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FIELD POTENTIALS AND EXCITATION OF PRIMATE SPINOTHALAMIC NEURONES IN RESPONSE TO VOLLEYS IN MUSCLE AFFERENTS

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SUMMARY

1. In anaesthetized monkeys, stimulation of muscle afferents results in a sequence of cord dorsum potentials. These include a group I volley followed by several negative potentials called here the NI, NII and NIII waves.

2. Evidence based on the effects of graded stimulus strengths, measurements of latencies, and the results of anodal blockade of large muscle afferents indicate that the NI, NII and NIII waves are evoked, respectively, by group I, II and III muscle afferents.

3. The NII and NIII waves appear to be confined to the lumbosacral enlargement when evoked by hind limb muscle afferents. However, the group I volley and NI wave can be detected at least as far rostrally as L 3.

4. The NII and NIII waves were mapped in the depth of the cord. The maxima for these waves were found in the neck of the dorsal horn. The waves reversed to become positive in the ventral horn.

5. Using graded electrical stimulation of muscle nerves it was possible to demonstrate that a few spinothalamic tract neurones could be activated monosynaptically by group I volleys; other spinothalamic cells may have been activated polysynaptically by group I volleys. The lack of any substantial excitation of spinothalamic neurones by intra-arterial injections of succinylcholine suggests that these group I actions may have been due to group Ib afferents from Golgi tendon organs.

6. The most potent excitation of spinothalamic tract cells was due to the action of middle sized and small muscle afferents. Evidence was obtained for an excitatory action of group II, III and IV afferents. There was a good correlation between the effects of graded stimulation in evoking discharges in separate bursts associated with the arrival of volleys in group II and group III afferents and the generation of the NII and NIII waves.

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7. Some spinothalamic neurones, including several located in lamina I, were unaffected by the muscle afferent volleys used. It is suggested that such neurones might help to signal well localized pain, whereas the cells which respond to a variety of cutaneous and muscle afferents might be involved in signalling poorly localized pain which is subject to referral.

INTRODUCTION

The spinothalamic tract is regarded as the major pathway for nociception in primates, including man (Foerster & Gagel, 1931; Kuru, 1949; Morin, Schwartz & O'Leary, 1951; White & Sweet, 1955). Recent studies have shown that it is possible to identify spinothalamic tract neurones in recordings from the spinal cord by antidromic activation of these cells from the thalamus (Dilly, Wall & Webster, 1968; Trevino, Coulter & Willis, 1973; Albe-Fessard, Levante & Lamour, 1974). In monkeys, such neurones are commonly activated by cutaneous nociceptors, and usually also by cutaneous mechanoreceptors (Willis, Trevino, Coulter & Maunz, 1974). Many of the nociceptive-specific spinothalamic tract neurones are located in the vicinity of the marginal zone, a region which contains a high proportion of neurones excited by Aδ mechanical nociceptors and often also by C polymodal nociceptors (Christensen & Perl, 1970; Kumazawa, Perl, Burgess & Whitehorn, 1975; Cervero, Iggo & Ogawa, 1976; Kumazawa & Perl, 1978). Other nociceptive-specific spinothalamic neurones are located in deeper regions of the dorsal horn, including the area equivalent in the monkey to lamina V of the cat (Rexed, 1952; Willis *et al.* 1974). However, most of the spinothalamic neurones in the neck of the dorsal horn are activated by both cutaneous mechanoreceptors and nociceptors and thus have a 'wide dynamic response' range similar to that described for many interneurones in this part of the dorsal horn (Wall, 1960, 1967; Mendell, 1966).

In addition to a cutaneous input, many of the interneurones in lamina V of the cat dorsal horn receive excitatory connexions from group III muscle afferents (Pomeranz, Wall & Weber, 1968). Furthermore, interneurones activated by group II muscle afferent fibres are found in laminae IV–VI of the cat dorsal horn (Fukushima & Kato, 1975). There is evidence that the spinothalamic tract conveys nociceptive input originating from tendons (Yoss, 1953), and at least some spinothalamic tract cells have receptive fields in deep tissues of the hind limb (Willis *et al.* 1974) or can be activated by electrical stimulation of muscle nerves (Foreman, Applebaum, Beall, Trevino & Willis, 1975). It seemed likely to us that many spinothalamic tract neurones in the monkey would have potent connexions from muscle afferents. However, additional information is needed before it will be possible to specify what types of deep receptors can activate spinothalamic neurones. This and the companion paper (Foreman, Schmidt & Willis, 1978) contain the results of an investigation of the effects of electrical, chemical and mechanical stimulation of muscle afferent upon spinothalamic tract cells in the monkey. Preliminary results have been reported (Foreman, Schmidt & Willis, 1977*a*, *b*).

METHODS

The experiments were done on forty-one cynomologous monkeys (*Macaca fascicularis*). Anaesthesia was induced by a mixture of halothane, nitrous oxide and oxygen, and maintained by an intravenous dose of α-chloralose (80 mg/kg) followed by an infusion of sodium pentobarbital (2 mg/kg per h). The animals were paralysed with gallamine triethiode and artificially ventilated. End-tidal CO_2 was kept between 3·5–4·5%. Arterial blood pressure was often monitored, and body temperature was maintained at 37–38 °C.

The spinal cord was exposed by a laminectomy. A craniotomy allowed the introduction of a concentric bipolar steel stimulating electrode into the right thalamus. Glass micro-electrodes filled with 4 M-NaCl (initial resistances of 5–15 MΩ) were used to explore the grey matter of the left side of the lumbosacral spinal cord for antidromically activated spinothalamic tract cells. The criteria for recognition of antidromic invasion in these cells are described in full elsewhere (Trevino *et al.* 1973); they included a constant latency, following at a high frequency, and collision at appropriate intervals with orthodromic activity. The spikes were displayed on an oscilloscope screen, along with a recording from the dorsal surface of the spinal cord made with a ball-tipped platinum electrode.

Orthodromic spikes were evoked by electrical stimulation of peripheral muscle or cutaneous nerves (0·1 msec pulses of variable amplitude, usually repeated at 1 per sec). Field potentials were recorded either from the surface of the cord with the ball-tipped electrode or from the substance of the cord with the micro-electrode. The field potentials were often averaged, using a digital computer or a hard-wired signal averager. Contour plots of the distribution of the field potentials were calculated on a digital computer and plotted on an electrostatic printer-plotter (see Beall, Applebaum, Foreman & Willis, 1977). Anodal blockade of activity in large myelinated afferent fibres was done according to the method described by Brown, Hamann & Martin (1975).

RESULTS

Field potentials evoked by muscle afferent volleys

Before describing the responses of spinothalamic tract neurones to muscle afferent volleys, it will be convenient first to characterize the spinal cord potentials produced by such volleys in the monkey. The reason for doing this is that high threshold muscle afferents evoke larger cord dorsum negative waves in the monkey than they do in the cat (see Eccles & Lundberg, 1959), and these negative waves can be used as an index of the central actions of the several myelinated fibre groups in the muscle nerves of the monkey.

The sequence of potentials which follow stimulation of muscle afferents is shown in Fig. 1. After a triphasically recorded volley (V), there are several negative waves that we will call the NI, NII and NIII waves. Which of the negative waves are present depends upon the stimulus strength. When a low stimulus strength is used, only the NI wave is seen (Fig. 1*A*). At a higher strength, the NII wave appears, superimposed upon the NI wave (Fig. 1*B*). Finally, still higher stimulus strengths evoke the later NIII wave (Fig. 1*C*). Similar waves were recorded in the intermediate region of the cat dorsal horn by Coombs, Curtis & Landgren (1956), who called them the group I, II, and III responses, and by Fu, Santini & Schomburg (1974), who named them the group I, II and III focal synaptic potentials. Earlier, Bernhard (1953) recognized an early and a late negative wave in recordings from the cord dorsum following stimulation of low threshold and group III fibres, respectively, in the cat.

The conduction velocity of the fibres responsible for the afferent volley was estimated from measurement of the latency of the initial positive peak from the

stimulus artifact and from measurement of the distance from the cathode on the muscle nerve to the recording site on the cord. For five determinations, the conduction averaged 105 ± 18 (S.D.) m/sec. This value for the macaque is in between the upper limit of conduction velocities of group I fibres in the baboon (Eccles, Phillips & Wu, 1968; Cheney & Preston, 1976) and in the cat (Hunt, 1951). The initial negative wave was graded in size with the group I volley and is therefore produced by group I fibres. This is the justification for naming the initial wave the NI wave.

When the stimulus strength was graded to levels above those needed to evoke a maximum group I afferent volley, the second negative cord dorsum wave appeared. Its threshold (T) varied from 1·3 to 4·8 times that of the group I fibres, and the

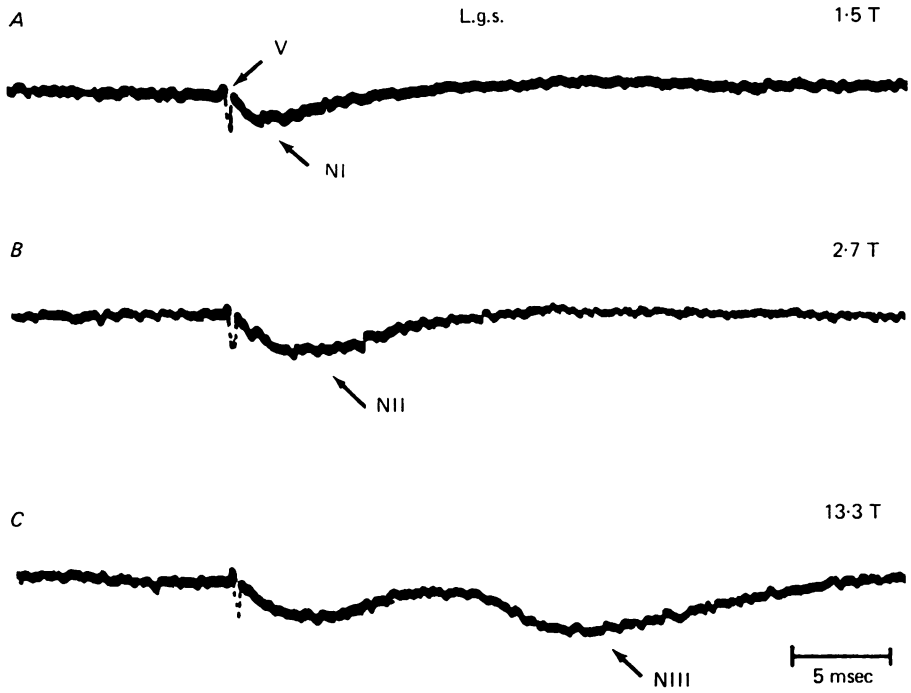

Fig. 1. The cord dorsum potentials produced by myelinated muscle afferents. The recordings were made from the dorsal surface of the lumbosacral enlargement following stimulation of the lateral gastrocnemius-soleus (l.g.s.) nerve, using RC coupled amplifiers. The time constant was approximately 150 msec for this and Fig. 2. The stimulus strength was increased progressively for the records in *A*, *B* and *C*. Strengths are expressed as multiples of threshold (T) for the largest afferent fibres of the nerve. The group I volley, V, is indicated by the arrow in *A*. The other arrows are placed by the NI, NII and NIII waves. The time scale applies to all the records.

second negative wave reached a maximum at strengths above 3·9 times. If the assumption is made that this wave is evoked monosynaptically by the responsible afferent fibre group, the minimum conduction velocity of the fibres can be calculated. The average value was 64 ± 20 (S.D.) m/sec for five determinations (based on the conduction distance and the latency of the wave after subtraction of the NI wave). These values for the stimulus strength range and for the minimum conduction

velocity of the afferents producing the second negative wave suggest that the fibres responsible to group II (see Table 1 for values in the cat). For this reason, we call the wave the NII wave.

Finally, when the stimulus strength exceeded a value of 2·2–15 T, a late negative potential was seen. This reached a maximum at strengths above 10 T. The latency of the wave, determined by subtraction of the NI and NII waves, is consistent with a monosynaptic event produced by fibres conducting at 23 ± 7 (S.D.) m/sec. These observations suggest that the late negative wave is due to group III fibres (see Table 1 for values in the cat) and justify the name NIII wave.

TABLE 1. Values for stimulus strengths producing threshold and maximum volleys in muscle afferent fibre groups in the cat, expressed as multiples of threshold (T) for the largest muscle afferents

Maximum group I	Threshold group II	Maximum group II	Threshold group III	Reference
1·6–4 T	1·3–2·6 T	—	2·4–5 T	Brock, Eccles & Rall, 1951
1·8 T	1·4–3·4 T	3·6 T	2–6 T	Coombs *et al.* 1956
—	About 2 T	8–10 T	About 10 T	Eccles & Lundberg, 1959
—	Less than 2 T	—	2·5 T	Pomeranz *et al.* 1968
—	1·5 T	—	6·7 T	Coppin, cited in Matthews, 1972
1·6–2·3 T	1·5–2·3 T	—	6–8 T	Fu *et al.* 1974

TABLE 2. Time Course of NI, NII and NIII waves in the monkey (values in msec $\pm$ S.D., $n = 10$, except for time to peak from onset, which is the difference between the first two columns)

(Average latency of group I volley from stimulus = 3·0 msec)

	Latency from stimulus	Time to peak from stimulus	Time to peak from onset	Duration
NI	$3{\cdot}6 \pm 0{\cdot}7$	$4{\cdot}7 \pm 0{\cdot}6$	1·1	$4{\cdot}6 \pm 1{\cdot}3$
NII	$4{\cdot}6 \pm 1{\cdot}0$	$7{\cdot}6 \pm 1{\cdot}7$	3·0	$10{\cdot}6 \pm 1{\cdot}7$
NIII	$12{\cdot}4 \pm 2{\cdot}0$	$16{\cdot}4 \pm 2{\cdot}8$	4·0	$13{\cdot}1 \pm 3{\cdot}1$

The average latency, time to peak, and duration of the NI, NII and NIII waves in the monkey spinal cord are given in Table 2. There was no obvious correlation between the thresholds for the NII and NIII waves; that is, a low threshold for the NII wave did not imply a low threshold for the NIII wave within the ranges of values for these thresholds.

Following the N waves there may be a positive or P wave. This is presumably equivalent to the P wave produced by muscle afferents in the cat and can be attributed to primary afferent depolarization (Eccles, Magni & Willis, 1962).

Support for the interpretation that the NIII wave is due to group III fibre activity comes from three successful experiments in which the discharges of the largest afferent fibres were blocked with anodal current (Fig. 2). The NIII wave could be evoked independently of the NI and NII waves during anodal blockade of conduction in the large and medium sized muscle afferents.

The distribution of the NII and NIII waves evoked by afferents of the gastrocnemius-soleus nerve is shown in Figs. 3 and 4. The rostrocaudal spread of the waves was limited chiefly to the lumbosacral enlargement, with a peak effect at L 7 (Fig. 3; cf. Fu *et al.* 1974). However, a small group I volley and NI wave could be seen as far rostrally as L 3, presumably reflecting an input to Clarke's column.

The contour plots in Fig. 4 show that the NII and NIII waves are distributed over much of the extent of the dorsal horn. The maximum negativity of both waves is centred over the neck of the dorsal horn in the area equivalent to laminae IV–VI in the cat (Rexed, 1952). The waves reverse to become positive in the ventral horn. This distribution is similar to that of the group II and group III responses in the cat (Coombs *et al.* 1956; Fu *et al.* 1974). No attempt was made to map the distribution of the NI wave in a systematic fashion.

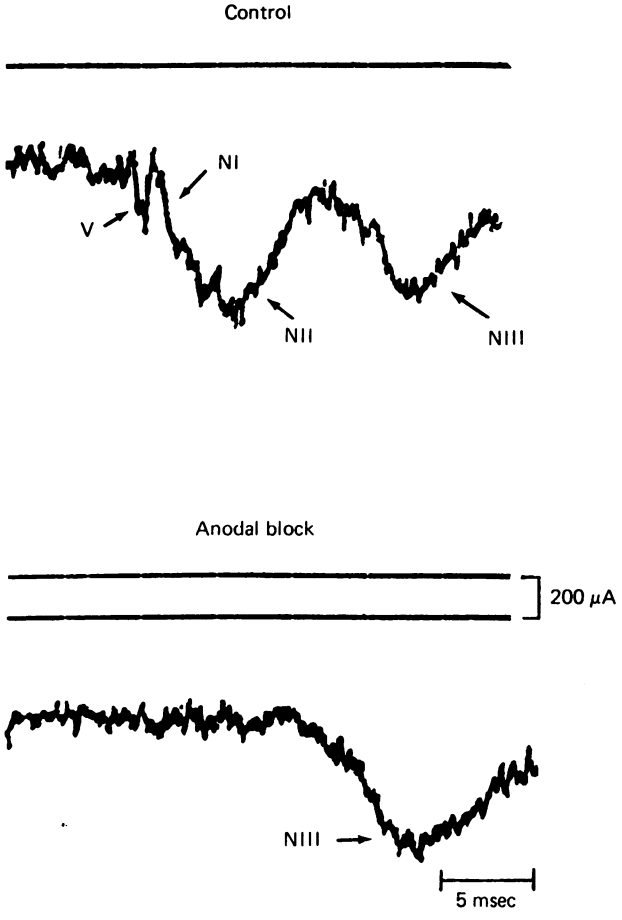

Fig. 2. Effect of anodal block on N waves. The records at the top show the group I volley and the NI–III waves produced by stimulation of the l.g.s. nerve (lower trace) and a current monitor (zero current, upper trace). The records at the bottom were taken during anodal blockade of the group I (and presumably II) fibres. Only the NIII wave is seen.

Activation of spinothalamic tract cells by muscle afferent volleys

The responses of ninety-two spinothalamic tract neurones to electrical stimulation of one or more muscle nerves were examined. Of these cells, fifty were part of the study reported in the companion paper concerned with the effect of chemical and mechanical stimulation of muscle afferents (Foreman *et al.* 1978). The activity of these cells was recorded in preparations which had a partially or completely

denervated hind limb, and so the cutaneous receptive field properties could not be determined. However, the skin was innervated in the experiments in which the other forty-two recordings were made. Such experiments permit analysis of the muscle afferent input onto spinothalamic cells having different types of cutaneous receptive fields.

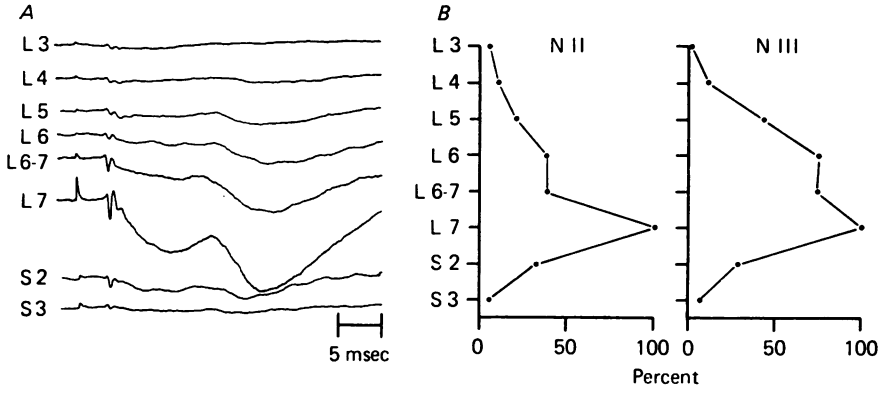

Fig. 3. Longitudinal distribution of N waves evoked by muscle afferents. The recordings in *A* were made at the segmental levels indicated following stimulation of l.g.s. nerve, using signal averages of twenty-five consecutive sweeps. Amplifier time constant 10 sec for this and Fig. 4. The sizes of the NII and NIII waves are plotted in *B* as a percentage of the size of the waves at the L 7 segmental level. The amplitude of the NIII wave was determined by subtraction of records made with a stimulus strength just supramaximal for the NII wave from the records shown.

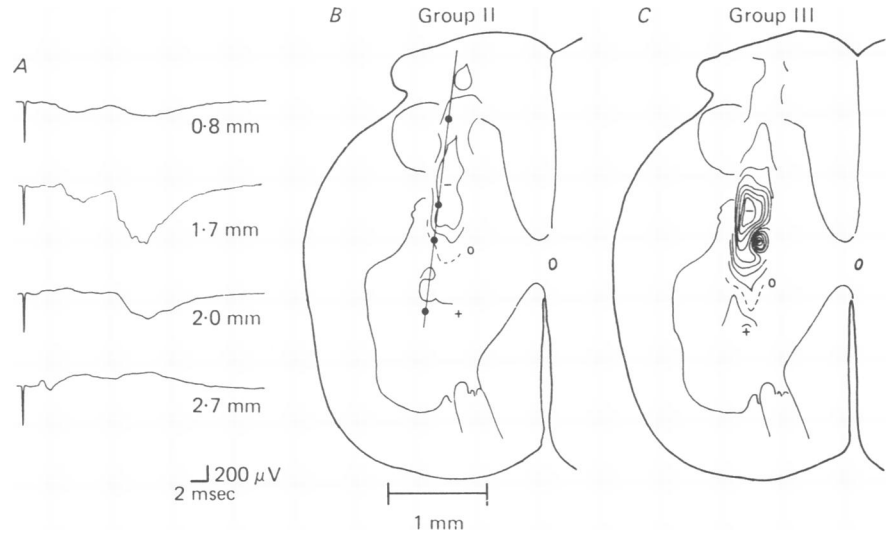

Fig. 4. Distribution of the field potentials produced by group II and III muscle afferents in the g.s. nerve. The field potentials shown in *A* were recorded at the depths indicated along the track drawn in *B*; the waves reached a maximum in the neck of the dorsal horn and reversed to become positive in the ventral horn. The contour plots in *B* and *C* show isopotential lines for the field potentials evoked by group II and III fibres, respectively. The times for measurement of the waves corresponded to the peaks of the waves near the surface of the cord.

For many of the experiments, three different muscle nerves were prepared for electrical stimulation: the hamstring, lateral gastrocnemius-soleus (l.g.s.) and medial gastrocnemius (m.g.) nerves. Sometimes the nerves to the triceps surae muscles were combined (g.s.). In addition, one or more cutaneous or mixed nerves were usually available for electrical stimulation.

The sizes of muscle afferents which can excite spinothalamic tract neurones were determined by examining the effects of graded volleys, ranging from near threshold for group I afferents to suprathreshold for group III (or in some cases, group IV) afferents. Supportive evidence for an action by the more rapidly conducting afferents came from measurements of the latency of the initial action potential evoked by a muscle afferent volley. Furthermore, excitatory effects could often be attributed to group II or group III fibres by correlating the number of discharges evoked by various stimulus strengths with the sizes of the NII and NIII waves.

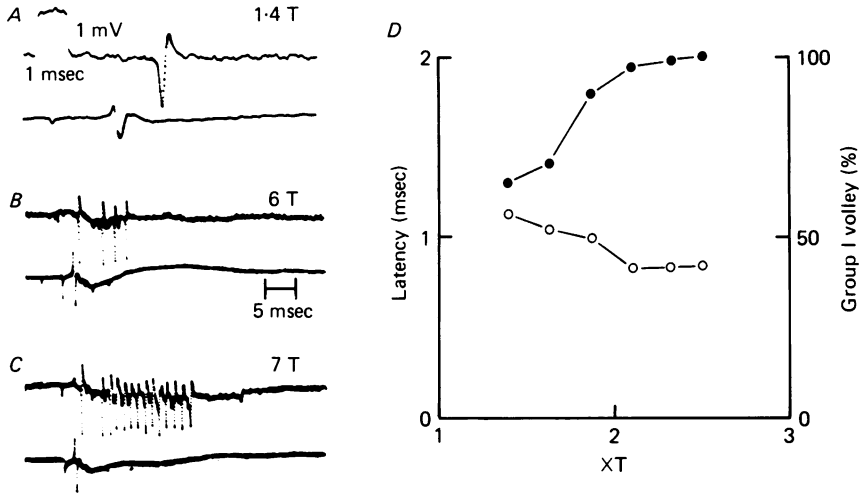

Fig. 5. Responses of a spinothalamic tract neurone to graded stimuli. The upper records in *A–C* were made extracellularly from a spinothalamic tract neurone which had been identified by antidromic activation from the contralateral thalamus. The lower records were made from the cord dorsum. The cell was excited following stimulation of the hamstring nerve. In *A*, the stimulus strength was 1·4 T, and the cell responded with a single spike at a monosynaptic latency. The graph in *D* shows that the latency of the spikes (open circles, left ordinate scale) was reduced to below 1 msec as the size of the group I volley (filled circles, right ordinate scale) was increased to its maximum. The brief burst of three spikes following the initial group I evoked spike in *B* was attributed to volley in group II fibres (stimulus 6 T), while the later discharges in *C* were due to group III fibres (stimulus 7 T). Note the development of an NIII wave in *C*.

Excitation of spinothalamic neurones by large muscle afferents

The recordings in Fig. 5 show the responses of a spinothalamic tract cell to stimuli which activated just group I fibres (Fig. 5*A*), group II fibres (Fig. 5*B*) and group III fibres (Fig. 5*C*) in the hamstring nerve. This particular spinothalamic tract neurone was exceptional in that it was excited monosynaptically by group I muscle afferent fibres. The graph in Fig. 5(*D*) shows that the highest threshold

portion of the group I volley was involved, since strengths below 1·4 T were ineffective. The latency of the spike decreased to less than 1 msec from the arrival time of the group I volley at the cord as the stimulus strength was elevated from 1·4 to 2 T. When group II fibres were activated by stimuli of 2 T or greater, a burst discharge resulted (Fig. 5*B*), and the burst was considerably prolonged when the strength exceeded threshold for group III fibres (e.g. Fig. 5*C*; note the presence of an NIII wave in the lower trace).

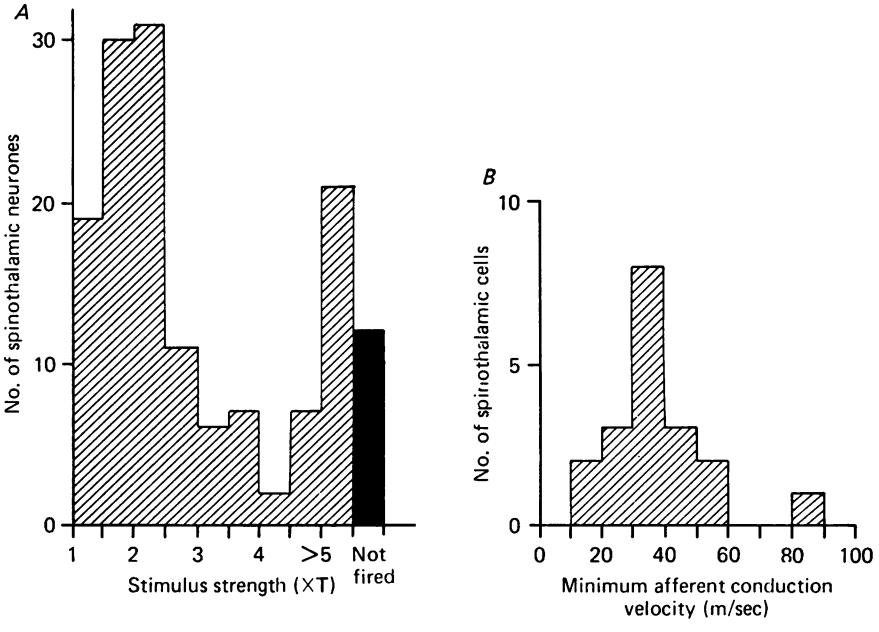

Fig. 6. The stimulus strengths required to activate spinothalamic neurones by muscle afferent volleys and the minimum afferent conduction velocities for the volleys triggering the initial discharge. The histogram in *A* shows the numbers of spinothalamic neurones (ordinate) which could be activated by volleys evoked by stimulus strengths at or above the indicated levels (abscissa). Twelve neurones could not be activated by any strength tried. The histogram in *B* shows the minimum afferent conduction velocity calculated for the volley responsible for the initial spike in the burst discharges of a series of spinothalamic cells. It is assumed that the initial spike was triggered monosynaptically and that the central delay was 1 msec.

Only three other spinothalamic tract cells were found in this study which could be discharged at a monosynaptic latency by group I fibres; all discharged at latencies of 1·3 msec or less from the arrival of the afferent volley at the cord (cf. Eccles, Fatt & Landgren, 1956, who found a latency range of 0·75–1·7 msec for spikes evoked monosynaptically in neurones of the intermediate region). However, as Fig. 6(*A*) shows, it was not uncommon for a spike to occur when stimuli of less than 2 T were used. This occurred in 37 % of 134 trials in recordings from sixty-three spinothalamic cells. We suspect that group I fibres were involved in exciting many of these cells, although we cannot rule out the alternative explanation that low threshold group II fibres were in fact responsible. However, in 14 % of the trials, a stimulus strength of less than 1·5 T was effective, which suggests that group I fibres were able to

excite spinothalamic neurones in many of these cases (see Table 1). On the other hand, the majority of trials showed that it was necessary to activate group II or even group III fibres to excite spinothalamic neurones.

Another approach to the question of how commonly the largest muscle afferents excite spinothalamic tract neurones is the determination of the minimum conduction velocity of the afferents which trigger the initial response. Assuming that the afferents terminate monosynaptically on the spinothalamic tract cells and assuming a 1 msec central delay, the minimum conduction velocity can be calculated from the following measurements: (1) the distance from the cathode on the peripheral nerve to the recording site and (2) the latency of the initial spike from the shock artifact, less 1 msec (cf. Foreman *et al.* 1975). If a multisynaptic pathway is involved,

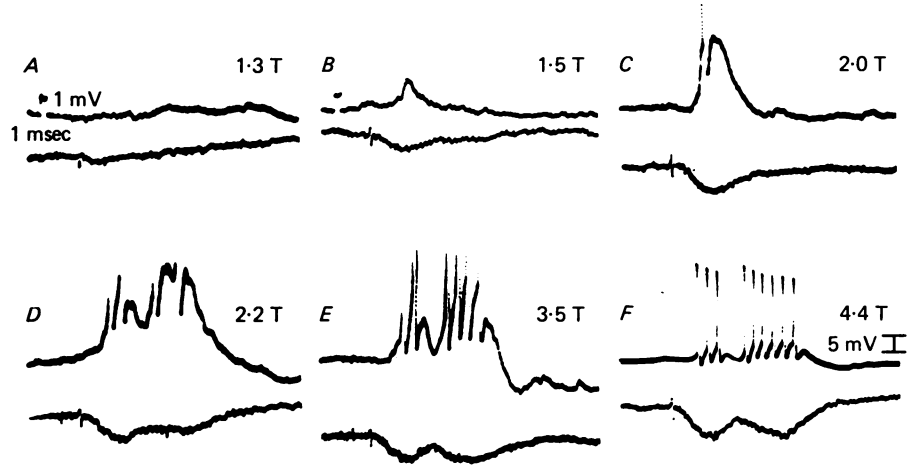

Fig. 7. Intracellular recordings from a spinothalamic neurone excited by muscle afferents. The upper traces are intracellular records from a spinothalamic tract identified by antidromic activation from the contralateral thalamus. The lower traces are recordings from the cord dorsum. The l.g.s. nerve was stimulated at the indicated intensities. The time calibration in *A* applies to all the records. However, the voltage calibration is for only the upper traces in *A–E*; a separate voltage scale is given for *F*.

the conduction velocity so calculated will be underestimated. Fig. 6(*B*) shows the minimum afferent conduction velocities determined for nineteen spinothalamic tract cells activated by a muscle nerve volley. In only one case was the minimum afferent conduction velocity in the group I range, and the cell is among the four mentioned above which were monosynaptically excited by group I fibres. Since the thresholds for excitation of many of the cells for which minimum afferent conduction velocities were determined were below 2 T or even 1·5 T, it is possible that some spinothalamic tract cells are excited by group I fibres through a di- or polysynaptic pathway.

Excitation of spinothalamic tract cells by small muscle afferents

Most of the excitatory effects of muscle afferents on spinothalamic tract cells could be attributed to group II and III fibres. For example, the cell in Fig. 5 discharged only once in response to group I volley (Fig. 5*A*), but four times in response to a volley which included group II fibres (Fig. 5*B*) and a total of fourteen times

when group III fibres were activated as well (Fig. 5*C*). Occasionally, it was possible to record intracellularly from spinothalamic tract cells. Such recordings are useful in unveiling subthreshold effects. For instance, in Fig. 7 graded stimuli applied to the l.g.s. nerve had no appreciable effect until the strength was sufficient to activate group II fibres (Fig. 7*A–C*). Stimulation of group III fibres (Fig. 7*D–F*) evoked a late e.p.s.p. The group II e.p.s.p. triggered three spikes, while the group III e.p.s.p. evoked six (Fig. 7*F*).

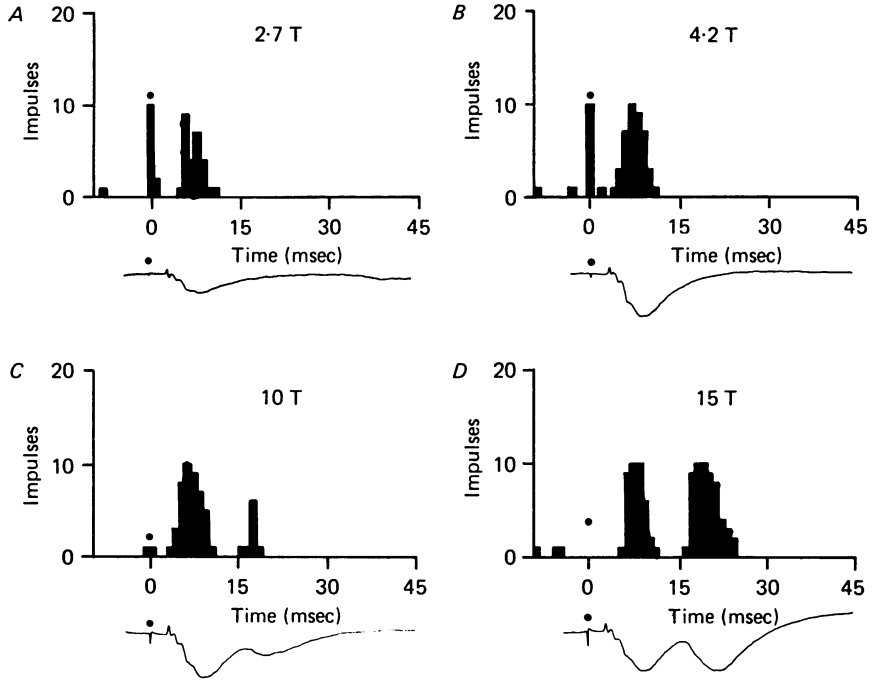

Fig. 8. Relationship between burst discharges in a spinothalamic cell and the N waves. The histograms in *A–D* were compiled from ten successive responses of a spinothalamic neurone to stimulation of the g.s. nerve at the indicated strengths (bin width 1 msec). The input to the computer was from a window discriminator which was triggered by the spike potentials of the unit. The stimulus artifact also fell within the window for the stimuli used in *A* and *B*, but not in *C* and *D*. The peaks in the histograms in *A* and *B* shown by the dots are thus due to the stimulus artifact. The times of occurrence of the stimuli in *C* and *D* are also shown by dots. Signal averaged cord dorsum recordings of the group I afferent volley and N waves were made at the same stimulus strengths at a different time during the experiment. These have been enlarged to the same time scale as the histograms and are shown below the appropriate histograms.

Post-stimulus time histograms are shown in Fig. 8 for the discharges of a spinothalamic tract cell which was excited by group II and group III muscle afferents. The histograms show that there were two separate burst discharges of the cell. The graph in Fig. 9*A* shows that the first burst resulted from stimulation of afferents by strengths above 1·55 T and that the second burst resulted from strengths exceeding 8 T. That these increments were related to the successive growth of the group II and group III volleys is supported by the correlation between the output of the

cell and the sizes of the NII and NIII waves (cf. histograms and records in Fig. 8; Fig. 9*A* and *B*). Similar results were found in eighteen other cells for which comparable measurements were made.

In three experiments, it was possible to show that strong stimulation of muscle nerves produced a discharge in spinothalamic tract neurones at a latency which was consistent with that of a volley in unmyelinated or group IV fibres. Such a case is illustrated in Fig. 10.

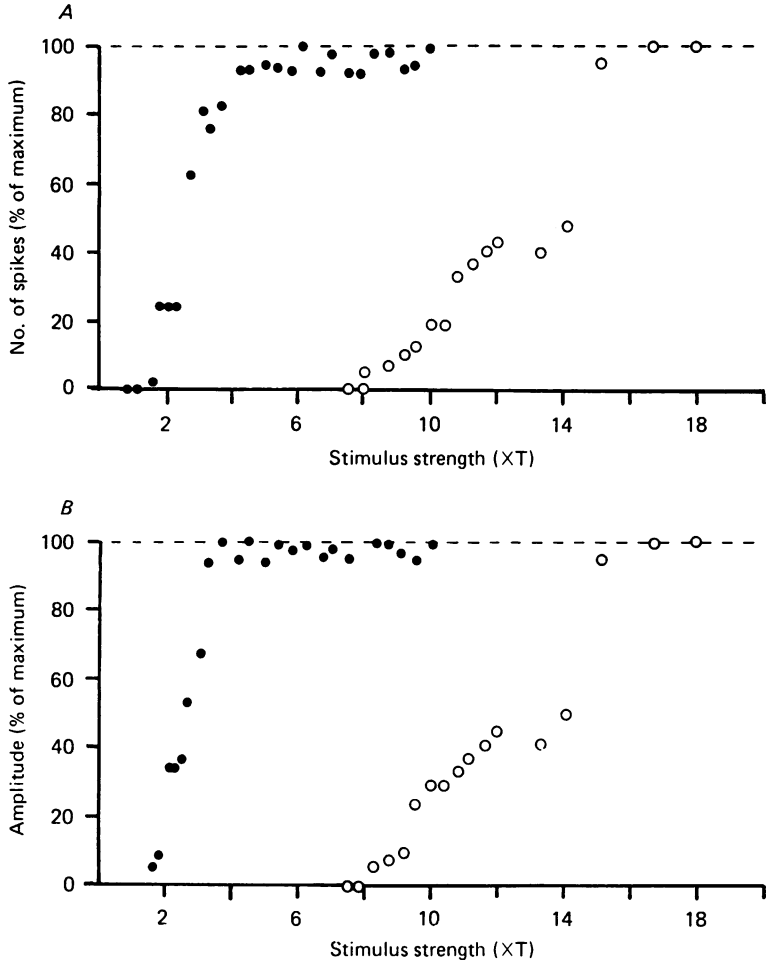

Fig. 9. Early and late burst discharges in a spinothalamic cell and sizes of the NII and NIII waves. The graph in *A* shows the number of spikes as a percentage of maximum in the early (filled circles) and late (open circles) burst discharges for a variety of stimulus strengths applied to the g.s. nerve. The graph in *B* shows the sizes of the NII (plus NI) wave and the NIII wave evoked by the same stimuli. The N waves were recorded using a signal averager, and the NIII wave was measured from subtracted records (NI–NIII waves minus NI–II waves). The experiment was the same as that illustrated in Fig. 8.

Failure of muscle afferent volleys to excite spinothalamic tract cells

Afferent volleys in one or more muscle nerves failed to excite a total of twelve spinothalamic tract neurones (Fig. 6*A*). In six of these cases, the spinothalamic tract neurones were located in the vicinity of lamina I; in three other cases, the cells were in the neck of the dorsal horn but were nevertheless judged to be nociceptive-specific, based on their responses to natural stimulation of their receptive fields.

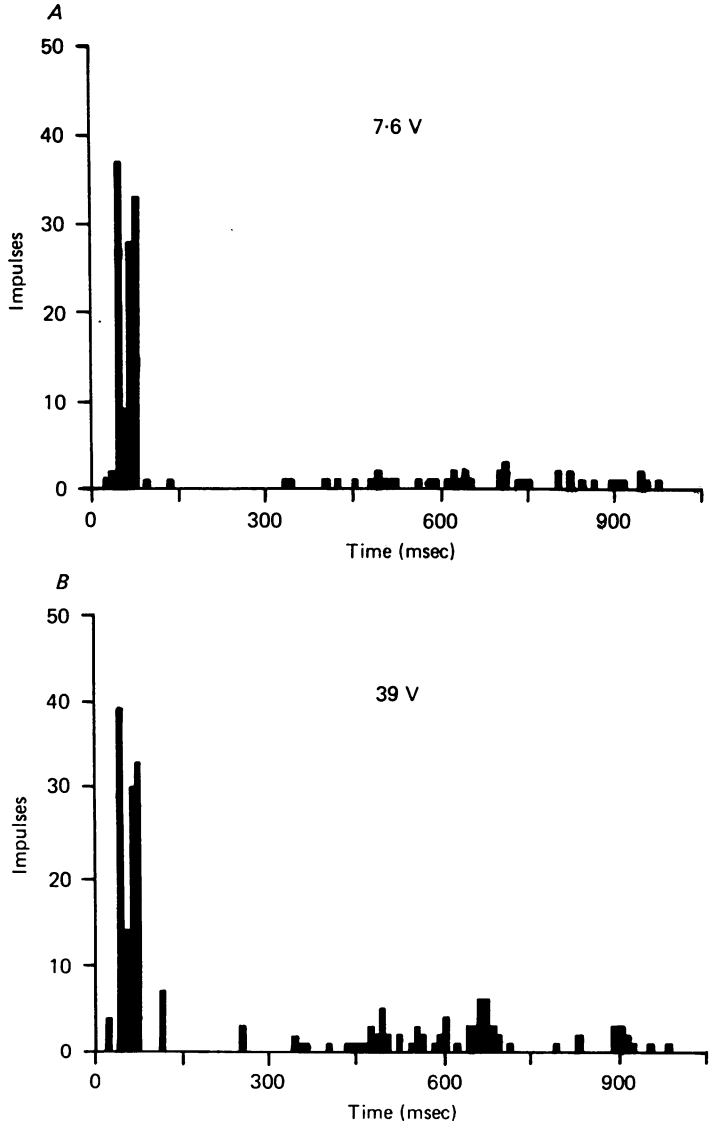

Fig. 10. Responses of a spinothalamic tract cell to unmyelinated muscle afferents. The post-stimulus time histograms show the sum of ten responses of a spinothalamic tract cell (bin width 10 msec) to stimulation of the g.s. nerve by stimuli of 7·6 V (*A*) and 39 V (*B*). The stimulus duration for these records was 1 msec. Note the late activity, much of which can be attributed to the group IV fibre input. The early and late bursts due to group II and III afferents are seen at the left of each histogram.

It should be mentioned that another four spinothalamic tract cells in the region of lamina I and three high threshold spinothalamic tract cells deeper in the dorsal horn were excited by afferent volleys in at least one muscle nerve. On the basis of either the stimulus strength required for evoking a discharge or the minimum afferent conduction velocity, all but one of these cells could be fired only by small muscle afferents, in the group III range (2·4–37 T; 10·3–28·7 m/sec).

DISCUSSION

The observation that muscle afferent volleys in the monkey evoke a series of prominent negative field potentials when recordings are made from the dorsal surface of the spinal cord is of interest in that these waves serve as a way of monitoring the central actions of muscle afferent fibres of different diameter. Evidence from measurements of conduction velocity and of thresholds to graded strengths of electrical stimuli suggests that the waves named here NI, NII and NIII are due, respectively, to fibres belonging to groups I, II and III (cf. Bernhard, 1953; Coombs *et al.* 1956; Fu *et al.* 1974).

A few spinothalamic tract cells were found which could be excited monosynaptically by group I muscle afferent fibres. It is likely that other spinothalamic cells are also excited by group I fibres, but after two or more synaptic delays. We did not have any direct evidence in these experiments as to whether the group I fibres which excited spinothalamic cells originated from primary endings of muscle spindles or from Golgi tendon organs. The cells were never excited by the lowest threshold group I fibres, but this may reflect a need for spatial summation rather than for an input from higher threshold, possibly group I*b*, muscle afferents. However, in the companion paper (Foreman *et al.* 1978) evidence is given that group I*a* muscle spindle afferents are unlikely to have significant connexions with spinothalamic tract cells, since injections of succinylcholine into the arterial circulation of the triceps surae muscles had very little effect upon the background activity of spinothalamic tract cells, despite the fact the same dose of succinylcholine produced a powerful excitation of the group Ia afferent fibres sampled (Granit, Skoglund & Thesleff, 1953). Dorsiflexion of the ankle typically produced a slowly adapting discharge of spinothalamic tract cells which received an excitatory input from receptors located in the triceps surae muscles. This response may have been due to group I fibres which arise from Golgi tendon organs. Alternatively, group II or even group III afferents may have been responsible (see below; Bessou & Laporte, 1961; however, cf. Paintal, 1960).

There is a more significant input to spinothalamic tract cells from group II and III fibres than from group I fibres. Group II and III volleys generally evoke a burst discharge, whereas group I fibres, when effective, elicit only a single discharge. We do not know if the group II fibres which excite spinothalamic tract cells arise from secondary endings of muscle spindles. If they do, then group II muscle spindle afferents could certainly account for the slowly adapting responses of many spinothalamic tract cells following dorsiflexion of the ankle (Foreman *et al.* 1978). However, intra-arterial injections of succinylcholine excite secondary, as well as primary, endings of muscle spindles in the cat (Fehr, 1965). Thus, if secondary endings of

muscle spindles in monkeys are also sensitive to succinylcholine in the dose used, an explanation is needed for the fact that many spinothalamic tract cells respond to group II afferents in the nerves to the triceps surae muscles but not to succinylcholine injections into the arterial circulation of the same muscles. A possible answer to this question is that some of the group II fibres in the monkey triceps surae nerves may supply pressure-pain endings, and these fibres may be the ones which activate the spinothalamic tract cells (see, Paintal, 1960). There is a similar difficulty with respect to the group IIinput to spinal motoneurones (Matthews, 1972). Alternatively, succinylcholine may have little effect on secondary endings in the monkey; this agent is relatively much less effective in exciting secondary endings than primary endings in the cat (Fehr, 1965).

It is of interest that group II and III afferents can be classified together with many types of cutaneous and joint afferents as 'flexion reflex afferents' (Eccles & Lundberg, 1959) since their activation evokes a pattern of motoneuronal activity which resembles that seen during the flexion reflex (Sherrington, 1910; Paintal, 1961). It is not surprising to find that spinothalamic cells, which are thought to participate in nociception (including that associated with stimulation of nociceptors in the Achilles tendon; Yoss, 1953), can be activated by the same spectrum of muscle afferent fibre types which trigger flexion reflexes. The additional observation that group IV (unmyelinated) muscle afferents also excite spinothalamic tract cells is in keeping with this finding, since group IV (C) fibres can also evoke a flexion reflex (Voorhoeve, Laporte & Bessou, 1958; Franz & Iggo, 1968; Burke, Rudomin, Vyklický & Zajac, 1971). However, the activation of spinothalamic neurones is more likely to be associated with flexor withdrawal reflexes than with flexion reflexes which accompany locomotion. Additional evidence concerning the excitation of spinothalamic tract cells by group III and IV muscle afferents comes from experiments in which algesic chemicals were injected intra-arterially into the circulation of the triceps surae muscles (Foreman *et al.* 1978). The algesic chemicals used are known to activate group III and IV fibres in a selective fashion (Mense & Schmidt, 1974; Mense, 1977).

The fact that some spinothalamic tract cells could not be excited by muscle afferent volleys is of interest, especially since a number of such cells were located in the region of lamina I. The cells of lamina I are often nociceptive-specific, and they typically have relatively restricted receptive fields. Thus, we speculate that cells of this type, whether located in lamina I or in deeper layers of the dorsal horn, may be used for the localization of cutaneous noxious stimuli. Some of the cells in lamina I (see Cervero *et al.* 1976) do have an input from high threshold muscle afferents, as do the wide dynamic range spinothalamic neurones in the deeper layers of the dorsal horn. We suppose that such cells might signal the poorly localized, aching type of pain described by Lewis (1942) which arises from muscles or other deep tissues and which is often referred to superficial structures.

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