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INTRAMUSCULAR PROPAGATION OF SENSORY IMPULSES

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There is now overwhelming evidence of different kinds that in the Pacinian corpuscle there is no detectable propagation of impulses in the non-myelinated ending, either antidromic (Diamond, Gray & Inman, 1958*a*) or orthodromic (Diamond, Gray & Sato, 1956; Diamond, Gray & Inman, 1958*b*; Loewenstein, 1958; Loewenstein & Rathkamp, 1958). Another point that seems to have been established is that the after-effects of an antidromic impulse on the ending are similar to those of an orthodromic one (Diamond *et al.* 1958*a*). This was shown clearly earlier in the sensory cell of the crayfish stretch receptor (Eyzaguirre & Kuffler, 1955).

If direct evidence could be obtained these properties would probably also be found in other visceral and somatic sensory receptors. However, at present it is only possible to obtain indirect evidence in these receptors. Such evidence, which happens to be conclusive in the present instance, has been obtained in muscle stretch receptors of the cat and is presented in this paper. The essence of the experiments lies in the procedure for determining intramuscular conduction time accurately. This has been described briefly already (Paintal, 1958). The basis of this procedure rests on the assumption that recovery of the ending following an antidromic impulse is identical with that following an orthodromic one. The experiments have shown that this assumption is correct.

METHODS

Experiments were carried out on adult cats anaesthetized with chloralose (80 mg/kg). The left hind limb of the cat was immobilized by transfixing the lateral malleolus with a steel pin, applying firm pressure on the pelvis and supporting the thigh. The sciatic nerve was exposed and a length of about 1–2 cm of the lateral gastrocnemius-soleus nerve was separated from the rest of the sciatic nerve at a point about 50–90 mm central to its entry into the muscle. At this point filaments from the nerve were dissected and action potentials recorded according to methods described previously (Paintal, 1953). In some experiments potentials were also recorded from filaments of the medial

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gastrocnemius nerve and the nerve to the tenuissimus. A pair of stimulating electrodes were placed under the nerve close to the point of entry of the nerve into the muscle. Isometric contractions of the gastrocnemius-soleus muscle were recorded by connecting the tendo Achillis to a strain gauge and d.c. amplifier.

In some experiments an electromagnetic puller was used for applying brief pulls of about 3 msec duration to the muscle. This puller was powered by an audioamplifier whose output was regulated by the intensity of square-wave pulses from a stimulator, which in turn was synchronized with or triggered by the oscilloscope sweep. In these experiments the tendon was connected directly to the puller and the changes in muscular tension produced by the puller were recorded by a strain gauge applied laterally to the string connecting the puller to the muscle. By using two strain gauges (the second representing the muscle), it was confirmed experimentally that the phasic change in tension recorded by the lateral strain gauge was a constant fraction of the actual tension applied to the muscle. Absolute values of tensions developed in the muscle by the puller were not determined, as this information was not necessary for the purpose of the present experiments.

About 3–5 times the amount of tubocurarine necessary to produce complete extrafusal neuromuscular block was injected intravenously. This was probably adequate for producing intrafusal neuromuscular block as well (cf. Hunt, 1952; Granit, Skoglund & Thesleff, 1953).

The conduction velocities of individual afferent fibres were determined by using techniques and criteria described previously (Paintal, 1953).

RESULTS

Figure 1 shows the type of responses obtained by pulling the muscle briefly for about 3 msec with the puller. The upper trace is a record of the tension recorded by the lateral strain gauge; the lower one shows the appearance of an

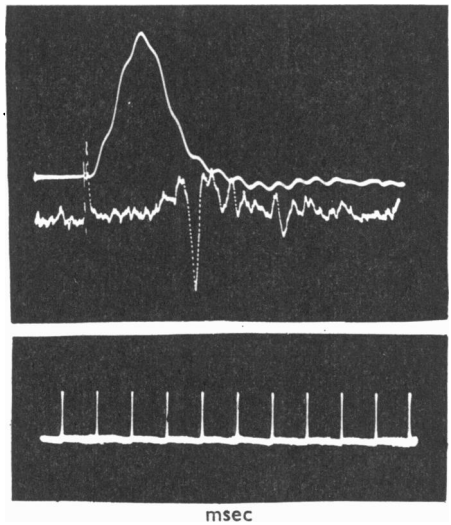

Fig. 1. A typical record from a gastrocnemius-soleus stretch receptor showing the type of response obtained by pulling the muscle briefly with a puller. The upper trace is a record of tension recorded with the lateral strain gauge. The lower trace shows the appearance of an impulse with a pull-impulse latency of 2·58 msec. The initial artefact is due to the electrical pulse delivered to the puller by the stimulator. Graph of Fig. 4 was plotted from this receptor.

orthodromic impulse at the recording electrodes after a certain pull-impulse latency, in this case 2·58 msec. This pull-impulse latency which is reckoned from the beginning of the pull includes, in addition to the time required for impulse initiation at the ending, the total conduction time from the ending to the recording electrodes. This conduction time is made up of intramuscular conduction time (t_i) from the ending to the cathode of the stimulating electrodes (placed close to the entry of the nerve into the muscle) and extramuscular conduction time (t_0) from the stimulating to the recording electrodes.

If a brief pull is applied at a constant interval after an orthodromic impulse belonging to the steady discharge in an adapted receptor, then the pull-impulse latency very often does not vary by more than 0·1 msec. Expressed as a percentage of the total pull-impulse latency this amounts to a variation of about 3%; frequently the variation is less, and rarely it may exceed 5%. The variation is of the same order if the pull is applied at a fixed interval after an antidromic stimulus, provided that no orthodromic impulse belonging to the steady discharge falls immediately before the stimulus. This is because, as was shown by Matthews (1933), the conditioning effect of a preceding orthodromic impulse on the effect of an antidromic one can be considerable if the latter falls in the early part of the impulse cycle. This influence of the orthodromic impulse on the effect of an antidromic stimulus on pull-impulse latency (see below) is insignificant if it appears more than 2–3 msec before the antidromic stimulus. Therefore, in this investigation and in the accompanying one (Paintal, 1959) only those observations have been considered in which this modifying influence of preceding orthodromic impulses has been excluded wherever necessary.

The normal time of appearance of the pull impulse at the recording electrodes (i.e. *average* pull-impulse latency) serves as a convenient reference point to describe the position in time of another event, e.g. an antidromic stimulus. The same purpose could be achieved by using the beginning of the pull as a reference point, but if this is done the resulting graphs such as that of Fig. 2 become unduly complicated because it then becomes necessary to assign positive and negative values for impulses appearing before and after the beginning of pull, respectively.

Plotting the pull-impulse latency (ordinate) against the interval between an antidromic stimulus and the normal time of appearance of a pull impulse (abscissa) yields a recovery curve of the type shown in Fig. 2 (○). If the stimulus is applied too near to the expected appearance of the pull impulse then the latter does not appear. This is due to the fact that the pull pulse lasts only about 3 msec so that if the antidromic stimulus is applied close enough, the period of depression will outlast the pull pulse, resulting in the absence of the pull impulse.

If the pull pulse is applied at varying intervals after an orthodromic impulse

belonging to the steady discharge of impulses in an adapted receptor, the resulting recovery curve is identical in shape with that obtained with an antidromic stimulus, except that it is displaced horizontally to the left. This was confirmed in several instances e.g. Fig. 2 (●); it is clear that the two curves are identical in shape and that they are displaced by a fixed interval at all parts of the curve. This difference may vary somewhat at the lower parts of the curve in some cases (but not in that shown in Fig. 2) owing to errors introduced by the curves flattening out.

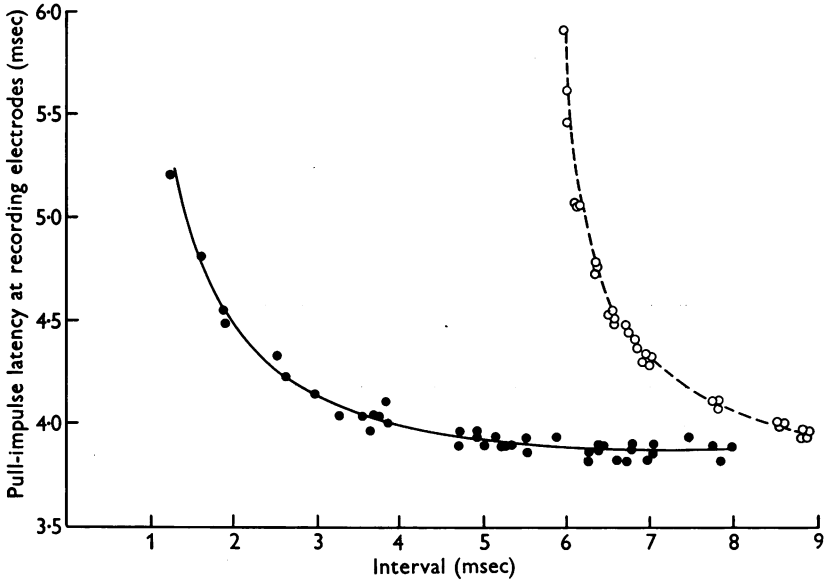

Fig. 2. Recovery curves showing effects of a preceding orthodromic impulse ● and an antidromic stimulus ○ on pull-impulse latency of a tenuissimus stretch receptor (receptor no. 1 in Table 1). Abscissa represents interval between orthodromic impulse or antidromic stimulus and normal time of appearance of pull impulse at the recording electrodes. From this and similar curves the intramuscular conduction distance was computed and tabulated in Table 1. The two curves can be superimposed; the apparent difference in shape is an optical illusion.

Assuming that recovery following antidromic and orthodromic impulses is identical (Eyzaguirre & Kuffler, 1955; Diamond *et al.* 1958*a*), it was expected that the horizontal displacement of the two curves in Fig. 2 would be due to the difference in the conduction times involved in the two cases. Whereas the interval difference between an orthodromic impulse belonging to the steady discharge and a pull impulse at the recording electrodes represents for practical purposes the actual difference in interval between the two impulses at the receptor itself, it is not so in the case of the antidromic stimulus.

Suppose that, as is shown in Fig. 3, a pull impulse appears at the recording

electrodes at moment P on the oscilloscope. For this to happen the impulse must have been initiated at the ending at moment P', i.e. at t_1+t_0 msec before arrival of the impulse at the recording electrodes. Now if an antidromic *stimulus* were applied at moment A, then, ignoring setting-up time at the stimulating electrodes (Blair & Erlanger, 1936) for the present, the antidromic impulse will arive after t_1 msec at moment A', i.e. I_a msec before the normal time of initiation of the pull impulse at the ending. The interval that can be measured on the oscilloscope is I (interval between antidromic stimulus and pull impulse at recording electrodes), so that it is obvious from Fig. 3 that the actual interval I_a between arrival of the antidromic impulse at the ending and normal moment of initiation of the pull impulse at the ending is equal to I minus $2t_1+t_0$ msec.

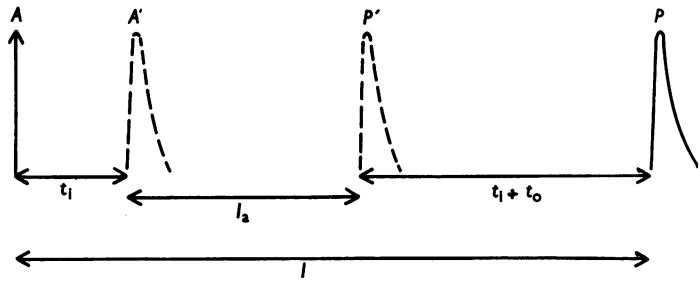

Fig. 3. Schematic drawing showing that actual interval between arrival of the antidromic impulse A' at the ending and the normal time of initiation of a pull impulse P' at the ending is equal to I_a. I = interval between the antidromic stimulus A and the normal time of appearance of pull impulse P at the recording electrodes.

It therefore follows that the two curves in Fig. 2 should be displaced horizontally by $2t_1+t_0$ msec. Since t_0 is determined experimentally t_1 can be computed, thus permitting evaluation of total conduction time from the ending to the recording electrodes. In practice the *measured* value of t_0 includes the relatively insignificant and unknown factor of setting-up time at the stimulating electrodes. This factor is eliminated in the calculation of t_1, so that the intramuscular conduction time so determined is the actual conduction time from the ending to the stimulating electrodes. Assuming unchanged conduction velocity of the afferent fibre in its intramuscular course, intramuscular conduction distance can therefore be determined. In order to prove that these conclusions were correct, experiments were done on stretch receptors of the tenuissimus muscle. The following experimental procedure was adopted.

Stimulating electrodes were placed under the tenuissimus nerve (or a branch of the nerve) close to the muscle and impulses were recorded from afferent fibres dissected off the nerve 30–50 mm more proximally. The muscle was connected to the puller and sufficient initial tension was applied in order to produce a regular discharge of 20–50 impulses/sec in different afferent fibres

from stretch receptors. The conduction velocity of the fibre was then determined. After this pull impulses were generated and the effects of orthodromic and antidromic impulses on pull-impulse latency recorded. The muscle was then crushed progressively and the position of the receptor in the muscle established as being between the last ineffective crush and the effective crush that abolished activity from the ending. Keeping the muscle moderately stretched the respective conduction distances from the points of crushing (effective and last ineffective crush) to the cathode of the stimulating electrodes was measured with a pair of dividers. These were the experimentally determined limits of intramuscular conduction distance (columns 6 and 7 in Table 1). Finally, intramuscular conduction distance was computed from recovery curves plotted from the records. This is given in column 5 of Table 1. Altogether, ten such experiments were performed and they are summarized in Table 1. With the exception of one ending (no. 6, Table 1), the correspondence between the computed and experimentally determined intramuscular conduc-

TABLE 1. Comparison of intramuscular conduction distances from stretch receptors in the tenuissimus to the stimulating electrodes obtained by crushing the muscle and from recovery curves respectively

Serial no. of receptor	Position of receptor*	Conduction velocity (m/sec)	Intramuscular conduction time (msec)	Intramuscular conduction distance (mm)		
				From recovery curves	By crushing muscle	
					Effective crush	Ineffective crush
1	Tibial	28·5	1·91	54·5	57·0	59·0
2	Tibial	62·6	0·11	6·9	8·5	12·0
3	Pelvic	40·3	0·60	24·1	24·0	26·0
4	Pelvic	27·3	0·32	8·7	7·5	8·5
5	Tibial	25·8	0·74	19·1	15·0	22·0
6†	Pelvic	37·6	1·15	43·2	10·5	17·0
7	Tibial	30·8	2·54	75·4	74·0	78·0
8	Tibial	39·8	1·13	45·0	43·0	47·0
9	Tibial	35·4	0·37	13·1	12·0	18·0
10	Pelvic	93·3	0·41	38·2	37·0	40·0

* Terminology according to Adrian (1925). † See text for remarks.

tion distances is most striking, particularly in those fibres in which the position of the receptor could be narrowed down to within a few millimetres, e.g. fibres 1, 3, 4, 7, 8, and 10 (Table 1). The correspondence is true for widely varying conditions such as extramuscular conduction distance, conduction velocity of the fibres, and the relative positions of the receptors in the muscle. The difference in the computed and actual intramuscular conduction distance in the case of fibre no. 6 was due to the fact that the measured conduction distance did not provide a measure of the true intramuscular conduction distance, because the afferent fibre made a loop in the tibial part of the muscle before entering the nerve trunk.

Since the results recorded in Table 1 have shown that determination of

intramuscular conduction time from recovery curves is satisfactory and that total conduction time from the ending to the recording electrodes can be accurately computed, it is now possible to study the time course of initiation of nerve impulses in muscle stretch receptors and the effects of antidromic impulses on them.

Relation of pull-impulse latency to pull intensity

If pull-impulse latencies are plotted against pull intensity, then a curve typical of Fig. 4 is obtained. This is similar to those obtained in Pacinian corpuscles (Gray & Malcolm, 1950) and cutaneous receptors (Gray & Malcolm, 1951; Jarret, 1956). Figure 4 was plotted after allowing for total conduction time which amounted to 1·4 msec (t_1 = 0·7 msec, t_0 = 0·7 msec). The minimum pull-impulse latency was 1·22 msec with pulls of maximum intensity. As the intensity of pull was reduced the latency increased. The time to peak pull was 1·55 msec and the pull pulse was over by 3·2 msec (Fig. 1). In the receptor of Fig. 4, therefore, the impulse was initiated before peak pull was reached, i.e. it was excited by the rising phase of the pull pulse of maximum intensity. At latencies of 1·6–1·7 msec the receptor was presumably excited during the peak of the pulse, assuming negligible distortion of the pulse at the ending. Since it was a stretch receptor, and since there is no break or inflexion in the curve, it follows that the impulses with latencies greater than 1·7 msec must also have been excited by the peak of the pull pulse and not by the falling phase of the pulse. A similar conclusion can be drawn from Fig. 5 in which the minimum pull-impulse latency was 0·6 msec. The greater latencies must therefore be due to greater excitation times at lower intensities of mechanical stimulation. This is in agreement with the observations of Gray & Malcolm (1950).

The minimum pull-impulse latencies together with certain other pertinent information are given in Table 2. As expected, these latencies varied from one receptor to the other and they bore no relation to the conduction velocity of their afferent fibres; nor was there any relation to the position of the receptor in the muscle. An important point in this connexion is that the pull pulse as recorded near the tendon may not represent the exact shape of the pulse experienced by the ending; there may also be a small delay in the arrival of the pull pulse at the receptor, in which case the actual pull-impulse latencies will be less. The minimum pull-impulse latencies are of the same order of magnitude as those found in the Pacinian corpuscle (Gray & Malcolm, 1950).

Effect of an antidromic impulse

It is possible to study the effect of an antidromic impulse on the relation of pull intensity to pull-impulse latency by positioning an antidromic impulse before initiation of the pull impulse. This will be referred to as antidromically

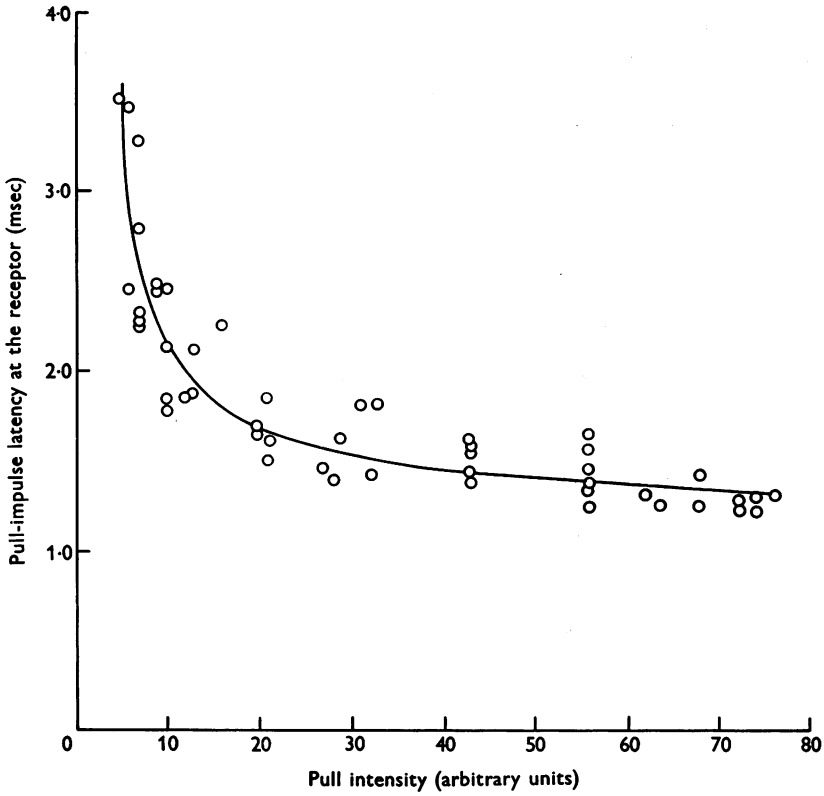

Fig. 4. Graph showing relation of pull-impulse latency to pull intensity of a lateral gastrocnemius-soleus stretch receptor. Plotted from receptor illustrated in Fig. 1. Total conduction time from the ending to the recording electrodes was 1·4 msec.

TABLE 2. Minimum pull-impulse latencies and conduction times in stretch receptors of lateral gastrocnemius-soleus and tenuissimus muscles

Serial no. of receptor	Conduction velocity of afferent fibre (m/sec)	Intramuscular time (msec)	Total conduction time (msec)	Minimum pull-impulse latency at ending (msec)
1	73·0	0·70	1·40	1·22
2	106·0	0·17	0·58	0·75
3	97·5	0·24	0·68	1·09
4*	28·5	1·91	2·77	1·09
5	82·8	0·30	0·86	0·61
6	65·0	0·48	1·08	2·46
7*	37·6	1·15	2·02	2·64
8	90·8	0·85	1·30	1·78
9	?	?	?	<1·0
10*	30·8	2·54	4·10	1·18

* From tenuissimus muscle.

conditioned pull-impulse latency curve. With a fixed position of the antidromic stimulus therefore, pull-impulse latencies and antidromically conditioned pull-impulse latencies can be recorded for particular values of pull intensities and curves of the type shown in Fig. 5 obtained. By varying the position of the antidromic stimulus a family of curves can be obtained. In

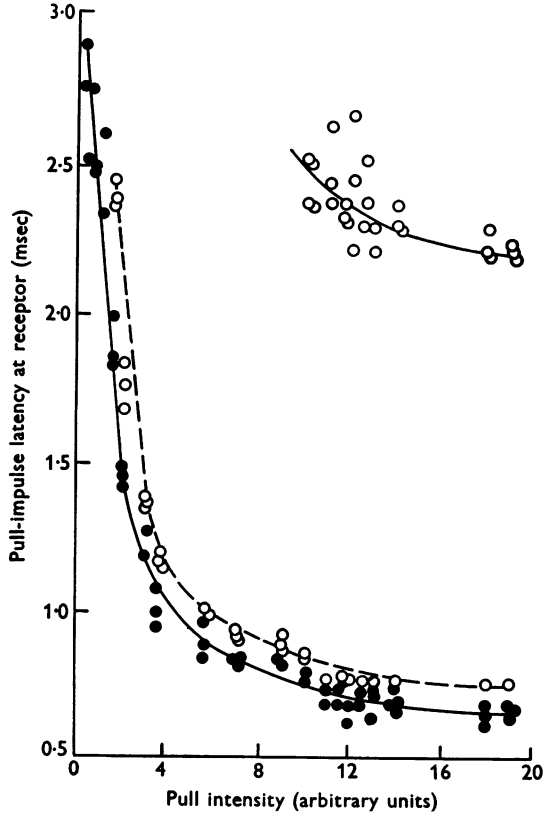

Fig. 5. Graphs showing relation of pull intensity to pull-impulse latency and antidromically conditioned pull-impulse latency in a lateral gastrocnemius-soleus stretch receptor. Graph ●—● = pull-impulse latency; graph ○- - -○ = antidromically conditioned pull-impulse latency with antidromic stimulus 4·9 msec before arrival of pull impulse at recording electrodes; graph ○—○ = antidromically conditioned pull-impulse latency with antidromic stimulus 0·4 msec before arrival of pull impulse at recording electrodes.

Fig. 5 curves for two positions of the antidromic stimulus are shown. Exactly the same type of curve would be obtained with orthodromic impulses provided the relation of the impulse to the pull could be kept constant, which is technically somewhat complicated owing to problems connected with triggering the stimulator at exactly the same part of the impulse each time.

The antidromically conditioned curves in Fig. 5 are displaced upwards and

to the right, because the threshold of the receptor is increased and because a minimum recovery time is necessary after the antidromic impulse before an orthodromic impulse can be initiated. The displacement becomes greater as the antidromic impulse is brought closer to the pull impulse (Fig. 5). This is obviously because of greater depression of excitability during the pull.

If the curves of Fig. 5 were plotted in terms of multiples of threshold equal to 1 in each case, then all the curves would be superimposed in the initial part and there would be the same upward displacement in the latter part as in Fig. 5. This procedure has been used by Gray & Malcolm (1950) and Jarret (1956). However, it has not been used in the present investigation (and especially in Paintal, 1959) because it tends to mask certain changes in recovery of excitability by artificially increasing the slope of the curve of antidromically conditioned pull-impulse latency. It is for this reason that arbitrary units of stimulus intensity have been used (Figs. 4, 5); these units are proportional to the actual tension applied to the muscle.

DISCUSSION

The results of Table 1 have shown that the method used for computing intramuscular conduction time is quite satisfactory because the experimental procedure assured random selection of the endings and the precise location of these endings was confirmed repeatedly in the tenuissimus muscle. From these results the following conclusions follow: (1) If it is assumed that with the tenuissimus moderately stretched there are no more undulations in the intramuscular course of the afferent *fibre* than there are in the nerve outside the muscle, then it follows that the conduction velocity of the fibre is unchanged from the ending to the spinal cord. If the above assumption is incorrect then the conduction velocity of the intramuscular part must be a little greater than the extramuscular part. (2) Since these experiments were based on the assumption that recovery of the ending following an antidromic impulse is identical with that following an orthodromic one, it follows that this assumption is correct. (3) There is probably no propagation of the nerve impulse in the non-myelinated ending. If there is, it must be over a distance of less than 50 μ, because non-myelinated propagation of 50 μ would involve intramuscular conduction time of about 0·05 msec, which in some instances would have revealed itself as an excess of about 15–40 % in the computed intramuscular conduction distance (Table 1). 50 μ would amount to only 5–10 % of the total length of the non-myelinated segment of the primary ending which has been computed to be about 0·5–1 mm in length if the ending is uncoiled (Dr Sybil Cooper, personal communication).

The sensory terminations in muscle stretch receptors are non-myelinated (see Barker, 1948) and if, as the present evidence reveals, there is no propagation of impulses in this region, these terminations must therefore be

concerned with local non-propagated events, e.g. generation of spindle potentials, as in the Pacinian corpuscle (Diamond *et al.* 1956; Loewenstein, 1958). In contrast, from evidence obtained by stimulating the outer and inner surfaces of the skin, Catton (1958) concluded there was some non-myelinated propagation of sensory impulses near the endings in frog's skin.

Under constant conditions the relationship of the curves of pull-impulse latency (●, Fig. 5) and antidromically conditioned pull-impulse latency (○, Fig. 5) to each other is unchanged. The difference between the two groups of curves depends on the degree of recovery of excitability of the ending. If, therefore, with a fixed position of the antidromic stimulus the relationship between the two curves is altered by some agent (e.g. drug), it will follow that certain recovery processes have been altered. Since plotting the graphs after the administration of a drug may be difficult in the presence of rapid changes in responses, the same purpose can be achieved by plotting the graphs (as in Fig. 5) first and evaluating the change in the antidromically conditioned response with reference to the pull-impulse latency after the drug. On this basis changes in recovery of excitability following an antidromic impulse have been evaluated in stretch receptors after repetitive antidromic stimulation, adrenaline and asphyxia in the accompanying paper (Paintal, 1959).

SUMMARY

1. A satisfactory technique is described for computing intramuscular conduction time in afferent fibres by pulling a muscle briefly, and comparing the effect of a preceding antidromic stimulus with that of an orthodromic impulse on pull-impulse latency in muscle stretch receptors of cats. Proof of the validity of this technique was provided by showing that the position of ten stretch receptors in the tenuissimus muscle determined in this way corresponded very closely to that established by crushing the muscle.

2. The results have shown that there is no detectable propagation of sensory impulses in the non-myelinated part of the endings and that recovery of excitability of the ending after an antidromic impulse is identical with that after an orthodromic one. They have also provided a means for determining total conduction time in any afferent fibre whose receptor has a regular discharge of impulses and is amenable to precise mechanical stimulation.

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