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CONDUCTION VELOCITY IN PROXIMAL AND DISTAL PORTIONS OF FORELIMB AXONS IN THE BABOON

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SUMMARY

1. Peripheral nerves of the baboon's forelimb were stimulated at different sites, and the latencies of antidromic action potentials were measured in intracellular records from forelimb motoneurones.

2. The conduction velocity of single motor axons was slower in the brachial plexus than in the nerves of the arm and forearm. This proximal slowing of conduction velocity was more marked for rapidly conducting axons than for the more slowly conducting ones.

3. Gross recordings from dorsal and ventral roots showed that the conduction velocity was slower in the brachial plexus than in the arm for fast afferent as well as efferent nerve fibres.

4. The proximal slowing of conduction velocity was shown to be due neither to errors of measurement nor to proximo-distal differences of temperature.

INTRODUCTION

Measurements of conduction velocity in peripheral nerves are of importance for many types of studies in experimental as well as in clinical neurophysiology. With respect to motor axons, for instance, it has been shown that differences in conduction velocity are related to differences in properties of the motoneurones as well as of the motor units (e.g. Eccles, Eccles & Lundberg, 1958; Bessou, Emonet-Denand & Laporte, 1963; Kernell, 1966; Burke, 1967). For studies involving measurements of axonal conduction velocity it is of interest to know if the conduction speed may change along the peripheral courses of single nerve fibres. Previous studies

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on man have indicated that, within a limb, conduction velocity becomes progressively slower in the more distal portions of a given nerve (Gassel & Trojaborg, 1964; Trojaborg, 1964; Mawdsley & Mayer, 1965; Mavor & Atcheson, 1966). During intracellular studies on forelimb motoneurones in the baboon we discovered that, at least in this animal, there is a marked slowing of conduction velocity in the most proximal portion of single nerve fibres; the conduction velocity was found to be slower within the brachial plexus (between spinal cord and shoulder) than within the arm. In the present paper these new findings are described, and some possible explanations for the results are discussed.

METHODS

The experiments were performed on young baboons of either sex weighing between 4·7 and 7·0 kg. Methods of anaesthesia and intracellular recording from motoneurones were the same as those of Clough, Kernell & Phillips (1968). During experiments the animals were anaesthetized by intravenous injections of pentobarbitone or by nitrous oxide in combination with hexobarbitone. Intracellular records from motoneurones innervating muscles of forearm and hand were obtained from segments C7–8 with conventional micro-electrodes filled with 2 M potassium citrate. Dorsal and ventral roots were intact, and the motoneurones were identified by their antidromic response to stimulation of forelimb nerves. Antidromic spikes usually preceded the onset of post-synaptic potentials (cf. Clough *et al.* 1968), and there was never any difficulty in distinguishing antidromic action potentials from these generated by synaptic action. After the end of some experiments, gross recordings were taken separately from dorsal and ventral roots while peripheral nerves were stimulated. In intracellular recording the latency of antidromic spikes was measured from the onset of the shock artifact to the onset of the action potential in the motoneurone (Fig. 1*A–D*). In root recordings the initial volley was usually diphasic (positive-negative), and the latency was measured to the initial, positive peak (Fig. 1*E–H*). All measurements were done on records consisting of many superimposed sweeps (Fig. 1). Stimuli applied to peripheral nerves had a duration of about 0·12 msec, and they were always kept well above threshold for the unit studied.

The motoneurones belonged to extensor digitorum communis (EDC), other radial forearm muscles, and intrinsic hand muscles innervated by the ulnar or median nerves. For each motoneurone, antidromic action potentials could be elicited by at least two different stimulating electrodes along the same peripheral nerve. Bipolar sleeve electrodes were fitted to nerves exposed *in situ*, and, on the completion of this procedure, the skin wounds were closed (Hern, Landgren, Phillips & Porter, 1962). Proximal stimulating electrodes were placed on radial, ulnar and median nerves respectively within the proximal half of the upper arm. The distal stimulating electrodes were for EDC cells placed on the nerve branch to EDC, for radial cells on the radial nerve at elbow, and for neurones of intrinsic hand muscles on ulnar and median nerves respectively within the distal half of the forearm (close to the wrist). For many of the ulnar neurones, one pair of electrodes in proximal forearm and another in distal upper arm were also used besides the two mentioned above. All stimulating electrodes were bipolar, the cathode was proximal, and measurements of distance from electrodes were always taken from the respective cathodes. During experiments, the spine was in a horizontal position, the upper arm hung vertically and the elbow was at a right angle.

In several experiments subcutaneous temperature was measured simultaneously from the

middle of the upper arm and the middle of the forearm respectively. Rectal temperature was measured in all animals, and it was kept between 36 and 39° C.

After the end of an experiment, conduction distances from the various stimulating electrodes to the spinal cord were measured by laying a thread along the respective nerves *in situ*.

RESULTS

The intracellular records of Fig. 1*A–D* are from an ulnar motoneurone, and they show the latency of the antidromic action potential as the ulnar nerve was stimulated at four different sites along its course in the arm. From records such as these, the latency obtained with one distal and one proximal stimulus site (see Methods) were measured in seventy-nine forelimb motoneurones (nineteen radial, twenty-five EDC, thirty-four ulnar and one median). For each cell a distal conduction velocity was calculated from the conduction distance between the two stimulating cathodes and the difference in latency between the antidromic spikes elicited from these two cathodes. A proximal conduction velocity was calculated from the antidromic latency to proximal stimulation and the conduction distance from the proximal stimulating electrode to the spinal cord. The proximal conduction velocity was slower than the distal one for seventy-six of the seventy-nine motoneurones. Distal conduction velocities ranged from 41 to 87 m/sec, and the proximal ones from 38 to 62 m/sec. In Fig. 2 the relation between proximal (ordinate) and distal (abscissa) conduction velocity is plotted for all the motoneurones. The cells were collected in four groups with different distal conduction velocities (see Fig. 2, legend), and for each group the average proximal conduction velocity has been plotted against the average distal one. Although the scatter of values was rather large, there was an obvious correlation between the two conduction velocities (Fig. 2). The correlation coefficient was $+0{\cdot}56$, and the correlation was statistically highly significant (t-test, $P < 0{\cdot}001$). Thus, either estimate of conduction velocity could be used for comparisons of relative conduction velocity between different motoneurones. It is evident, however, that the two conduction velocities are not directly proportional; a straight line drawn through the values of Fig. 2 would cross the unity line somewhere around a value of 42 m/sec, and it would cross the ordinate at roughly 20–25 m/sec. Thus, the proximal slowing of conduction velocity was more marked for fast axons than for the slower ones. For the fastest group of Fig. 2 the proximal conduction velocity was 74 ± 1 (S.E.)% of the distal one, and for the slowest group the proximal velocity was 90 ± 3 (S.E.)% of the distal one. This difference between fast and slow axons was equally marked when comparing only motoneurones belonging to the same nerve and having about the same axonal conduction distances.

We made some dissections of osmium fixed forelimb nerves, and these

studies showed that bundles of nerve fibres were usually zig-zag folded within the sheath. Thus, the real conduction distances (and conduction velocities) of the single fibres were probably greater than those estimated on the basis of length measurements along the nerve trunks. The zig-zag folding of the nerve fibres was presumably produced by elastic forces

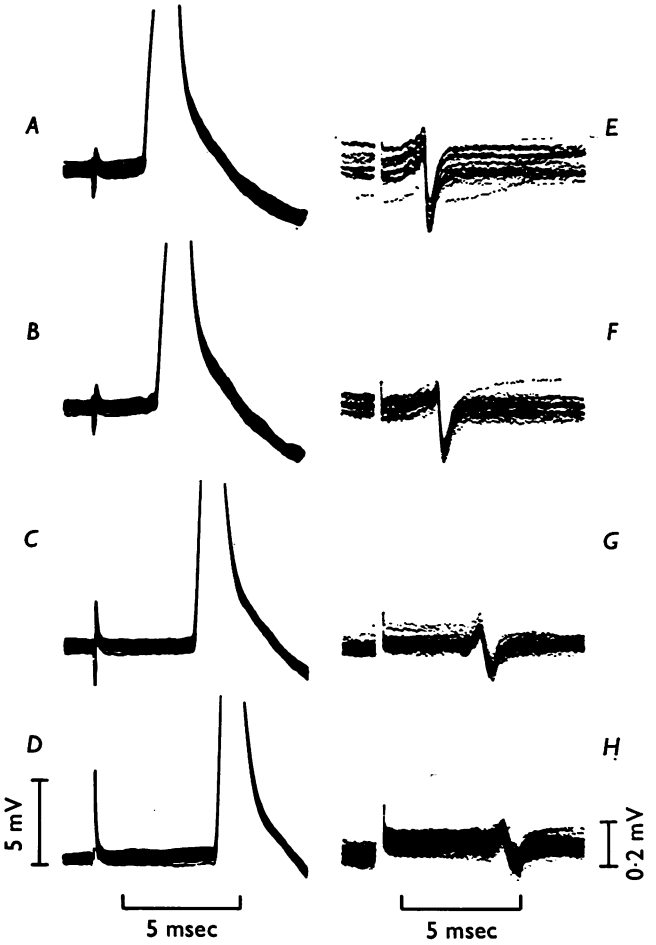

Fig. 1. *A–D.* Intracellular records from ulnar motoneurone belonging to intrinsic hand muscle, showing latency of antidromic spike when ulnar nerve was stimulated in proximal upper arm (*A*), distal upper arm (*B*), proximal forearm (*C*), and distal forearm (*D*).

E–H. Records obtained with an electrode (silver wire) on intact ventral root C8. The 'indifferent' electrode was thrust into muscles of the back. Records show latency of antidromic volley when ulnar nerve was stimulated in proximal upper arm (*E*), distal upper arm (*F*), proximal forearm (*G*), and distal forearm (*H*). Negativity is downwards for all records (*A–H*), and each record consists of several superimposed sweeps.

in the nerve sheath, and it would enable the nerve trunks to elongate during movement without any lengthening of the single nerve fibres. If the zig-zag folding were produced by such purely mechanical factors, then one would expect this folding to be about the same for different nerve fibres irrespective of their diameters (or conduction velocities). Our dissections of osmium fixed forelimb nerves from the baboon showed that each folded

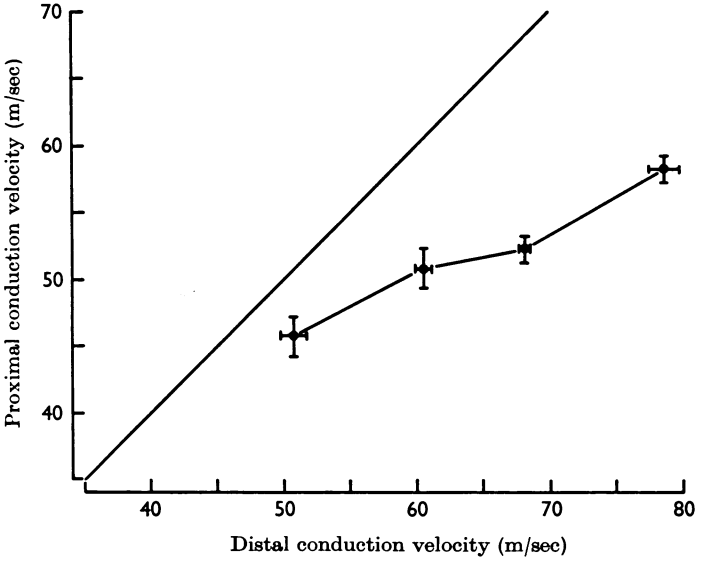

Fig. 2. Diagram showing relation between proximal and distal conduction velocity for axons of seventy-nine motoneurones innervating muscles in forearm and hand. For each motoneurone spikes were elicited by stimulation of its nerve at one proximal and one distal site (see Methods). Conduction velocity was calculated for the portion of the nerve fibre lying between the two stimulus site (distal) and for the part of the fibre lying between the proximal stimulus site and the cell body in the spinal cord (proximal). Motoneurones collected in four groups with distal conduction velocity < 55 m/sec (n = 15), 55–64 m/sec (n = 25), 65–74 m/sec (n = 29), and > 75 m/sec (n = 10). For each group the mean value of proximal conduction velocity is plotted: mean values have been connected by straight lines. Horizontal and vertical bars give the standard error of the respective means. Diagonal line is the unity line.

fibre bundle consisted of axons of all different sizes; these direct observations strongly indicate that the zig-zag folding is actually about the same for small and large nerve fibres. Within a given portion of the nerve, the difference between estimated and real conduction distance would then be the same for all fibres, and, consequently, the estimated conduction velocities would be directly proportional to the real ones. If proximal and distal portions of the nerve fibres had the same real conduction velocity, but differed in their degree of zig-zag folding, then the relation between

estimated proximal and distal conduction velocities would be one of direct proportionality. The findings of Fig. 2 indicate that proximal condudtion velocities are *not* directly proportional to the distal ones. Thus, it seems unlikely that the proximal slowing of conduction velocity would be due simply to an excessive zig-zag folding of the single nerve fibres along their more proximal course.

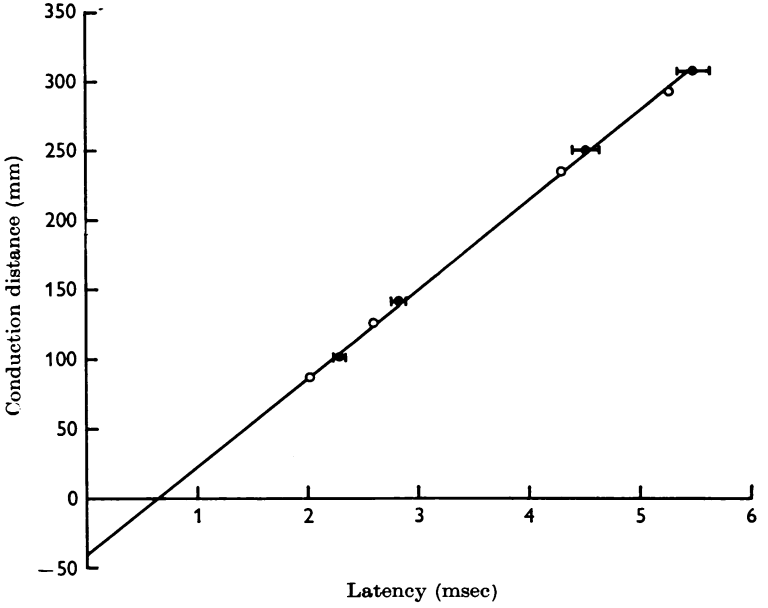

Fig. 3. Diagram showing relation between conduction distance and spike latency for axons of nine ulnar motoneurones (filled circles) and for the fastest group of ulnar fibres in ventral root C8 (open circles). All results are from the same animal, and the ulnar nerve was stimulated at four fixed sites. Conduction distances are given from the recording site (ventral horn and ventral root respectively) to the cathode of each stimulating electrode-pair. For single units conduction distance has been plotted against mean latency of antidromic spikes (filled circles), and horizontal bars given the standard error of the respective means. The regression line was calculated from mean values for single units (filled circles) by the method of least squares. Plotted conduction distances for ventral root recordings (open circles) are 15 mm less than those for single units (see text). Latencies of ventral root volleys were measured to initial positive peak of ventral root records (cf. Fig. 1*E–H*).

More detailed studies of proximal and distal conduction velocities were done on the axons of twenty-four ulnar motoneurones. In these experiments stimulation was given at four different sites along the ulnar nerve (Fig. 1*A–D*), and the typical findings are illustrated in Figs. 3–5 for nine cells from one animal. In Fig. 3 the four different values of conduction distance to the spinal cord have been plotted against the mean values of the

respective antidromic latencies (filled circles). The regression line was calculated from these mean values by the method of least squares. The regression line obviously does not pass through zero; it transects the abscissa at around 0·64 msec and the ordinate at about −40 mm. The conduction velocity between the most proximal electrode and the spinal cord is apparently much slower than the average conduction velocity between the four stimulating electrodes.

The regression line of Fig. 3 passes much too far from zero for the results to be explainable simply as errors of measurement. Latencies were measured with an accuracy of at least ± 0·05 msec, and the duration of the stimulating current pulse was only about 0·12 msec. Measurements of conduction distance were repeatable to within ± 2·2 mm (± 2·3 %) for the distance between the proximal electrode and the spinal cord, and to within ± 0·5 mm (± 0·8 %) for distances between electrodes in the arm. The latter distances were measured *in situ* with the ulnar nerve exposed along its whole course. The distance from the proximal electrode along the brachial plexus to the cord was measured by a thread introduced through the axilla with the help of a long straight needle, and made to emerge through the appropriate root canal in the vertebral column. In one case the central portion of the ulnar nerve was dissected out and measured under full visual control, and the difference between this measurement and the one obtained in the usual manner was 3 mm (3 %).

In Fig. 4 the average conduction velocity is shown for each of four different portions of the ulnar axons (between arrows), and zero on the abscissa corresponds to the site of the spinal cord. The results demonstrate that there was no progressive slowing of conduction velocity from the periphery towards the centre. Conduction velocity was very slow between spinal cord and upper arm, it was fast within the upper arm, and it became a little slower again towards the elbow and within the forearm (Fig. 4). The conduction velocity of the most proximal part of the axons was, however, much slower than that of the most distal portion of the same fibres (Fig. 4), and the difference between these two mean values of conduction velocity is statistically highly significant (*t*-test, $P < 0{\cdot}001$). While the records were being obtained from these nine cells (Fig. 4), the mean rectal temperature was 38·4 ± 0·3° C (mean ± S.E.), the subcutaneous temperature of the upper arm was 36·8 ± 0·6° C, and that of the lower arm 32·7 ± 0·3° C. Within the trunk (between spinal cord and shoulder) the temperature of the nerve should be close to the rectal temperature, and within the arm the nerve temperatures would presumably have values somewhere in between the rectal (body) temperature and the respective subcutaneous temperatures. Thus, in these experiments (Fig. 4) the nerve was apparently warmer proximally (within the trunk) than distally

(within the arm). Such a temperature gradient would tend to make proximal conduction velocities faster than the distal ones. Therefore, the proximal slowing of conduction velocity (Figs. 3–4) could not have been due to the proximo-distal gradient of temperature.

In the animal of Fig. 4 the proximo-distal gradient of subcutaneous temperature was unusually marked (see above), and the progressive slowing of conduction velocity towards *distal* parts of the limb might to a

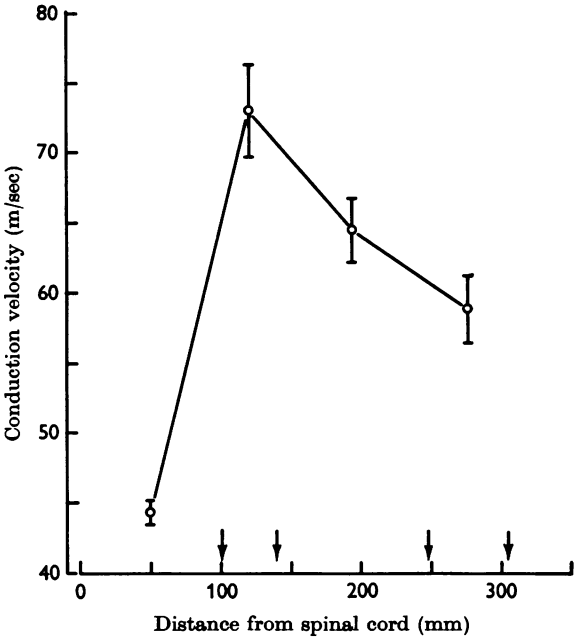

Fig. 4. Diagram showing mean conduction velocity of motor fibres at various distances from the spinal cord. Results are from the same nine ulnar motoneurones as those of Fig. 3, and the ulnar nerve was stimulated at four fixed sites (arrows). Values along the abscissa give distances from spinal cord measured along the ulnar nerve. For each of four portions of the nerve (between arrows) the mean conduction velocity of the nine single units has been plotted against the mean distance from the spinal cord, and plotted mean values have been connected by straight lines. Vertical bars give the standard error of the respective mean value of conduction velocity. It should be noted that values refer to the mean conduction velocity *within* each portion of the motor axon.

large extent have been due to a corresponding gradient of temperature close to the nerve. In other animals a distal slowing of conduction velocity within the arm was seen also when the difference of subcutaneous temperature between upper and lower arm was relatively slight (0·5° C). No specific attempts were made, however, to decide to what extent factors other than temperature might be responsible for this variation in

conduction speed. The distal slowing of conduction velocity was about equally marked for fast and slow nerve fibres. A distal slowing of conduction velocity within limbs has previously been found in man, and such studies have indicated that factors other than temperature would be responsible for much of the phenomenon (Gassel & Trojaborg, 1964; Mawdsley & Mayer, 1965; Mavor & Atcheson, 1966).

In animal experiments, conduction velocity is often calculated from measurements of spike latency and conduction distance with only one

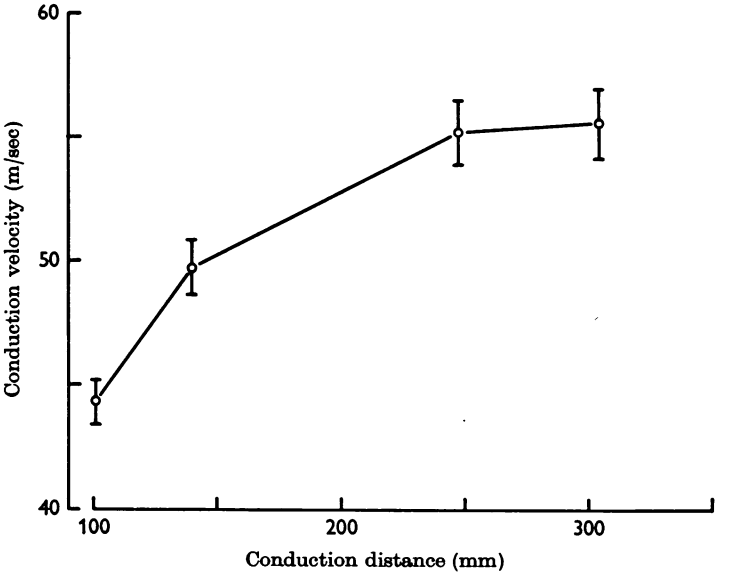

Fig. 5. Diagram showing the different conduction velocities that would have been measured if the stimulating cathode had been placed at different positions along the course of the ulnar nerve. Results are from the same nine ulnar motoneurones as those of Figs. 3–4, and the ulnar nerve was stimulated at four fixed sites. For each stimulus site the conduction velocity of single units was calculated from measurements of antidromic latency and conduction distance to the spinal cord. For each stimulus site, the mean conduction velocity of the nine single units has been plotted against conduction distance, and plotted mean values have been connected by straight lines. Vertical bars give the standard error of the respective mean values of conduction velocity.

stimulating cathode on peripheral nerve. The diagram of Fig. 5 demonstrates the different conduction velocities that would have been measured in such experiments on baboons if the stimulating cathode had been placed at proximal or distal sites along the peripheral nerve. Values are from the same nine ulnar cells as those of Figs. 3–4, and the conduction velocity has here (Fig. 5) been calculated for each site of stimulation from total spike latency and total conduction distance to the spinal cord. It is seen

that the more distal the electrode is placed, the faster is the mean conduction speed. Such results are, of course, what would be expected from those already shown in Figs. 3–4.

In four different baboons separate recordings were obtained from dorsal and ventral roots. Stimulation was given at four sites along the ulnar nerve, and typical recordings from a ventral root are shown in Fig. 1*E–H*. The latency of the initial volley was measured in ventral as well as in dorsal roots (see Methods), and with either type of root the results were similar to those obtained from motoneurones (Figs. 2–5). The open circles of Fig. 3 represent values from a ventral root in the animal from which the single units of the same diagram were recorded. Values from the ventral root (open circles) are seen to follow the straight line drawn through values from single units (filled circles). Conduction distances were estimated to be 10–15 mm shorter for the ventral root recording than for recordings from motoneurones, and the values from the root have been plotted with 15 mm shorter distances in Fig. 3. The experiments on dorsal and ventral roots showed (i) that the main site of the proximal slowing of conduction velocity was not within the spinal cord, and (ii) that the proximal slowing of conduction velocity was a property of afferent as well as efferent nerve fibres from the baboon's forelimb.

DISCUSSION

The results have shown (Figs. 1–5) that conduction velocities measured in single axons of the baboon's forelimb nerves are much slower within the most proximal part of the fibres (between spinal cord and shoulder) than within their more distal portions (within the forelimb). The experiments have also shown that the proximal slowing of conduction velocity could not be due simply to errors of measurement or to differences in temperature. The difference between fast and slow axons (Fig. 2) made it seem unlikely that the proximal slowing of conduction velocity would be due merely to an excessive zig-zag folding of single nerve fibres within the proximal portions of the nerves. Thus, although more evidence is needed for a conclusive proof, the results strongly indicate that the conduction velocity of single myelinated axons is genuinely slower in portions lying within the brachial plexus than in parts lying within the arm. In previous studies, no comparisons seem to have been made between the properties of nerve fibres running within the plexus and within the nerves of the limbs.

The proximal slowing of conduction velocity obviously has to be taken into account when conduction velocities measured over different portions of peripheral nerves are to be compared. In some recent experiments on

the baboon's forelimb nerves, for instance, a higher maximal conduction velocity for sensory fibres was found in the ulnar and median nerves (McLeod & Wray, 1967) than in the nerve to extensor digitorum communis (Eccles, Phillips & Wu Chien-ping, 1968). In the former study the conduction velocities were measured between different stimulating electrodes in the forearm (McLeod & Wray, 1967) and in the latter the measurements were done between one stimulating cathode at the elbow and the recording site at the spinal cord (Eccles *et al.* 1968). According to the present results (Figs. 1–5) a higher value of conduction velocity would be expected by the method of measurement used by McLeod & Wray (1967).

The conduction velocity in a myelinated axon is determined by many different factors, such as the properties of the nodal membrane and geometrical dimensions of the fibre which are important for the passive spread of currents (e.g. internal diameters, myelin thickness, internodal distance (Huxley & Stämpfli, 1949; Rushton, 1951; Hodgkin, 1963). The proximal slowing of conduction velocity could be due to proximo-distal differences in one or several of these different factors, and in addition there might be some proximo-distal difference in zig-zag folding; elaborate anatomical and physiological investigations would be needed for a full explanation of the present findings. The functional significance of the proximal slowing of conduction velocity is probably very slight, and it seems likely that the phenomenon is an 'accidental' by-product of the events taking place in the outgrowth and maturation of peripheral nerves.

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