Neurophysiological Changes Following Spinal Cord Lesions In Man

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SUMMARY: *A study has been made of the neurophysiological changes that follow spinal cord lesions in man. The Achilles tendon reflex (ATR) is used to estimate transmission in the Ia monosynaptic pathway, and the tonic vibration reflex (TVR) to estimate transmission in the Ia polysynaptic pathway to motoneurons. The inhibition of the H reflex by vibration is used as an estimate of presynaptic inhibition of the Ia monosynaptic pathway. Immediately following a complete lesion of the spinal cord presynaptic inhibition of the Ia monosynaptic pathway appears to be greatly increased. This enhanced inhibition may last several months but it eventually declines and in some instances becomes less than normal. Transmission in the Ia polysynaptic pathway is permanently abolished by a complete spinal lesion. A hypothesis is developed from these findings to explain the evolution of some of the clinical features that follow complete spinal lesions in man. Distinct differences are observed when the spinal lesion is incomplete. Transmission in the Ia polysynaptic pathway may be preserved and there may be no increase in presynaptic inhibition. These differences may depend upon the integrity of certain spinal long tracts which cannot be tested clinically.*

RÉSUMÉ: *Une étude a été faite sur les changements neurophysiologiques résultant des lésions de la moelle épinière chez l'homme. Le réflexe du tendon d'Achille (RTA) est utilisé pour évaluer les transmissions dans la voie monosynaptique Ia, et le réflexe de vibration tonique (RVT), pour évaluer la transmission dans la voie polysynaptique Ia aux motoneurones. L'inhibition du réflexe H par vibration est utilisée comme évaluation de l'inhibition présynaptique de la voie monosynaptique Ia. Immédiatement après une lésion complète de la moelle épinière, l'inhibition présynaptique de la voie monosynaptique Ia semble être grandement accrue. Cette inhibition peut durer plusieurs mois, mais elle décline éventuellement et dans quelques cas, devient moins que normale. La transmission dans la voie polysynaptique la est abolie en permanence par une lésion de la moelle épinière complète. Une hypothèse est émise à partir de ces expériences pour expliquer l'évolution de quelques faits cliniques qui suivent les lésions complètes de la moelle épinière chez l'homme. Des différences nettes sont observées quand la lésion de la moelle épinière est incomplète. La transmission dans la voie polysynaptique Ia peut être préservée et il peut ne pas y avoir d'augmentation dans l'inhibition présynaptique. Ces différences peuvent dépendre de l'intégrité de certaines voies spinales longues, par des lésions qui ne peuvent être vérifiées cliniquement.*

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INTRODUCTION

The clinical features that follow transection of the spinal cord have been well documented both in animals (Sherrington, 1910) and man (Riddoch, 1917) but the underlying neurophysiological changes are still unclear.

Immediately following a lesion of the spinal cord there is a profound depression of muscle tone and a reduced response to afferent stimuli. This may be associated with a transient reduction in fusimotor drive in man (Weaver et al., 1963) and in animals (Zapata, 1966) although this has been considered to be minor (Hunt et al., 1963). Hyperpolarization of motoneurons has been demonstrated in animals (Barnes et al., 1962) but in man the excitability of the motoneurons, as determined by the H reflex, is normal or only slightly reduced (Weaver et al., 1963; Diamantopoulos and Zander Olsen, 1967).

After a variable interval, depending on the species, tendon reflexes return, muscle tone increases and the response to afferent stimuli becomes exaggerated. At this stage fusimotor drive may be increased in man (Deitrichson, 1973), although this is disputed (Landau, 1969) and has not been confirmed in animals (Meltzer et al., 1963). Renshaw cell inhibition (Veale et al., 1973), and presynaptic inhibition (Delwaide, 1973) may be less effective. The excitability of motoneurons in man, determined by the H reflex, may be increased (Deitrichson, 1971) although there is considerable overlap within the normal range. Most of these neurophysiological changes are of minor degree and seem inade-

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quate to account for the profound changes observed clinically.

In an attempt to obtain a clearer understanding of the sequence of neurophysiological changes that may follow spinal transection in man, the activitiy in three segmental reflex pathways has been measured in normal subjects and in a series of patients with physiologically complete spinal lesions of varying duration. Substantial alterations in the depression of the monosynaptic reflex by vibration and in the tonic vibration reflex (TVR) were observed following complete spinal lesions in man, confirming the preliminary findings of Ashby et al. (1974). A hypothesis to explain some of the clinical features that follow spinal cord lesions in man is proposed. The findings in patients with complete and incomplete spinal lesions are compared. There are significant differences in segmental reflex activity in the two groups that may depend on the integrity of certain long tracts which cannot be tested clinically.

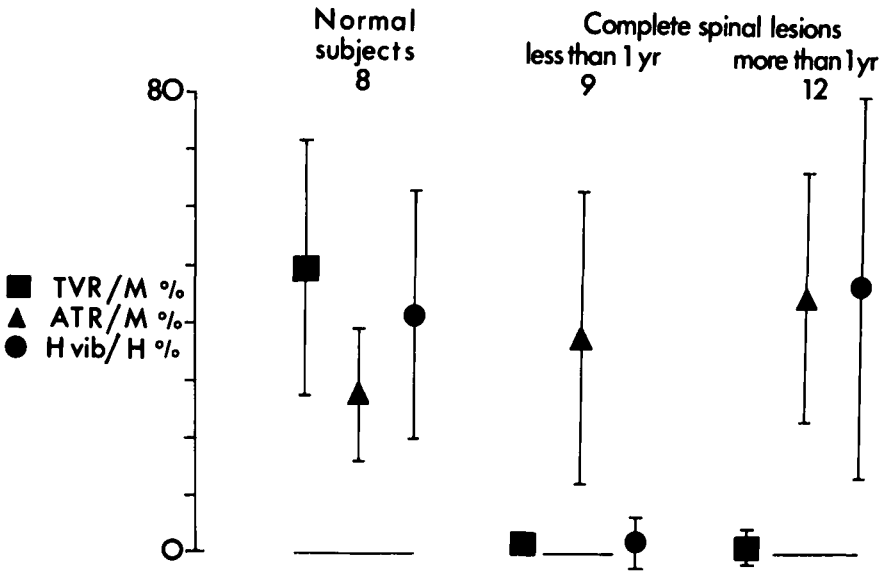

Figure 1—Activity in 3 reflex pathways in normal subjects (8 studies), patients with recent complete spinal lesions (9 studies) and patients with complete spinal lesions of long duration (12 studies). The tonic vibration reflex (TVR) can be used as an estimate of transmission in the Ia polysynaptic pathway to motoneurons. Transmission in this pathway is abolished following a complete spinal lesion. The H vibration/H control ratio can be used as an estimate of presynaptic inhibition of the Ia monosynaptic pathway. Presynaptic inhibition is increased immediately after a complete spinal lesion but later declines. The Achilles tendon reflex (ATR) can be used as an estimate of transmission in the Ia monosynaptic pathway to motoneurons. In this series there is no significant difference between the groups. (means and standard deviations)

METHODS

Studies were carried out on 8 normal subjects, 8 patients with physiologically complete spinal lesions of less than 1 year duration and 9 patients with complete spinal lesions of more than 1 year duration. In 4 instances studies were repeated on the same individual after a prolonged interval. In addition, studies were performed on 7 patients with severe, but incomplete, spinal lesions. All medications that could affect muscle tone were discontinued three days prior to testing (except studies 20 and 25).

Studies were performed with the subject lying prone. The leg to be examined was immobilized in a padded frame with padded clamps gripping the malleoli. The sole of the foot rested against a foot board pivoted at the level of the malleoli. The ankle joint was fixed as close to 90° as possible.

Square wave stimuli, 1 msec duration, generated by a Grass S 88 stimulator were delivered to the popliteal nerve in the popliteal fossa using a bipolar surface electrode. The electrode was positioned to produce a reflex response at the lowest possible threshold and then immobilized with a rubber strap. The stimulator was triggered by a Digital PDP 12 computer programmed to deliver 10 impulses at random intervals between 2 and 3 sec. The stimulus current was increased in increments until a complete H-M recruitment curve had been obtained; a further increase of at least 25% ensured that a supramaximal M response had been recorded.

The Achilles tendon reflex (ATR) was evoked with supramaximal mechanical stimuli delivered with a tendon hammer that triggered the oscilloscope sweep and the averaging program. These stimuli were given at random intervals between 2 and 3 sec. The responses were monitored on a Tektronix storage oscilloscope so that responses that were not supramaximal could be rejected. Vibration was applied to the tendon Achilles with a Wahl Jumbo vibrator (frequency 60 Hz; undamped amplitude 3 - 4 mm).

The compound action potential of the soleus was recorded with 2 cm diameter disc surface electrodes. The active electrode was placed over the belly of the soleus and the reference electrode 8 cm distally over the tendon Achilles. A 4 cm square lead plate over the upper gastrocnemius acted as ground.

Action potentials were amplified by a Tektronix (type 2A-60) amplifier with filter settings 0.1 Hz and 0.1 MHz and monitored on a Tektronix (RM 564) storage oscilloscope. This signal was digitalized (1,000/sec) by the PDP 12 computer and 3-5 (mechanically) or 10 (electrically) induced responses were averaged. These responses were plotted with an incremental plotter (Complot 7) and the peak to peak amplitude of the H and M responses and the ATR were measured from the plotting paper.

The force generated by plantarflexion of the foot was measured with a two arm strain gauge connected to the foot plate, activiated by a 7PIC low level DC preamplifier and recorded on a Grass Model 7B ink writing polygraph.

When the experimental conditions appeared stable the following procedure was adopted. Three or more supramaximal electrical stimuli were delivered to the popliteal nerve to elicit a maximal contraction of the soleus muscle. The developed tension was recorded on the polygraph. Vibration was applied to the Achilles tendon to evoke a TVR. The vibration was maintained until the developed tension reached a plateau. This was repeated three or more times. Next the H-M recruitment curve was recorded. At each stimulus level, control runs and runs with vibration were alternated. After each run with vibration 90 sec was allowed to elapse to avoid the long lasting depression of the H reflex

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TABLE 1 NORMAL SUBJECTS

Study		Sex	Age	TVR/M %	ATR/M %	H/M %	Hvib/H %
1	MV	F	25	48.0	41.0	41.0	17.0
2	PT	M	30	49.0	28.0	62.0	58.0
3	PB	F	26	33.0	15.0	36.0	11.0
4	BF	M	40	28.0	47.0	79.0	71.0
5	DA	M	26	35.0	23.0	40.0	50.0
6	JD	M	42	51.0	15.0	58.0	52.0
7	GT	M	37	98.7	27.3	40.3	24.1
8	PA	M	37	52.7	21.5	50.8	48.5
MEAN			32.9	49.4	27.2	50.9	41.5
SD			6.9	22.0	11.5	14.7	21.4

(Arcangel et al., 1971). Finally, 3 groups of 3-5 ATRs were averaged.

The compound action potential of the soleus resulting from supramaximal electrical stimulation of the popliteal nerve was assumed to represent the activity of 100% of the soleus motor units. The compound action potential produced by the ATR could be compared to this value and the ATR expressed as a percentage of the motoneuron pool activated by the Ia monosynaptic pathway. The peak tension resulting from supramaximal electrical stimulation of the popliteal nerve was assumed to represent the activity of 100% of soleus motor units. By comparing the tension produced by the TVR with that developed by supramaximal stimulation of the popliteal nerve the TVR could also be expressed as a percentage of the motoneuron pool reflexly activated. The ratio of the maximum H (vibration) to the maximum H (control) was used to indicate the extent of presynaptic inhibition of the Ia monosynaptic pathway induced by vibration. Student's 't' test and the correlation coefficient were used to compare results in normal subjects, patients with recent and longstanding complete spinal lesions and patients with incomplete spinal lesions. Probabilities of less than 0.05 (two-tailed) were considered to be significant.

RESULTS

Normal subjects

Vibration of the tendon Achilles produced a slowly augmenting TVR in all subjects activating approximately half of the motoneuron pool of the soleus (Table 1). The ATR activated a mean of almost one third of the motoneuron pool of the soleus. Vibration produced substantial inhibition of the H reflex in every subject reducing the amplitude to a mean of 40% of the control value.

Patients with recent complete spinal lesions

In this group, vibration of the tendon Achilles did not produce any appreciable activation of the motoneuron pool of the soleus (Table 2). The mean TVR/M ratio (Fig. 1) is significantly below that of the normal subjects ($t=6.5$; $p<0.001$).

TABLE 2 COMPLETE SPINAL LESIONS, LESS THAN 1 YEAR DURATION

Study		Sex	Age	Level	Cause	Duration Months	TVR/M %	ATR/M %	H/M %	Hvib/H %
9	DW	M	51	C7	Trauma	2	4.0	8.0	27.0	0
10	BD	M	19	C7	Trauma	3	4.0	15.0	61.0	0
11	BD	M	19	C7	Trauma	8	5.0	41.0	36.0	0
12	TV	M	25	C5	Trauma	2	0	39.7	80.6	0
13	TH	F	18	C7	Trauma	0.5	0	64.3	91.3	0
14	LS	F	20	C8	Trauma	4	0	48.0	68.4	11.5
15	ML	F	42	C7	Trauma	6	0	75.8	73.7	0
16	HF	M	29	C5	Trauma	3	0	46.5	68.1	8.2
17	HP	M	23	T8	Trauma	4.5	0	0	5.0	0
MEAN			27.3			3.7	1.4	37.6	56.8	2.2
SD			11.6			2.3	2.2	25.4	28.1	4.4

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TABLE 3 COMPLETE SPINAL LESIONS, MORE THAN 1 YEAR DURATION

Study		Sex	Age	Level	Cause	Duration Months	TVR/M %	ATR/M %	H/M %	Hvib/H %
18	BH	M	21	T7	Trauma	18	0	55.0	42.0	74.0
19	NG	M	23	C5	Trauma	27	0	49.0	119.0	64.0
20	NG	M	24	C5	Trauma	40	0	77.3	101.8	22.8
21	SJ	M	57	T6	Trauma	30	0	15.0	40.0	95.0
22	RR	F	38	T7	Trauma	12	7.0	54.0	100.0	15.0
23	LB	M	24	C4	Trauma	72	0	30.0	75.0	77.0
24	LB	M	25	C4	Trauma	84	0	38.6	94.7	43.1
25	CD	F	30	C7	Trauma	60	0	31.0	54.0	28.0
26	CD	F	31	C7	Trauma	72	0	46.8	67.6	4.0
27	DC	F	19	C2	Trauma	24	0	16.5	55.8	47.4
28	MB	M	27	T6	Trauma	60	7.5	87.5	105.9	93.1
29	JZ	M	26	C6	Trauma	96	0	36.3	49.0	0
MEAN			28.8			49.6	1.2	44.8	75.4	47.0
S.D.			10.2			28.0	2.8	21.9	27.8	33.6

The ATR/M ratio was surprisingly high, even in one patient (study 13) examined 2 weeks after the onset of the lesion. The mean ATR/M ratio does not differ statistically from that of the normal subjects.

In almost all instances vibration completely abolished the H reflex. The mean H vibration/H control ratio is significantly smaller than that of the normal subjects ($t=5.4$; $p< 0.001$).

Patients with complete spinal lesions of long duration

Vibration did not produce any appreciable activation of the motoneuron pool of the soleus (Table 3). The mean TVR/M ratio is significantly below that of the normal subjects ($t = 7.6$; $p < 0.001$). Although the ATR activated a larger proportion of the motoneuron pool in this group than in the normal subjects the difference is not statistically significant.

Vibration produced much less inhibition of the H reflex in the patients with longstanding lesions. The mean H vibration/H control ratio is significantly above that of the patients with recent lesions ($t=3.9$; $p< 0.001$). This change appears to occur very gradually (Fig. 2). Thus profound inhibition of the H reflex by vibration persisted in one patient 8 months after the lesion (study 11) and the largest H vibration/H control ratio was seen 2½ years after the lesion (study 21). However, following this interval the H vibration/H control ratio showed considerable variation and some patients with lesions of very long duration had low ratios (eg. study 29).

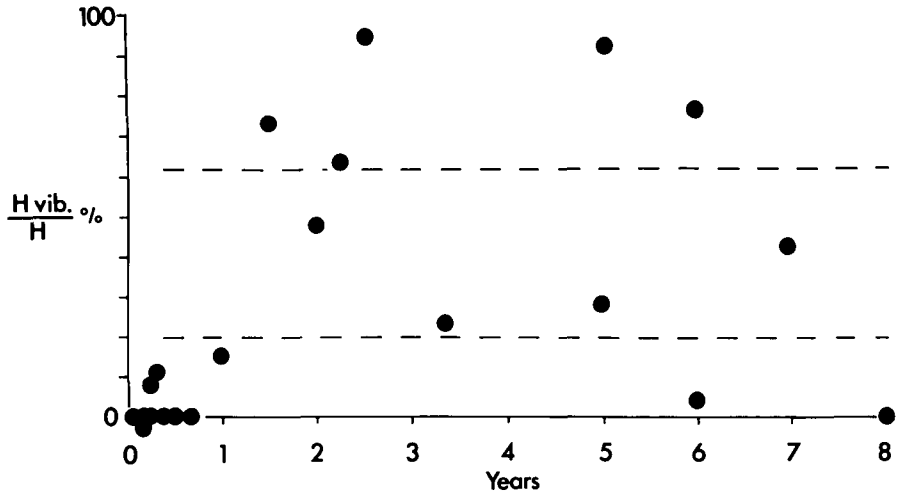

Figure 2—Evolution of the H vibration/H control ratio following complete spinal lesions in man. The ratio may be used as an estimate of presynaptic inhibitiion of the Ia monosynaptic pathway. The increase in presynaptic inhibition seen immediately following a complete spinal lesion in man remains for almost one year. The dashed lines represent the data from 8 normal subjects (mean ± 1 standard deviation).

Patients with recent incomplete spinal lesions

All of the patients in this group had a severe neurological deficit. Only H.K. (study 31) could walk (with assistance) at the time of the study. This group (Table 4) is somewhat older and contains a

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TABLE 4 INCOMPLETE SPINAL LESIONS, LESS THAN 1 YEAR DURATION

Study		Sex	Age	Level	Cause	Duration Months	TVR/M %	ATR/M %	H/M %	Hvib/H %
30	SS	M	54	T7	Trauma	6	32.0	31.9	20.0	93.8
31	HK	M	33	T12	Trauma	5	10.0	21.0	48.0	40.0
32	FH	F	51	T10	Trauma	0.25	37.0	66.0	108.0	9.0
33	BF	M	19	L1	Trauma	3.5	13.5	27.5	72.6	43.2
34	PM	M	70	T12	Metastatic Ca	0.25	0	2.0	7.0	0
35	NL	M	43	C6	Trauma	1.75	7.6	24.2	3.3	0
36	HK	M	46	C7	Post operative	3.5	12.7	13.0	6.8	17.2
MEAN			45.1			2.9	16.1	26.5	38.0	29.0
S.D.			16.2			2.2	13.4	20.0	40.1	33.5

larger proportion of patients with paraplegia than the group with recent complete lesions, but the lesions are of comparable duration (mean durations not statistically different). The ATR/M ratios are similar in the two groups. A TVR was obtained in all but one of this group and the mean TVR/M ratio is significantly greater in this group (Fig. 3) than in the group with recent complete lesions ($t = 3.3$; $p < 0.01$).

Vibration does not produce the same profound inhibition of the H reflex that is seen in the patients with complete lesions. The mean H vibration/H control ratio is significantly higher in the incomplete group ($t = 2.4$; $p > 0.05$).

The preservation of the TVR or of a "normal" H vibration/H control ratio could not be related to the integrity of any of the long tracts which can be clinically tested.

When the data from all 36 studies are pooled the values of the ATR/M and those of the maximum H/M ratio show a close correlation ($r = 0.74$; $p < 0.001$) suggesting that these measurements provide similar estimates of the excitability of the monosynaptic arc to single volleys. Neither the ATR/M or the H/M show any relationship to the H vibration/H control ratio and the TVR/M also appears independent of the other variables.

DISCUSSION

The limitations of the testing procedures used in this study must be defined. The mechanical tap of the ankle tendon will excite many muscle and cutaneous afferents but, as only the Ia afferents make monosynaptic connection with motoneurons (Lloyd, 1943), it appears justifiable to use the ATR to estimate transmission in the Ia monosynaptic pathway to motoneurons. The proportion of the motoneuron pool that is activated by this Ia monosynaptic pathway can be estimated from the ATR/M ratio provided certain limitations are recognized. For example, motor units evoked reflexly may not be from the same motoneuron pool as those activated by direct stimulation of the

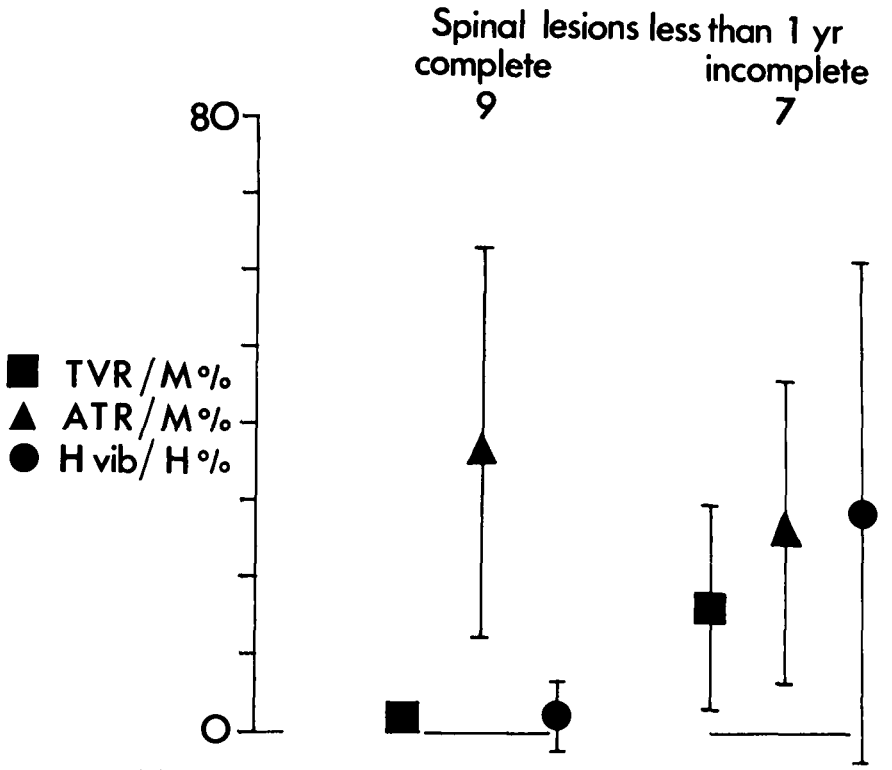

Figure 3—Activity in 3 reflex pathways in patients with recent complete spinal lesions (9 studies) and recent incomplete spinal lesions (7 studies) of comparable duration. The tonic vibration reflex (TVR), which can be used as an estimate of transmission in the Ia polysynaptic pathway to motoneurons, is preserved when the lesion is incomplete and the H vibration/H control ratio, which can be used as an estimate of presynaptic inhibition of the Ia monosynaptic pathway, is not so profoundly depressed (means and standard deviations).

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motor nerve, and the reflex compound action potential will always be slightly more dispersed and of lower amplitude because of its longer latency. When the recording electrodes were placed close together over the soleus, however, the compound action potential of the soleus always resembled that of the equivalent M response so these effects are considered to be minimal. When the muscle is at a fixed length and the mechanical stimulus is supramaximal the ATR/M ratio will depend on the level of fusimotor drive and the excitability of the motoneuron pool.

The primary ending appears to be the receptor whose excitation leads to the TVR (Matthews, 1966); these endings are the most sensitive to vibration in the cat (Brown et al., 1967) and can be readily activated by vibration in man (Hagbarth, 1973). The TVR can be reduced by procaine block of fusimotor nerves (De Gail et al., 1966) suggesting that it is dependent upon the muscle spindle, and autogenic excitation and reciprocal inhibition can be demonstrated which are characteristic of the reflex effects of the primary ending (Lance et al., 1966). Burke et al. (1972) found that the TVR of an extensor muscle, in man, could be potentiated either by increasing muscle length or by the Jendrassik maneuver and that these effects occluded one another, also implying that the TVR depends upon the muscle spindle and upon the primary rather than the secondary ending. The secondary endings and Golgi tendon organs are relatively insensitive to vibration in the cat (Brown et al., 1967) and are unlikely to contribute to the TVR in man as activity in their afferents results in the inhibition of extensor motoneurons (Burke and Lance, 1973); pacinian corpuscles respond optimally to vibration of higher frequencies (Sato, 1961). It has been clearly demonstrated that cutaneous receptors are not required for the TVR in the cat (Gillies et al., 1971) and it is likely that this is also true for man since the TVR is maximum when vibration is applied to a muscle or its tendon and is unaffected by local anaesthesia of the overlying skin (Hagbarth and Eklund, 1965). It is also likely that the TVR employs a polysynaptic pathway to motoneurons. Homma et al. (1973) have shown that vibration produces both a direct and an "augmentative" excitatory postsynaptic potential in motoneurons, the latter attributable to polysynaptic activation. In man, vibration produces a slowly augmenting muscle contraction with asynchronous firing of motoneurons, during which transmission in the monosynaptic arc may be completely inhibited. Drugs that block polysynaptic pathways can abolish the TVR but leave the monosynaptic reflex unchanged (De Gail et al., 1966). The polysynaptic pathway may lie at segmental level in the cat since the TVR, reduced by a lesion of the lateral vestibular nucleus, can be restored by stimulation of the vestibulospinal fibers caudal to the lesion (Gillies et al., 1971). From the above evidence, it may be concluded that while vibration of a muscle tendon in man is likely to have complex reflex effects, the contraction that develops in the vibrated muscle depends predominately on activity in a polysynaptic pathway from the Ia afferents to the motoneurons.

In this study the TVR (tension)/maximum M (tension) ratio is used to indicate the proportion of the motoneuron pool that can be activated by vibration. This requires several assumptions. The tension arising from synchronous discharge of motor units may be somewhat higher than expected from a sum of its components (Merton, 1954), but this effect is likely to be small. The motor units recruited by the Ia barrage may not be from the same motoneuron pool as those activated by supramaximal stimulation of the motor nerve, but they are likely to be the same as those recruited by the Ia volley of the ATR where this effect has been considered negligible. Vibration could spread through the limb and evoke a reflex contraction of the antagonist muscles producing a falsely low tension. However, Hagbarth (1973) has indicated that vibration is not a potent stimulus for the spindles of antagonist muscles, especially if they are slack. Finally, as the relationship between the amplitude of the compound action potential and the developed tension of triceps surae is linear (unpublished observations) it appears justifiable to use the ratio of action potentials and the ratio of developed tensions as parallel estimates of the proportion of the motoneuron pool that is activated under a variety of circumstances. With a given vibratory stimulus and the muscle at a fixed length, the TVR/M ratio will depend not only upon the level of fusimotor drive and the excitability of the motoneuron pool in common with the ATR, but also upon the excitability of the interneurons in the Ia polysynaptic pathway.

Vibration of a muscle may also result in inhibition of the monosynaptic reflex in animals and in man (Lance et al., 1973). In animals, this inhibition is considered to be presynaptic since it can be blocked by picrotoxin, is accompanied by depolarization of Ia terminals, and can occur while the excitability of the motoneurons to direct stimulation is unchanged (Gillies et al., 1969; Barnes and Pompeiano, 1970). In man, the evidence that the effect is presynaptic is less direct. The inhibition, however, cannot be attributed to occlusion of the Ia pathway (Lance et al., 1973) or to postsynaptic inhibition resulting from the spread of vibration to the antagonist (Dindar and Verrier, 1975) and the excitability of the motoneurons, tested through other reflex pathways, is not depressed (Delwaide, 1973). It therefore seems reasonable to assume that the inhibition in man is similar to that seen in the experimental animal. The depression of the monosynaptic reflex by vibration has been used as an estimate of presynaptic inhibition in man (Delwaide, 1973). The H reflex rather than the ATR should be used for this purpose as the H reflex is less influenced by alterations in fusimotor drive (Arcangel et al., 1971). The complete H-M recruitment curve must be plotted to ensure that the maximum H (control) and maximum H (vibration) are ob-

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tained. With the muscle at a fixed length and with a standard vibratory stimulus the H vibration/H control ratio can be used to compare the degree of this inhibition of the Ia monosynaptic pathway in different individuals.

One further limitation of the present method must be emphasized. All reflex studies depend upon the integrity of peripheral pathways as transmission lines to and from the spinal cord. Spinal cord lesions may be complicated by peripheral nerve lesions (Cooper and Sherrington, 1932; Landau and Clare, 1959; Weaver et al., 1963) or secondary changes in the anterior horn cells (Nyboar and Johnson, 1971). If the superimposed lower motoneuron lesion is severe, reflex testing cannot be performed. Two patients were rejected from the present series as neither the ATR or H reflex could be obtained. The population that can be examined is, to this extent, potentially selected. The method is not invalidated by minor complications of this type if activity in each of the reflex pathways is expressed in terms of the fraction of the (existing) motoneuron pool that is activated.

Patients with complete spinal lesions

In the patients with complete spinal lesions, either recent or longstanding, the TVR was either absent or extremely small. This is in keeping with previous observations (Lance et al., 1973); the TVR is apparently abolished in most instances by complete spinal transection in man. Gillies et al. (1971) found that the TVR of the triceps surae of the decerebrate cat, obtained with vibration parameters sufficient to render it independent of fusimotor drive, could be abolished by spinal transection or greatly reduced by selective lesions of the ventral column or the ipsilateral vestibular nucleus. The TVR could be restored to its former amplitude by stimulation of the vestibulospinal fibers caudal to the latter lesion, suggesting that the vestibulospinal tract was a major source of facilitation for the TVR. It is reasonable to suppose that the loss of some similar supraspinal support may account for the present findings in man. Since fusimotor drive and the excitability of the motoneuron pool are common to the TVR and the ATR, the reduced TVR may be tentatively attributed to alterations in the excitability of the interneurons involved in the transmission of the TVR. The ATR activated a surprisingly large fraction of the motoneuron pool in the patients with recent complete spinal lesions. This may be explained by the relatively long interval between the lesion and the examination. Weaver et al. (1963) and Diamantopoulos and Zander Olsen (1967) obtained H reflexes of large amplitude and ATR's of small amplitude immediately after spinal cord lesions in man, implying a reduction in fusimotor drive. However, this reduction in the ATR/H ratio was most obvious in the first few days following the lesion and lasted about 4 weeks. This interval is in keeping with clinical experience (Riddoch, 1917; Guttman, 1970). Most patients with "recent" lesions in the present study were examined after this interval, the ATR/M ratio was not reduced, an observation in keeping with the apparently transient nature of the depression of fusimotor drive following spinal lesions in man. A larger ATR/M ratio was observed in the patients with longstanding complete spinal lesions although the ratio was not, statistically, different from normal. While there is evidence for increased fusimotor drive following longstanding lesions in man (Deitrichson, 1973) its importance is disputed (Landau, 1969). Presynaptic inhibition of the Ia monosynaptic pathway appears to be enhanced immediately following a complete lesion of the spinal cord in man. The enhancement of this inhibition following spinal transection suggests that the inhibition in man is normally subject to supraspinal inhibitory control. Lundberg and Vyklicky (1966) observed that dorsal root potentials, evoked by stimulation of primary afferents, could be inhibited from the caudal medial reticular formation, in the cat, the effect being mediated by ventral spinal pathways. A similar system may exist in man. Could the clinical features observed following a complete spinal lesion in man be due to the release of this powerful spinal inhibitory mechanism? The reduced reflex excitability immediately following spinal transection is generally attributed to loss of supraspinal facilitation (Liddell, 1934) but Ruch and Watts (1934) documented an increase in forelimb extensor reflexes following a thoracic spinal transection in the spinal animal, the "Schiff-Sherrington" phenomenon, implying the existence of inhibitory neurons at segmental level active in the acute spinal preparation and Liddell (1934) observed that a stimulus applied to the sciatic nerve was capable of producing prolonged inhibition of the monosynaptic reflex in the acute, but not the chronic, spinal animal. Van Harreveld (1940) found that the hypotonic state that followed spinal transection could be curtailed by asphyxia of the cord and postulated that this state resulted from the dominance of a spinal inhibitory mechanism.

As the interval following the lesion becomes longer the enhancement of this inhibition gradually fades and in some instances the inhibition becomes less than normal. Delwaide (1973) found that presynaptic inhibition was significantly reduced in patients with longstanding neurological lesions but in this series the mean H vibration/H control ratio was not statistically greater than normal. In some patients with extremely longstanding lesions the H vibration/H control reflex was low. These changes in presynaptic inhibition are extremely gradual occurring over 1-2 years. This time course is reminiscent of the gradual disappearance, over 50 to 60 days, of the increased inhibitability of the extensor reflex following spinal transection in the cat (Liddell, 1934) and can be contrasted with the transient alterations in fusimotor drive reported to last a few minutes in the cat (Hunt et al., 1963) and a few days in man (Weaver et al., 1963). Clearly different mechanisms are involved in the evolution of these changes. The extremely gradual alterations in pre-

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synaptic inhibition raise the possibility that structural changes are occurring in the cord. McCouch et al. (1958) have suggested that sprouting of dorsal root afferents may occur following spinal transection. The present findings could be explained if the sprouting of dorsal root afferents resulted in the creation of new synapses upon the motoneurons that were not equipped with presynaptic inhibitory terminals. The observed changes in presynaptic inhibition of the Ia monosynaptic pathway appear to have remarkably little influence upon the transmission of single volleys such as the ATR or H reflex. This is not entirely unexpected since a single, synchronous, volley in the Ia monosynaptic pathway will reach the motoneuron before this presynaptic mechanism can be activated. The second of a pair of volleys, however, would be expected to be influenced by presynaptic inhibition induced by the first. In this regard it is of interest that the second of two afferent volleys results in a reduced motoneuron discharge immediately after a spinal lesion (Diamantopoulos and Zander Olsen, 1967) and an enhanced discharge after longstanding lesions (Takamori, 1967; Zander Olsen and Diamantopoulos, 1967). Alterations in presynaptic inhibition may have contributed to these findings. The presynaptic mechanism would be expected to have its greatest effect upon recurrent afferent volleys such as the physiological discharge in Ia afferents produced by passive stretching of muscles. This is in accord with the authors' clinical impression that the H vibration/H control ratio could be correlated with the patient's muscle tone.

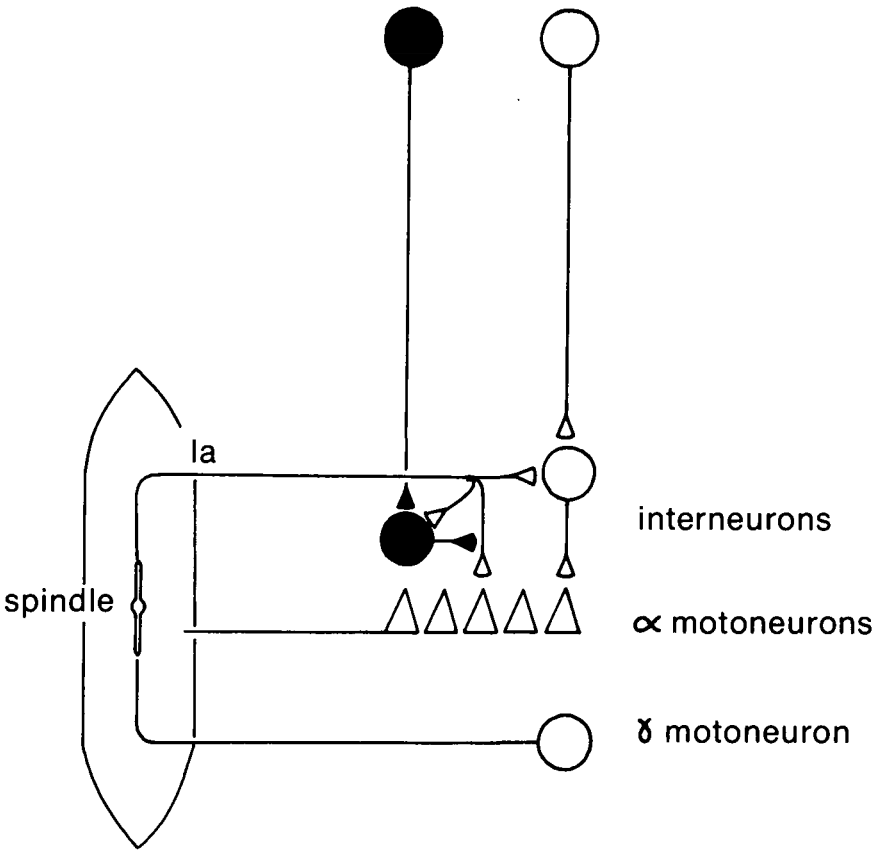

Figure 4—A hypothetical arrangement of segmental reflex pathways to explain the clinical features that follow spinal cord lesions in man (see text). The Ia afferents make monosynaptic and polysynaptic (light interneuron) connection with the motoneuron pool (triangles) and activate a presynaptic inhibitory mechanism (dark interneuron) which will have its most noticable effect on recurrent Ia volleys. The interneurons are influenced from supraspinal centres. Immediately following a complete spinal lesion presynaptic inhibition is increased, support for the Ia polysynaptic pathway is lost and a transient depression of fusimotor drive may occur. At this stage, although the H reflexes may be normal, the tendon reflexes are reduced. Muscle tone is reduced as the recurrent afferent volleys produced by passive muscle stretch activate the enhanced presynaptic inhibitory mechanism. The polysynaptic tonic vibration reflex is permanently abolished. Normal or enhanced fusimotor drive may be established within a few days but the increase in presynaptic inhibition lasts many months. At this intermediate stage the tendon reflexes may be exaggerated although muscle tone remains reduced. After a longer interval the presynaptic inhibitory mechanism becomes less effective. There is now reduced damping of recurrent afferent volleys in the Ia afferents which may account for the exaggerated response to passive muscle stretch.

The present findings can be incorporated into a hypothesis that may explain the evolution of some of the clinical features following a complete spinal lesion in man (Fig. 4). It is postulated that immediately following spinal transection, presynaptic inhibition is increased; support for the Ia polysynaptic pathway is lost and a transient depression of fusimotor drive may occur. At this stage, although the H reflex may be large the tendon reflexes are reduced, the response to recurrent afferent volleys (for example those produced by the passive extension of a muscle) is reduced and the tonic vibration reflex permanently abolished. Normal, or enhanced, fusimotor drive may be established within a few days but the increase in presynaptic inhibition of the Ia monosynaptic pathway persists for months. During this intermediate stage the tendon reflexes may be exaggerated while muscle tone remains reduced. After a further interval, possibly because of anatomical rearrangements occurring at segmental level the presynaptic inhibitory mechanism becomes less effective. Afferent volleys now result in an exaggerated and prolonged motoneuron response that may result in increased tone. The final clin-

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ical picture at any time will depend on a multitude of factors including alterations in the bias upon reflex pathways (Burke and Lance, 1973) and upon slow plastic changes in the neuromuscular apparatus (Edstrom, 1970; Herman, 1970).

Patients with recent incomplete lesions

When a recent spinal lesion is incomplete, transmission in the Ia polysynaptic pathway may be preserved, and presynaptic inhibition of the Ia monosynaptic pathway does not increase so dramatically. It is likely that this is related to the preservation of certain long tracts in the spinal cord. In this small series the presence of a TVR or of a normal H vibration/H control ratio could not be related to the preservation of any of the clinically testable long tracts. As a working hypothesis for future studies it could be suggested that the facilitation of the TVR (Gillies et al., 1971) and the control of presynaptic inhibition (Fulton et al., 1930; Lundberg and Vyklicky, 1966) may be transmitted by ventral pathways. Recently, investigators have been seeking new ways to assess patients with acute spinal injuries (Perot, 1973). It is possible that neurophysiological measurements as employed in this study could be used as an adjunct to clinical examination in the assessment of patients.

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