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Percutaneous electrical stimulation of lumbosacral roots in man

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SUMMARY High voltage percutaneous electrical stimulation over the lumbosacral spinal column was used to assess conduction in the cauda equina of 13 normal subjects. Electromyographic activity elicited by such stimulation was recorded from various muscles of the lower limbs. The stimulating cathode was placed over the spinous process of each vertebral body and the anode kept on the iliac crest contralateral to the studied limb. Shifting the cathode in a rostro-caudal direction shortened the response latency in quadriceps, tibialis anterior and extensor digitorum brevis muscles. At moderate intensities (60% maximum), this occurred abruptly when the cathode was placed at levels corresponding to the exit sites from the spinal canal of the roots innervating these muscles. At these intensities, the size of the response in each muscle was largest when the cathode was placed over the conus medullaris or at or below the exit of the motor roots from the spine. Latencies were always equal to or shorter than those obtained with F-wave measurements, suggesting that peripheral motor axons, rather than intraspinal structures were activated by the stimulus. Collision experiments demonstrated that activation occurred at two sites: near the spinal cord and at the root exit site in the vertebral foramina. Recordings made from soleus indicated that larger diameter proprioceptive afferent fibres also could be activated. This technique might have useful clinical applications in the study of both proximal and distal lesions of the cauda equina and provide a non-invasive method of localising such lesions electrophysiologically.

In 1982, Marsden, Merton and Morton[1] discovered that high voltage electrical stimulation over the cervical or lumbar spinal columns produced short latency EMG responses in relaxed muscles of the arm and leg respectively. Theoretically, various neural structures could be excited by this technique: motor and sensory intra- and extradural roots, motoneuron cell bodies, spinal interneurons and fibre tracts in the spinal cord. In a recent study, Mills and Murray[2] have shown that such stimuli applied over the cervical column activate preferentially the motor roots near their exit from the spine. This form of stimulation can therefore provide a useful direct method of measuring peripheral motor conduction delays to muscles of the upper limb. The technique has advantages over conventional F-wave methods. It is quick, and at supramaximal intensities can activate all the motoneurons supplying a muscle, as compared with the small fraction tested with F-waves. The disadvantage of spinal stimulation is that a small section of peripheral nerve, from the motoneuron to the root exit, is not tested. At cervical levels this represents a distance of about 2 to 4 cm, or some 0·6 ms conduction time.[2]

Although the method preferentially activates cervical motor nerve roots at their spinal exit, at higher intensities, long spinal tracts also may be stimulated. Responses can be recorded at short latency in muscles of the legs after stimulation over cervical cord.[2 3] This technique may prove to be of use in localising the level of a spinal cord lesion.

Little is known about the site of stimulation when electrodes are placed over the lumbar cord even though intradural segments of lumbosacral roots are much longer than at cervical levels (mean: 112 mm for L3, 143 mm for L5 and 156 mm for S1).[4] Swash and Snooks,[5] recording from external sphincter and

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puborectal muscles, have used EMG latency difference obtained when stimulating over the spinal column at L1 and L4 levels to investigate the function of the S3 and S4 roots in the cauda equina. They found that slowing of conduction in the cauda equina was a useful indicator of damage to intraspinal nerve roots. However, the precise site of stimulation was not defined in these experiments: it was necessary only to assume that the same site was activated in each individual when a given electrode montage was used. It was the aim of the present study to extend this technique further by investigating the possible sites at which stimulation occurs and documenting their differential thresholds.

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Subjects and methods

Thirteen normal subjects (12 male, 1 female; age range: 28–64 years) were studied. All gave informed consent and approval of the local Ethical Committee was obtained. Additional experiments were performed on six of the subjects. Recordings were made from the following muscles of the right lower limb: quadriceps femoris (rectus), tibialis anterior, soleus and extensor digitorum brevis (EDB). In three subjects, additional recordings were collected from abductor hallucis brevis (AHB).

Muscle activity (EMG) was recorded with Ag-AgCl surface cup electrodes placed 2–3 cm apart, over the muscles bellies. Signals were amplified with Devices 3160 preamplifiers (filters at 80Hz and 2·5 kHz) and Devices 3120 amplifiers. Data were recorded with a PDP 12 computer and stored on floppy discs. Latency and size of the potentials were calculated by the computer, using programs devised by Mr H B Morton. For each signal, two different gains of amplification were used (0·2 mV/V and 2 mV/V) to allow accurate measurements of latency and size of the potentials.

Stimulation over the vertebral column was achieved by using a prototype of the commercially available Digitimer D180 built by Mr H B Morton, with a maximal output of 750 V and a decay constant of 50 μs. In this paper, the intensities of stimulation used are expressed as a percentage of the maximal output of the device. Stimuli were delivered through Ag-AgCl cup electrodes fixed to the skin with tape.

Previous investigators have used bipolar stimulation with both electrodes place longitudinally over the lumbar or sacral vertebrae.[6 7] Although this is an effective method, it is not clear at what point stimulation occurs: Snooks and Swash[6] suggested that activation may take place at some point mid-way between the electrodes. In order to reduce uncertainty over the site of stimulation, the present experiments were performed with the cathode over the spinal column, and the anode over the iliac crest contralateral to the leg being examined. A contralateral anode was chosen to prevent activation of peripheral nerves in the lumbosacral plexus, at some point between the two stimulating electrodes. Cathodal stimulation over the cord was preferred since it produced responses from all levels of cord at a slightly lower intensity than anodal stimulation. The precise location of the anode was not crucial: responses of similar latency were observed when the electrode was on the buttock or on the 12th rib. However, if the anode was moved nearer to the spinal column, the responses at any given intensity gradually became smaller.

In the main series of experiments, we analysed the differences in threshold, latency and size of responses obtained in leg muscles when the stimulating cathode was shifted rostrocaudally over the vertebral column, from T11 to S1. The responses were also compared with those elicited by stimulation of the corresponding peripheral nerves.

Latencies obtained in EDB were compared with peripheral latencies calculated using conventional F-wave methods.[8] Supramaximal pulses were delivered to the deep peroneal nerve at the ankle by a DISA type 15E constant current unit, through conventional bipolar electrodes. At least 15 successive F-waves were recorded from EDB to define the shortest F-wave latency for this muscle. Total peripheral motor conduction time was calculated from the formula $\frac{F + M - 1}{2}$, where F = latency of F-wave; M = latency of M-wave.

In three subjects we investigated whether stimulation over the spinal column could produce an F-wave in addition to direct M-wave responses. The F-wave in AHB was revealed using a collision technique.[8 2] At the same time as a stimulus was given to the spine, supramaximal peripheral nerve stimuli were delivered to both the posterior tibial and deep peroneal nerves at the ankle. The antidromic volley from the peripheral nerve shock collides with and abolishes the orthodromic M-wave from spinal stimulation, leaving only the F-wave (from spinal stimulation) intact.

Results

With cathodal stimulation over the spinal column and an anode over the contralateral iliac crest, the intensity needed to elicit EMG responses in leg muscles was 30–60% of the maximal output of the stimulator. Maximal size potentials were usually obtained with an intensity of 60–80%. Such stimuli caused only moderate discomfort to the subject, due to contraction of the paravertebral muscles.

(1) *Rostrocaudal displacement of the cathode*

Progressive rostrocaudal displacement of the stimulating cathode from T11 to S1 vertebrae resulted in sudden shortening of the latencies of EMG responses from quadriceps, tibialis anterior and EDB in all 13 subjects (fig 1). In soleus, the situation was somewhat different and will be described separately.

The latency difference between stimulation over T11 and S1 vertebrae at a moderate intensity of about 60% max in all 13 subjects was 1·4, 0·6 ms (mean, SD) for quadriceps, 2·4, 1·2 ms for tibialis anterior and 3·0, 1 ms for EDB (fig 2). At these intensities of stimulation, the EMG latencies did not shorten progressively at intermediate electrode positions. An

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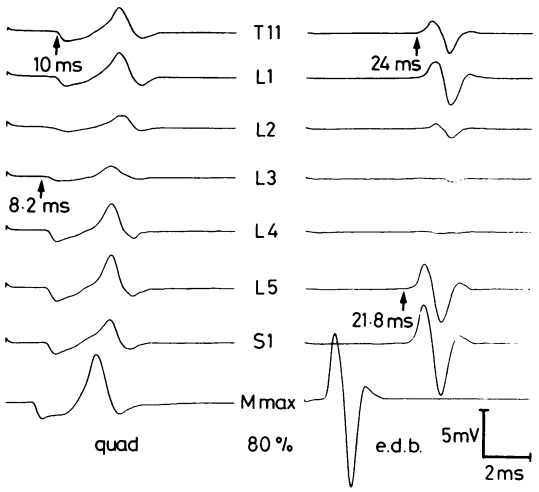

Fig 1 *EMG responses recorded from right quadriceps (quad) and extensor digitorum brevis (EDB) muscles in one subject illustrating the effects of shifting the stimulating cathode from T11 to S1 spinous processes. (Stimulus intensity: 80% maximum output). The anode was kept over the left iliac crest (on the side contralateral to the above muscles). The latency of the EMG response in quadriceps shortens markedly when the stimulating cathode is placed over the L3 spinous process. When placed over L5, the latency of the response in EDB shortens. The size of the response is greater with the cathode over the conus medullaris or near the site of exit from the spinal canal of the roots innervating these muscles. The bottom traces show the responses recorded in the same muscles following supramaximal peripheral nerve stimulation. The traces are the average of five consecutive trials*

abrupt shortening of the latencies was observed in each muscle at critical positions of the cathode: over L2–L3 for quadriceps, L4–L5 for tibialis anterior and L5–S1 for EDB (fig 1).

The size of the response also changed as the cathode was moved down the spine. With minor variations from subject to subject, the responses recorded in each muscle were largest when the cathode was placed over T11–L1 or L4–S1 (fig 1). When stronger stimuli were used, the latency change was more gradual as the cathode was moved down the spine, and the size differences at each site were not so pronounced. The shape of the maximal responses elicited by spinal stimuli and peripheral nerve shocks (M-waves) was very similar (fig 1).

The size ratio between the largest responses to spinal stimuli and maximal M-waves was not studied systematically. However, in quadriceps, tibialis anterior and EDB of three subjects this ratio was of the order of 40–80% when stimulating over the conus medullaris (T11–L1) and 70–90% when stimulating at the exit of the corresponding roots from the spine.

(2) *Comparisons with F-wave latencies*

In nine subjects, latencies of the responses in EDB to spinal stimulation over T11 and S1 were compared with conventional estimates of peripheral motor conduction times using the F-wave technique (fig 3). Stimulating over T11, the latencies of the responses to spinal stimuli were always equal to or slightly shorter than $\frac{F + M - 1}{2}$. The mean difference in nine subjects was 0·7 ms. This difference was 2·6 ms when stimulating over S1.

(3) *Collision experiments*

The finding that peripheral conduction latencies were slightly shorter with stimulation over the spinal column than with conventional F-wave techniques suggests that spinal stimulation activates the peripheral motor axons directly rather than exciting spinal motoneurons via spinal tracts or interneurons. In order to investigate this further, we used a collision technique to test whether spinal stimulation produced both a direct M-wave and an antidromic F-wave in the AHB of three subjects. When supramaximal peripheral nerve stimuli were given to the deep peroneal and tibial nerves at the ankle at the same time as a spinal stimulus, F-waves could be recorded (at high gain) in all three subjects. Their latency was an average of 2·2 ms longer than the response to spinal stimulation alone over T11. With stimulation over S1, the latency difference was 7·8 ms (fig 4). These latency differences were the same for a range of intensities of spinal stimulation, from 60–90% maximal.

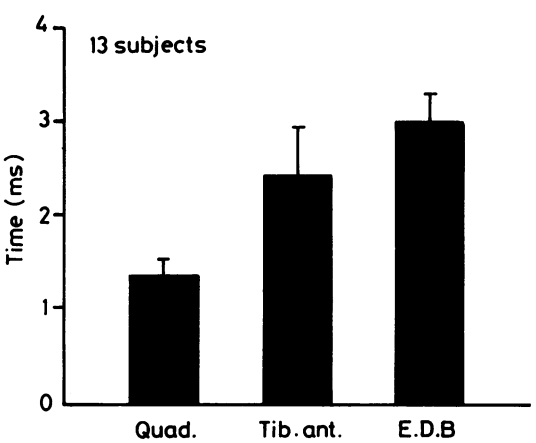

Fig 2 *Mean (1 SD) difference in latency of the EMG responses to spinal stimulation, recorded from quadriceps, tibialis anterior and EDB of 13 subjects, with the stimulating cathode over T11 and S1 vertebrae (stimulus intensity: 60% maximum). The difference is 1·4 ms in quadriceps, 2·4 ms in tibialis anterior and 3 ms in EDB.*

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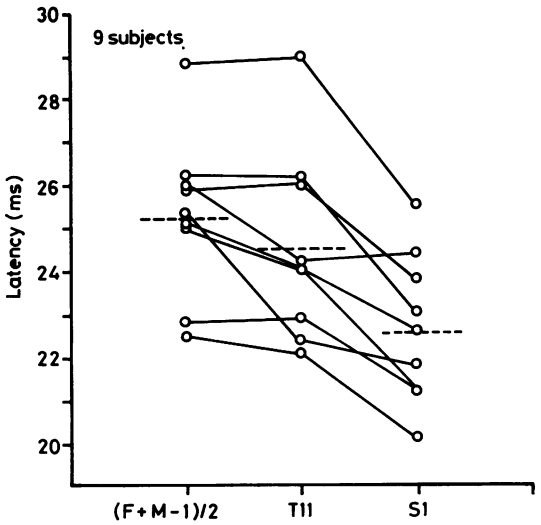

Fig 3 *Comparison of the latencies of EMG responses recorded in EDB of nine subjects to cathodal stimulation over T11 and S1 vertebrae, with those obtained using the F-wave technique by recordings from the same muscle following supramaximal stimulation of the deep peroneal nerve at the ankle. The shortest F-wave latency was determined after at least 15 successive peripheral nerve stimuli (see text for details). Stimulating over T11, the latency of the response in EDB was always equal to or slightly shorter than that obtained with F-wave technique (mean difference: 0·7 ms). The mean difference was 2·6 ms when stimulating over S1. Average values of the data points are indicated by the horizontal dotted lines.*

If spinal stimuli were given at an intermediate level over L3, the latency difference between F-wave and direct activation was similar to that observed with electrodes over T11. This latency difference increased and the latency of the direct response decreased by the same amount, if high intensities of stimulation were used (up to 100% maximum) (fig 5).

(4) *Recordings made for soleus*
As mentioned in (1) above, EMG responses recorded from soleus were somewhat different from those of other muscles. With low and moderate intensities of stimulation (40–80% output) the latency of the response sometimes were difficult to define. However, the timing of the main peak of the response in all subjects was longer for more caudal sites of stimulation (fig 6), suggesting that afferent rather than efferent structures were excited. With stronger stimuli (80–100% output) a different pattern was observed in seven subjects, consisting of two peaks separated by an increasing interval as the cathode was moved distally (fig 7). The latency of the first peak became shorter while that of the second component increased. The latter had a lower threshold, except in two subjects who showed first a small early component when stimulating over L5 or S1.

At a given site of stimulation, for example S1, increasing the stimulus intensity resulted in a progressive reduction of the amplitude of the second peak in parallel with an increase of the size of the first one (fig 6). In some individuals, the late component disappeared when very strong shocks were used.

Background voluntary contraction of the soleus markedly enhanced the late response whereas contraction of the antagonist muscles or vibration applied on the Achilles tendon prior to and during the shock reduced it (fig 7). When only a late response was observed it behaved in a similar manner. Background contraction or vibration did not have this effect on responses in other leg muscles.

Discussion

Several previous investigators[1 5–7] have used high voltage stimulation over the lower spinal column to elicit EMG responses in relaxed muscles of the legs. Rossini *et al*[7] and Snooks and Swash[6] used a longitudinal stimulating electrode montage, with the anode rostral in the first case and caudal in the second, but they could not elicit responses if the electrodes were placed over low lumbar or sacral levels. This was not the case in the present study. With the anode on the iliac crest contralateral to the leg under investigation and the cathode over the spinal column, responses could be obtained at levels from T11 to S1 in all subjects tested. Preliminary experiments showed that if the anode was moved nearer the spinal column, the size of responses obtained with the present montage was reduced. It may therefore be that the large interelectrode distance used in the present study provided a more efficient method of stimulation than that used previously.

The EMG responses in all muscles changed as the cathode was displaced caudally from T11 to S1. In EDB, tibialis anterior and quadriceps muscles, there were two principal effects. (1) At moderate stimulation intensities, the latency decreased in a stepwise fashion at a particular segmental level. This level was more rostral for quadriceps than it was for tibialis anterior or EDB. (2) The amplitude of the response first decreased caudal to T11/T12, and then began to increase at about the same level as the latency jump occurred. These findings suggest that for each muscle, there are two preferred sites at which stimulation occurs: at the level of the conus medullaris (from T11 to L1) and at the level at which the motor roots exit

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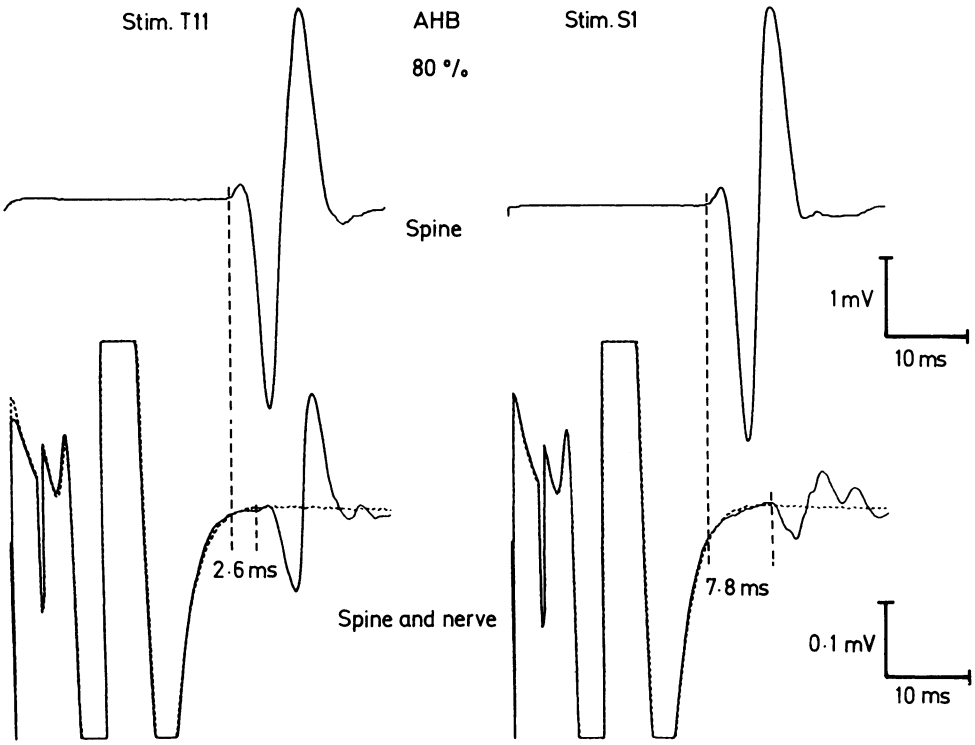

Fig 4 *Upper traces: EMG responses (single trials) recorded from abductor hallucis brevis (AHB) when stimulating over T11 and S1 spinal levels in one subject (stimulus intensity: 80% maximum). Lower traces: EMG responses in AHB after collision following simultaneous spinal stimulation and supramaximal stimulation of the posterior tibial and deep peroneal nerves at the ankle. The deep peroneal nerve was stimulated at the same time as the posterior tibial nerve, to ensure that no farfield EMG activity occurred at the latency of the F-wave. The first component of the response is the M-wave due to the peripheral nerve shock, which saturates the amplifiers. The M response to spinal stimulation (top traces) was completely annihilated by the antidromic volley from the peripheral nerve stimulus (bottom traces). The remaining response is an F-wave following spinal stimulation. In this subject, the difference in latency between F- and M-waves to spinal stimulation is 2·6 ms when the cathode is over T11, 7·8 ms when the cathode is over S1 (see text for details). The dotted traces are the responses to peripheral nerve stimulation alone. Note the different calibration of the upper and lower traces.*

from the spine (L2/L3 for quadriceps; L4/L5 for tibialis anterior and L5/S1 for EDB). The mean differences in latency obtained when stimulating over T11 and S1 were 1·4 ms for quadriceps, 2·4 ms for tibialis anterior and 3 ms for EDB. If we assume that the motor conduction velocity in the roots to the leg is about 50 m/s,[9] these latencies correspond to conduction distances of some 7 ± 2·5 cm (mean, SD) for quadriceps, 12, 6·5 cm for tibialis anterior and 15, 5 cm for EDB. These values are slightly shorter than those quoted by Sunderland[4] for the lengths of the lumbosacral roots to L2, L5 and S1: 11·2, 14·3 and 15·6 cm respectively. This might be explained by the possibility that motor conduction velocities in the proximal segments of the roots are less than 50 m/s, or that stimulation over T11 activates the roots at some distance from the cord.

Stimulation at both levels seems to involve direct activation of motor axons rather than spinal tracts or interneurons. This is because (1) peripheral motor delays estimated using F-wave latencies were always slightly longer than those with direct spinal stimulation, and (2) spinal stimulation at both sites produced both a direct M-wave and an indirect F response. At T11, the average peripheral motor delay to EDB calculated using F-wave latencies was 0·7 ms longer than when using direct stimulation, whilst the average interval between the M and the F-waves pro-

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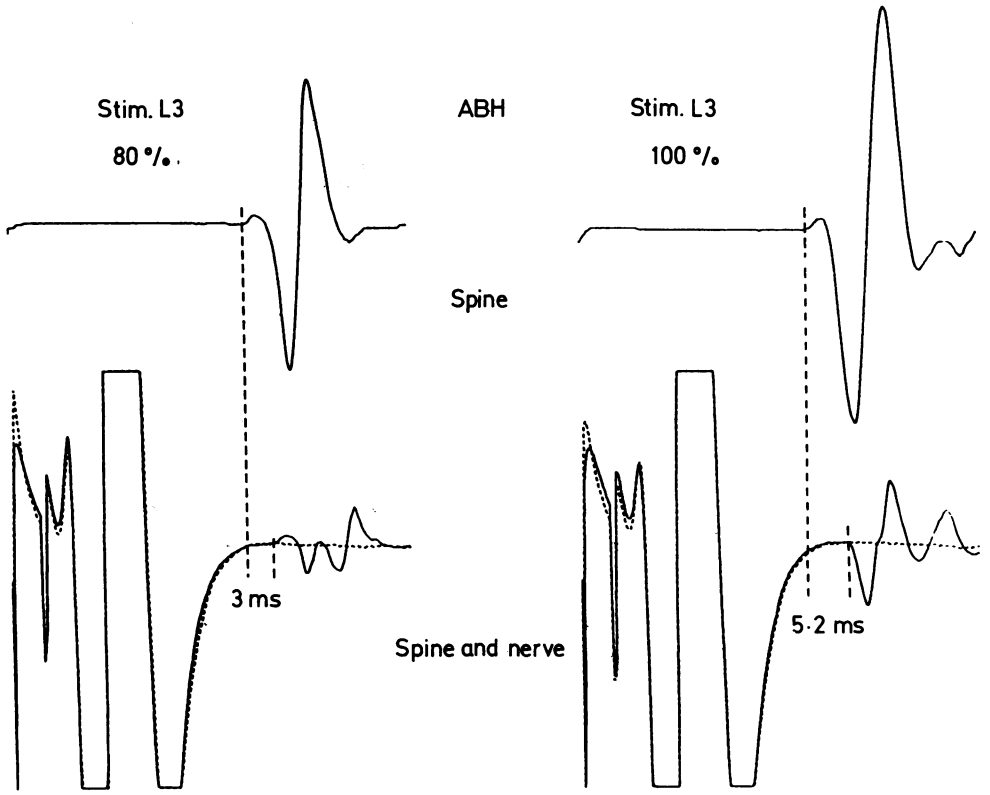

Fig 5 *Same as in fig 4, but the stimulating cathode was placed over L3, intermediate between T11 and S1. With moderate stimuli (80% maximum) the difference in latency between F and M responses to spinal stimulation was very similar (3 ms) to that obtained when stimulating over T11. With very strong stimuli (100% maximum), this difference increased, showing that in this case, activation of motor roots occurred at some intermediate level in the cauda equina, between their origin from the cord and the foramina (see text for details).*

duced by direct stimulation was 2·2 ms. If we subtract 1 ms from the latter to account for the turn-round time of the F-wave,[2 10] and then divide the result by two (since the F-wave travels both antidromically back to the motoneurons and the orthodromically under the stimulating electrodes) we obtain a conduction delay of 0·6 ms. Thus at the level of the conus, stimulation of motor axons must occur only 0·6 or 0·7 ms distal to the cell body. At 50 m/s, this would correspond to a distance of 3–3·5 cm. It should be noted that this calculation assumes M and F-waves are propagated at the same velocities. It is not known whether this is true. F-waves involve only a small proportion of the motoneuron pool and are not necessarily associated with the fastest motor axons.[11] Thus, measurement of F-wave latencies might lead to a slight overestimate of peripheral motor conduction times. Correspondingly, this would place the site of spinal stimulation closer to the spinal cord than the figure estimated above. It may even be that, at this level, stimulation occurs at the axon hillock, a region known to be of high electrical excitability.[12] Unfortunately, there is no straightforward way to test this hypothesis.

Although stimulation may occur preferentially at two sites, shortening of response latencies at high intensities seems to suggest that it is possible to stimulate at levels intermediate between the conus and root exit. Interpretation of this latency decrease is complicated by the fact that the responses also increase in size, so that part of the effect could be due to recruitment of faster conducting motor axons. Results from the collision experiments in AHB are useful in resolving this problem. These showed that as the stim-

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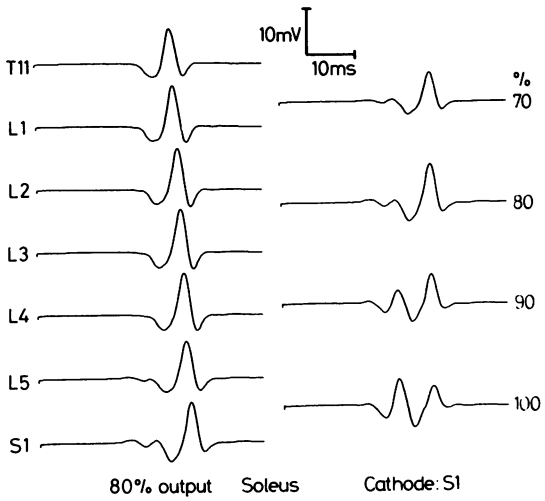

Fig 6 *Left: EMG responses (each trace represents the average of five trials) recorded in soleus of one subject, for stimulation at 80% maximum at different spinal levels. When the stimulating cathode is moved down the spine from T11 to L4, the latency is longer for more caudal sites of stimulation, until an early component becomes apparent over L5 and S1. Right: for a constant position of the cathode (S1), increasing the stimulus intensity results in the appearance of an earlier component of the response in soleus, the size of which increases (and the size of the later peak becomes smaller).*

ulus intensity was increased the interval between M and F-waves set up by stimulation over L3 decreased by the same amount as the latency of the direct (M) response. The most likely explanation for this is that at higher intensities, F-waves continued to be initiated at a proximal, more excitable site, whereas the site for initiation of the direct (M) response became more distal.

Recordings made from soleus indicate that afferent structures are also excited by spinal stimulation. With weak stimuli, the latency of the response in soleus increased as the cathode was moved more caudally. With stronger stimuli, the response was often preceded by a first peak which came earlier at low stimulation sites. Thus, the two components were separated by a greater interval when the cathode was moved down the cord.

It is well known that stimulation of the sciatic nerve usually evokes an H-reflex in soleus, by activation of large diameter Ia proprioceptive afferent fibres.[13] This reflex usually has a lower threshold than the direct M-wave, its size is increased by background voluntary contraction of the soleus,[13] whereas it is reduced by activation of antagonist muscles or by a vibration applied over the muscle tendon.[14 15]

In our experiments, the lower threshold of the late response observed in soleus and the fact that voluntary background contraction of this muscle increased its size while dorsiflexion of the foot or vibration (50

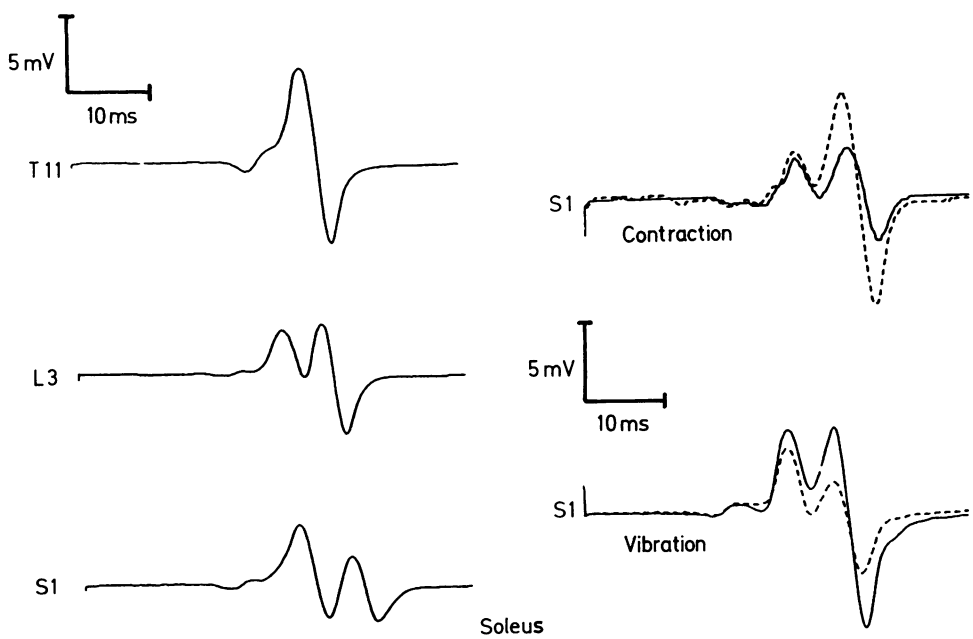

Fig 7 *The effects of cathode position, voluntary activity and vibration on EMG responses (each trace represents the average of five trials) in soleus muscle. Left: with strong stimuli (100% maximum) the response in soleus comprises two peaks separated by an increasing interval when the stimulating cathode is shifted caudally. Right: voluntary background contraction of the soleus enhances the size of the late component of the response (upper trace), while vibration over the Achilles tendon reduces it (lower trace). Solid traces: controls, dotted traces: conditioned. Stimulus intensity: 70% max.*

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Hz) applied over the Achilles tendon prior to the stimulus markedly reduced it, suggest that this late component was an H-reflex. This implies that spinal column stimulation activates large diameter proprioceptive fibres as well as motor axons.

From this study, we conclude that high voltage electrical stimulation over the lower vertebral column can activate motor roots at two sites, depending on the position of the stimulating cathode. At T11–L1 levels, overlying the conus medullaris, intradural motor axons are preferentially excited near the cord. When the cathode is placed lower, over the exit sites of the roots from the spinal canal, they are probably activated at the level of the vertebral foramina, where they might be more easily reached by the stimulus. When very strong stimuli are used, it is also possible to activate the roots at intermediate sites in the cauda equina. Proprioceptive sensory fibres are also excited, as shown by H-reflexes recorded from soleus.

As noted originally by Swash and Snooks,[5] these results have some potential clinical applications. The technique enables study of the cauda equina by a non-invasive method. Attention can be focused on selected roots by recordings from appropriate muscles and stimulating at two sites: over the conus medullaris (T11–L1 levels) and over the exit of the corresponding roots from the spine. Comparing the latency of responses elicited by stimulation at these points might give valuable information about the integrity of a given root in the cauda equina. Stimulation at some intermediate site is probably less useful, because the actual point where excitation of the motor roots occurs depends on the intensity of the stimulus.

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