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INTERNEURONES AND RIGIDITY OF SPINAL ORIGIN

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The extensor paralysis, or hind-limb rigidity produced by temporary ischaemia of the lumbosacral spinal cord, and analysed in this paper, is due exclusively to a spinal cord lesion. This extensor hypertonus is readily induced in cats previously spinalized (van Harreveld & Marmont, 1939). Similarly, we found that such chronic rigidity in dogs with undivided cords is not significantly modified by subsequent mid-thoracic cord transection. This rigidity is also enduring. There is no attenuation of the pillar-like rigidity with time, as there is of functional defects after cortical lesions or spinal semisection. There is no 'plasticity' of functioning neurones in the spinal cord with such an ischaemic lesion. We have not observed any obvious abatement of the rigidity in dogs kept for as long as 204 days.

The hind-limb rigidity of spinal origin resembles decerebrate rigidity in several ways: it appears promptly upon recovery from anaesthesia used for the temporary ischaemia by thoracic aorta occlusion, it is most intense in the antigravity muscles and it persists indefinitely. The differences, however, are fundamental. The decerebrate rigidity is of supra-spinal origin and for its manifestation, in contrast to the spinal rigidity, it is essential that the pathways from brain stem to spinal cord should be intact. Chronic decerebrate cats, which can walk and run, exhibit rigidity in all four legs only when the extremities are free from any phasic activity. Even when standing such cats do not exhibit an exaggerated positive supporting reaction (Bard & Macht, 1958). In rigidity of spinal origin the muscular spasm of the hind limbs is continuous and unremitting, regardless of the position or activity of the animal. The hind limbs never exhibit any phasic activity and when awkwardly dragged by foreleg movement remain as rigidly extended as when the animal is lying or sitting. In addition to the extensor paralysis there is very little or no reaction to cutaneous stimulation of hind limbs. Reactions to noxious stimuli, when present, do not include flexion of the hind limbs. It is impressively difficult to flex the rigid limb and the lengthening reaction

cannot be demonstrated. The rigidity can be reduced or abolished only by anaesthesia.

The evidence to be presented indicates that the functional disorganization of the spinal cord, as manifested by the rigidity, fundamentally consists in and is a consequence of the destruction of spinal interneurones relaying excitatory and inhibitory impulses to motoneurones. Since all, or nearly all, impulses normally descending upon spinal motoneurones from higher centres are also relayed by spinal interneurones, this rigidity of spinal origin is not entirely unrelated to rigidities and spasticities of supraspinal origin. In the latter the impulse traffic descending upon spinal interneurones is altered or reduced. In the former the interneurones are destroyed.

It must be pointed out at the outset that after some days of maintained extensor rigidity of the hind limbs, a 'contracture' develops in the affected muscles which is superimposed upon the shortening maintained by motoneurone activity. This supervening phenomenon, a shortened resting length of the muscles, is identical with the shortening which has been known for some years to develop after fixation at a given length in a plaster cast, tenotomy or localized poisoning with tetanus toxin. Although usefully designated by Ranson & Dixon (1928) as 'myostatic contracture', the latter is not a physiological contracture, as defined by Gasser (1930). Motor innervation, for the active contractile shortening of the muscle, is necessary for the genesis of the 'contracture', but once this shortened state of the muscle has developed it persists, in contrast to the neural hypertonus, after motor denervation. Also in contrast to the rigidity of spinal origin, in which the hypertonic muscles temporarily relax during general anaesthesia, the myostatic contracture is not abolished by any depth of anaesthesia. Even after a lethal dose of anaesthetic the affected muscles retain their shortened state, passing eventually into rigor mortis, which this 'contracture' resembles. We did not systematically study the latency of onset of the myostatic contracture but, with possibly one exception, the earliest that we have noted it is 5 days after the establishment of rigidity by lumbosacral cord ischaemia. A minimal, but unmistakable, residual resistance to flexion of the knee may be observed at this time after elimination of the hypertonus by general anaesthesia. This residuum, a shortened length of the muscles, grows with the duration of the neurally maintained shortening, or hypertonus. On the other hand, in those instances where the rigidity lasted only about 48 hr, after which the hind-limb paralysis became completely flaccid, we have never observed a myostatic contracture. The latent period for the latter, as induced by localized tetanus toxin, is 5–7 days after intramuscular injection of the toxin (Davenport, Ranson & Stevens, 1929). Preliminary accounts of some phases of this work have already been published (Gelfan & Eurnekian, 1956; Gelfan, Eurnekian & Tarlov, 1957).

METHODS

Experimental rigidity

Spinal ischaemia by ligation of the abdominal aorta dates back to Stenno in the seventeenth century. High thoracic occlusion is necessary in order to render the lumbosacral cord ischaemic in cats and dogs. Our surgical procedure for temporary occlusion of the dog's thoracic aorta was essentially the same as the one adopted by Tureen (1936) for cats. Tureen's cats did not survive aortic occlusion of more than 15 min duration and all the survivors regained hind-leg motor power within 24 hr. More than 60% of our 120 dogs subjected to 40–50 min of aortic occlusion survived the stress. Some of the non-survivors died within 24 hr after occlusion and the others within 4 days. The hind legs in almost all these non-surviving animals, however, became markedly rigid upon recovery from the Nembutal anaesthesia (pentobarbitone; Abbott Laboratories). Some 62% of the survivors exhibited permanent rigidity of the hind limbs. The rest exhibited either permanent flaccid paralysis or temporary weakness or were normal. More than 50 min of ischaemia usually resulted in flaccid paralysis. Less than 40 min of aortic occlusion did not usually produce an extensor paralysis in dogs but only some motor weakness and some incoordination, from which the animals fully recovered within about a week.

In addition to the lumbosacral cord, most of the rest of the posterior half of the body is also subjected to ischaemia by the aortic occlusion. However, we have not observed any obvious histological damage to the dorsal root ganglia of rigid animals killed several weeks after the occlusion. Also, the magnitude of primary afferent volleys arriving at the medullary part of the cord in rigid dogs is not smaller than in normal ones (Text-fig. 1). Isolated mammalian peripheral nerves promptly recover from 1 hr of complete anoxia (Gelfan & Tarlov, 1956). Ischaemia limited to the hind limbs, by occlusion of abdominal aorta just above the iliac bifurcation for 1 hr did not damage either the peripheral nerves or muscles, as judged by clinical testing. An additional ischaemia of both limbs in the same animal 2 days later, by sphygmomanometer cuffs maintained at 250 mm Hg for 1 hr, also did not result in any sensory or motor defect.

Oscillographic recording of spinal cord activity

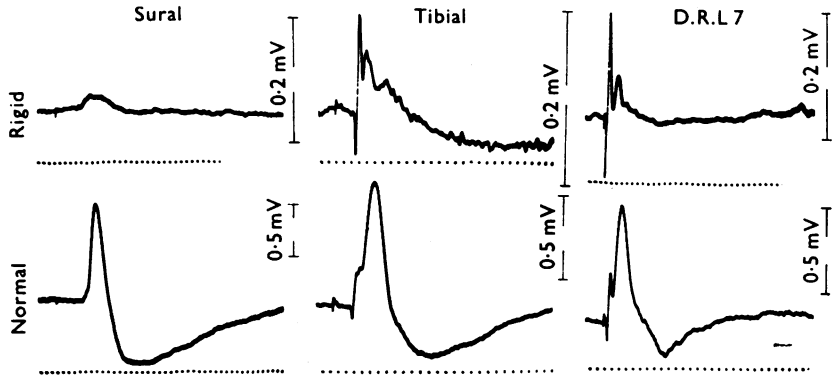
For oscillographic analysis of spinal neurone activity the spinal cords of chronically rigid dogs were exposed by laminectomy under either light allobarbitone anaesthesia or after decapitation. Only one dose of thiopentone anaesthesia was used for the latter. Decapitate preparations were used mostly as normal controls. The exposed cord, spinal roots and peripheral nerves were under warm mineral oil saturated with 95% O_2 + 5% CO_2. Spinal cord potentials, in response to afferent stimuli, were picked up by one platinum electrode in contact at the mid line with the dorsal surface of the cord and another indifferent one in contact with adjacent non-neural tissue. Recordings, as in Fig. 1, were made with the cord dorsum electrode placed at the optimal recording zone, i.e. at the entry zone of the stimulated nerves or roots. Reflex ventral root potentials were recorded with the usual platinum hooks in contact with cut ventral roots. The acute experiments in the chronic animals were carried out 10 or more days after production of lumbosacral cord ischaemia.

RESULTS

Excitatory interneurones in rigid dogs

The spinal cord potential. This potential, recorded from the dorsal surface of the exposed cord, provides a large and unmistakable sign of interneuronal activity. It is generally agreed, since such potentials were first recorded by Gasser & Graham (1933), that the large negative wave (negative intermediary potential, N wave) of the composite cord dorsum potential, taking off from the primary afferent spike, is generated by interneurones responding to the

afferent volley. In decapitate or anaesthetized normal preparations the large N wave is very easily elicited. In the rigid animals, however, the magnitude of this interneuronal component is very small even at higher amplifications (Text-fig. 1). Indeed, the total response to maximal cutaneous, mixed-nerve or whole-dorsal-root stimulation in chronically rigid animals consists of very little besides the primary afferent component. The first half of the spinal cord potential elicited by maximal sural nerve stimulation in the rigid preparation, as in Text-fig. 1, represents the somewhat dispersed primary afferent signal. The remainder, the interneuronal component, is less than 0·1 of the magnitude

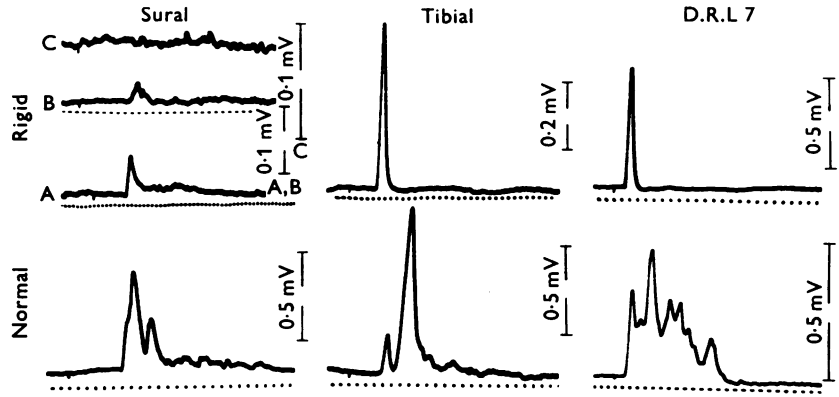


Text-fig. 1. Spinal cord potentials from normal and rigid dogs in response to maximal stimulation of sural nerve, tibial nerve and dorsal root L7, recorded from mid line of cord dorsum at optimal recording zone in each case. Note differences in amplification; all calibrations in mV; time scale under each record in msec. Upper sural and D. R. L7 records from animal 10 days after establishment of hind-limb extensor rigidity: upper tibial record from animal after 27 days of rigidity. All decapitate preparations.

of the same response in the normal dog. Since at least part of the normally large negative wave of the spinal cord potential is generated by interneurones relaying afferent impulses to suprasegmental levels (Bernhard & Widén, 1953), the little concern or utter indifference of such chronically rigid dogs to severely noxious stimulation of hind limbs is understandable. The large positive wave of the spinal cord potential normally observed with maximal stimulation, also of post-synaptic origin and considered, at least in part, as signalling activity of propriospinal neurones (interneurones) (Bernhard & Widén, 1953), is completely absent in the rigid record.

When the normal negative intermediary potential is temporarily depressed, as by asphyxia, an early component may be revealed which has been considered as most likely of presynaptic origin, probably afferent terminals (Lloyd & McIntyre, 1949; Bernhard, 1953; Austin & McCouch, 1955). This component is normally observed in the rigid preparation without any experimental manœuvres for its disclosure. It is the first sharp negative elevation after the

large afferent spike, in response to tibial and particularly dorsal root stimulation in Text-fig. 1. Intramedullary afferent conduction, as well as the primary afferent spike, therefore, appears to be relatively normal in the rigid animal. The interneuronal response, on the other hand, even when maximally stimulating a whole dorsal root, and taking into account the amplification difference between the normal and rigid records, is virtually zero. All experimental manœuvres, under optimal conditions of recording, fail to improve this response in rigid animals. It is always observed, on the other hand, in normal preparations, even when in poor condition or deteriorating. The responses from rigid animals in Text-fig. 1 are unmistakably similar to the spinal cord



Text-fig. 2. Reflex responses to maximal stimulation of sural nerve, tibial nerve and dorsal root L7 in normal and rigid dogs recorded from cut L7 ventral root. Note differences in amplification; all calibrations in mV; time scale under each record in msec. Upper sural record C, upper tibial and D.R. L7 records are from same respective decapitate preparations as rigid records in Fig. 1. Upper sural records A and B from dogs, under allobarbitone anaesthesia, which had been rigid 97 and 28 days respectively.

potentials as modified after about 4 min of asphyxia or thoracic aorta occlusion in acute experiments on normal dogs (Gelfan & Tarlov, 1955, 1956). The greatly reduced or completely absent interneuronal component in the cord dorsum response from chronically rigid preparations, which had undergone 40–50 min of lumbosacral ischaemia, is consistent with the observations on maximum duration of anoxia compatible with recovery of the interneuronal component in the acute preparation (Gelfan & Tarlov, 1955).

Mono- and polysynaptic ventral root reflexes. The counterpart to the interneuronal deficit in the elicited cord dorsum potentials of rigid dogs is the similarly very meagre polysynaptic reflex response to peripheral stimulation, as exemplified by the ventral root records in Text-fig. 2. The total polysynaptic response to supramaximal sural-nerve stimulation in each of the three sample records from different rigid animals varies from about 15% (sural record *A*) of the normal deflexion to essentially zero (sural record *C*). Similarly, the

polysynaptic component of the reflex ventral root response to supramaximal stimulation of mixed nerve, such as the tibial, or whole dorsal root, is completely absent from the records of rigid preparations reproduced in Text-fig. 2. These two records show only monosynaptic responses. The polysynaptic reflex, as the full cord dorsum response, but in contrast to the monosynaptic reflex response, is very readily elicited in all normal dogs. Also in the acute normal preparation, even with anaesthesia, stimulation of a cutaneous nerve like the sural, when the other nerves and spinal roots are intact, produces powerful contraction of flexor muscles. It is remarkable, on the other hand, how little of such reflex flexor contraction is observed under the same conditions in rigid preparations. Therefore, interneurones, such as are found in the intermediate nucleus of Cajal, relaying afferent impulses to motoneurones, are also permanently affected by the ischaemic episode which produces hind-limb rigidity.

The amplitude of the unpotentiated monosynaptic reflex response in rigid dogs is consistently larger than in normal dogs, under as near the same conditions as it is possible to duplicate in acute experiments. Although not as yet subjected to quantitative analysis, this difference is nevertheless unmistakable and significant. This applies to the monosynaptic component of the total response to mixed-nerve or whole-dorsal-root stimulation, as well as to the purely monosynaptic response to gastrocnemius nerve stimulation. The stimulus threshold for the reflex ventral root response, as a whole, is about the same for both normal and rigid dogs, but the reflex output is decidedly different. The maximum possible motoneurone response, as revealed by post-tetanic potentiation, is not greater in the rigid dogs (Text-fig. 6). If anything, it is usually somewhat smaller when the results on the total number of rigid dogs so tested are compared with those for normals. But of the total surviving motoneurones in any pool in the rigid dog a relatively greater fraction will be discharged by an unpotentiated primary synaptic volley. Conversely, in the normal animal, a greater fraction remains in the subliminal fringe. The extent of this 'exaggerated' monosynaptic excitability, also, appears to be inversely proportional to maximum available polysynaptic reflex output in any rigid dog. That is to say, the evidence strongly suggests that a decrease in the interneuronal population relaying afferent impulses to motoneurones increases the excitability of the latter.

When clinically tested, a very active knee jerk, in contrast to the absence of a flexion reflex, is the prelude to the developing hind-limb rigidity during recovery from anaesthesia, some 2 hr or so after a 40–50 min thoracic aorta occlusion. This is in general agreement with van Harreveld & Marmont's (1939) observations on spinal cats which had undergone lumbosacral cord ischaemia.

The greater vulnerability of flexor reflexes to lumbosacral cord anoxia had been observed by clinical testing in spinal cats by van Harreveld & Marmont

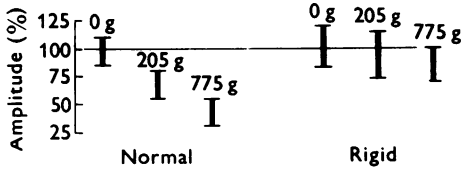
(1939) and in rabbits by Krogh (1945, 1950). The latter ascribed this to selectively greater destruction of flexor motoneurones. This possibility had also been considered by the former, but van Harreveld (1944) later abandoned it. He called attention to the polysynaptic nature of the flexion reflex and its consequently greater vulnerability because of the increased number of asphyxial targets, or the possibility of a greater sensitivity of interneurones to O_2 lack. With the direct demonstration of functional failure of interneurones in chronically rigid dogs the assumption of a greater mortality among flexor motoneurones would appear to be no longer necessary in order to explain the earlier failure of flexion reflexes. This explanation, of course, is not incompatible with a concomitant greater mortality of flexor motoneurones. It does account for the impairment or complete loss of sensation and motor paralysis in the rigid animals. However, it does not account for the extensor character of the rigidity in the chronic animals unless it is assumed that the extensor hypertonus is reflex in origin. It is shown in a later section, however, that the afferent inflow is not indispensable for the continuous motoneurone discharges responsible for maintaining the hind-limb rigidity in the chronic dogs. A greater destruction of flexor motoneurones, therefore, could explain the extensor character of the rigidity. But the following observations cannot be readily harmonized with such a proposal. Kosman, Hill & Snider (1951) reported continuous activity of both flexor and extensor muscle groups in chronic cats and dogs with severe extensor rigidity, as recorded electromyographically. We have repeatedly observed during acute experiments on rigid dogs that flexor muscles, as well as extensor ones, readily responded to stimulation of their nerves or ventral roots when very little or no flexor reflexes could be elicited. The rigidity in extension, on the other hand, could be due either to a greater 'spasticity' of extensor motoneurones or simply to a dominance of extensor muscles, as is assumed to be the case in decerebrate rigidity and during periods of extensor rigidity in strychnine and tetanus-toxin poisoning. We have no data on the former and the few attempts to test the latter by cutting the nerves to the quadriceps muscles or patellar tendon on one side of rigid dogs failed to provide a decisive answer. With relatively shorter durations of lumbosacral ischaemia Krogh (1950) obtained purely adductor or flexor hypertonus in rabbits. We have never observed flexor rigidity in dogs. This aspect of the problem requires further experimentation and clarification.

Inhibitory interneurones

As in the case of interneurones relaying excitatory impulses, there is also in rigid dogs a deficiency of interneurones which normally exert an inhibitory action upon motoneurones. Among all the excitatory afferents to the spinal cord at least one type, the Group Ia fibres from the annulospiral endings of the muscle spindle, terminate directly upon motoneurones. 'Direct' inhibition

of motoneurones to antagonistic muscles by collaterals of such annulospiral fibres (Lloyd, 1941, 1946), according to Eccles and his collaborators (Eccles, 1957), is also mediated through one interneurone. It is agreed, in any case, that inhibition by Group Ib muscle afferents from Golgi tendon organs, Group II and III muscle and cutaneous afferents is through interneurones.

Autogenetic inhibition. In addition to the well-known excitatory effects of muscle stretch, it has also recently been established that stretch and contraction can also produce inhibition of the monosynaptic response (Henneman, 1951; Hunt, 1952; Granit, 1955). This is the basis of autogenetic inhibition and the lengthening reaction in decerebrate preparations. The effect of static loading upon the amplitude of the monosynaptic response in a rigid dog, as compared to a normal one, is illustrated in Text-fig. 3. The intact gastrocnemius nerve, after cutting nerves to other muscles of the leg, was maximally stimu-



Text-fig. 3. Effect of static muscle tension on reflex monosynaptic ventral root responses to intact gastrocnemius nerve stimulation in normal dog and in one which had been rigid for 13 days. Each of the six heavy vertical lines gives the amplitude range of ten consecutive responses to stimulation at 1 c/s. 100% = average of the ten response amplitude measurements, in each animal, when the muscle was under zero tension; all determinations expressed as percentage of this value.

lated at 1 c/s, with and without weights attached to the cut Achilles tendon. Ten consecutive reflex monosynaptic responses recorded from the cut S1 ventral root in each instance constituted the basis of comparison. The measured amplitude of the responses in the case of the loaded muscles was plotted as percentage of the unloaded values, the average of the latter ten determinations constituting 100%. As has been recognized by others (Henneman, 1951; Hunt, 1952; Granit, 1955), the absolute amount of inhibition of the monosynaptic response by graded static tension is not very predictable and varies from one normal preparation to another in acute experiments. It is sufficiently clear, however, that in rigid preparations tension has consistently very little influence on the reflex monosynaptic response. Similarly, very little, if any, inhibition of the monosynaptic response was evident in rigid animals when the intact gastrocnemius nerve was tested during tetanus of the muscle by 100 c/s stimuli of distal cut end of a ventral root, in the manner of Hunt (1952). The latter obtained in this manner nearly complete inhibition in normal spinal cats. If the tetanized muscle is also stretched, responses to 1 c/s monosynaptic testing was even facilitated somewhat during the tetanus in some rigid

preparations. Stretch, in these instances, had only an excitatory influence upon motoneurones.

The effect of muscle stretch upon gamma ventral horn cells, in contrast to the effect upon alpha motoneurones, is only inhibitory in normal preparations (Hunt, 1951; Granit, 1955). To test the effect of stretch upon gamma motoneurones in a rigid dog, a filament from a S1 ventral root, which had monosynaptically responded to gastrocnemius testing, was separated and placed upon the recording electrodes. All the muscle nerves except those to the gastrocnemius-soleus had been cut. The spinal cord of this animal also had been transected at the mid-thoracic level 40 days before the ischaemic episode which produced the hind-limb rigidity. The 'resting' base-line activity of several gamma fibres, with the muscle slack, is shown in the upper record of Text-fig. 4. The occasional larger deflexions are considered as coming from alpha fibres included in the ventral root filament. Although under light

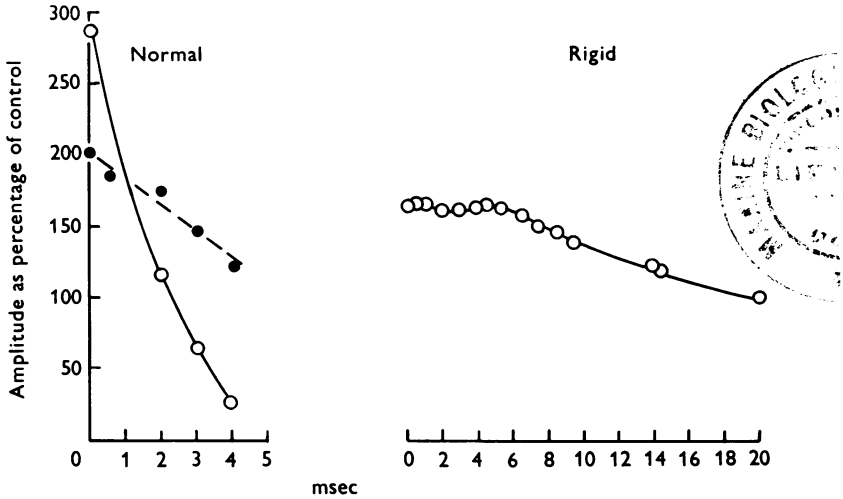
Text-fig. 4. Small motoneurone activity on 60 c/s base line, recorded from S1 ventral root filament of dog which had been rigid for 97 days and with mid-thoracic spinal cord transection for 137 days. Nerves to triceps surae muscle intact. Upper record obtained when muscle was slack; lower record when muscle was under 205 g tension.

allobarbitone anaesthaesia, the spontaneous activity of the alpha motoneurones was not completely suppressed. It is difficult to see in the lower record that stretching the muscle with a 205 g weight had any inhibitory effect upon the gamma motoneurone activity. These small efferent fibres in the ventral root filament were not identified as innervating the gastrocnemius muscle spindles, but all other filament samplings from this root failed to show any obvious inhibition of gamma activity by stretch. The origin of stretch afferents for gamma inhibition is not settled yet, but there is no reason to suspect that the peripheral portions of the gamma loop is not essentially intact in the rigid animals. The central pathway of such inhibiting stretch afferents, whether directly to the gamma motoneurones or via interneurones, also is not known. If such impulses are relayed by interneurones, the failure to inhibit the gamma motoneurones by muscle stretch in the rigid preparations could also be due to destruction of interneurones.

Hunt & Paintal's (1958) studies, published after completion of this manuscript, strongly indicate that the small gamma motoneurones, for which they propose the name 'fusimotor neurones', are innervated only by polysynaptic pathways. They also failed to confirm Hunt's earlier report

(1951) of autogenetic inhibition of these small motoneurones. In the earlier paper the peripheral destination of the small fibres in the ventral root filament, whose discharges were inhibited by muscle stretch, was not determined. The observed inhibition therefore, Hunt & Paintal now contend, may not have been autogenetic. Since we also did not know the peripheral destination of the small afferent fibres in the rigid preparation, the inhibition we were looking for may also not have been originally autogenetic.

Facilitation of the monosynaptic response, by barely threshold shocks to the nerve of one head of the gastrocnemius as the test shock is delivered to the nerve of the other head of gastrocnemius, is easily obtained in the rigid preparation. Strong conditioning volleys increase the facilitation in the normal dog,

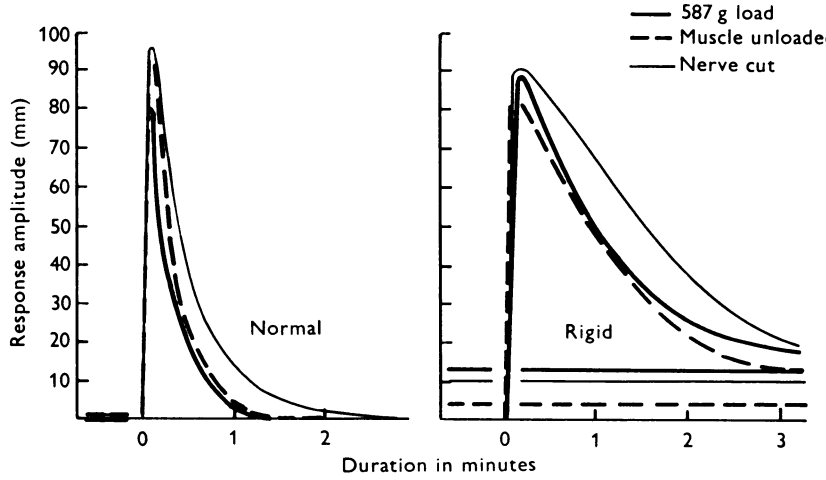


Text-fig. 5. Facilitation of medial gastrocnemius reflex by conditioning volleys in lateral gastrocnemius nerve, recorded from cut ventral root, in normal dog and in one which had been rigid for 27 days. 100% on ordinate = control amplitude of reflex response to test shock alone. Conditioned responses plotted as function of time interval between conditioning and test volleys. Facilitation curve from normal dog (filled circles) obtained by use of threshold conditioning volleys. With strong conditioning shocks the initially higher facilitation (open circles) is succeeded by secondary inhibition in the normal dog but not in the rigid one.

but as the interval between these conditioning and test shocks is increased by more than 0·5 msec the subsequent course is interrupted by secondary inhibition, as was found by Lloyd in normal cats (1946; see also Laporte & Lloyd, 1952) and shown in Text-fig. 5 for normal dog. This inhibiting action of ipsilateral interneurones, in combination with direct action of primary afferent fibres upon extensor motoneurones, is absent in the rigid preparation. The curve in the latter case shows only facilitation. Its somewhat bizarre shape is most likely due to the greater excitability of motoneurones in rigid preparations.

An indirect inhibitory influence of muscle end organs upon the monosynaptic reflex response is also revealed when the muscle nerve tested for post-tetanic

potentiation is not severed from the muscle, particularly when the latter is under tension, as recently shown by Granit (1956). Very little of this inhibitory influence can be demonstrated in rigid preparations. Post-tetanic potentiation curves from one rigid dog are compared to those of a normal one in Text-fig. 6. In both instances the gastrocnemius nerve, after initial testing at 1 c/s, was stimulated maximally at 500 c/s for 10 sec, after which the testing continued at the original rate, in the manner described by Lloyd (1949). The small



Text-fig. 6. Post-tetanic potentiation curves of reflex monosynaptic responses to gastrocnemius nerve stimulation at 1 c/s, as recorded from cut ventral root, in normal dog and in one which had been rigid for 10 days. Zero time on abscissae in each case is the end of a 10 sec tetanus to gastrocnemius nerve at 500 c/s. Response amplitude is in millimetres on face of cathode ray tube. The control response levels, on the left, are continued as horizontal lines in the rigid set of curves for reference purpose. Same amplification used in both experiments. Stretching the triceps surae muscle depressed the unpotentiated response in the normal dog from about 2 mm to practically zero, and reduced the maximal potentiated response by about 15%. Stretch had only an excitatory effect in the rigid preparation. Cutting the nerve increased the duration of potentiation in the normal dog but not in the rigid animal. The duration of potentiation, under all these conditions, was considerably greater in the rigid animal.

unpotentiated control responses are practically obliterated when the triceps surae muscle of the normal dog was stretched. The potentiated responses in the normal preparation, large as they are, were also measurably reduced by muscle stretch. The duration of potentiation when the severed nerve was stimulated was invariably longer than when the nerve was intact, in the normal animal. The effect of muscle stretch on the unpotentiated responses in the rigid animal, on the other hand, was excitatory rather than inhibitory, as is also shown in Text-fig. 3. Muscle stretch had no effect upon the potentiated responses in the rigid animal. Cutting the nerve influenced the slope of the

potentiated curve from this rigid animal but not the total duration of potentiation. The most obvious difference between the two sets of curves is the longer-lasting potentiation in the rigid animal. Since the duration and frequency of the tetanus was the same in both cases, it is assumed that the rate of decay of the potentiated effect of the monosynaptic reflex afferent fibres and transmitter action following the tetanus was also essentially the same in both instances. The longer-lasting post-synaptic effect of the tetanus in the rigid animal may therefore be considered as a reflexion of the greater excitability of the subliminal fringe, as well as of the rest of the motoneurone pool, in these animals. This is not unreasonable in view of the fact that these motoneurones in chronically rigid animals, before the acute experiment, were discharging sufficiently and continuously to produce rigidity in the hind limbs.

Tetanization of the ipsilateral peroneal nerve during monosynaptic reflex responses of an extensor muscle, elicited at regularly recurring intervals, also reveals the inhibitory influence of interneurones. In the normal dog such monosynaptic reflex responses of the gastrocnemius could be completely inhibited by a 500 c/s tetanization of the common peroneal nerve, as was also observed by Lloyd in cats (1949). The maximum amount of such inhibition observed in one of the tested rigid dogs was about 60%; the others exhibited less. The response regained its normal amplitude promptly after cessation of the tetanus in all cases, but some rigid preparations exhibited, in addition, post-inhibitory facilitation. This fractional inhibition in rigid animals may be due to interneurones which survived the ischaemia, or may represent the 'directly' inhibiting component in the common peroneal nerve, or both. In any case, an interneuronal deficit in rigid dogs is clearly indicated.

Effect of dorsal root section

It is evident from the foregoing results and considerations that lumbosacral motoneurones in the rigid animals have lost the normal polysynaptic influence as a result of interneurone destruction. This includes supraspinal as well as segmental afferent input, and is the reason for the paralysis. The monosynaptic endings of the large muscle proprioceptive fibres, however, remain intact and lumbosacral dorsal roots were severed bilaterally in order to determine if they are indispensable for triggering the 'spastic' discharges of the surviving motoneurones in the chronic preparations. Rhizotomy in dogs which had been rigid for one or more weeks gave inconclusive results. Enough myostatic contracture had developed in the rigid hind-limb muscles by this time to interfere with reliable assessment of the effects of de-afferentation. Indeed, the contracture may be so severe that anaesthesia and even ventral root section may have very little effect upon the rigidity, which is now characterized by a permanent shortening of the resting length of the muscle. The chances of surviving lumbosacral rhizotomy 1, 2, or even 3 days after an ischaemic bout

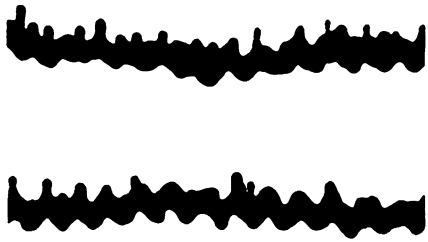
of 40–50 min are poor. After 5 days of rigidity, at which time the myostatic contracture was minimal, as established by anaesthesia, bilateral intradural rhizotomy from L2 to S2 inclusive temporarily abolished the hind-limb rigidity. After about 24 hr, however, the extensor rigidity gradually returned and was severe enough several days later to support the weight of the paralysed hind quarters when the animal was placed in a standing position. Van Harreveld (1943) had also noted the abolition or reduction of rigidity in one hind limb of his spinal cats immediately after unilateral rhizotomy, but only the acute preparations were observed. On the basis of his own experience and that of others before him, Ranson (1928) emphasized that 'dorsal roots cannot be cut without damage to spinal cord'. It is possible, therefore, that the temporary abolition of the rigidity by de-afferentation was due to this trauma and depression of motoneurones.

To obtain a less equivocal answer to the question concerning the role of primary afferent endings in the chronic preparations, the thoracic aorta was occluded in the usual manner for producing rigidity some time after the hind limbs had already been de-afferented. In order to minimize trauma to the spinal cord and to avoid also the inevitable adhesion of the dura after intradural root section, the L2 to S1 dorsal roots were severed extradurally on both sides. The small S2 dorsal roots in the dog, in contrast to the larger roots above it, cannot be separated and cut extradurally without injury to the ventral components. Since S2 spinal roots do not contribute to the innervation of knee extensors (quadriceps in the dog is innervated by L4, L5 and L6), sparing this dorsal root was not considered as introducing uncertainty into the significance of the observed results. Such de-afferentation produces profound motor impairment in the hind limbs of normal dogs. Similar effects of forelimb de-afferentation have been known for some time. The paralysis is always flaccid. The maximal degree of motor restitution observed 4 weeks after such bilateral de-afferentation was a paddling-like attempt at locomotion by the hind legs. The animal was incapable of raising its hind quarters or of standing on its hind legs.

Successful aortic occlusion in dogs with chronically de-afferented hind limbs produced typical rigidity. The animal in Pl. 1, fig. 1 was photographed 24 hr after a 45-min occlusion of thoracic aorta carried out 29 days after bilateral rhizotomy (L2 to S1 inclusive). The rigidity at this time was severe enough to support easily his now paralysed hind quarters when he was propped up in a balanced position. The imposed and static balance is temporary but the collapse is not caused by collapse of the anti-gravity muscles but by loss of the artificial balance. Hind-limb extension is maintained during the fall sideways. The persistent priapism, usually present in rigid male dogs with intact dorsal roots, had not been observed in this animal at any time during the de-afferented period before the lumbosacral ischaemia by aortic occlusion. As in

the animals with intact dorsal roots, the rigidity in rhizotomized ones endures without any abatement. This animal survived 83 days in the rigid state. The inevitable myostatic contracture also developed in the rhizotomized rigid animals. Seven days after rigidity was induced in the animal in Pl. 1, fig. 1, the first indication of a shortened resting length of muscle became evident; a small but unmistakable residuum of resistance to flexion of the knee remained after anaesthetization. This myostatic contracture, which tended to confuse the issue initially, was of confirmatory value in these instances, since it does not develop until after a period of maintained neurogenic shortening of muscle: no contracture without rigidity first.

It is difficult to see any dependence of continuous motoneurone discharges in chronically rigid animals upon intact primary afferent endings when section of dorsal roots failed either to abolish permanently the rigidity already established or to prevent rigidity from developing. Whatever influence the



Text-fig. 7. Upper: small motoneurone activity on 60 c/s base line from L7 ventral root filament in dog which had been rigid for 17 days, 3 days after bilateral and intradural section of dorsal roots L2 to S2 inclusive; light allobarbitone anaesthesia. Lower: activity from another L7 ventral root filament during same experiment 1 hr after decapitation through atlanto-occipital membrane. Cathode ray beam slightly out of focus in order to fatten the small deflexions.

muscle afferents may continue to exert upon the 'spastic' motoneurones, they are not the indispensable triggers for the continuous motoneurone discharges in this experimental rigidity. If rigidity in some way results from a disturbance of the normal balance between influences of interneurones and afferent fibres which terminate directly upon motoneurones, the former destroyed by the lumbosacral ischaemia but leaving the latter intact, this balance is not re-established by complete de-afferentation.

Small gamma motoneurones, as large alpha ones, also are not silenced by bilateral de-afferentation of the rigid animal. In the normal cat acute de-afferentation abolishes the 'resting' background activity of gamma motoneurones (Hunt, 1951). The small-nerve activity recorded from an L7 ventral root filament, shown in the upper record of Text-fig. 7, is from a rigid dog 3 days after bilateral and intradural section of dorsal roots L2 to S2 inclusive. This may be compared with the gamma motoneurone activity from a rigid animal with intact dorsal roots but whose spinal cord had been transected

before it was made rigid (Text-fig. 4). Although acute spinal transection in normal cats also does not abolish the resting motoneurone discharges (Hunt, 1951), the de-afferented rigid preparation was nevertheless decapitated some time after the upper record in Text-fig. 7 was obtained, in order to ascertain whether the observed resting discharge was in this case maintained by supra-spinal centres. Immediately after decapitation through the atlanto-occipital membrane, and institution of artificial ventilation, filaments from the same ventral root were silent. One hour after decapitation, however, activity, although considerably reduced, was evident in gamma motoneurones which now were free from anatomical connexions with supra-spinal centres, as well as from afferent connexions with muscle spindles (lower record in Text-fig. 7). The initial silence and reduced activity later was most likely due to spinal shock and inadequate circulation through the L7 segment (severance of anterior spinal artery by decapitation; right and left dorsal and one ventral root cut).

Neuronal destruction

The topography of the cellular destruction observed in the spinal cords of chronically rigid dogs is strikingly illustrated in Pl. 1, fig. 2. The greater mortality of centrally located neurones, as observed by Krogh (1945, 1950) in the anterior horns of rabbits, and by Kosman *et al.* (1951) in the anterior horns of cats and dogs, is shown here to extend from the dorsal horn, through the intermediate zone, to the anterior horn. The glaring swath of neuronal destruction clearly includes loci of interneurone pools. The relay sites of the larger sural nerve fibres and Group III afferents, according to Coombs, Curtis & Landgren (1956), are in the dorsal horn, dorsolateral to the intermediate nucleus; those of Groups Ib and II muscle afferent fibres, in the intermediate zone. Large motoneurones in the ventral horns are discernible in this photograph at very low magnification. This spinal cord was removed from a dog whose hind limbs had been severely rigid for 31 days. A detailed histological account is in preparation, but it is pertinent here to mention that, in agreement with Krogh (1945, 1950), surviving motoneurones were always found in rigid dogs. Complete neurone destruction is associated only with flaccid paralysis. Van Harreveld (1941) reported a greater decrease of 'medium sized nerve cells' in the anterior horn and gray commissures after lumbosacral ischaemia of spinal cats. We have also observed instances of practically zero mortality among neurones with axons in ventral roots. It is probable, therefore, that cellular destruction in the spinal cord of some animals exhibiting rigidity may be limited essentially to interneurones. In any case, interneuronal destruction must be the reason for the much reduced or absent interneurone responses in the electrophysiological observations.

DISCUSSION

The anoxic destruction of spinal interneurones accounts for the reduction or absence of those reflex responses, both excitatory and inhibitory, which normally can be secured only through the intermediation of one or more interneurones. It is also the basis for the sensory and voluntary motor loss in such rigid animals. Interneurones in the spinal cord are not limited to the dorsal horns and intermediate zones. There are also many interneurones in the motor nuclei of the ventral horns, and, as emphasized in Balthasar's (1952) histological studies of normal cat anterior horns, such interneurones in the tibial and peroneal nuclei outnumber by far the motoneurones. He estimated that the interneurone to motoneurone ratio in this pool is 4:1 for tibial and 16:1 for the peroneal nuclei. In this light, van Harreveld & Marmont's (1939) impression that more of the smaller cells throughout the cord are destroyed by a given duration of anoxia than larger ones is significant. This is to be expected if the relation between peripheral fibre diameter and resistance to anoxia also holds for cell body size. There are, however, also small motoneurones in the anterior horns and how uniform the relation between cell size and capacity for recovery from a given duration of anoxia might be in such a mixed neural population is not known. It is clear enough that at least some small motoneurones, as well as large ones, survive the lumbosacral ischaemia (Text-figs. 4, 7). Krogh (1945) also called attention to the purely vascular aspects in the rabbit's anterior horns as favouring a pre-emption by peripherally placed neurones of any available O_2 in the slow small trickle of blood which may reach the cord during the aortic occlusion. It is doubtful whether this could have been a contributory factor in van Harreveld & Marmont's (1939) cats, since these workers produced ischaemia of the posterior segment of the transected cord (with permanent extradural ligature) by raising the intradural pressure above systolic pressure. The greater destruction throughout the centre of the gray matter is unmistakable (Pl. 1, fig. 2; also Kosman *et al.* 1951). But the available maps of motor nuclei in the anterior horn (Romanes, 1951; Balthasar, 1952) do not justify any correlation between the distribution of the anoxic lesion and the location of nuclei innervating different muscle groups. Such maps do show that motor nuclei are clustered primarily in the medial and lateral portions of the anterior horn and that the neurones in the centre must consequently consist essentially of interneurones. The cellular destruction above the anterior horns is almost exclusively an interneuronal lesion (all spinal neurones whose short or long axons relay impulses within the C.N.S. are considered as interneurones). Such chronic lesions, so far, can be produced only by temporary ischaemia.

The functional role of interneurones is not limited to segmental reflexes. It is generally recognized that descending projection systems, including

cortico-spinal ones, exert their excitatory and inhibitory influences upon spinal motoneurones in almost all known instances through the intermediation of one or more spinal interneurones (cf. Lloyd, 1944, for discussion and references). Spinal interneurones are also convergence centres for afferent inflow (Kolmodin, 1957) and such interneuronal activity can, in addition, be influenced by impulses descending from higher spinal and supraspinal centres (Lindblom & Ottosson, 1953, 1956). Indeed, a single cat spinal interneurone may be influenced not only by more than one afferent source but by both excitatory and inhibitory fibres (Kolmodin, 1957). Thus the influence of this integrative level upon motoneurone activity can hardly be exaggerated, since almost all the impulse traffic converging upon the motoneurones is funnelled, as well as screened, by spinal interneurones. With the possible exception of a small percentage of pyramidal fibres, only Group Ia muscle afferents are known to terminate directly upon motoneurones. But, as shown histologically by Cajal, these monosynaptic fibres also send collaterals into the intermediate nucleus. It is therefore not impossible that even monosynaptically induced activity may thus also be modulated automatically by interneurones; as, for example, the depression of the monosynaptic responses to frequencies of stimulation as low as 0·1–10 per second (Eccles & Rall, 1951; Jefferson & Schlapp, 1953; Lloyd & Wilson, 1957). Monosynaptic reflexes, as already pointed out, are more readily elicited in the rigid preparation than in the normal one during acute experiments. If the negative feed-back system of Renshaw cells were to be firmly established as a fact it would mean that practically no monosynaptically induced activity of motoneurones is immune from interneuronal influence. Indeed, it has been proposed that this system of recurrent inhibition may play an important co-ordinating role in the normal animal (Brooks & Wilson, 1958).

Van Harreveld & Marmont (1939) considered the rigidity of their spinal cats as a 'high extensor tone' due to the damage of the 'tone inhibiting system' by the temporary anoxia of the lumbosacral cord, the normal tone balance between excitatory and inhibiting components in the spinal cord having been disrupted because of the greater resistance to anoxia of the excitatory component. The same explanation is applied to the increased reflex excitability of tendon reflexes, when the hypertonus was not severe enough to mask such reflexes in the unanaesthetized cats. Our demonstration of functional failure of interneurones relaying reflex excitatory (Text-figs. 1, 2), as well as inhibitory, impulses in rigid dogs cannot be fitted into van Harreveld & Marmont's thesis. Furthermore, motoneurones in chronically rigid dogs are not silenced after the last links with the periphery are severed by rhizotomy. This rigidity, therefore, may be considered as an exaggerated stretch reflex only in the same sense that this, as well as other reflexes, are overexcitable after subconvulsive doses of strychnine. But the depolarization and moto-

neurone impulse discharges, after convulsive doses of strychnine, also occur in isolated and de-afferented segments of mammalian spinal cord (Brooks & Fuortes, 1952; Brooks & Koizumi, 1953). Similarly, the motoneurone discharges and consequent rigidity are not abolished or prevented by section of dorsal roots (Pl. 1, fig. 1).

Any outline of the functional disturbance, the disruption of the normal neuronal organization of the spinal cord by the temporary lumbosacral ischaemia, must also account for the continuous motoneurone discharges which characterize chronically rigid animals. It is not only a problem of identifying the neural elements destroyed, but also one of understanding the relation between such destruction and the altered excitability of surviving motoneurones. Large-motoneurone destruction can be expected to result only in motor deficits. Interneurone destruction, on the other hand, reduces the integrative influence upon motoneurones, reduces the impulse traffic and denervates motoneurones. Such destruction is the structural basis for the difference in the consequent functional manifestations between the rigid preparation on the one hand, and spinal or semi-spinal preparations, or those with supraspinal lesions, on the other, Motoneurones in the rigid dogs are denervated to the extent that interneurones, which link with them, are destroyed by the ischaemic-anoxic episode. Interruption of descending pathways, on the other hand, denervates interneurones rather than motoneurones. Even section of dorsal roots denervates principally interneurones, and motoneurones only, at most, to the extent of the monosynaptic-fibre fraction of the total fibre population of dorsal roots.

It is therefore proposed that motoneurones, like denervated muscle fibres or denervated sympathetic ganglia, also become 'spontaneously' active when denervated. It is also proposed that the 'spontaneous' discharges of such denervated motoneurones are directly responsible for the unremitting and enduring rigidity. The alteration in the excitability of such motoneurones is related to the anatomical isolation, or denudation of cell body and dendrites of nerve endings. Mere physiological isolation of motoneurones from monosynaptic impulses, or presynaptic silencing without denervation, as effected by extraganglionic dorsal root section, only produces 'atrophy' of excitability (Eccles & McIntyre, 1953). The prompt development of rigidity may appear as too rapid to be accounted for by motoneurone denervation. But if the degeneration rate of the short intramedullary axons is not slower than that of peripherally cut axons, i.e. about 2 mm/hr initially (Luco & Eyzaguirre, 1955), the onset of rigidity with recovery from anaesthesia would still be consistent with the very limited length of such interneuronal axons. However, the denervation of motoneurones by ischaemia does not depend upon degeneration of intramedullary axons but upon failure of the latter to recover from the anoxic episode. The anoxic mortality rate of interneuronal axons and

their cell bodies, for any given duration of ischaemia, determines the degree of denervation of those surviving motoneurones upon which they terminated.

Cannon & Rosenblueth (1949) were explicitly aware of the possible relation between the fibrillary activity of denervated muscle, the spontaneous random discharges of denervated sympathetic ganglia and the general sensitization of structures after denervation. They clearly did not wish to imply, however, a strict similarity between the spontaneous phenomena and the supersensitivity to chemical agents and impinging nerve impulses. The difference between the two phenomena may or may not be purely quantitative. In any case, the interruption of descending pathways, denervating spinal interneurones, leads to supersensitivity but not to spontaneous activity of motoneurones (Cannon & Rosenblueth, 1949). Section of dorsal roots, denervating to some degree motoneurones, as well as interneurones, also leads to supersensitivity but not to spontaneous activity of motoneurones (Drake & Stavraky, 1948; Teasdall & Stavraky, 1953). Complete nervous isolation of a spinal cord segment in puppies, by intradural and bilateral section of lumbar and sacral dorsal roots plus cord transections above and below the de-afferented segment, also does not induce spontaneous activity of motoneurones in dogs surviving 2–6 months (Tower, 1937). This led Tower to conclude that 'autochthonous' activity is not a property of the mammalian spinal cord. These observations were confirmed in monkeys studied for only 2 weeks (Tower, Bodian & Howe, 1941). Hind-limb hypertonus also was not reported in cats maintained for 11–14 days after such lumbosacral cord isolation (Mark & Gasteiger, 1953). Again, it will be noted, interneurones rather than motoneurones are principally denervated in such isolated segments. Cardin (1952), on the other hand, repeating this de-afferentation and isolation procedure in adult dogs, reported an extensor hypertonus developing in the hind limbs 3 to 4 weeks after the surgery. His conclusions are opposite to those of Tower but he offers no explanation for the discordant results.

In contrast to the concept of alteration of excitability by denervation, McCouch, Austin, Liu & Liu (1958) contend that reflex exaggeration and 'spasticity' in spinal animals is due to replacement of degenerated terminals of descending tracts by sprouts from neighbouring afferent fibres, the latter thus gaining an abnormal control over interneurones. The growth and maturation time of eventually functioning sprouts accounts for the two or more weeks' latency for the onset of spasticity. In the case of partially denervated sympathetic ganglia, it is to be noted, re-innervation of sprouts from uncut preganglionic fibres is accompanied by a decrease in supersensitivity of both effector organs and ganglion cells (Murray & Thompson, 1957), In any case, the latency element precludes terminal sprouting as a factor in the rigidity after temporary lumbosacral ischaemia, since the hind-limb rigidity develops promptly with recovery from anaesthesia. In view of this, a consideration of

the possibility of motoneurones becoming targets for sprouting afferent terminals in the case of our rigid dogs, instead of interneurones as in the case of spinal animals, is irrelevant at this point. McCouch *et al.* (1958), however, also state that their results do not support the sensitization hypothesis. The interneuronal component of the spinal cord potential, they argue, should increase to a greater extent than the potentials attributable to afferent terminals if sensitization of spinal neurones occurs after decentralization. They found instead that the relation of afferent terminal input to interneuronal output was the same in the chronic semisected side as in the control side of their preparations. We wonder, however, whether the internuncial component of the spinal cord potential can be used as an indicator for the presence or absence of sensitization. The synaptic organization of interneurones is different from that of motoneurones. A maximal interneuronal potential is rapidly secured with increasing stimulus strength and when the afferent spike is only about 70% of its maximal value (Bernhard, 1953). The difference in behaviour between interneurones and motoneurones during the onset of anoxia led to the proposal that a subliminal fringe is absent in the interneuronal organization (Gelfan & Tarlov, 1955). Lloyd (1949) had previously come to essentially the same conclusion from his failure to obtain convincing evidence of post-tetanic potentiation in the polysynaptic reflex. We have confirmed this observation in the dog. Furthermore, in contrast to post-tetanic potentiation of the monosynaptic reflex response, easily obtained in both normal and rigid dogs, we failed to obtain evidence of such potentiation of the interneuronal component of the cord dorsum potential in normal dogs. Finally, there is no facilitation of this component (Hughes & Gasser, 1934; Bernhard, 1953).

Since the demonstration some years ago that skeletal muscle behaves like a stretch receptor in Ca-free saline, that the spontaneous discharges which occur in the Ca-free medium are preceded by slow potential changes (prepotentials), suggesting a parallelism to rhythmic oscillations in the C.N.S. (Adrian & Gelfan, 1933), the capacity for spontaneous discharges of other normally non-spontaneous excitable tissues, particularly nerves, has been observed. Bremer (1953) has admirably summarized this in his recent discussion of neuronal auto-rhythmicity. In addition, normal 'spontaneous' activity, resembling the cortical waves of the electroencephalogram, has been recorded from the dorsal surface of the cat's spinal cord (ten Cate, 1950; Mark & Gasteiger, 1953). Transection of the cord does not abolish or reduce the frequency of these low-voltage waves, generated presumably by interneurones in the dorsal horn. Such spontaneous activity, although reduced, was nevertheless recorded 11–14 days after de-afferentation and double transection. This is comparable to the majority finding of persistent spontaneous activity of neurologically isolated slabs of cortex in man and cats (summary and literature in Burns, 1958). In about 40% of the spinal interneurones

with proprioceptive connexions, as studied by Kolmodin (1957), no definite peripheral source in hind limbs was found for this resting activity. Regular oscillations of potential have also been recorded from the anterior horn of the curarized mammal, particularly with light strychninization or asphyxia of short duration (Bremer, 1953). Finally, Lorente de Nó (1947) has analysed the conditions in peripheral nerve which induce rhythmical oscillations of the electrotonic potential, initiating impulses. One may therefore visualize the soma surface of denervated motoneurones as sufficiently altered by denudation of presynaptic terminals to induce critical oscillations of membrane potential, or conditions or agents normally present in the cord environment becoming adequate stimuli for such altered somata. Denervation may also result in the elimination of components supplied by nerve endings which are indispensable for normal motoneurone excitability, in the same sense as removal of Ca increases the excitability of nerves and muscles.

SUMMARY

The nature of hind-limb rigidity produced by 40–50 min occlusion of the thoracic aorta was analysed in dogs.

1. This experimental rigidity, manifest upon recovery from anaesthesia, was always extensor. The milder consequences of the lumbosacral ischaemia, such as motor incoordination or 'spasticity', were temporary; there was full recovery, as judged clinically, within 1 week. The pillar-like rigidity, however, was permanent and could be abolished temporarily only by anaesthesia. Some chronic preparations were observed for over 200 days. The sensory and motor paralysis always accompanying this rigidity was also enduring.

2. The rigidity is of spinal origin, since it is independent of supraspinal connexions.

3. A 'myostatic contracture' of hind-limb muscles develops in addition to the neurogenic rigidity a few days after the establishment of the latter. This shortening of the resting length of muscle, which in contrast to the rigidity cannot be abolished by anaesthesia, may confuse the study of rigidity if not properly recognized.

4. Many of the lumbosacral spinal neurones do not survive ischaemia of such duration. This anoxic destruction of cells is most apparent histologically in the centre of the spinal gray matter.

5. A functional deficit of interneurones was directly demonstrated in chronically rigid dogs during acute experiments by recording spinal-cord and reflex ventral-root potentials.

6. Interneuronal responses to cutaneous and muscle-nerve stimulation and to muscle stretch in chronically rigid dogs were either very much reduced or absent.

7. The functional failure of lumbosacral interneurones includes those relaying excitatory as well as inhibitory impulses.

8. The interneuronal destruction includes those relaying impulses to supraspinal centres, as well as to spinal motoneurones, and must be the basis for the sensory paralysis in rigid preparations. It is also assumed to be the basis for the motor paralysis.

9. A considerably greater percentage of neurones in a rigid motoneurone pool responded to monosynaptic excitation than in a normal one during acute experiments.

10. This chronic rigidity cannot be considered as an exaggerated stretch reflex, since it was neither abolished nor prevented by section of dorsal roots.

11. The destruction of interneurones is considered responsible for the loss of normal regulation of motoneurone activity and consequent muscle responses. Destruction of interneurones also denervates motoneurones.

12. It is proposed that denervation increases the excitability of motoneurones to the point of discharging 'spontaneously'. It is also proposed that the 'spontaneous' discharges of such denervated motoneurones are directly responsible for the unremitting and enduring rigidity.

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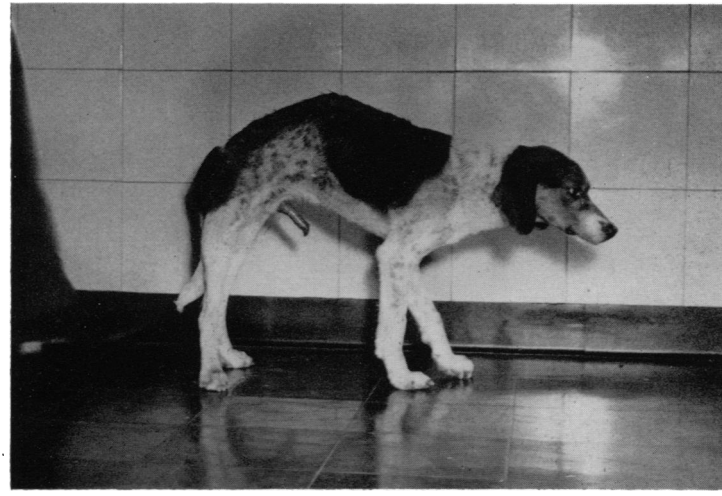

Fig. 1

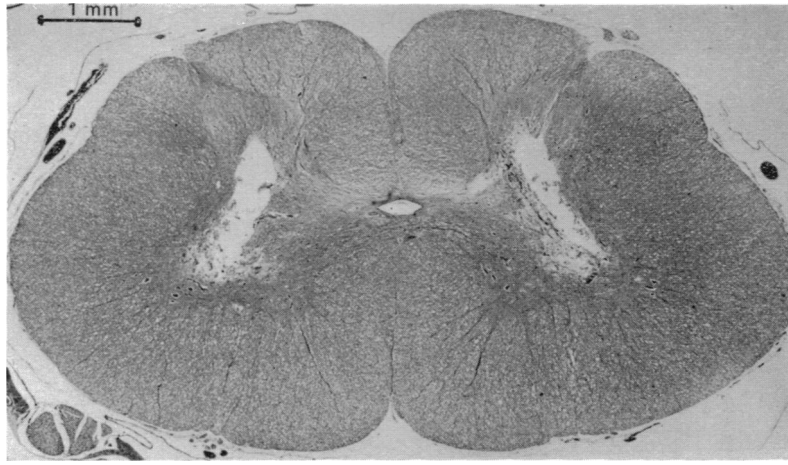

Fig. 2

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EXPLANATION OF PLATE

Fig. 1. Rigidity and priapism after 45 min of lumbosacral ischaemia in dog whose dorsal roots L2 to S1 inclusive had been bilaterally severed extradurally 29 days previously. The extensor hind-limb hypertonus easily supported the weight of the paralysed hind quarters of animal when propped up in balanced position. Before the aortic occlusion the de-afferented animal had very limited motor power in its hind limbs and could not raise its hind quarters; the paresis was flaccid.

Fig. 2. 6μ transverse section through spinal cord at L4–L5 from dog killed after 31 days of hind-limb rigidity. Haematoxylin-eosin stain.