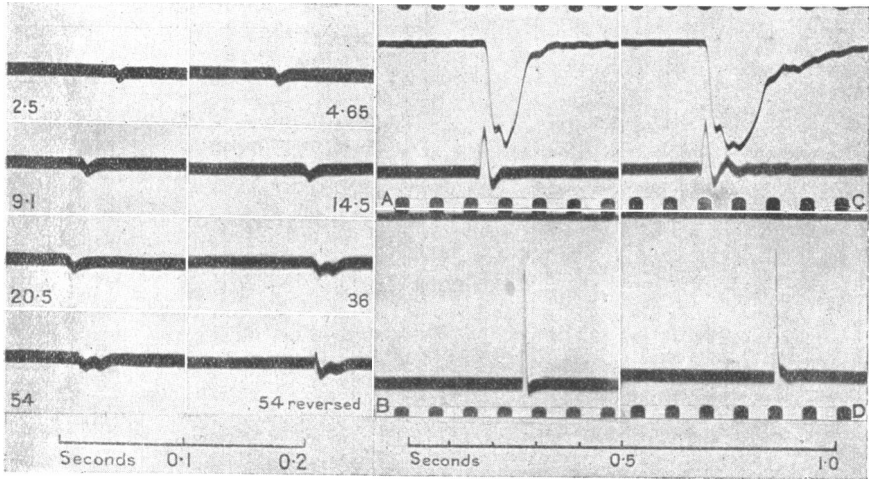


Fig. 12.

Fig. 15.

Fig. 12. Action current of internal saphenous nerve of rabbit in response to stimuli of different strengths, showing repetitive response with strong stimuli.

Fig. 15. A. Contraction (upper line), and action current (lower line) of tibialis anticus muscle in response to reflex stimulation of 120 units strength. B. Action current in afferent nerve (popliteal), 120 units. C. Stimulus of 320 units, repetitive response in muscle. D. Stimulus of 320 units, repetitive action current in afferent nerve.

of repeated action currents for about 0.2 second is evident in both afferent nerve and reflex muscle records. With these are contrasted in the figure corresponding records in the same experiment with a stimulus strong enough to evoke a response in each case on the plateau (*i.e.* maximal) but not strong enough to cause repetitive response. In the experiment made on the opposite limb of the same animal, repetitive discharge was found in the records of reflex muscle action current with all stimuli of over 50 units, and once with only 36 units. It is notable that the reflex responses (both mechanical and electrical) were consistently greater in this particular experiment than in any of the others. This is interesting in connection with the unusually small strength of stimulus at which repetitive reflex discharge appeared, and in connection with the comparison between our results and Sherrington's, to be discussed presently. Unfortunately, we made no record of the action currents in the afferent nerve of this limb.

In none of our records was there evidence of repetitive electric response in the muscle to motor nerve stimulation. It should be noted that none of the break shocks in our series were strong enough to evoke the well defined "supramaximal" contraction of the muscle to motor

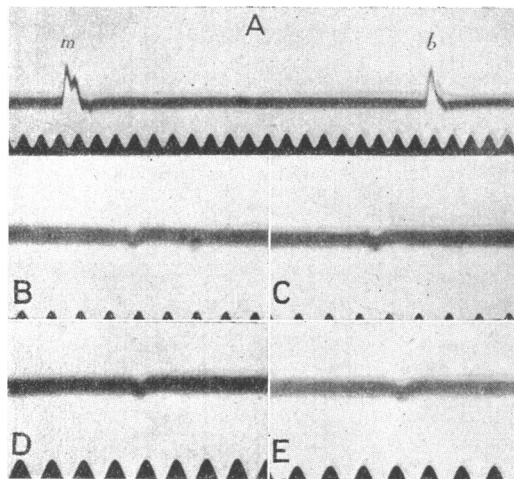


Fig. 16. A. Action current of external interosseous muscle, stimulus to motor nerve (395 Z units). Repetitive action current on make *m*, but not on break *b*. B–E. Popliteal tibial nerve muscle preparation, action current of nerve. B. Response to single stimulus. C. Double response to two stimuli at .00086 sec. interval. No muscular summation. D. Stimuli at .00095 sec. Muscular summation. E. Double response to single break shock of 630 Z units strength.

nerve stimulation, which Sherrington illustrates in Fig. 6 of his recent paper (14). Make shocks of great strength from a Berne coil with an iron core, have been found by one of us to cause when applied to the popliteal nerve a repetitive electric response in the external interosseous muscle of the foot (Fig. 16 A), although in the same experiment break shocks failed to do so. This is doubtless to be explained by the fact that make shocks last much longer than break shocks.

We may conclude from a survey of our experiments that the first and obvious source of gradation in reflex response to single shocks depends on the number of afferent fibres excited; and this stage of gradation corresponds with the initial rise in the curve before the "plateau" is reached. Any further increase in the size of response appears to consist in the appearance of repetitive discharge in the motor neurones, as Sherrington has inferred. In all but the last of our experiments the strength of stimulus required to evoke this repetitive reflex response seems to have been such as was also shown to set up repetitive discharge in the afferent nerve fibres.

*Repetitive discharge of central origin.* It will be interesting now to make a further comparison of our results with Sherrington's. In absence of a calibration which would tell us precisely the relative strengths of Sherrington's stimuli, we may yet arrive at a rough estimate of their probable values by assuming what is true for some coils at least, viz. that the stimulus decreases in strength roughly in proportion to the square of the increased coil distance beyond a point (say 10 cm.) near where they cease to overlap. Plotting a curve of the maximum heights attained in the myograms in Fig. 1 of Sherrington's paper against provisional units so obtained, gives a curve which rises rapidly at first and then much more slowly and does not differ from our curves as much as might be expected. But there is still a most important difference. Whereas we found reflex responses rarely exceeding in magnitude the maximal "neuro-myal" twitch of the muscle, and never exceeding it by a large amount, Sherrington found even at the beginning of this "plateau" a reflex response more than twice as large as the maximal twitch. This effect he ascribes to repetitive discharge in the motor neurones, and indeed there appears to be no other possible cause for it.

The most interesting feature of this result is that the repetitive motor discharge from the centre occurs in response to a single shock which is presumably too weak to produce repetitive impulses in the afferent nerve. The presumption that these stimuli of Sherrington's were too weak

to cause compound response in the stimulated nerve, is strengthened by our last experiment in which, as already noted, we regularly obtained repetitive electric responses in the muscle when reflexly excited by stimuli much weaker than we ordinarily found necessary to cause repetitive response in the afferent nerve. It is most unlikely that with 36 units we set up a double response in the afferent fibres, yet this stimulus sufficed to evoke a repetitive discharge from the centre. It is a striking fact that this type of discharge should result from a single simultaneous volley of afferent impulses. Our experiments indicate that in some preparations this does not occur: and the spinal centre evidently varies a good deal in its ability to respond with repetitive discharge to simple afferent volleys. In our last experiment, as already intimated, turning the animal over and repeating the procedures in the opposite limb was accompanied by a marked change in the size of response, and—what is more interesting—a change from a centre which could not respond by tetanus to a single afferent volley to a centre which could. Variability in the intensity and character of response to afferent impulses is a pronounced characteristic of reflex centres, even in the case of so simple and regular a response as the flexion reflex.

To account for this repetitive discharge from a centre, two different explanations have been put forward. Sherrington (*loc. cit.* p. 256) has suggested that there may be set up in the centre a sustained disturbance which might be different in kind from the transient disturbance which constitutes the impulse in a peripheral nerve fibre. We do not know enough of the nature of central activity to assert or deny the existence of such a disturbance, but there is also the possibility that the single impulse becomes multiplied because it passes into a number of dendrites or collaterals, all of which ultimately converge on the motor neurone. Unless the time spent in conduction is the same in every path a sequence of impulses will result (15).

*Different effects of strong stimuli applied to motor and sensory nerves.* We have already mentioned that strong single break shocks applied to the motor nerve failed to set up in the muscle more than a single response, although they frequently set up repetitive responses in the afferent nerve. At first sight this would seem to imply a great difference in the effect of a strong shock on motor and sensory fibres. This, however, is not an inevitable inference, for the strong stimulus might set up two responses in the motor nerve, although only one appeared in the muscle. Keith Lucas (16) has shown that in a frog's muscle nerve preparation it is usually possible to set up two impulses in the nerve so close together



that the second reaches the muscle at a time when it is unable to give a second response. The interval between the two stimuli can only vary within narrow limits if the effect is to be obtained, and it is sometimes absent altogether (17). But if two impulses are set up by a strong single stimulus we should expect them to be separated by the shortest possible interval, *i.e.* an interval only just longer than the absolute refractory period of the nerve, and with this interval the muscle might well be unable to respond to the second impulse.

To determine whether a similar effect occurred in a mammalian muscle nerve preparation proved a difficult matter because of the necessity of working at body temperature and of avoiding electrical artefacts. A method which has finally proved successful is as follows:

In a decerebrate cat the popliteal branch of the sciatic nerve was severed at the hip and dissected from the rest of the sciatic trunk for about 3 cm. in the thigh. Through a second incision in the popliteal space the nerve was again exposed and all muscular branches given off in this region were severed. The continuation of the nerve (tibial) was then exposed in the lower leg and dissected from the surrounding tissues for about 6 cm. Stimulating electrodes of the Sherrington shielded type in a glass tube were applied to the cut end at the hip. The proximal end of this tube was sealed with wax to prevent escape of current at this end. The thigh incision was then sewed around the neck of the tube in order to keep this portion of the nerve at body temperature. A second glass tube with a slot in the side was placed in the lower limb in such a way that two non-polarisable electrodes of the silver chloride type could be applied to it 16 mm. apart inside the glass tube and the nerve could be insulated from the surrounding tissues for the distance of 5.5 cm. This proved necessary to prevent the surrounding tissues from short-circuiting the action current. The skin was then sewed around the opening of the glass tube. In this way diphasic action currents could be recorded with the second phase following so close upon the first that the first phase appears as a sharp spike in the galvanometric record. The external interosseous muscle in the foot (innervated by this nerve) was exposed on its ventral aspect and leads were applied: the "proximal" to the middle of the muscle, the "distal" to its proximal end at the heel, for the reason that the propagated disturbance in this muscle was found to travel toward the heel. By means of a double-pole double throw switch the galvanometer could be connected with either the nerve or the muscle. A thread tied around the toes was connected with a light bell-crank lever in such a way that the contraction of this muscle could be recorded on a smoked drum. Two stimulating coils were connected with a Lucas pendulum capable of delivering two break shocks at intervals which may be determined accurately to within  $\pm 0.00003$  sec. The secondary coils were connected in parallel, and both connected with the stimulating electrodes so that the cathode on the break shock should in each case be distal.

It proved easy to tell with this arrangement whether a second response occurred in the muscle, by Boycott's method of noting whether the record on the smoked drum showed summated contraction or not. The electrical response of the muscle provided an additional check on this method. In two separate experiments with the external interosseous muscle, and in one similar experiment with the peroneal nerve and tibialis

anticus muscle, it has been found possible by proper timing of the second stimulus to obtain electrical records showing two responses in the nerve when the absence of summated contraction showed that there was only one response in the muscle. In each experiment this observation was made repeatedly. Freedom from confusion due to electrical artefact in the case of the popliteal nerve was shown in the following way: When the experiment had been completed the nerve was crushed a few millimetres distal to the point of stimulation to prevent impulses reaching the leads. Galvanometric records were then made while the strongest stimulus employed was applied to the nerve. The absence of any discernible excursions of the string sufficed to show that the well-defined excursions in the previous records had been due to action currents, not artefacts. Fig. 16 B-D, shows an example of double action currents in the nerve when only a single response occurred in the muscle. For comparison are shown also the response of the nerve to the first stimulus by itself and the double response when the second stimulus was so timed as to evoke a second response in the muscle.

In one of these experiments we found evidence bearing more directly on our question, viz. as to the possibility of repetitive impulses in the motor nerve in response to a single shock applied directly to it, failing to set up more than one response in the muscle. Fig. 16 E shows the record of the electrical response of the nerve to a single break shock of great strength. It is from the same experiment as the records in Fig. 16 B, C and D, and was taken immediately after them without in any way disturbing the apparatus or connections. It appears to reveal quite clearly a second nerve impulse. The contraction of the muscle was no more than a simple maximal twitch.

We may therefore conclude that the failure of a muscle to show repetitive response to single powerful shocks applied to its motor nerve, does not necessarily mean failure of the motor nerve itself so to respond. This conclusion tends to eliminate an apparent difference between sensory and motor nerve fibres. There is, however, a possibility which must not be overlooked. The peroneal and popliteal nerves contain both sensory and motor fibres: and it is conceivable that in the above experiments the double response only occurred in the afferent fibres, and that the motor fibres never responded twice without causing the muscle to respond twice. We see no reason to suppose this is so, but further evidence is needed to exclude the possibility completely.

## III. REMARKS.

The preceding experiments have shown that the sensory nerve fibre reacts on the all-or-nothing principle and they have confirmed the suggestion of Forbes and Gregg that the wide variation in reflex response to single stimuli is due to the setting up of more than one impulse when the stimulus is strong. This conclusion may not be true of all the fibres of a sensory nerve trunk, but it is at any rate true of the majority. That the same result is given by mammalian sensory nerves and by the motor nerves of the frog suggests that all medullated nerve fibre may be expected to react in the same way. The importance of this result for theories of hearing and vision is self-evident, though its extension to the optic and auditory nerve fibres cannot be regarded as absolutely certain. In the case of the optic nerve, however, Troland (18) has already brought forward some evidence for an all-or-nothing reaction, and Jolly (19) has shown that it is not incompatible with a photo-electric theory of vision.

It is possible that a sensory nerve may contain a few fibres which do give a graded reaction by conducting with a decrement. Non-medullated sensory fibres, if such exist, would probably conduct in this way, for Garten's work suggests that this is the normal type of conduction in non-medullated nerves. The presence of a few such fibres might account for the failure to reach a steady plateau in the action current of the afferent nerve or in the reflex response in some of our experiments. On the other hand we do not think that more than a few fibres of the internal saphenous can conduct in this way, since we found no signs of decremental conduction in the isolated nerve trunk. On general grounds we might expect that decremental conduction would not occur except to a trifling extent in the nerve fibres of vertebrates, since it would mean that reflex arcs with a short conducting path would be more effective than arcs with a longer path. In primitive animals with a diffuse nerve-network it may be an advantage for the reflex response to be most intense in the neighbourhood of the point stimulated, but such an arrangement would obviously not be adapted to the needs of the more complex organisms in which there is a central nervous system connected with the periphery by fibres of variable length. With such an arrangement it would seem almost essential that the impulse should be conducted without change of intensity in the peripheral nerve fibres.

Two other points deserve mention. The first relates to the identification of the nerve fibre as the ultimate conducting unit. We have assumed

throughout that the nerve fibre is such a unit and that it is not a bundle of neuro-fibrils each capable of independent activity. This assumption has been discussed elsewhere<sup>(20)</sup>: it is based on the observation of Keith Lucas<sup>(21)</sup>, that a muscle supplied by 10 nerve fibres but containing 150-200 muscle fibres shows not more than 10 different strengths of contraction in response to a continually increasing stimulus. We would point out, however, that the conclusions arrived at would not lose their force even though the ultimate unit were the neuro-fibril and not the nerve fibre. There would be a greater opportunity for the gradation of reflex effects by variation in the number of units in action, but it would still be impossible to set up impulses of different intensity under similar conditions and this would involve much the same consequences in regard to the central mechanism and to the nature of the nervous impulse.

The other point concerns the meaning to be attached to the statement that the nerve fibre reacts on the all-or-nothing principle. This phrase is sometimes used as though it meant that every impulse passing down the fibre must have the same intensity whatever the conditions of its propagation. There is abundant evidence that the nerve fibre does not react in this way and we have used the phrase to mean, not that the intensity is invariable, but that it depends only on the local conditions at the point at which it is measured. The intensity of each impulse will vary with the state of recovery of the fibre and therefore with the frequency of stimulation (within limits), but if the nerve gives an all-or-nothing reaction the intensity of the impulses cannot be altered independently of the frequency.

#### CONCLUSIONS.

1. In a motor nerve fibre under normal conditions the impulse follows the all-or-nothing principle. This does not hold in a region of decrement where the size depends on the distance the impulse has travelled, and if an impulse is set up in such a region its size will vary within limits with the strength of the stimulus. In this our experiments confirm those of Lodholtz and Rehorn.

2. If the decrement in conduction in unit length is small, there is little variation in the initial size of the impulse with stimuli of different strength; a wider variation is possible if the decrement in unit length is large.

3. A mammalian sensory nerve (the internal saphenous of the cat)

shows no clear evidence of a decrement in conduction when tested by two different methods. Thus very little gradation in the initial size of the impulse will be possible in sensory fibres unless there is some fundamental difference between motor and sensory fibres.

4. Impulses set up in the internal saphenous by stimuli of different strength are all equally capable of passing through a narcotised region, and when conduction fails for an impulse set up by a weak stimulus it fails also for a strong stimulus. The size of the impulse is therefore independent of the strength of the stimulus in the sensory as in the motor fibre.

5. The response of a sensory nerve trunk to a single, momentary stimulus may vary in two ways, (*a*) a strong stimulus will excite more fibres than a weak, and (*b*) a stimulus which is more than strong enough to excite all the fibres may set up two or more impulses in each fibre.

6. The response to stimuli of different strengths has been measured in different parts of the arc which is concerned in the flexion reflex in the spinal cat. With reflex stimulation the response of the muscle agrees very closely with that of the afferent nerve, and the gradation seems to depend on (*a*) the number of nerve fibres stimulated, and (*b*) the repeated excitation by strong stimuli.

7. When the motor nerve is stimulated the muscle does not give more than a single maximal twitch although the stimulus may be strong enough to give a double response in the nerve. Probably the second impulse has no effect because it reaches the muscle at a time when the latter is still in the absolute refractory state. In the reflex arc a second impulse due to strong stimulation of the afferent nerve has more chance of affecting the muscle owing to delay at various synapses, etc.

8. A single impulse in the afferent nerve may sometimes evoke two or more impulses in the efferent side of the arc. Whether it does so or not depends on the condition of the spinal centres.

9. In general the reactions of the reflex arc support the view that the large majority of sensory fibres react according to the all-or-nothing principle.

#### REFERENCES.

- (1) Cf. Adrian. *This Journal*, 47. p. 460. 1914.
- (2) Parker. *The Elementary Nervous System*, p. 101. (Lippincott.) 1919.
- (3) Verworn. *Irritability*, p. 122. Yale Univ. Press. 1913.
- (4) Lodholtz. *Ztsch. f. allgm. Physiol.* 15. p. 269. 1913.
- (5) Rehorn. *Ibid.* 17. p. 49. 1915.

- (6) Lucas. *This Journal*, 46. p. 478. 1913.
- (7) Adrian. *Loc. cit.*
- (8) Sherrington and Sassa. *Proc. Roy. Soc. B.* 92. p. 108. 1921.
- (9) Forbes and Gregg. *Amer. Journ. of Physiol.* 39. p. 211. 1915. 2,15
- (10) Garten. *Ztsch. f. Biol.* 52. p. 552. 1909.
- (11) Sherrington. *Proc. Roy. Soc. B.* 92. p. 245. 1921.
- (12) Forbes and Gregg. *Amer. Journ. Physiol.* 37. p. 168. 1915.
- (13) Martin. *The Measurement of Induction Shocks.* (Wiley and Sons.) 1912.
- (14) Sherrington. *Loc. cit.* p. 252.
- (15) Forbes. *Amer. Journ. of Physiol.* 56. p. 294; also Fig. 7. 1921.
- (16) Lucas. *This Journal*, 43. p. 46. 1911.
- (17) Adrian. *Ibid.* 55. p. 202. 1921.
- (18) Troland. *Journ. of the Optical Soc. of America*, p. 161. 1920.
- (19) Jolly. *Proc. Roy. Soc. B.* 92. p. 219. 1921. 2,27
- (20) Adrian. *This Journal*, 45. p. 411. 1912.
- (21) Lucas. *Ibid.* 38. p. 113. 1909.