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PLASTICITY OF Ia EXCITATORY POSTSYNAPTIC POTENTIALS AND MEMBRANE ELECTRICAL PROPERTIES IN CAT ANKLE EXTENSOR MOTONEURONS AFTER CHRONIC SPINAL CORD TRANSECTION

BY

SHAWN HOCHMAN

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

Department of Physiology
University of Manitoba
Winnipeg, Manitoba

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ABSTRACT

Intracellular recordings from ankle extensor alpha-motoneurons were used to compare Ia monosynaptic excitatory post-synaptic potentials (EPSPs) and motoneuron membrane properties between cats spinalized at L1-L2 6 weeks prior to the acute experiment and unlesioned, spinal cord intact, controls. Composite monosynaptic Ia EPSPs were evoked by low threshold electrical stimulation and recordings made from barbiturate-anesthetized animals in the four functional synergic motoneurons; medial gastrocnemius (MG) lateral gastrocnemius (LG) soleus (SOL) and plantaris (PL) motoneurons. Division of motoneurons into the 3 major motor-unit types, fast fatigable (FF) fast fatigue-resistant (FR) and slow (S) on the basis of their membrane electrical properties allowed the assessment of whether EPSP and membrane property alterations were related to motor-unit type.

Overall, composite Ia EPSPs were found to be increased in amplitude with faster risetimes and shorter half-widths. For "homonymous" EPSPs, these changes were most pronounced in LG motoneurons and FR motor-unit types. Low threshold EPSPs in MG motoneurons and FF motor-unit types were unchanged.

Motoneuron membrane time constant (τ_m) was lowered but equivalent cylinder electrotonic length (L) was unchanged suggesting an altered motoneuron geometry and reduced surface area to maintain a similar L in the presence of a decreased membrane resistivity. The voltage deflection at rheobase (V_{Th}) was increased but a subthreshold rectification process helped minimize the increase in rheobase current requirements. Although membrane properties were altered similarly among the motoneuron species tested, FF motor-units underwent the most significant changes while FR motor-units were unaltered. FR motor-units are prime candidates for

producing increased reflexes, undergoing a 62% increased ratio of low threshold EPSP amplitude to V_{Th}.

The decrease in EPSP risetime suggests a proximal shift in Ia synapses. While motoneurons from chronic spinal animals do not become hyperexcitable, the reported EPSP changes would contribute to hyperreflexia in six week chronic spinal animals.

ABBREVIATIONS

EPSP	-	excitatory post-synaptic potential
MG	-	medial gastrocnemius
LG	-	lateral gastrocnemius
PL	-	plantaris
SOL	-	soleus
LGS	-	lateral gastrocnemius/soleus
L1	-	first lumbar vertebra
L2	-	second lumbar vertebra
T	-	threshold
SPCT	-	short pulse current threshold
R_{in}	-	input resistance
R_{inS}	-	input resistance calculated from a 500 microsecond current pulse
R_{inL}	-	input resistance calculated from a 50 millisecond current pulse
τ_m	-	motoneuron membrane time constant
τ_1	-	equalization phase time constant
L	-	motoneuron equivalent cylinder electrotonic length
T_{Cap}	-	total cell capacitance
V_{Th}	-	threshold voltage
AHP	-	afterhyperpolarization
CV	-	axonal conduction velocity
FF	-	fast fatigable motor-unit type
FI	-	fast motor-unit with intermediate fatigability between FF and FR motor-unit types
FR	-	fast fatigue-resistant motor-unit type
S	-	slow motor-unit type

INTRODUCTION

I. Overview

Interruption of the descending pathways to motor nuclei which innervate hindlimb musculature results in their paresis in man and cat. After some time in both man and cat, augmented stretch reflexes are manifest as an increased contraction response to tendon tap, a condition clinically referred to as spasticity. Tendon tap stretches muscle and activates stretch-sensitive muscle spindle afferents (dynamic group Ia and static group II) originating in intrafusal muscle fibres. The increased stretch reflexes have been demonstrated after chronic spinalization in cat ankle extensor muscles and appear to display monosynaptic reflex components. Since Ia muscle spindle afferents activated by muscle stretch synapse directly onto alpha-motoneurons, this simple reflex pathway is an obvious target for electrophysiological investigations into the mechanisms underlying spinalization-induced hyperreflexia.

The experiments undertaken in this thesis utilize intracellular recordings from alpha-motoneurons to evaluate changes in the Ia monosynaptic excitatory post-synaptic potential (EPSP) and motoneuron membrane events that may contribute to the behavioral hyperreflexia seen in chronically spinalized cats. Composite Ia EPSPs were evoked by electrical stimulation of appropriate muscle nerves and recorded in ankle extensor alpha-motoneurons. Estimates of relevant motoneuron membrane properties were accomplished with known and accepted stimulating and recording techniques. Both the motoneuron membrane properties and the composite Ia EPSPs were compared between unlesioned and six-week spinalized cats (at the L1-L2 vertebral level). Recordings from four different ankle extensor motoneuron species allowed a comparison between Ia EPSP and membrane properties of close functional synergists which as

a group contribute to increased stretch reflexes. They are medial gastrocnemius (MG) lateral gastrocnemius (LG) soleus (SOL) and plantaris (PL). Motoneurons differ slightly in their electrical properties and Ia synaptic input based on the muscle fibre type they innervate (e.g. fast and slow twitch). Approximate division of motoneurons into the 3 major motor-unit types, namely, fast-twitch fatigable (FF) fast-twitch fatigue-resistant (FR) and slow-twitch fatigue resistant (S), allowed a comparison between EPSP and membrane electrical properties related to motor-unit type in unlesioned and chronic spinal preparations.

In order to provide a backdrop of the reflex system under investigation, sections II and III of this introduction briefly highlight the present knowledge on the characteristics of the group Ia muscle spindle connections onto motoneurons and the passive electrical and threshold properties of motoneurons. Section IV delineates the impetus for an examination of group Ia - alpha-motoneuron plasticity, reviewing past studies and examining their weaknesses. Section V lists the strengths of the experimental approach presently described. Finally, Section VI presents a general summary of the present experimental findings.

II. The Ia synapse

The pioneering intracellular recordings of Sir John Eccles and collaborators on from mammalian (cat) hindlimb motoneurons (Brock et al., 1952) have led to a wealth of information concerning their electrical properties (for reviews see Redman, 1976; Burke and Rudomin, 1977; Carlen et al., 1985; Schwindt and Crill, 1985) and synaptic input (for reviews see Burke and Rudomin, 1977; Redman, 1979; Baldiserra et al., 1981; Sypert and Munson, 1985). One of the most intensively studied central synapses *in vivo* continues to be the muscle spindle Ia afferent connections onto lumbosacral alpha-motoneurons, particularly those serving ankle extensors

(for reviews see Burke and Rudomin, 1977; Redman, 1979; Sypert and Munson, 1985). Past studies have shown that the majority of Ia synapses onto motoneurons are located on proximal dendrites (Conradi et al., 1983; also see Burke et al., 1979) with a most frequent distance of 0.4 space constants from the soma (Jack et al., 1971). Typically, a single Ia afferent fibre produces multiple synaptic contacts on most homonymous motoneurons (although single terminal boutons are not uncommon) the average number probably being greater than Iles' (1976) initial estimate of 1.8 contacts per motoneuron (Redman, 1979). The multiple bouton arrangement is characterized by either a series of *en passant* boutons with a terminal bouton, or a branching terminal axon with each branch containing a small cluster of boutons. Generally, the boutons from a single afferent synapse on a spatially discrete region along the proximo-distal surface of the dendrites (Brown and Fyffe, 1978) although it is not uncommon for the boutons to be spatially dispersed (Burke et al., 1979; Redman and Walmsley, 1983b). Ultrastructurally, Ia boutons are considered S-type (for spherical) (Conradi et al., 1983; Fyffe and Light, 1984) and disappear after dorsal root section (Conradi, 1969). They are often the postsynaptic elements of axo-axonic synapses with P-boutons (for presynaptic) which impinge upon them (Conradi et al., 1983; Fyffe and Light, 1984).

The intracellular excitatory synaptic action of Ia afferent fibres on motoneurons was first investigated by Sir John Eccles and colleagues (Coombs et al., 1955b). The Ia EPSP can reverse polarity in response to large injections of depolarizing current (Coombs et al., 1955b; Marshall and Engberg, 1973; Flatman et al., 1982) and thus appears to be due to the chemically mediated opening of conductance channels. Although the identity of the transmitter has yet to be identified, L-glutamate and substance P are candidates (see Redman, 1979). Hoping that Ia transmission was similar to that occurring at the neuromuscular junction (DELCastillo and Katz,

1954) the earliest investigators suggested a "quantal" type of neurotransmitter release (Katz and Miledi, 1963). For single afferent fibers each quantum produced a mean EPSP amplitude of approximately 100-200 μV (Kuno, 1964). Kuno, (1964) suggested that the variability in EPSP amplitude recorded with successive stimuli was fitted by either poisson or binomial probability distributions. It was thought that the amplitude fluctuations occurred at the level of the single bouton. However, thanks to the technical advancement of spike triggered averaging (Mendell and Henneman, 1971) accompanied by the more realistic statistical model of deconvolution (Redman and Walmseley, 1983a,b) the current view of synaptic transmission is probabilistic; that is, each bouton from a single Ia afferent fibre has a different probability of transmitter release. When transmission occurs at a bouton, it is all or none (Redman and Walmseley, 1983a,b). It is of interest that transmission probability is not static but modifiable by events such as presynaptic inhibition, post-tetanic potentiation, and facilitation (Clements et al., 1987; Hirst et al., 1981). Thus, although not yet investigated, an alteration in release probability may also partly account for the observed EPSP plasticity after events such as motoneuron axotomy, rhizotomy, spinal cord cold block, and acute and chronic spinal cord transection.

Detailed examination of composite Ia EPSPs evoked by peripheral nerve stimuli suprathreshold for recruitment of group Ia afferent fibres (Eccles et al., 1957; Eccles and Lundberg, 1958) revealed their widespread monosynaptic excitation of motoneurons from several pools, an organization seemingly related to their coactivation during movements (Lundberg, 1959; Lundberg, 1969). The organization was found to be more complex than the earlier predictions based on the hypothesis of the myotatic reflex (Liddell and Sherrington, 1924). Generally, Ia afferents from a particular muscle produce the largest composite EPSPs in motoneurons which innervate that muscle (homonymous) and smaller composite EPSPs in motoneurons of

other muscles considered to be functional synergists (heteronymous) (Eccles et al., 1957; Eccles and Lundberg, 1958). The composite Ia EPSP amplitude differences between homonymous and heteronymous motoneurons relate both to differences in both projection frequency (the number of motoneurons which receive projections from a single afferent) as well as synaptic density (the number of boutons) per Ia afferent fibre. For example, for medial gastrocnemius, a single Ia afferent has projections to most homonymous motoneurons and significantly fewer heteronymous ones (Mendell and Henneman, 1971; Nelson and Mendell, 1979; Munson et al., 1986). Single fibre Ia EPSPs are also larger in homonymous motoneurons (Mendell and Henneman, 1971; Scott and Mendell, 1976; Munson and Sypert, 1979; Harrison and Taylor, 1981).

The Ia monosynaptic EPSP characteristics are also related to the muscle fibre type innervated by motoneurons, with EPSP amplitude increasing in the order: fast fatigable (FF) < fast fatigue-resistant (FR) < slow (S) (for e.g. Burke et al., 1976; Fleshman et al., 1981). Although these differences in amplitude among motoneurons innervating different muscle fibre types have been ascribed to differences in Ia synaptic density and motoneuron size (Burke, 1981; Sypert and Munson, 1985; Heckman and Binder, 1988) no anatomic studies have been undertaken to support these assertions. In fact, Rall motoneuron modelling (see Rall, 1977) suggests that EPSP shape can be accounted for simply by the difference in passive membrane electrical properties between fast and slow motoneurons (Gustafsson and Pinter, 1984d).

III. Alpha-motoneuron membrane properties

As mentioned earlier, intracellular investigations of alpha-motoneurons were established by the pioneering studies of Sir John Eccles and collaborators (Brock et al., 1952). The popularity and success of

intracellular recording of motoneurons is due to the large somal size of these neurons (35-75 μm) (Brown and Fyffe, 1981; Ulfhake and Kellerth, 1981; Zwaagstra and Kernell, 1981) ease of antidromic identification (Brock et al., 1952) and obvious function as the "final common path" of motor behavior (Sherrington, 1947). Hindlimb motoneurons are located in Rexed's lamina IX of the lumbosacral enlargement. These motoneurons have extensive dendritic arborizations which extend up to 1,000 μm from the cell soma and dominate the cell's surface area (see Carlen et al., 1985). Thus, the passive electrical responses observed in motoneuron cell bodies are largely determined by the dendritic membrane (see Rall, 1977).

The motoneuron resting membrane potential in deeply anesthetized cats is thought to be about 80 mV (Gustafsson and Pinter, 1984a); however, such large values are rarely recorded because of depolarizations caused by impalement injury and possibly tonic synaptic activity. The resting membrane potential is presumed to be maintained largely by a high resting K+ conductance, low Na+ permeability, and the presence of an electrogenic Na+ - K+ pump (for review, see Burke and Rudomin, 1977). Even at subthreshold levels the membrane rarely behaves passively, but displays rectification processes such as: delayed rectification, a decrease in membrane resistance during large depolarizations (eg. Araki and Terzuolo, 1962); anomalous rectification, an increase in resistance during small depolarizing currents and decrease in resistance during small hyperpolarizing currents (Nelson and Frank, 1967); and a time-and voltage-dependent activation of a conductance producing a "sag" in steady-state voltage responses (Ito and Oshima, 1965; Gustafsson and Pinter, 1984b).

The passive electrical properties of the motoneuron membrane were also first assessed by Sir John Eccles and collaborators (Coombs et al., 1955a). The importance of the passive electrical properties and geometric structure of the motoneuron membrane relates to its function in the

reception and integration of synaptic input. Ultimately the net depolarizing and hyperpolarizing conductances produce voltage changes that overlap temporally and occur spatially throughout the dendritic arborizations. They propagate to the soma where they summate and continue to the lowest threshold region of the motoneuron, the initial segment, either promoting or impeding attainment of threshold (see Eccles, 1964). It is to Wilfrid Rall that we owe the first realistic appraisal of the effectiveness of the dendrites in charge transfer and the determination of a method to incorporate the essential electrical properties and anatomic features of dendritic branching into a mathematical model of the motoneuron (Rall, 1959; for a general review see Rall, 1977). Many of his theoretical assumptions about dendritic structure were histologically supported about 10 years later (Lux et al., 1970; Barrett and Crill, 1971; Barrett and Crill, 1974a,b). Both anatomic and electrophysiological techniques suggest that the lumbosacral alpha-motoneuron is electrically compact, with an average equivalent cylinder electrotonic length (L = physical length / space constant) of less than 1.5 (Nelson and Lux, 1970; Burke TENBruggencate, 1971; Gustafsson et al., 1982; Gustafsson and Pinter, 1984a; Redman et al., 1989). The consequence of such a short electrotonic length is that even distal dendritic synapses can propagate to the soma without drastic attenuation and thus affect motoneuron recruitment.

An important passive electrical property of the motoneuron is the membrane time constant (τ_m). Assuming a constant membrane specific capacitance, it can be used as a measure of membrane resistivity. The membrane time constant (τ_m) varies over an approximate six-fold range from 2 - 12 ms (Gustafsson and Pinter, 1984a; Nelson and Lux, 1970; Burke and TENBruggencate, 1971; Gustafsson et al., 1982). It is a critical factor in synaptic integration and motoneuron recruitment since it determines the duration of potential displacements (and thus temporal overlap) arising

from transient synaptic and other conductance changes.

Assuming the membrane behaves passively at rest (but see above) the voltage deflection produced by current injections allows for the calculation of total cell resistance (R_{in}) which depends on the specific resistivity of the cell membrane, cell size, and the geometric properties of the dendrites (see Burke and Rudomin, 1981). R_{in} values vary considerably, with mean values between .5 and 1.0 MΩ (Burke and Rudomin, 1981; Gustafsson and Pinter, 1984a). Traditionally, R_{in} has been used as an indirect estimate of cell size (eg., see Burke and Rudomin, 1977) in studies examining EPSP amplitude, motor-unit type, conduction velocity, and muscle tension (see Sypert and Munson, 1985). However, it has become clear that R_{in} is better related to membrane resistivity and motor-unit type than cell size (Gustafsson and Pinter, 1984a; Fleshman et al., 1981b).

Motor units (and thus motoneurons) are generally recruited in order of increasing muscle tension and organizational principles governing this ordering have been explored extensively (see Burke, 1981). The threshold properties of motoneurons determine membrane excitability and contribute to the variation in recruitment order of motor output (Gustafsson and Pinter, 1984b; Gustafsson and Pinter, 1985). Recruitment order was first thought to be organized according to cell size with other motoneuron characteristics covarying with cell size (eg. conduction velocity, synaptic input, motor-unit tension). This principle was originally proposed by Henneman (Henneman et al., 1965) and became known as Henneman's "size principle". However, with further experimentation, it became increasingly apparent that a variation in membrane resistivity correlated to the functional differentiation of motor-unit type better governed motoneuron threshold properties and recruitment order than did cell size (Pinter et al., 1983; Gustafsson and Pinter, 1984b; Gustafsson

and Pinter, 1985; Zajac and Faden, 1985).

IV. Investigations into the possible mechanisms behind increased stretch reflexes following chronic spinal transection

The monosynaptic excitation by Ia afferents of ankle extensor alpha-motoneurons is the most thoroughly investigated reflex within the mammalian central nervous system (as summarized in Sections II and III above). This is fortunate when pursuing the mechanisms underlying increased monosynaptic stretch reflexes after chronic spinalization since the methodologies used to explore the behavior of Ia EPSPs and alpha-motoneurons in cats with an intact spinal cord are well established and can be employed for similar investigations in chronic spinal cats. Thus, motoneurons can be impaled intracellularly and antidromically identified, their membrane properties can be recorded, and EPSPs produced in them by selective stimulation of Ia afferents can be viewed largely separately from other synaptic effects. Ia EPSP and motoneuron membrane properties can then be compared between chronic spinal and unlesioned cat preparations.

The increased stretch reflexes from ankle extensor muscles in cats (as shown by stretch of the achilles tendon) presents a good example of hyperreflexia and provides an opportunity to study its mechanisms (Bailey et al., 1980; Brothers et al. 1983; Teasdall et al., 1958, 1965; Hultborn & Malmsten, 1983). Since the degree of enhancement seems to be related to the rapidity of muscle stretch, one can tentatively attribute the resulting hyperreflexia to Ia muscle spindle afferents which respond most strongly to the dynamic components of muscle stretch. Accordingly, investigations have shown that both electrical and stretch stimuli that recruit Ia spindle afferents give rise to increased reflexes during hyperreflexia (Teasdale et al., 1958, 1965; Hultborn & Malmsten, 1983;

Brothers et al., 1983); one component of the increased Ia reflexes is assumed to be monosynaptic (Teasdall et al., 1958; Hultborn & Malmsten, 1983).

The most obvious difference in the spinal cord caudal to its transection is the loss of descending control over intrinsic spinal circuitry, perhaps altering the excitability of known reflex pathways (Hultborn and Malmsten, 1983; McCrea et al., 1985). However, the extent to which an altered reflex expression is triggered by other injury-related mechanisms like collateral sprouting (Tsukahara, 1985; Lui and Chambers, 1958; Goldberger, 1981; Goldberger and Murray, 1974; Murray and Goldberger, 1974; Goldberger and Murray, 1978; Goldberger and Murray, 1982; Goldberger and Murray, 1985) and denervation supersensitivity (Nygren et al., 1974; Nygren and Olson, 1976) remains unknown. In view of the complexity of afferent processing in the spinal cord (Baldiserra et al., 1981) it is useful to start by examining the simplest possible reflex system. The stretch reflex produced by an abrupt pull on a muscle (activating muscle spindle afferents) is one such system.

Generally, an increased Ia monosynaptic reflex response after chronic spinalization may be due to one or more of the three components in this reflex system: (a) An increased recruitment of Ia afferents by a given muscle stretch (due, for instance, to an increased fusimotor drive); (b) An increased synaptic output from each Ia afferent fiber (due to factors such as collateral sprouting or a decrease in presynaptic inhibition); and (c) An alteration in the membrane properties of motoneurons that would make a given synaptic conductance more efficient at recruiting that particular motoneuron.

With regard to possibility (a), there is no evidence of an increased fusimotor drive to muscle spindles (Bailey et al. 1980) or increased

spindle activity (Hagbarth et al., 1973) following chronic spinal cord transection (see also Burke, 1983). In reference to (b), although neuroanatomical studies have found considerable evidence of an altered synaptology within the CNS following chronic spinal cord lesions (Pullen & Sears, 1978; Goldberger & Murray, 1985; McCouch et al. 1957; Bernstein & Bernstein, 1977; Wall, 1988), there is no investigation that has studied the Ia afferent synapses onto motoneurons exclusively. Further, there is contrasting experimental support both for increases (Hultborn & Malmsten, 1983) and decreases (Naftchi et al. 1980) in presynaptic inhibition.

In regard to both (b) and (c), many investigators have attempted to associate the increased stretch reflex following chronic spinal cord injuries with either changes in Ia EPSPs or motoneuron electrical properties. This has encompassed both the recording of Ia EPSPs intracellularly from motoneurons (Nelson & Mendell, 1979; Munson et al. 1986; Mayer et al. 1984) as well as the measurement of motoneuron membrane properties (Czéh et al., 1978; Gustafsson et al., 1982; Munson et. al., 1986; Baker & Chandler, 1987). These latter areas of investigation are relevant to the experiments undertaken in this thesis and deserve further comment.

A. Previous investigations on the effects of chronic spinalization on monosynaptic Ia EPSPs within alpha-motoneurons

Investigations looking for changes in Ia EPSPs after chronic spinal transection (Nelson & Mendell, 1979; Mayer et al., 1984; Munson et al. 1986) have mainly concerned themselves with the EPSP responses from single afferent fibers in only one ankle extensor motoneuron species, medial gastrocnemius (MG). In these studies, a broad survey of different lesion levels and time periods was chosen (Nelson & Mendell, 1979; Munson et al. 1986). In fact, often a single cat and a single afferent fiber were used

to represent a lesion level - time period (Nelson & Mendell, 1979). Nelson & Mendell (1979) found a greater number of large unitary EPSPs after chronic spinalization. However, the significance of these increases depended on both time after transection and level of spinal cord lesion. Along with another study that looked at the changes in Ia composite EPSP amplitudes in MG motoneurons in three cats (Mayer et al. 1984) the overall conclusions (Nelson & Mendell, 1979; Mayer et al., 1984; Munson et al. 1986) were that EPSPs were not significantly altered by chronic spinalization and therefore could not contribute to the behavioral hyperreflexia seen. On the other hand the increases in stretch- and electrically-evoked reflexes suggest that monosynaptic Ia reflexes are increased (Brothers et al., 1983; Hultborn and Malmsten, 1983).

<u>These studies were limited in that</u>

1. They studied only one (MG) of many muscles with primary ankle extensor function (Sherrington, 1910) which as a group contribute to increased stretch reflexes (Brothers et al., 1983). It is possible that different motoneuron species are affected differently by chronic spinalization, especially since different muscles can have different populations or proportions of muscle fibre types (ie. fast and slow) (Ariano et al., 1973; Emonét-Denand et al. 1988; Burke et al., 1974). In fact, there is some evidence that the MG motor-unit population is somewhat unique in having a large proportion of FF units (Emonét-Denand et al. 1988).

2. Very few cats were used to characterize the changes for a given lesion level and time period. This is a potential problem considering the extent to which EPSP size can vary between cats (Munson et al. 1986; personal observations). EPSP size is probably influenced by several factors including anesthetic depth and circulatory status.

3. No study has compared the shape of Ia EPSPs between unlesioned and chronic spinal cats. For instance, it appears that EPSPs with the same amplitude but quicker rising phases have a greater probability of causing motoneurons to fire (Fetz & Gustafsson, 1983; Gustafsson & McCrea, 1984; Cope et al., 1987). In fact, a related study, in which axons of the ascending collateral branch of Ia fibres were chronically cut in the dorsal column of the lumbar cord, found increased monosynaptic reflexes (Decima and Morales, 1983) without an augmented Ia EPSP amplitude but with an increased EPSP rate of rise (Decima et al., 1986).

B. Previous studies on the effects of chronic spinalization on motoneuron electrical properties

Five studies have assessed the effects of chronic spinalization on motoneuron membrane properties (Czéh et al., 1978; Gustafsson et al., 1982; Cope et al., 1986; Munson et al., 1986; Baker & Chandler, 1987). Only two have properly compared the unlesioned and chronic spinal conditions (Cope et al., 1986; Munson et al., 1986).

Postsynaptic decreases in the threshold voltage of motoneuron recruitment could contribute to increased reflexes but the available evidence suggests that threshold intracellular current (rheobase) is either unchanged (Gustafsson, Katz & Malmsten, 1982; Chandler & Baker, 1987; Munson et al., 1986) or even increased (Cope, Bodine, Fournier & Edgerton, 1986) in chronic spinal cats. Postsynaptic changes in motoneuron passive membrane properties could also alter the size and shape of EPSPs and in this regard, an electrical "shrinkage" of the motoneuron in chronic lesioned animals has been reported (Gustafsson et al., 1982). These authors calculated the increase in EPSP amplitude that would be expected

from such changes in motoneuron membrane properties and raised the possibility that these mechanisms change the amplitudes and possibly risetimes and half-widths of Ia EPSPs in chronic spinal cats. However since the preparation used had chronic lesions of both the spinal cord and the dorsal roots, the relative contributions of rhizotomy and spinal transection to changes in EPSPs are unknown. More recently, it has been shown that chronic lesions of just the dorsal columns can result in an increased rate of rise of Ia EPSPs without an amplitude increase (Decima & Morales, 1986).

<u>These studies also suffered from important limitations:</u>

1. Not all of the relevant membrane properties were measured in the chronic spinal preparation (Cope et al., 1986; Munson et al., 1986). For instance, neither study estimated the equivalent cylinder electrotonic length (L) which is related to the effectiveness of charge transfer from synapses located on dendrites as they travel towards the soma. This has important consequences for synaptic integration. In fact the calculated membrane electrotonic length in cats with chronically deafferented motoneurons was reduced enough to theoretically increase EPSP size by 36% (Gustafsson et al., 1982).

2. There is reason to believe that the membrane property measurements made were from motoneurons with considerable impalement injury. The extent to which electrode-induced impalement injury may complicate an interpretation of changes in membrane properties is unknown and must be addressed. It is essential to record from motoneurons which are considered minimally damaged from electrode impalement (Gustafsson & Pinter, 1984a).

3. Once again, only a single ankle extensor motoneuron species (MG) was studied.

V. Summary of present thesis

The present experiments examine ankle extensor alpha-motoneurons in unlesioned and chronic spinal animals in an attempt to appreciate the changes in monosynaptic Ia EPSPs and membrane electrical properties that might contribute to increased reflexes. Four ankle extensor motoneuron species were surveyed in cats spinalized at a single lesion site (between L1 and L2) and a single interval (6 weeks). Measurements of the electrical properties were made in the same motoneurons in which the EPSPs were recorded. In the present thesis, mean EPSP amplitudes, 10 - 90% risetimes, and durations at half amplitude (half-widths) as well as an assortment of motoneuron electrical properties are compared in the unlesioned and spinal preparations in MG, LG, SOL, and PL motoneurons. Some of these results have been presented in abstract form (Hochman and McCrea, 1986, 1988; Hochman et al., 1987).

The most important contributions of the present study are:

1. The use of a large number of animals at a single lesion level and time period to reduce the unknown influence of inter-animal variability, different lesion levels, and different time periods on the experimental results.

2. A comparison of effects recorded from four rather than only one ankle extensor motoneuron species to assess the similarities and differences between close functional synergists.

3. The measurement of motoneuron membrane properties and Ia EPSPs from the same motoneurons in order to document and compare the relative changes in each.

4. The measurement of composite EPSPs rather than single fiber EPSPs to better relate to the composite EPSPs evoked by mechanical stimuli such as stretch.

5. The first measurements of changes in the shapes (EPSP risetime and half-width) of EPSPs after chronic spinalization. EPSP shape affects motoneuron firing (Fetz & Gustafsson, 1983; Gustafsson & McCrea, 1984) as well as being a useful measure of synaptic location (Rall et al. 1967). The latter property has been used to document the sprouting of synapses to novel locations on neurons in the red nucleus after chronic lesioning of certain afferent inputs (Tsukahara, 1985).

6. The use of motoneurons with superior electrode penetrations (Gustafsson and Pinter, 1984a) when evaluating membrane properties. It was decided that motoneurons with stable spike heights of 80 millivolts or greater would be considered acceptable. Most studies accept motoneurons with spike heights of 60 millivolts or greater. When action potential heights are reduced there is a deterioration in cell health as evidenced by decreases in resting membrane potential as well as changes in the measures of other recorded membrane properties (Gustafsson and Pinter, 1984a; personal observations).

VI. General Summary

The body of this thesis is divided into 3 separate sections. The first section describes a detailed analysis of Ia EPSP amplitude and shape in the four ankle extensor motoneuron species examined. Two important findings are reported. First, as a population, the mean Ia EPSP amplitude becomes slightly, though significantly, larger in the chronic spinal

population while the mean risetime and half-width of these EPSPs is significantly reduced. These changes in amplitude and shape would support increased reflexes. Secondly, the extent of these changes depends on the particular motoneuron species examined, with EPSPs recorded in LG motoneurons being altered the most and EPSPs recorded in MG motoneurons being unchanged. This latter finding is interesting in view of the fact that research into this area has been undertaken largely in MG motoneurons, a species which appears least affected by chronic spinal lesions.

The second section constitutes a detailed analysis of motoneuron membrane properties. Motoneuron properties from chronic spinal cats differ significantly from those in unlesioned animals. There is an overall decrease in the membrane time constant (τ_m). However, equivalent cylinder electrotonic length (L) is unchanged suggesting that motoneurons are anatomically more compact in the chronic spinal animal. This notion is supported by an overall reduction in estimated cylinder surface area (T_{Cap}). Unexpectedly, the measured voltage deflection at rheobasic current (V_{Th}) is increased in the chronic spinal preparation which should cause an overall decrease in motoneuron excitability. However, these same motoneurons also appear to have a change in subthreshold rectification processes that produce a greater voltage deflection per unit of injected current so that for a given threshold voltage, less current is required to reach threshold in the chronic spinal preparation. Unlike the composite Ia EPSP, membrane property changes appear to occur more uniformly among the motoneuron species. Finally, it is shown that all membrane property differences disappear when motoneurons with impalement injury (action potential heights greater than 60 but less than 80 mV) are compared, highlighting the importance of superior penetrations for an assessment of motoneuron membrane properties.

The final section utilizes cell input resistance and rheobase to electrically classify motoneurons into three groups that approximate the three major motor-unit types: fast fatigable (FF) fast fatigue-resistant (FR) and slow (S). Interestingly, both membrane properties and composite Ia EPSPs are differentially altered in the 3 motoneuron types after chronic spinalization. While FF motoneurons undergo the greatest change in membrane properties, EPSPs recorded in FR motoneurons undergo the greatest amplitude increases as well as risetime and half-width decreases. Further as shown by the ratio of EPSP amplitude to threshold voltage, FR motoneurons would be expected to be more easily recruited during a reflex.

Unlike previous attempts to explore the Ia EPSP and motoneuron membrane events subserving increased monosynaptic reflexes, the present results stress that both Ia EPSPs and motoneuron membrane properties are altered in chronic spinal cats, in a complex manner that varies with to motor-unit type, motoneuron species, and whether homonymous or heteronymous synaptic connections are considered. An overall hyperreflexia would be predicted from these "plastic" events, lending justification to further investigations into the possible physiological mechanisms involved.

METHODS

Dissection

16 adult female cats were spinalized at the L1-L2 level by sterile technique under sodium pentobarbital anesthesia (30 mg/kg intraperitoneally, supplemented with Halothane and nitrous-oxide/oxygen). A few drops of lidocaine were applied to the surface of the cord before the transection was performed using blunt dissection with fine forceps. Visual inspection under the dissecting microscope insured that the rostral and caudal cord segments were completely separated and a large piece of gelfoam was inserted within the canal space. Morphine was given in the immediate postoperative period, and penicillin G administered for the first five days following transection. No infections were encountered. Nursing care involved at least twice-daily manual expression of the bladder for the six week period prior to the acute experiment. Two cats were often housed together in double sized cages for companionship and all animals remained healthy, playful and affectionate. Most cats maintained or slightly increased their weights during the chronic spinal period. There were no differences in the average weights of animals selected for the spinalized (mean 2.60 kg) and unlesioned (mean 2.68 kg) groups (range 1.8 to 4.4 kg).

For the acute experiment, the initial anesthetic was Halothane in a nitrous oxide/oxygen mixture. A tracheotomy was performed and cannulae inserted into a forelimb vein and the right femoral artery and vein. A buffer solution (5% glucose and 0.84% sodium bicarbonate, 2 ml/hour) was infused slowly throughout the surgery and recording periods. Atropine (0.12 mg) was administered subcutaneously and dexamethasone (4 mg) intravenously. Peripheral nerves in the left (ipsilateral) hindlimb were

cut and dissected free of surrounding tissue to allow subsequent mounting on bipolar stimulating electrodes. These included the medial gastrocnemius (MG), lateral gastrocnemius-soleus (LGS) and plantaris (PL) nerves. In most experiments the SOL nerve was freed distally to allow antidromic identification of SOL motoneurons. An L4-6 laminectomy exposed the lumbar enlargement. Halothane anesthesia was discontinued and sodium pentobarbital given intravenously (30 mg/kg initially). Additional barbiturate was given throughout the experiment in order to maintain a deep level of anesthesia. Enough barbiturate was given so that further additions resulted in a fall in the mean arterial blood pressure below 120 mmHg. After transfer to the recording frame, the animal was artificially respired and paralyzed with gallamine triethiodide, and a bilateral pneumothorax was performed to reduced respiratory movements. Mineral oil pools over the back and leg were constructed from skin flaps and kept warm by radiant heat. Animal temperature, arterial blood pressure and end expired CO_2 (kept at ≈4%) were monitored throughout the experiment.

Intracellular recording

Intracellular recordings from lumbar alpha motoneurons were obtained with 2M potassium citrate-filled electrodes with tip diameters of 1.5-2.2 μm and resistances of 2-7 MΩ. The electrodes were selected initially for good current-passing properties. In addition, during the search for motoneurons, the ability of these electrodes to pass short duration (.5 ms) extracellular current pulses (20 nA) without generating voltage transients with an obvious time constant was continually monitored and electrodes discarded if they became unsuitable. This ensured that a large number of motoneurons impaled had electrodes with suitable current passing capabilities. Cord dorsum records were obtained from a 1.5 mm diameter silver electrode placed on the surface of the spinal cord adjacent to the L7-S1 dorsal root entry zone. Motoneurons were impaled in the L7 or S1

ventral horn and their species identified by antidromic activation from peripheral nerves. Constant current stimuli (0.2 ms duration) were applied to the peripheral nerves with electrically isolated stimulators (Eide, 1972). Great care was taken in defining the threshold of nerve stimulation. High gain cord dorsum recordings were examined and sometimes averaged to detect small deflections in the cord dorsum recordings. Threshold was defined as the minimum stimulation required to produce such a deflection and all stimulus intensities were expressed as multiples of threshold (T). Threshold stimulation level was determined upon penetration and monitored throughout recording from each motoneuron. Cord dorsum, microelectrode, and current monitor recordings were amplified and displayed on two oscilloscopes.

Section A

Comparison of Ia EPSPs in Unlesioned and Chronic Spinal Preparations

Analysis of composite Ia EPSPs

Composite Ia epsps evoked by electrical stimulation of peripheral nerves were photographed and averaged online (32 sweeps, usually 40 μs per point). Single shock stimuli were given to peripheral nerves at a rate no greater than 4 Hertz (to prevent the possibility of contamination by long duration polysynaptic effects; see Baldissera et al., 1981). The averaging program also allowed analysis of rise time, amplitude, and decay of the EPSPs as well as permitting the normalization of one record to another. The computer was a Motorola 68000 based system (Cromemco) running under the Cromix operating system and using programs written in the laboratory.

While it is possible to identify many species of motoneurons by the

size and pattern of monosynaptic Ia EPSP input (Eccles et al., 1957) similar mean amplitudes of EPSPs evoked from heteronymous and homonymous afferents in LG (Eccles et al. 1957) may prevent the unambiguous classification of some motoneurons (see Fig. 2B). Furthermore, since chronic spinalization might alter the relative differences in the size of heteronymous and homonymous Ia EPSPs, it was essential to keep the ventral roots intact to allow antidromic motoneuron identification. Leaving the ventral roots intact introduces two complications; 1) the size and particularly the risetime of the EPSP cannot be measured accurately when stimulating above threshold for antidromic activation of the motoneuron, and: 2) recurrent IPSPs produced by the activation of other motoneurons can contaminate the falling phase of the Ia EPSP. Therefore, composite Ia EPSPs were evoked in each motoneuron at stimulation intensities below threshold for antidromic activation of that motoneuron (mean antidromic threshold 1.7T). Thus no attempt was made to maximally activate all of the Ia afferents in a particular nerve. The use of hyperpolarizing current to prevent antidromic invasion and allow recruitment of all Ia afferents in the peripheral nerve (Burke et al., 1976) was undesirable since the current might affect EPSP size and shape (Coombs et al., 1955; Nelson and Frank, 1967) and the remaining M-spike would have prevented an accurate estimation of EPSP risetimes. Higher stimulation strengths would also contaminate the EPSP decay by increased activation of recurrent and group I oligosynaptic inhibition.

A stimulus intensity of 1.2T was chosen as the "standard" strength to reduce the influence of IPSPs on EPSP decay. Only about 6% of the motoneurons encountered were antidromically activated at this threshold. Data from these cells were not included in the analysis. Occasionally small amounts (1 - 5 nA) of hyperpolarizing current were used to prevent orthodromic activation of motoneurons (predominantly in SOL and PL). Composite "homonymous" (see below) Ia EPSPs were, therefore, recorded

using stimulation strengths of 1.1, 1.2, and 1.4 times threshold. Infrequently, the rising phase of small amplitude EPSPs was contaminated by extracellular fields. These EPSP risetimes were not estimated. Further, in some motoneurons EPSPs were obviously contaminated by spinal inhibition so their half-widths were not estimated. This occurred predominantly in the chronic spinal preparations. All heteronymous effects were measured at 2T since there was no antidromic activation, and orthodromic action potentials were never elicited at 2T in these experiments. Because of the high stimulation strengths used, half-widths were not measured for heteronymous EPSPs.

The SOL nerve was dissected between the LG and SOL muscles and mounted in a nerve cuff for antidromic activation of SOL motoneurons. However, the LG and SOL nerve branches were not stimulated separately from each other because of potential damage to Ia afferents during distal dissection of the nerve. Thus EPSPs recorded in both LG and SOL motoneurons were not purely homonymous but combined homonymous and heteronymous effects from the LGS nerve. "Homonymous" EPSPs were thus defined as those resulting from stimulation of the LGS nerve while recording from LG or SOL and those evoked by stimulation of MG or PL afferents while recording from MG or PL motoneurons respectively. Heteronymous EPSPs were those evoked from MG afferents and recorded in LG motoneurons and those evoked from stimulation of the LGS nerve and recorded in MG motoneurons. Composite Ia EPSP amplitudes and shape parameters (10-90% risetime and EPSP duration at half maximal amplitude) were compared between unlesioned and 6-week chronically spinalized (L1-L2) cats.

Section B

Comparison of Motoneuron Electrical Properties in Unlesioned and Chronic Spinal Preparations

Analysis of Motoneuron Membrane Properties

After motoneuron impalement and antidromic identification, 2-3 minutes were given for the cell to stabilize. The current required to just evoke an action potential using 0.5 ms current pulses, the short-pulse current threshold (SPCT), was then determined and used as a measure of impalement stability (Gustafsson & Pinter, 1984b). SPCT and the resulting action potential height were determined several times throughout the recording period, always bracketing other electrical measurements. Capacity compensation was carefully adjusted to ensure accurate estimates of action potential height. Only those electrical properties within a single neuron where SPCT remained relatively constant throughout the recording procedure (ie. changed by < 10%) were considered acceptable and, as a result, many motoneurons impaled were excluded from this section of the study.

Rheobase current was determined using 50 ms current pulses. The voltage deflection between rest and firing level (threshold voltage, V_{Th}) was measured from multi-sweep photographs of oscilloscope traces (Fig. 9E,F). In such a measure it was important to ensure that the electrode was properly balanced and did not polarize during current injection. Electrode polarization was infrequent, occurring only in those motoneurons requiring large rheobase currents. Because such measurements were discarded, V_{Th} data may be biased by a selective under-representation of high rheobase current motoneurons. Evidence of electrode polarization occurred in ≈ 12% of the motoneurons in both preparations.

Passive motoneuron membrane properties were estimated by analysis of the voltage transient produced by .5 ms, 5-20 nA hyperpolarizing current pulses. The magnitude of the current pulse was adjusted so that peak voltage deflections were usually between 2 and 3 mV. If, after data collection, the electrode displayed an extracellular time constant that

could contaminate the intracellularly measured voltage transient, the data were discarded. The voltage transients were digitized at 40 μs between samples and averaged on-line (256 responses) (Fig. 9B). Motoneuron membrane time constant (τ_m) was measured from the decay of the averaged voltage transient plotted semilogarithmically using a peeling technique (Rall, 1969) (see Figure 9C,D). Cursors were placed by eye on a linear portion of the data and linear regression used to determine the slope of the longest exponential decay. A second and earlier time constant, the equalizing time constant (τ_1) was "peeled" by subtraction of the earlier data points from the interpolated membrane time constant slope. Electrotonic length (L) was calculated by the formula (Rall, 1969):

$$L = \frac{\pi}{\sqrt{(\tau_m/\tau_1 - 1)}} \qquad (1)$$

Total cell capacitance (T_{cap}) is given by (Gustafsson & Pinter, 1984a):

$$T_{cap} = \frac{\tau m * L}{R_{in} * \tanh(L)} \qquad (2)$$

and is used as an estimate of cell surface area (see discussion in Gustafsson & Pinter, 1984a).

One problem arising in the measurement of motoneuron membrane properties is the presence of a voltage-dependent membrane conductance, the SAG conductance, which is activated by small voltage deflections from rest (Ito & Oshima, 1965; Nelson and Frank, 1967). SAG processes probably produce the overshoot of the AHP (Gustafsson & Pinter, 1984c) and can be seen as a sag in the voltage response during, and an overshoot following the long duration current pulse injections used to measure R_{in} and τ_m (Ito and Oshima, 1965; Burke and ten Bruggencate, 1971; Nelson and Lux, 1970; Gustafsson and Pinter, 1984a; Zengel et al., 1985; Rose and Dagum, 1988). The presence of a SAG process can also be seen on a semilogarithmic plot of the voltage decay from brief current pulses (0.5 ms) (compare Fig. 9C

with 9D) (see also Gustafsson and Pinter, 1984a). SAG has been shown to cause an underestimate of both τ_m and R_{in} (Burke and TENBruggencate, 1971; Zengel et al., 1985) without substantially affecting the calculation of L (Gustafsson & Pinter, 1984a; Rose & Dagum, 1988). Considering that SAG may be a time- and voltage-dependent process (Nelson and Lux, 1970; Gustafsson and Pinter, 1984a; Rose and Dagum, 1988) small-amplitude short-duration current pulses were used in an attempt to reduce the development of the SAG process. In most of the semilogarithmic plots there was no deviation from a straight line slope of τ_m at the end of the voltage decay.

Input resistance (R_{in}) was calculated in two ways. First, input resistance was calculated from the peak voltage deflection resulting from a 1-2 nA, 50 ms, hyperpolarizing current pulse (R_{inL}) (averaged: 64 responses) (Fig. 1A). Secondly, input resistance (R_{inS}) was calculated by integration of the voltage transient and division of its area by the area under the injected current pulse's trajectory (Barret and Barret, 1976; Carlen and Durand, 1981). Since the rising phase of the voltage transient was contaminated by stimulus artefact (Fig. 1B), an estimate of this portion of the integral was made by assuming that the rising voltage transient slope was the hypotenuse of a right-angled triangle whose height (peak transient voltage deflection) and base (current duration) were known. The area of this triangle was added to the area of the voltage transient occurring after 0.5 ms (current pulse duration). Since the rising voltage transient is probably more like a two exponential (τ_m and τ_1) charging of the motoneuron membrane than a straight line, the triangular estimate will underestimate the true area of the early portion of the voltage transient. To evaluate the seriousness of this error, a 10 compartment Rall model (Rall, 1964; 1967) simulation of soma current pulse injection was carried out and the actual area (two exponential) and triangular estimate of the area compared. Using mean values of motoneuron

electrical properties to obtain compartmental values, the difference between total voltage transient area made with the early portion being a double exponential or a triangle was less than 5%. Because the error is small, the triangular area of the early transient was used in all R_{inS} calculations.

One advantage of using the short pulse voltage integral method for estimating cell input resistance (R_{inS}, see Methods) is that it ensures that all passive membrane properties (R_{in}, τ_m and L) are obtained under identical recording conditions.

Afterhyperpolarization (AHP) duration and amplitude were measured following action potentials evoked by supra-threshold .5 ms current pulses. AHP duration was measured from the onset of the spike to the return of membrane potential to baseline from the average of 64 responses. AHP peak amplitude and duration of half decay from peak AHP amplitude (AHP 1/2 decay time) are also reported.

Section C

Relating Changes in Ia EPSPs to Membrane Electrical Properties

The third section combines data obtained from Section A for Ia EPSPs with those from Section B for motoneuron membrane properties in the same population of motoneurons. In this section, motoneurons were divided into 3 groups that approximate the major motor-unit types by a method utilizing membrane input resistance and rheobase (Zengel et al., 1985). Motoneuron penetrations having action potential heights ≥ 60 mV were included in this part of the analysis, but the large majority of motoneurons (94%) had action potential heights ≥ 70 mV (with 70% ≥ 80 mV). This included "homonymous" EPSPs evoked at 1.2 times threshold (T) as well as

heteronymous EPSPs evoked at 2T (Section A).

Since mean "homonymous" EPSP amplitude, risetime and half-width differ slightly between motoneuron species in both unlesioned and chronic spinal preparations (Results of Section A) there is the possibility that an over- or undersampling of a particular motoneuron species in either preparation might produce a sampling bias when the preparations are compared according to presumed motor-unit type. However, each preparation had the same approximate proportional composition of motoneuron species (see Table 9) thereby preventing this possibility. Also, the heteronymous EPSP amplitudes of MG and LG motoneurons were combined for the presumed type comparison. The pooling of these values in the present analysis did not create a sampling bias since the mean heteronymous EPSP amplitudes within MG and LG motoneurons were similar when compared in either chronic spinal or unlesioned preparations.

Unless otherwise stated, all statistical comparisons were made using a Student's t-test.

RESULTS

Section A

Comparison of Ia EPSPs in Unlesioned and Chronic Spinal Preparations

I. Sample

Composite Ia EPSPs were recorded from the following sample. In unlesioned preparations there were 65 MG, 48 LG, 15 SOL, and 31 PL motoneurons for a total of 159 motoneurons in 15 cats; the corresponding numbers in spinal preparations were 68, 44, 19, and 43 for a total of 174 motoneurons in 12 cats. All motoneurons were antidromically identified. Only cells with action potential heights greater than 60 mV were accepted. Such low values were rarely encountered; mean action potential heights were 82.0 ± 9.9 mV (median 83 mV) in unlesioned and 82.6 ± 10.2 mV (median 84 mV) in chronic spinal preparations. Mean resting membrane potentials were identical in unlesioned (66.7 ± 8.8 mV) and chronic spinal (66.2 ± 8.5 mV) preparations.

For reasons outlined in Methods, it was important to examine Ia EPSPs at low stimulation strengths and 1.2T was chosen as the standard test strength. This approach allowed a comparison between the chronic spinal and control populations using a large number of observations at the same stimulation intensity. These results, therefore, were obtained for the most part with selective stimulation of low threshold group I afferents. Values in Table 1 at other stimulation strengths (1.1 and 1.4T) were usually derived from the same motoneurons in which the 1.2T data were obtained.

II. The composite Ia EPSP

Details of the shape and size of sub-maximal composite Ia EPSPs have not been reported before; it is important to document the relation between EPSP shape and stimulation intensity. Examples of low threshold evoked composite EPSPs are presented in Fig. 1. Panels A to D are from an MG motoneuron and show both raw (A) and amplitude-normalized (B,C) averaged records of the homonymous EPSP evoked at stimulation strengths of 1.1, 1.2, and 1.4T. Fig. 1A illustrates the amplitude increase with increasing stimulation strength. In Fig. 1B, amplitudes of EPSPs evoked at 1.1 and 1.4 T have been normalized to the 1.2T EPSP height and the traces superimposed; note the striking similarity of EPSP shape at different thresholds. This similarity was common in motoneurons sampled in both preparations. Closer examination of Fig. 1B reveals a small change in the latency of EPSPs evoked at different stimulation strengths, with higher stimulation strengths evoking an EPSP sooner. As stimulation intensity is increased, the activation time of low threshold nerve fibers will decrease resulting in an earlier arrival at the spinal cord. This phenomenon may have been somewhat exacerbated by our use of 200 μs stimulus pulse widths and made evident by the fast digitizing rates (40 μs) used for averaging. In Fig. 1C the normalized EPSP traces have been shifted slightly horizontally in order to superimpose the rising phases of the EPSPs. Shifts of around 80-120 μs were usually sufficient to align the rising phases of the amplitude normalized EPSPs.

While similar EPSP shapes at different thresholds were predominant, many composite EPSP risetimes were also found to decrease or increase as stimulus intensity increased. In Fig. 1E, the rising phase of the EPSP is longer at the lower stimulation strength (1.1T) as can be seen in the amplitude-normalized superimposed traces (lower pair). In Fig. 1F, the larger EPSP evoked at 1.4T has a slower rising phase than the smaller EPSP. No attempt was made to quantify variations in EPSP risetimes within

single motoneurons at various thresholds or to explore those EPSPs evoked at higher stimulation intensities. As mentioned in Methods, increasing stimulation intensities should recruit inhibitory spinal pathways which would hasten the decay phase of the EPSP. While the decay at 1.4T stimulation was often the same as lower strength EPSP decay (Fig. 1C and E) more rapid EPSP decays were dominant (Fig. 1F). Fig. 1D shows the derivative of the EPSP with respect to time and will be discussed later.

Unless otherwise stated, comparisons of "homonymous" Ia EPSPs between preparations refer to the 1.2T EPSP. The primary reasons for presenting 1.1 and 1.4T EPSP data as well (Table 1) are twofold. First, they show that mean EPSP shape is usually similar regardless of the stimulus strengths tested even though considerable differences can be seen within some motoneurons (Fig. 1E,F). Second, it also shows some instances where EPSP shape is sensitive to stimulus strength, suggesting that factors covarying with stimulus strength like Ia axon diameter, may have differential effects on EPSP shape.

III. Composite Ia EPSP amplitude in spinal and unlesioned preparations

"Homonymous" EPSP amplitudes were compared between the chronic spinal and unlesioned preparations as shown in Table 1, left column. The most striking difference in the size of EPSPs was seen in LG motoneurons where in unlesioned animals there were 12 of 48 LG motoneurons where "homonymous" LGS EPSPs evoked at 1.2T were $\leq$ 200 μV; such small EPSPs were never encountered in the chronic spinal animals (Fig. 3B). These low amplitude values were found in 4 of 15 animals. Since six of these 12 LG motoneurons were in a single cat it is possible that peripheral nerve damage contributed to this high incidence. In order to demonstrate that afferent damage is an unlikely explanation, Fig. 2 illustrates EPSPs from four motoneurons in this experiment. Panel A is a SOL motoneuron showing

EPSPs produced by 1.2 and 1.4T stimulation of the LGS nerve. In the next cell penetrated, an LG (Fig. 2B) LGS stimulation produced only minimal EPSPs at 1.2 and 1.8T. This same cell had substantial heteronymous EPSPs from MG afferents which also illustrates why antidromic identification of LG motoneurons in these experiments was essential (see Methods). The LGS-evoked EPSPs in the LG motoneuron in panel C and in the MG motoneuron in panel D were recorded soon afterwards indicating that damage of the LGS nerve is an unlikely cause of this phenomenon. While it is possible that only the LG afferents were damaged in the LGS nerve, the fact that LG and SOL branches were left unseparated makes it unlikely that selective damage to LG afferents occurred in all four experiments where very small LG EPSPs were seen in some cells. There were also four instances in unlesioned animals where heteronymous 2T stimulation evoked EPSPs of amplitude $\leq$ 200 μV; three of these were evoked by MG afferents in LG motoneurons. One PL cell in unlesioned and two in chronic spinal preparations also had homonymous EPSPs less than 200 μV at 1.2T.

Notches on the rising phase of Ia composite EPSPs were seen occasionally in both unlesioned and chronic spinal cats; an example is shown in Fig. 2C. Composite EPSPs with rising phase notches were seen in PL, LG, and MG motoneurons from stimulation of both heteronymous and homonymous afferents. The short latency of these notches (< 1 ms) is similar to that of the notches or double peaks seen in unitary EPSPs (Mendell & Henneman, 1971; Munson & Sypert, 1979) making it unlikely that they were due to a disynaptic event. In the case of unitary EPSPs these have been attributed to a particular Ia afferent having synapses at two distinct electrotonic distances from the soma.

Calculation of mean EPSP amplitude in samples containing EPSPs smaller than 200μV was done by assigning each EPSP a value of 200 μV. In Table 1A where data are pooled without regard to motoneuron species, chronic spinal

EPSP amplitudes evoked at 1.2T were significantly larger than those in unlesioned controls. The percentage increase due to spinalization at 1.2T (expressed as percent change from the unlesioned value) was 16% ($p < .05$) when EPSPs $\leq$ 200 μV were excluded from the comparison and 26% when these EPSPs were included and assigned a value of 200 μV. Fig. 3A shows the frequency distribution of EPSPs evoked at 1.2T in all motoneurons. The increase in mean EPSP amplitude in the chronic spinal preparation seems to come from an increase in EPSPs of around 2 mV amplitude rather than an increased number of larger EPSPs. Note also the decreased number of the smallest amplitude EPSPs in the chronic spinal preparation.

Although the pooled data in Table 1A show an overall increase in chronic spinal EPSP amplitude, in the individual motoneuron species these increases were only found in LG motoneurons (at 1.2T). However, if data from SOL and PL are pooled, a mean amplitude of 2.52 mV at 1.2T is obtained in chronic spinal animals which is significantly larger ($p < .05$) than the pooled mean of 1.99 mV in unlesioned animals. Thus it is likely that the smaller sample sizes and large standard deviations obscure the significance of increases in PL and SOL motoneurons. In MG, larger sample sizes and the similarity of mean values in unlesioned and chronic spinal preparations are strong evidence for a lack of change in MG amplitudes as noted before (Mayer et al., 1984), stressing its individuality among the four motoneuron species examined. Fig. 3B and C show the distribution of EPSP amplitudes evoked at 1.2T in MG and LG motoneurons. In MG (3B) there appears to be a loss of the larger EPSPs and an increase in mid-range values resulting in an unchanged mean amplitude value in chronic spinal preparations. In LG motoneurons (3C) there were no EPSPs smaller than 500 μV in chronic spinal but 12 in unlesioned preparations. PL and SOL EPSP amplitude distributions (not illustrated) were similar in both preparations.

Chronic spinalization also resulted in a significant increase in heteronymous 2T composite EPSP amplitudes evoked by stimulation of MG or LGS afferents and recorded in LG or MG motoneurons respectively (Table 2). Four neurons in unlesioned preparations without detectable heteronymous EPSPs were excluded from the data presented in Table 2 but are included in Figure 4. Heteronymous EPSP amplitudes increased by 90% in MG and 76% in LG motoneurons (Table 2). Increased heteronymous EPSPs in MG have been reported before (Munson et al., 1986) but only at a shorter chronic spinal interval (1-3 weeks). At intervals similar to or longer than the 6 week one employed here, both Munson et al. (1986) and Mayer et al. (1984) found no significant increase in LGS-evoked heteronymous EPSPs in MG motoneurons (see Discussion). The increase in heteronymous EPSPs in the present study was characterized by an increase in large value EPSPs as shown in Fig. 4A. Heteronymous EPSPs in SOL motoneurons and those evoked by stimulation of the PL nerve were not investigated.

In order to explore the relationship between heteronymous and "homonymous" EPSPs within single motoneurons, regression statistics were calculated for their amplitudes. Calculation of the regression of heteronymous EPSP amplitude against "homonymous" amplitude produced a significant correlation in both preparations ($r=0.61$ for unlesioned and 0.62 for chronic spinal). Thus for LG and MG motoneurons, larger "homonymous" EPSPs tended to be associated with larger heteronymous EPSPs.

Experiment-to-experiment variability in Ia EPSP amplitudes has been noted before (Munson et al., 1986) and Fig. 5 illustrates the great variability in low threshold EPSP amplitude recorded in both preparations in the present material. Fig. 5 shows mean amplitudes and standard deviations of 1.2T-evoked EPSPs recorded in several experiments in unlesioned (5A) and chronic spinal (5B) cats. For comparison, the horizontal line in Fig. 5A shows the mean value for all EPSPs recorded in

spinal preparations and that for unlesioned animals in 5B. Clearly, single experiments were not often representative of mean values, and EPSP amplitude variability occurred despite the experimental conditions' being as similar as possible in all experiments and all lesioned animals' being examined at one post-operative interval (six weeks) and one transection level (L1-L2). Although casual inspection of Fig. 5 suggests that there may be less variability in homonymous EPSP amplitudes in MG than other species, this was not explored.

In summary, in 6 week spinal cats, pooled "homonymous" EPSP amplitudes evoked by low threshold electrical stimulation were increased significantly over those in unlesioned controls (Table 1A). This was also the case for heteronymous effects evoked at 2T in MG and LG motoneurons (Table 2).

IV. Decrease in EPSP risetime in chronic spinal preparations

The 10 to 90% risetimes of composite Ia EPSPs were compared among the four ankle extensors and among preparations (Table 1, middle). In both chronic spinal and unlesioned preparations, the 1.2T mean EPSP risetime increased in the order MG < LG < PL < SOL. After spinalization, mean EPSP risetimes became more similar among motoneuron species with the difference between the shortest (MG) and longest (SOL) mean risetime at 1.2T being 0.48 ms in unlesioned and 0.21 ms in chronic spinal preparations.

Note that in chronic spinal animals in individual motoneuron species, EPSP risetimes were the same at different thresholds of nerve stimulation while in unlesioned preparations, risetimes in both PL and MG motoneurons were longest at the lowest stimulus intensities; by 1.4T they were significantly shortened ($p < .05$).

Table 1A shows that in all motoneuron species the 1.2T composite EPSP risetimes were significantly decreased in chronic spinal preparations. At 1.2T the mean risetime of EPSPs in unlesioned preparations (Table 1A) decreased 21% from 0.71 ms to 0.56 ms in chronic spinal ($p < .001$). Mean chronic spinal EPSP risetimes were reduced in all motoneuron species and at all thresholds tested.

Fig. 6 contains histograms of the 1.2T EPSP risetimes and shows that the decrease in mean risetime in spinal animals was associated with a loss of the longer risetimes in all motoneuron species. Note that several risetimes in SOL motoneurons and one in PL (Fig. 6C and D) were shorter in spinal cats than the shortest risetime in unlesioned cats. Heteronymous EPSP risetimes (MG onto LG; LGS onto MG) were also reduced significantly in chronic spinal preparations (Table 2; Fig. 4B). In LG and MG motoneurons in chronic spinal animals, both heteronymous and "homonymous" composite EPSP risetimes decreased to similar mean values. Fig 4B presents the distributions of heteronymous risetimes and shows that in chronic spinals, there was only one EPSP with a risetime greater than 0.7 ms whereas approximately half of the EPSP risetimes in unlesioned preparations were greater than 0.7 ms.

For a period after chronic L4 spinalization, there is an increased incidence of large-amplitude short-risetime unitary Ia EPSPs (Nelson & Mendell, 1979). The present material similarly shows an increased number of short-risetime composite EPSPs with larger amplitudes (Fig. 7). For instance, as compared to EPSPs from unlesioned cats, the percent increase in EPSP amplitude in chronic spina animals with EPSP risetimes between 0.2 and 0.4 ms was 141% while the longer duration EPSP risetimes increased by only 23%.

In addition to measurements of 10 - 90% risetimes of Ia EPSPs, the

maximum rate of EPSP rise of the 1.2T EPSP was obtained from the derivative of the EPSP with respect to time (Fig. 1D). For representative samples of motoneurons, the mean maximum dV/dt of "homonymous" EPSPs was 5.59 V/s (n= 56) in the unlesioned animals; in chronic spinal animals this value was 69% greater at 9.44 V/s ($n = 49$; $p < .005$). The mean maximum dV/dt values for the individual motoneuron species increased in the order LG < PL < SOL < MG in both unlesioned and chronic spinal preparations. In all motoneuron species there were significant maximum dv/dt increases in EPSPs from chronic spinal as compared to unlesioned preparations ($p < .05$). Thus a decreased mean risetime was also associated with an increased mean maximum dv/dt. In individual cells, however, the slower risetimes were not necessarily associated with the lower dv/dt values. Since the 10 - 90% risetime represents more of an average rate of rise than the peak dv/dt, it is likely that other measures (for example, 30 - 70% risetime) would show a closer correspondence between maximum derivative and risetime. This was not investigated.

In summary, mean 10% - 90% risetimes of "homonymous" Ia EPSPs in triceps surae and plantaris motoneurons are decreased in the chronic spinal preparation with those in MG changing the least. Chronic spinalization also resulted in a decrease in the mean risetime of heteronymous Ia EPSPs evoked by stimulation of the MG and LGS nerve and recorded in LG and MG motoneurons respectively. While membrane hyperpolarization can decrease EPSP risetime (Coombs et al. 1955, Nelson & Frank 1967; Shapovalov & Kurchavyi, 1974) the similarity of both action potential height and resting membrane potential in unlesioned and chronic spinal preparations (see Sample, p. 36) suggests that the reported risetime differences did not result from the effects of membrane hyperpolarization.

V. Decrease in EPSP half-width in chronic spinal preparations

The mean half-width of composite Ia EPSPs in MG, LG, SOL, and PL motoneurons decreased significantly in chronic spinal preparations (Table 1, right column). In unlesioned preparations, the half-widths of EPSPs in MG and LG were similar and were shorter than those in SOL and PL. The greatest change in EPSP half-width occurred in LG motoneurons at all stimulus strengths tested. Expressed as percentages, the change of the 1.2T EPSP half-width was 46% in LG, about 30% in SOL and PL, and 23% in MG motoneurons. In Fig. 8 the half-widths of EPSPs evoked at 1.2T are plotted against their risetimes. This figure shows that the decrease in mean half-width values is attributable to a shift towards lower values with the shortest occurring in the chronic spinal preparations. This was most obvious in LG motoneurons (Fig. 8B).

In both unlesioned and spinal cats, half-widths tended to shorten as stimulus strength increased (Table 1). Since the number of motoneurons antidromically activated at 1.4T (the highest threshold tested) in this study in both the unlesioned and chronic spinal preparations was similar and quite small, recurrent inhibition is unlikely to be responsible for the shorter half-width values seen as threshold for nerve stimulation is increased. On the other hand, inhibition evoked from Ia and Ib afferents in triceps surae nerves is well documented at low stimulation strengths (Fetz et al., 1979; Jankowska and McCrea, 1983, their Figure 1). The finding of decreased half-widths at higher stimulus strengths in either preparation is, therefore, suggestive of an increase in group I non-reciprocal inhibition (Jankowska et al., 1981) in these motoneurons.

Table 1 also shows that chronic spinalization resulted in a greater percent decrease in EPSP half-width than in risetime. This is partly

attributable to an increase in inhibitory and other conductance mechanisms which have a greater influence on EPSP half-width than risetime.

In both unlesioned and chronic spinal preparations, there was a significant positive relation between EPSP risetime and half-width. Linear regression equations of half-width against risetime for EPSPs evoked at 1.2T and pooled from all motoneuron species were as follows; half-width = 4.53 * risetime + 2.46ms, r = 0.66 for unlesioned; half-width = 6.51 * risetime + 0.3ms, r = 0.62 for chronic spinal). The shape index plots (Rall et al., 1967) in Fig. 8 show the relationship between half-width and risetime in each motoneuron species and illustrates the large variability between any given risetime and half-width, particularly for MG (Fig. 8A). There is, however, a clustering of short risetime and half-width values in chronic spinal preparations and in particular for those EPSPs recorded in LG motoneurons (Fig. 8B).

Section B

Comparison of Motoneuron Electrical Properties in Unlesioned and Chronic Spinal Preparations

I. Sample

Results in this section were obtained from 39 adult female cats in 23 unlesioned and 16 chronic spinal preparations. Unless otherwise stated, all data are from cells with stable impalements and with action potential heights ≥ 80 mV. Table 3A shows that the mean action potential height (88 mV) and resting membrane potential (72 mV) were identical in unlesioned (n=87) and chronic spinal preparations (n=108). Electrical properties from a second group of motoneurons with action potentials 60-79 mV will be presented separately in Table 5. Mean action potential height (71 mV) and resting potential (57 mV) in this latter group were also the same in unlesioned (n=65) and chronic spinal (n=63) preparations. In most cases those data were obtained from the same cells as those of Section A of this thesis.

II. Passive membrane properties

A comparison of motoneuron input resistance following six week L1-L2 chronic spinal section to values obtained in unlesioned controls shows that there was no significant difference in R_{in} in either the pooled sample of triceps surae and PL motoneurons (Table 3B) or in the individual motoneuron species (Table 4). This is consistent with other reports in MG (Munson et al., 1986) and SOL motoneurons (Cope et al., 1986) in chronic spinal cats and from pooled data in chronic spinal-deafferented cats (Gustafsson et al., 1982).

Table 3B also shows that mean R_{inL} and R_{inS} values were identical in cells with action potentials 80 mV or greater. In Fig. 10, R_{inL} measurements are plotted against R_{inS} values obtained in the same cell. In unlesioned (10A) and chronic spinal (10B) preparations there is a strong correlation (unlesioned r=.95, spinal r=.86) between these two measurements with slopes close to unity (unlesioned =.92, spinal =1.02). Note, however, the increased scatter in the chronic spinal preparation. The similarity in mean values between R_{inS} and R_{inL} within both preparations suggest that SAG conductances, which should affect measurements obtained from long duration current pulses more than short (Gustafsson and Pinter, 1984a) are unlikely to substantially distort R_{inL} measurements in the present study. This is in agreement with previous estimates where the effect of a SAG process on long pulse R_{in} measurements was modelled and found to be minor (Gustafsson and Pinter, 1984a; Rose and Dagum, 1988; but see Zengel et al., 1986).

Mean membrane time constant (τ_m) decreased 17% in chronic spinal motoneurons ($p < .001$, Table 3B). Fig. 11 shows that although the shortest values in either preparation are similar, there is an increased incidence of motoneurons with short τ_m's in the chronic spinal preparation. For example, 21% of the observed τ_m's in unlesioned animals were less than 4.0 ms while in chronic spinal this proportion increased to 43%. Figure 11 also shows that although there is a relation between τ_m and R_{inS} (unlesioned r=.73, spinal = .62) there is considerable scatter so that for a given τ_m, a wide range of R_{inS} is seen. As mentioned in Methods, SAG processes are often visible from voltage records of long duration current pulses (Ito and Oshima, 1965; Zengel et al., 1985) and are detectable by the hastened decay of the semilog plot of voltage transients produced by long (Burke and TENBruggencate, 1971; Zengel et al., 1985; Rose and Dagum, 1988) and short duration currents (Gustafsson and Pinter, 1984a; Fig. 9D). Although in the present sample such occurrences were rare with short

duration currents in unlesioned animals (2 of 71 cases) their incidence in chronic spinal preparations increased to 26 of 91 cases. Since the presence of a SAG conductance may cause an under-estimation of τ_m and R_{inL} (Burke and TENBruggencate, 1971; Zengel et al., 1985; Gustafsson and Pinter, 1984a; Rose and Dagum, 1988) these means were calculated again but excluding motoneurons exhibiting an obvious SAG in the short pulse voltage transients. Mean τ_m and R_{inS} were unchanged by this exclusion in both preparations, suggesting that increased SAG processes, if present in the chronic spinal preparation, are not responsible for the decrease in τ_m. Table 4 shows that mean τ_m was lower in the chronic spinal state in each of the individual motoneuron species. Small sample sizes, however, may have precluded the ability to detect significant differences in some of these cases.

A sample of motoneurons (consisting of LG and MG) was used to compare the difference between estimates of τ_m from voltage transients produced by brief (.5 ms) and long (50 ms) duration current pulses in motoneurons from both preparations (n = 28 in both cases). In both cases a peeling procedure (Rall, 1969) was used to estimate τ_m. It was found that the estimate of τ_m was 9% lower using long current pulses in both preparations. Thus, although brief current pulses may not prevent a contamination of the measurement of passive membrane properties by SAG, it certainly helps reduce it and by a similar amount in motoneurons from both preparations. This observation is consistent with the view that SAG is a time- and voltage-dependent process implying that a sufficiently brief current pulse should limit its activation (Nelson and Lux, 1970; Gustafsson and Pinter, 1984a).

Neither mean electrotonic length (L, Table 3B) nor the range and distribution of L (ordinates, Fig. 12) were changed following chronic spinalization. Table 3B shows the reduction in τ_1 that accounts for the

unchanged L when there was a 17% decrease in τ_m (equation 1). These findings contrast with the reduction of L observed in motoneurons from cats in a preparation with both a 3 week chronic spinal transection and rhizotomy (Gustafsson et. al., 1982).

As discussed by Gustafsson and Pinter (1984a) for an equivalent cylinder model of the motoneuron with length l and diameter d:

$$L \propto 1/\sqrt{d} * 1/\sqrt{\tau m} \qquad (3)$$

and that given a constant geometry (i.e. constant $1/\sqrt{d}$), the regression of L and $1/\sqrt{\tau_m}$ will pass through the origin. As shown here (Fig. 12A) and by Gustafsson & Pinter (1984a), L and $1/\sqrt{\tau_m}$ are weakly related ($r = .50$, Fig. 12A) but the intercept deviates significantly from the origin at .88. As discussed previously (Gustafsson and Pinter, 1984a) a regression line deviating from an intercept at the origin suggests a variation in the geometrical structure of motoneurons with different τ_m's as, for instance, with motoneuron type (Cullheim et al., 1987). In motoneurons from chronic spinal animals, there is no relation between L and $1/\sqrt{\tau_m}$ (Fig 12B) suggesting, perhaps, that motoneuron geometry has altered to assume an even greater importance in the determination of L.

Total cell capacitance (T_{Cap}) was calculated according to equation 2 and is believed to be an estimate of cell surface area (Gustafsson & Pinter, 1984). Table 3B shows that T_{Cap} was reduced 11% in the chronic spinal preparation ($p < .05$). Accordingly, there may be a slight shrinkage of the motoneuron following spinalization as was suggested for chronic spinal-deafferented motoneurons by Gustafsson et al. (1982).

III. Threshold properties

Mean rheobase current, as assessed by long (50 ms) current pulses, increased by 14%, although not significantly, in the chronic spinal

preparation (Table 3C). This agrees with other reports of a non-significant rheobase increase in the MG motoneuron pool (Munson et al., 1986) and in motoneurons from chronic spinal-deafferented preparations (Gustafsson et al., 1982) but differs from a reported significant increase after chronic spinalization in SOL motoneurons (Cope et al., 1986). Previous studies have shown that in MG the proportion of motoneurons innervating type FR muscle fibers decreases in the chronic spinal state with a shift to "faster" motor-unit types (FI and FF) (Mayer et al., 1984; Munson et al., 1986). While mechanical typing of motoneurons was not attempted in the present study, the ratio of rheobase/R_{inL} has been shown to be a good predictor of motoneuron type in both unlesioned (Zengel et al.) and chronic spinal (Munson et al., 1986) cats. Since type FF units tend to have higher rheobase currents (Fleshman et al., 1981), an increased number of these units could increase the mean (population) rheobase current, but not significantly if only a small proportion of the motoneuron pool changed. The slight increase in rheobase/R_{inL} ratio in Table 3C is in keeping with previous findings on the increase in the number of faster motoneurons. Table 4 shows that larger mean rheobase/R_{in} values were found in all motoneuron species; however, except for PL, these increases were not significant. The greater change occurring in PL (Table 4) is interesting in view of its relatively larger number of fatigue-resistant motor-unit types compared to the other ankle extensors in the unlesioned state (Emonét-Denand et al., 1988). Further relations between motoneurons tentatively classified according to motor-unit type make up the third section of this thesis.

A second measure of threshold current, the short duration current pulse threshold (SPCT) was 22% higher in the population of motoneurons from chronic spinal cats ($p < .001$; Table 3C). The distribution of SPCT values can be seen along the ordinate in Fig. 13B; note the increased incidence of SPCT values above 60 nA in the spinal preparation. Use of an equivalent

cylinder neuron model, it has been shown that SPCT is unaffected by the range of τ_m found in motoneurons but increases with increases in motoneuron surface area (estimated by T_{Cap}), electrotonic structure, and threshold voltage (V_{Th}) (Gustafsson and Pinter, 1984b). Since L was unchanged and T_{Cap} decreased, the increases in chronic spinal SPCT are best explained by an increased V_{Th}.

Threshold voltage (V_{Th}) was measured directly and is plotted against rheobase current in Fig. 13A. As shown in Table 3C, and in support of an increased SPCT, there was a significant increase in measured V_{Th} in the chronic spinal preparation ($p < .01$). Note the tendency for motoneurons to have higher V_{Th} values particularly at the higher range of rheobase currents (> 20 nA) but not at the lowest in Fig. 13A. As a further indication of the shift to higher V_{Th} values in the chronic spinal population, only 9% of the unlesioned values were above 15 mV, while in chronic spinal cats this proportion increased to 29%. An examination of individual motoneuron species (Table 4) shows that the most significant increase occurred in MG. Mean values were higher in chronic spinal than unlesioned animals in both LG and PL but not SOL. Measured V_{Th} and calculated VTh (R_{inL} * rheobase) values can be compared from Table 3C. Note that they were essentially the same in unlesioned preparations. In chronic spinals, however, measured V_{Th} was significantly higher than calculated ($p < .05$) suggesting an increased incidence or magnitude of subthreshold rectification processes such as anomalous rectification (Nelson and Frank, 1967).

In the absence of subthreshold rectification, V_{Th} should be the product of rheobase current and R_{in}. In the present material, calculated V_{Th} was the same in both preparations (Table 3C). This is in contrast to other reports of an increased calculated V_{Th} after chronic spinal lesions (Gustafsson et al., 1982; Cope et al., 1986). While I am uncertain of

the explanation for this discrepancy, this present study differs in that only motoneurons with action potential heights ≥80 mV were chosen, and in that the comparison between chronic spinal and unlesioned was made in populations demonstrated to have the same action potential size and resting membrane potential (Table 3A).

Fig 14A shows that the decrease in chronic spinal τ_m was evident over the entire rheobase range. Although there is no obvious relationship between τ_m and V_{Th} in either preparation, Fig. 14B illustrates the tendency for a disappearance of chronic spinal motoneurons with large τ_m and low V_{Th} values concomitant with an increased number of short τ_m and large V_{Th} values. Using a 15 mV V_{Th} to divide the data into low and high V_{Th} groups shows that lower-V_{Th} motoneurons from chronic spinals had mean τ_m values 18% lower than in unlesioned preparation. For those motoneurons with larger V_{Th}, the mean τ_m was the same in both preparations.

IV. Afterhyperpolarization

Previous investigations in chronic spinal animals have found AHP durations to be shorter in SOL (Czeh et. al., 1978; Cope et al. 1986) and MG motoneurons (Munson et al., 1986). The present data (Table 3C) also show that both the duration and the half decay time of AHP are shorter in motoneurons from chronic spinal animals ($p < .05$) and that these decreases occur in all motoneuron species, particularly SOL (Table 4). Fig. 15 shows that the decrease in AHP duration is characterized by an increased number of motoneurons with short AHP durations, the shortest ones occurring in motoneurons from chronic spinal cats. Further, within individual neurons, short chronic spinal AHP durations were often associated with lower τ_m's (Fig. 15). Decreased AHP durations are consistent with either a shift towards faster motor-unit types (Mayer et

al., 1984; Munson et al., 1986) or an increased SAG conductance (Gustafsson and Pinter, 1984c). Although the difference was not statistically significant, motoneurons from chronic spinal animals had a 12% greater mean peak AHP voltage, even though resting potential and spike height were identical in both preparations. While the reduction in AHP duration but not amplitude could be accounted for by a change in the time course of AHP conductance, no estimates of conductance during the AHP were made.

V. Conduction velocity

Since conduction velocity should not be affected by the quality of cell penetration, these data were pooled from all motoneurons with action potentials ≥ 60 mV. Conduction velocity was not significantly different between unlesioned and spinal preparations when values from all motoneurons were pooled (unlesioned 79.5 ±9.6 m/s; chronic spinal 82.1 ±13.8 m/s). However, when individual motoneuron species were analyzed separately, conduction velocity was significantly lower in the population of LG and MG motoneurons from chronic spinal animals (from 88.4 ±10.1 to 80.5 ±9.5 m/s in LG and from 87.5 ±12.7 to 80.4 ±9.4 m/s in MG; $p < .05$) PL was unchanged (mean = 78 m/s in unlesioned and 81 m/s in chronic spinal) while in SOL motoneurons conduction velocity was increased (from 62.3 ±7.7 to 69.3 ±5.5 m/s; $p < .05$). Both the decreased conduction velocity in MG motoneurons (Munson et al., 1986) and the increased conduction velocity in SOL motoneurons (Cope et al., 1986) has been noted before in chronic spinal animals.

VI. The importance of "healthy" impalements

Table 5 presents data similar to those in Table 3 except that

measurements are presented from motoneurons with action potential heights between 60 and 80 mV instead of ≥ 80 mV as in Table 3. Thus Table 5 represents a population of motoneurons with a mean action potential height that is 17 mV lower than the population of Table 3. Presumably, the decreased spike amplitude reflects a poorer intracellular impalement and a considerable leak conductance resulting in estimates of membrane properties which differ from those in a "healthier" population (Table 3). Others have discussed the effects of cell health on experimentally measured parameters such as V_{Th} (Gustafsson & Pinter, 1984b) and effects on passive membrane properties have been estimated theoretically (Jack, 1979; Gustafsson and Pinter, 1984a). A greater leak conductance will reduce the estimated R_{in} values when R_{in} is determined solely by passive membrane properties (Gustafsson and Pinter, 1984a). A comparison of Table 3B to Table 5B shows that whereas there are slight differences in R_{inS}, R_{inL} actually increases in "unhealthy" penetrations. This suggests that a rectification process more than counters the expected reduction in R_{in} produced by membrane injury (Gustafsson and Pinter, 1984a). The different R_{in} values between long and short pulse measurements (Table 5B) further support the notion that long duration current injections produce voltage deflections that alter conductances that are not as affected by brief pulses. Estimates of τ_m do not appear to be altered in either sample (compare Table 3B with 5B) yet theoretical estimates based on a purely passive motoneuron membrane would predict a decrease (Gustafsson and Pinter, 1984a). AHP duration becomes larger (compare Table 3D with 5D) possibly because of a reduction in the driving force of the SAG conductance (Ito and Oshima, 1965); a rectification process like SAG may be lost or masked by a change in the driving potential underlying the SAG current in unhealthy motoneurons. SPCT is considerably lowered due to the concomitant decrease in V_{Th} (compare Table 3C with 5C). Whereas resting membrane potential decreases by ≈ 13 mV, $V_{Th,}$ measured from the long duration current pulse duration, is decreased only by ≈ 4 mV indicating

the presence of additional processes altering V_{Th} other than resting membrane potential (e.g. accommodation). Motoneurons can be classified into three groups based on the quotient of rheobase and R_{in} (Zengel et al., 1985) with larger-ratio values being associated with "fast" motor units. A comparison of Table 3C to 5C suggests that this criteria for distinguishing motor-unit types is sensitive to cell health and would result a lesser proportion of neurons classified as "fast" in a motoneuron population with relatively greater impalement injuries. This observation suggests that the use of rheo/R_{inL} to divide motoneurons into 3 groups that approximate motor-unit type is sensitive to the health of the motoneuron when these measurements are taken. Lastly, AHP peak voltage is increased with a greater displacement from the K+ equilibrium potential (compare 3D to 5D).

More important in the present context, however, is the fact that significant differences between unlesioned and chronic spinal preparations in Table 3 disappeared in a population of cells with less satisfactory impalements (Table 5). Thus recordings from deteriorated cells can hide the existence of changes between the preparation types, leading to potentially erroneous conclusions. The extent to which even the data in Table 3 are affected by impalement injury is of course unknown, but the mean resting potential in Table 3A is only 4 mV less than the best published data from motoneurons (Gustafsson & Pinter, 1984).

Section C

Relating Changes in Ia EPSPs to Membrane Electrical Properties

I. Sample

The first two sections of this thesis have examined Ia EPSPs and motoneuron electrical properties either collectively or partitioned according to the muscles they innervate. This section relies on motoneuron membrane electrical criteria to divide motoneurons from all ankle extensor muscles examined into three groups that approximate motor-unit types. The present data are from a subset of motoneurons analyzed in Sections A and B for which measurements of both membrane property and composite EPSPs were available. The unlesioned population was composed of 124 motoneurons from 19 female cats: 49 MG, 39 LG, 21 PL, 9 SOL, and 6 LGS. The chronic spinal population was composed of 141 motoneurons from 15 female cats: 55 MG, 38 LG, 33 PL, 9 SOL, and 6 LGS. In most cases, electrically evoked Ia EPSPs and electrical properties were obtained from the same motoneurons.

II. Divisions of motoneurons into 3 groups that approximate motor-unit type

In MG motoneurons from barbiturate anesthetized cats, the ratio of rheobase to R_{in} reasonably predicts motor-unit type in both unlesioned (Zengel et al., 1985) and chronic spinalized preparations (Munson et al., 1986). Figure 16 depicts this relationship in ankle extensor motoneurons from both preparations. The two lines emanating from the origin represent slopes of 7 and 18 nA/MΩ that should according to those studies, approximately separate motoneurons into the 3 major motor-unit types: slow (S) fast fatigue-resistant (FR) and fast fatigable (FF) and the groups of motoneurons separated by these lines will hitherto be described as

"presumed" S, "presumed" FR, and "presumed" FF motoneuron types respectively. Note that the relationship between rheobase and R_{in} within single motoneurons is similar in both unlesioned and chronic spinal preparations.

Table 6 presents the percentage of each presumed motoneuron type in both preparations for LG, PL, and MG motoneuron species, either collectively or separately. As compared to the unlesioned distribution of motor-unit types, the chronic spinal population is characterized by having an overall increased percentage of presumed FF motoneurons and a corresponding decrease in the percentage of presumed S motoneurons. Examination of the presumed type distribution of the separate motoneuron species shows that in general these changes occur similarly in all 3 species. Note however, that the greatest relative increase in presumed FR motoneurons occurs in LG. The lower section of Table 6 shows that the distribution of presumed motoneuron types for MG in the present unlesioned and chronic spinal sample populations corresponds well with previous distributions obtained by mechanical typing of MG motoneurons (Mayer et al., 1984; Munson et al., 1986). This supports the presumption that the present method of "electrical" typing of motoneurons reflects the actual type distribution (however, see Discussion).

Whereas all soleus motoneurons are classified as "slow" as expected in unlesioned preparations (Burke et al., 1974) one soleus motoneuron (out of 9), is classified as presumed FR in chronic spinal preparations, consistent with the notion of a conversion of some motor-unit contractile properties into FR types (Cope et al., 1986; Alaimo et al., 1984).

III. Comparison of EPSP properties of the 3 presumed motoneuron types

Composite and unitary Ia EPSPs vary in both size and shape among motor-

unit types, with EPSP 10-90% risetime, half-width and amplitude decreasing in the order S > FR > FF (Burke, 1968; Burke, Rymer, and Walsh, 1976; Zengel et al., 1983; Fleshman et al., 1981; Mayer et al, 1984; Munson et al., 1986). This relationship is preserved in chronic spinal preparations for both unitary and composite Ia EPSP amplitude in MG (Mayer et al., 1984; Munson et al., 1986) while EPSP shape has not been previously examined. Table 7 presents mean values for "homonymous" composite EPSP risetime, half-width and amplitude at 1.2T as well as heteronymous 2T risetime and amplitude for the 3 presumed motoneuron types. It can be seen that for both unlesioned and chronic spinal preparations, "homonymous" risetime, half-width and amplitude as well as heteronymous risetime and amplitude decrease in the same order as for mechanically typed motoneurons: presumed S > FR > FF.

IV. Assessment of EPSP changes after chronic spinalization in presumed motor-unit types

Table 7 compares mean EPSP properties between unlesioned and chronic spinal preparations. As compared to unlesioned preparations, motoneurons both from presumed FR and S populations in spinal animals receive EPSPs with significantly shorter mean "homonymous" risetimes and half-widths as well as increased amplitudes. EPSP risetime decreases occurred in the order FR (25%) > S (15%) > FF (2%) as did half-width; FR (31%) > S (24%) > FF (18%). The increases in amplitude are FR (69%) > S (38%) > FF (17%). Thus, after chronic spinalization, the "homonymous" Ia EPSPs in presumed FR motoneurons were changed the most. Presumed S motoneurons underwent similar though smaller changes, while EPSPs in presumed FF motoneurons were unaltered (except for half-width; however, see Discussion). Unlike "homonymous" EPSP changes, heteronymous EPSP risetime and amplitude were altered similarly in all 3 presumed motor-unit types in the chronic spinal preparation. There is an 86% increase in heteronymous EPSP amplitude for

presumed FF motoneurons while presumed S motoneurons increased by 105%. Mean EPSP amplitude for presumed FR motoneurons also increased by 86% but the increase was not statistically significant: the small sample size may have masked the presence of significant differences. Heteronymous risetime increased by 41% for presumed FR, 36% for FF, and 25% for S.

Figure 17 plots the relation of "homonymous" EPSP risetime and half-width, the shape index plot (Rall et al., 1967) for the 3 presumed motor-unit types in both unlesioned and chronic spinal preparations. Note that for all plots, the correlation coefficients are low, ranging from an r of 0.41 (in unlesioned presumed FR) to 0.55 (in chronic spinal presumed FR) (see figure legend). Presumed FF motoneurons (17A) have a similar distribution in both preparations with the exception that the shortest half-width values occur in chronic spinal preparations. For presumed FR motoneurons (17B) the chronic spinal preparation is characterized by the appearance of motoneurons with both short risetime and half-width values. In presumed S (17C) there is an absence of motoneurons from chronic spinal preparations with longer risetime and half-width values. Thus chronic spinalization appears to produce unique shifts in the distribution of EPSP shape for each presumed motor-unit type.

Figure 18 compares the distribution of "homonymous" EPSP amplitudes between the two types of preparation for each presumed motor-unit type. Note that in all 3 histograms, the chronic spinal preparation has a decreased percentage of motoneurons with EPSPs smaller than 0.5mV. Otherwise, the distribution of presumed FF and S Ia EPSPs is similar in both preparations (18A and 18C respectively). As compared to unlesioned animals, the presumed FR distribution in chronic spinal preparation is characterized by an increased number of larger amplitude EPSPs (18B). For example, in unlesioned preparations, only 8% of presumed FR motoneurons have EPSP amplitudes > 2.0 mV; in chronic spinal preparations this number

is 39%.

Considering there is a tendency for composite EPSPs with shorter risetimes to have larger amplitudes in chronic spinal preparations (Section A) and for both presumed FR and S motoneurons to have mean decreases in risetime and increases in amplitude after spinalization, the relationship between risetime and amplitude was explored in individually typed FR and S motoneurons in both unlesioned and chronic spinal preparations. EPSPs in these motoneuron groups were divided in half by their median risetime values and the mean amplitudes of both short and long risetime EPSPs compared. For both presumed FR and S, short risetime mean EPSP amplitudes were slightly larger (in chronic spinal: 10% and 23% respectively for both motoneuron types) than long risetime EPSPs. Thus, there was a slight tendency for shorter risetime EPSPs to undergo greater amplitude increases.

In summary, the effect of chronic spinalization upon ankle extensor motoneuron "homonymous" Ia EPSPs is not generalized but related to the particular presumed type, with presumed FR motoneurons undergoing the greatest relative changes in "homonymous" EPSP size and shape. Although there is an overall increased percentage of presumed FF motoneurons, their mean "homonymous" Ia EPSP properties are unchanged. In contrast, heteronymous EPSP amplitude and risetime changes were more uniform between the presumed types.

V. Contribution of EPSP amplitude to threshold excitability

One obvious question concerns the extent to which an increased Ia EPSP amplitude could contribute to increased reflexes, especially since threshold voltage (V_{Th}) also increases in the same chronic spinal population of motoneurons (Section B). Included in Table 7 is the ratio

of "homonymous" amplitude to threshold voltage (amp/V_{Th}). This ratio provides a measure of the contribution of a 1.2T Ia EPSP to the threshold depolarization required for firing in individual motoneurons. The presented mean values include only those motoneurons with "homonymous" EPSPs with amplitudes > 200uV (see METHODS, Section A). Note that, as compared to the unlesioned preparation, presumed FR motoneurons from chronic spinal preparations undergo a 62% increase in this ratio (from 13% to 21% of threshold voltage: $p < .01$). In both presumed FF and S amp/V_{Th} remains unchanged.

In both preparations approximately 1/4 of the presumed S motoneurons are soleus motoneurons, and it is possible that these are affected differently than "slow" motoneurons innervating mixed muscles. Separating soleus motoneurons from the mixed muscle presumed S motoneurons shows that soleus motoneurons undergo an approximate 56% amp/Vth increase (from 0.25 to 0.39) as compared to only a 6% increase in mixed nerve "slow" motoneurons (from 0.32 to 0.34) suggesting that slow motor units to the soleus muscle differ from those to mixed muscles and may in fact significantly increase their reflex response to Ia stimuli (if a larger sample size were examined). This difference is interesting considering the known differences in muscle fibre properties between the targets of mixed muscle type S and soleus motoneurons (e.g. differences in twitch contraction time and tetanic tension; see Burke, 1978).

VI. Motoneuron membrane properties

Table 8 provides the mean values of measured motoneuron membrane properties for the 3 presumed motoneuron types. Previous findings suggest that, as one proceeds from FF to FR to S, mean τ_m, R_{in}, and AHP duration increase while CV, rheobase, V_{Th}, and cell surface area decrease (Burke, 1967; Burke and TENBruggencate, 1971; Fleshman et al., 1981b; Zengel et

al., 1983; Gustafsson and Pinter, 1984a;b; Zengel et al., 1985; Munson et al., 1986; Cullheim et al., 1987; Hultborn et al., 1989). In Table 8, all differences in mean membrane property values among the 3 presumed motor-unit types agree with previous findings, again supporting the present classification scheme.

Membrane electrical properties become altered after chronic spinalization (Section B) and like Ia EPSPs, the changes are not similar in the 3 presumed motoneuron types. Table 8 shows that presumed FF motoneurons undergo the most extensive membrane property changes after chronic spinalization, having a significantly lower τ_m, AHP, T_{Cap}, and CV while their AHP peak voltage (AHP_{mV}) and SPCT increase. In contrast, the electrical properties of presumed FR motoneurons are completely unaltered. Presumed S motoneurons have significant reductions in τ_m and T_{Cap} in chronic spinal preparations.

DISCUSSION

Section A

Comparison of Ia EPSPs in Unlesioned and Chronic Spinal Preparations

I. Summary

Ia EPSPs in ankle extensor motoneurons were examined in cats spinalized at the L1-2 level six weeks before the acute experiment and compared to unlesioned controls. With reference to Table 1A where data from the different motoneuron species are pooled, there is an increased composite Ia EPSP amplitude, and decreased risetime and half-width in ankle extensor motoneurons in chronic spinal animals. These changes would contribute to an overall enhancement of monosynaptic reflexes evoked by electrical stimulation of Ia afferents in these nerves in the chronic spinal preparation. A comparison of low threshold composite EPSPs between MG, LG, SOL, and PL motoneurons reveals that changes were most pronounced in LG and least in MG motoneurons.

II. Increased Ia EPSP amplitudes in chronic spinal preparations

EPSP amplitudes in chronic spinal motoneurons using data pooled from all four species were significantly larger than in unlesioned controls (Table 1A). When EPSP amplitudes were divided according to the individual motoneuron species in which they were recorded, differential changes among these close functional synergists were observed. The lack of amplitude increase in MG homonymous composite EPSPs (Table 1B) is in agreement with other reports of both composite (Mayer et al., 1984) and unitary EPSPs (Munson et al., 1986; Nelson & Mendell, 1979) although the latter studies indicate that it may depend on both duration and level of spinal lesions.

On the other hand, low threshold EPSPs evoked in LG, SOL, and PL motoneurons appear larger after spinalization.

The differences in LG EPSP amplitudes between unlesioned and chronic spinal cats deserves further comment. Whereas the occurrence of minimal "homonymous" EPSPs (i.e. < 200 μV) in the unlesioned sample of LG motoneurons was common (12 of 48 cases at 1.2T) the smallest EPSPs evoked at 1.2T in motoneurons from chronic spinals had amplitudes greater than ≥ 500 μV. The increased size of the smallest composite EPSPs could result from either an increased strength of pre-existing synapses (Nelson & Mendell, 1979) or an increased projection frequency of Ia afferents. An increased projection frequency of heteronymous MG Ia afferents to LGS motoneurons in chronic spinal cats has been demonstrated before (Mendell, Cope & Nelson, 1982) and is consistent with our observation of increased heteronymous EPSP amplitudes in LG motoneurons. An increased projection frequency would increase composite Ia EPSP amplitudes in the absence of changes in unitary EPSP amplitude.

Unlike homonymous EPSPs, heteronymous EPSPs in MG were substantially increased in the present study of 6 week L1-2 chronic spinal cats (Table 2); in contrast, a previous investigation (Munson et al., 1986) found such increases only after shorter periods of spinalization. The differences between this and other studies (Mayer et al., 1984; Munson et al., 1986) may result from differences in level and duration of spinalization as well as experiment-to-experiment variability. An additional factor that complicates comparing EPSPs between unlesioned and chronic spinal preparations is the fact that EPSP amplitudes vary between different motor-unit types (Fleshman, Munson and Sypert 1981; Munson et al., 1986; Mayer et al., 1984). Thus an oversampling of one motor-unit type could bias the difference between unlesioned and chronic spinal EPSP amplitudes. This is more likely a problem with smaller sample sizes such as those in

Table 2 and in some of the individual motoneuron species in Table 1. Following chronic spinalization the percentages of the different types of motor-units in MG may be altered (Munson et al., 1986; Mayer et al., 1984). The possibility of preferential amplitude increases in particular motor-unit types in the other ankle extensors is examined in Section C of this thesis.

In the present study there was considerable variability in EPSP amplitudes between experiments (Fig. 5). This occurred despite the use of identical procedures and, in the lesioned animals, the use of one time period after a single level of spinal cord lesion. This underscores the need to use data from several experiments to represent EPSPs at a particular time interval and lesion level. This consideration is, of course, in addition to the influence of time and level of lesion on changes in Ia EPSPs emphasized by previous investigations (Nelson & Mendell, 1979; Munson et al., 1986).

III. Comparison of composite EPSP shape to unitary EPSPs

It is worthwhile to compare shapes of unitary EPSPs reported elsewhere with those of composite Ia EPSPs recorded here. Mean homonymous composite EPSP risetimes in unlesioned preparations (Table 1, 1.2T) were shortest in MG (0.57 ms; LG=0.74, SOL= 0.95, PL=0.85) and compare favourably with unitary EPSP risetimes (MG =0.7, LG=0.9, SOL=1.2 ms: Scott and Mendell, 1976; SOL = .96ms: Cope et al. 1988). The range of times to peak (from foot of EPSP to peak) of composite MG EPSPs in the present unlesioned data was 0.55-2.6 ms (mean 1.16 ms) and is again comparable with that of unitary EPSPs (0.3-3.0 ms: Mendell and Henneman, 1971). Like unitary EPSP risetimes, mean composite homonymous Ia EPSP risetimes from unlesioned animals are shorter in MG (0.57 ms) than heteronymous EPSPs evoked by LGS nerve stimulation (0.76 ms) (Munson and Sypert 1979; Scott and Mendell

1976). However, in LG motoneurons the composite heteronymous risetime evoked from MG afferents (0.67 ms) was more similar to the risetime of "homonymous" EPSPs from LGS nerve stimulation (0.74 ms). The risetimes of unitary heteronymous and homonymous EPSPs are also more similar in LG than MG motoneurons (Scott & Mendell,1976).

As with risetimes, half-widths of composite Ia EPSPs are in the range of half-widths of unitary EPSPs. For example, mean composite Ia half-width in SOL at 1.2T was 7.20 ms compared to a mean of 6.51 ms for unitary EPSPs (Cope et al., 1988). Ranges of half-widths in the present material (2 - 13 ms in the unlesioned animals) are similar to those for unitary Ia EPSPs (Scott & Mendell, 1976; Cope et al., 1988). The mean half-widths of composite Ia EPSPs evoked at 1.2T in pooled data from LG, SOL and MG motoneurons was 5.53 ms and can be compared to the approximate 4.3 ms value for those evoked in the same species at stimulation strengths maximal for recruiting Ia afferents (Burke, 1968); this exemplifies the contaminating influence of spinal inhibitory pathways recruited at higher stimulation strengths, reducing EPSP half-width.

IV. The acute spinal cat is not an appropriate control population

The primary goal of the present study was to look for changes in composite Ia EPSPs during a period when the chronic spinal cat is hyperreflexive. Thus while the Ia EPSPs were changed compared to the unlesioned preparation, the time course of this change was not examined. In the present study, the chronic spinal preparation was compared to the unlesioned and not the acute spinal cat. While it would be desirable to simply remove descending influences and compare EPSPs with those in the chronic spinal state, this cannot be achieved in the acute spinal preparation because of the possibility of complex effects of acute

spinalization on unitary EPSPs. For instance, compared to the unlesioned state, acute transection results in increased amplitude and decreased risetime of unitary EPSPs (Nelson et al., 1979; Cope et al., 1988) yet Mendell and coworkers have demonstrated that acute transection rostral to the level of a chronic spinal section also alters unitary EPSPs (Cope et al., 1980). Thus acute spinalization may compromise an assessment of the "simple" effects of lost descending activity with "plastic" changes at the Ia EPSP-motoneuron synapse in the chronic spinal state. Future studies might benefit from a detailed comparison of EPSP amplitude and shape in chronic spinal preparations with those in the reversible cold block preparation. Preliminary investigations (Walmsley and Tracey, 1983) suggest that composite EPSPs are little changed in both acute spinal and cold block preparations (however see discussions in Mendell, 1988; Cope et al., 1988).

V. Implications of the present results

In the present study, composite Ia EPSP risetimes were decreased and amplitudes increased after 6 week chronic spinalization (Table 1A). Fig. 7 shows that compared to the unlesioned preparation, chronic spinalization resulted in the appearance of a greater number of larger-amplitude, shorter-risetime EPSPs. Nelson and Mendell (1979) report an increased incidence of large-amplitude short-risetime unitary Ia EPSPs for a period after chronic spinalization. The appearance of such unitary EPSPs would contribute to the decreased risetime and increased amplitude of composite EPSPs reported here.

Theoretical (Rall, 1964; 1967) and experimental studies on Ia EPSPs (Rall et al., 1967; Jack et al., 1971; Gustafsson and Pinter, 1984) suggest that EPSP shape, as defined by risetime and half-width, is determined by the electrotonic location of the synaptic terminals on the

motoneuron dendritic tree with longer risetimes and half-widths associated with greater electrotonic distances from the soma. The shape indices in Fig. 8 show that chronic spinalization produced a shift towards shorter EPSP risetime and half-width values. While passive membrane properties of the motoneurons also influence EPSP shape (Gustafsson and Pinter 1984e, Rall et al., 1967), a preliminary analysis suggests that differences in membrane properties alone cannot fully account for the observed changes in EPSP shape (Hochman et al., 1987). Therefore, present observations of decreased composite EPSP risetime and half-width in spinal animals are more easily explained by a relative proximal shift of the mean dendritic electrotonic location of Ia synapses. Investigations utilizing neuron modelling to estimate synaptic location given both passive electrical properties and Ia EPSPs within individual motoneurons would help assess the possibility of a proximal shift in Ia synapses.

Since Ia afferents with the fastest conduction velocities project to motoneurons with greater frequency (Clamann et al., 1985) and generate larger unitary EPSPs than slower afferents (Mendell and Henneman, 1971; Sypert et al., 1980; Clamann et al., 1985) faster afferents should have more or larger synaptic contacts with motoneurons. If this were true, then the faster conducting afferents would be more likely adjacent to motoneuron dendritic areas with degenerating synaptic contacts following chronic spinalization. This in turn might promote a preferential increase in the synapses of faster conducting Ia afferents, either by increasing the surface area of pre-existing boutons or by the formation of new sprouts (reviews in Hillman and Chen, 1985; Raisman, 1985; and Tsukahara, 1985). In this respect, it is interesting that in MG, SOL, and PL motoneurons, the greatest percentage increase in EPSP amplitude upon spinalization occurred at the lowest tested relative stimulus strength (1.1T), at which one would expect the fastest Ia afferents to be recruited. Although in LG motoneurons the 1.1T EPSP amplitude is also

increased after chronic spinalization, the 1.4T EPSPs underwent the largest percentage amplitude increase. One possible explanation for this apparent contradiction is that SOL afferents in the LGS nerve change more than LG afferents but are only recruited at higher thresholds of LGS nerve stimulation. Evidence for a higher threshold electrical recruitment of SOL than other ankle extensor Ia afferents comes from a generally slower conduction velocity of SOL than MG afferents (Hunt, 1954).

The best way to assess the effects of chronic spinalization on EPSP amplitude in ankle extensor motoneurons would be to activate both heteronymous and homonymous EPSPs by stimuli such as stretch of the achilles tendon. The demonstrated increase in EPSP amplitude upon low threshold electrical stimulation of single muscle nerves suggests, however, that composite EPSP amplitude is increased 6 weeks after L1-L2 spinalization and that this would contribute to hyperreflexia. The present finding of decreased risetimes and increased rate of rise of Ia EPSPs in triceps surae and plantaris motoneurons may also have implications for increased motoneuron recruitment in the chronic spinal state. Several studies (eg. Fetz and Gustafsson, 1983; Gustafsson and McCrea, 1984) have shown that larger rate of rise of EPSPs of similar amplitudes increase the probability of a motoneuron's firing. Increases in EPSP peak derivative in chronic spinal animals of the magnitude found in the present study are likely to significantly increase steady state firing (see Figure 3 of Fetz and Gustafsson, 1983). Thus regardless of the effects of chronic spinalization on EPSP amplitude, changes in EPSP shape could increase motoneuron recruitment and result in exaggerated reflexes. For instance, short latency reflexes have been shown to increase after chronic L3 dorsal column lesions (Decima and Morales, 1983) which are associated with increased rates of rise of Ia EPSP but not with increased amplitude (Decima et al., 1986).

Section B

Comparison of Motoneuron Electrical Properties in Unlesioned and Chronic Spinal Preparations

I. Summary

This section of the thesis shows that many membrane properties of motoneurons from chronic spinal preparations have been significantly altered. Mean membrane time constant (τ_m), cell surface area (T_{Cap}), and AHP duration have decreased while threshold voltage (V_{Th}) and short pulse current threshold (SPCT) have increased. Spike height, resting membrane potential, input resistance (R_{in}), electrotonic length (L) and rheobase were unchanged.

In general, it appears that the population of motoneurons from chronic spinal preparations differs in two fundamental ways from those in unlesioned. First, as judged by the decrease in τ_m and assuming an unchanged specific capacitance, membrane resistivity is lowered. This seems to be coupled to a change in dendritic architecture (Fig. 12) and size (T_{Cap}) so as to maintain the same electrotonic length. The decrease in resistivity in the population is due to an increased number of motoneurons with low τ_m values.

Secondly, as measured from the voltage deflection at threshold currents (rheobase) and as suggested by the increase in SPCT, V_{Th} has increased in chronic spinal preparations. While one might assume that an increase in V_{Th} would increase the amount of intracellular current required to produce action potentials, rheobase was not significantly altered. In this respect it is interesting that, unlike motoneurons from unlesioned animals, the mean rheobase value was significantly lower than that expected from calculation of V_{Th} and R_{in} in chronic spinal animals ($p < .05$). Thus the

expected decrease in excitability produced by an increased V_{Th} was partly offset by a subthreshold rectification process (e.g. anomalous rectification; Nelson and Frank, 1967) probably acting to reduce the rheobase current required for a particular V_{Th}. Unfortunately, this was not further explored by examining responses to a series of hyperpolarizing and subthreshold depolarizing currents (I-V curves).

As compared to previous investigations, the present study offers a more complete assessment of the effect of chronic spinal transection on membrane electrical properties by including estimates of τ_m, L, and T_{Cap} as well as directly measuring threshold voltage (V_{Th}) in four ankle extensor motoneuron species. Further, in order to reduce the effects of impalement injury, only motoneurons with action potential heights ≥ 80 mV were used in the analysis. This study confirms the lack of change in MG motoneuron R_{in}, rheobase, and perhaps AHP (Munson et al., 1986), but further shows that τ_m is lowered while V_{Th} is increased (Table 4). Although the present sample of SOL motoneurons is small (Table 4) there is general agreement with previous findings (Czéh et al., 1978; Cope et al., 1986) of an increased rheobase and tendency for a decrease in AHP and R_{in}. Table 4 also suggests that the reported changes in membrane properties are similar in all ankle extensor motoneuron species.

II. Effect of membrane resistivity

Specific membrane resistivity (as calculated from τ_m) appears to help govern the variation in R_{in}, AHP duration, and motoneuronal threshold properties (Gustafsson and Pinter, 1984a,b). Although the lowered τ_m in motoneurons from chronic spinal preparations was associated with a reduction in the AHP duration (Fig. 15), it did not appear to significantly reduce R_{in} (Fig. 11) or rheobase (Fig. 14A). The reduction in mean τ_m results partly from a loss of large-τ_m, low-V_{Th} motoneurons as

well as an increased number of low-τ_m, high-V_{Th} values (Fig. 14B).

Given an unchanged L and a 17% decrease in τ_m, equation 3 suggests that the ratio of equivalent cylinder length to diameter has increased in the chronic spinal preparation. Thus both the probable change in $1/\sqrt{d}$ (Fig. 12B) and the decrease in estimated T_{cap} (Table 1) are compatible with the suggestion (Gustafsson et al., 1982) that the motoneuron equivalent cylinder may shrink following chronic spinal lesions.

III. Effect of motor-unit type

Each motoneuron membrane property varies over a considerable range (Gustafsson and Pinter, 1984a,b) partly associated with the muscle fiber type it innervates (Fleshman et al., 1981; Pinter et al., 1983; Zengel et al., 1985). Since there appears to be an increased percentage of fast-fatigable motoneurons after chronic spinalization (Tables 3 and 6; Mayer et al., 1984; Munson et al., 1986) it is not surprising that the present distribution of motoneuron properties have an increased proportion of motoneurons with characteristically "fast" membrane properties. Thus, the chronic spinal cat tends to have a population of ankle extensor motoneurons with lowered τ_m, R_{in}, and AHP duration values, while rheobase and threshold have increased. Since "fast" motoneurons tend to have larger V_{Th}s (Gustafsson and Pinter, 1984b) an increased V_{Th} in the chronic spinal preparation may also be accounted for by an increased number of fast-fatigable motoneurons. However, although motoneurons become "faster" in their average electrical properties, their membrane surface area (as estimated by T_{Cap}) decreases, possibly to accommodate to a loss of descending synaptic input. Therefore, "fast" motoneurons from chronic spinal preparations may differ in some respects from those in unlesioned (see Results Section C, Table 8).

IV. Effect of SAG

The SAG conductance (evoked by long duration current pulses) is thought to produce underestimates in τ_m and R_{in} (Burke and TENBruggencate, 1971; Zengel et al., 1985; Gustafsson and Pinter, 1984a; Rose and Dagum, 1988), as well as τ_1 (Gustafsson and Pinter, 1984a; Rose and Dagum, 1988) and T_{Cap} (Rose and Dagum, 1988) while not substantially affecting the estimate of L (Gustafsson & Pinter, 1984a; Rose and Dagum, 1988). A computer model that simulates most features of SAG for longer duration current pulses has been reported to reduce the estimate of τ_m with brief current pulses (Gustafsson et al., 1984a). However, considering that this model causes deviations in the exponential decay of τ_1 which are not seen experimentally (present sample; Gustafsson and Pinter, 1984a), it may be that SAG is activated at a later time than proposed by model simulations, thereby having a lesser effect on τ_m from brief current pulses (0.5ms) than is theoretically ascribed to it.

As mentioned in Results, motoneurons from chronic spinal preparations appear to have an increased incidence of SAG conductances activated by short duration, low amplitude voltage transients (from 2 of 71 in unlesioned to 26 of 91). As shown in Table 3, the alterations in electrical properties in motoneurons from chronic spinal animals are in the direction that would be produced by large increases in SAG conductance (e.g. lowered τ_m, τ_1, R_{in}, and T_{Cap}). However, when those motoneurons with evidence of a SAG process in their short pulse voltage transients were removed from the statistical comparison, the remaining population had nearly identical mean passive membrane values. Thus when the voltage transient produced by brief current pulses activate a SAG conductance, the conductance appears to be insufficient to account for the changes in passive membrane properties recorded in the present population of chronic spinal motoneurons.

It is interesting that there appears to be both an increased incidence of SAG as well as "fast" motoneurons in the present sample since "fast" motoneurons may have a more developed SAG process (Gustafsson and Pinter, 1984e). The decreased AHP duration may significantly affect the firing properties of motoneurons, but this was not presently explored.

V. Previous investigations on membrane electrical properties

Previous studies of membrane electrical properties in chronic spinal preparations (Czéh et al., 1978; Gustafsson et al., 1982; Cope et al., 1986; Munson et al., 1986; Baker and Chandler, 1987) suggest that, if anything, the membrane becomes less excitable and consequently cannot account for a behavioral hyperreflexia. Thus, while there appears to be no large change in R_{in}, AHP, or rheobase in MG motoneurons (Munson et al., 1986), SOL motoneurons appear to have a decreased AHP duration (Czéh et al., 1978; Cope et al., 1986) as well as an increase in rheobase and calculated threshold voltage (Cope et al., 1986). A related study that attempted to maximize motoneuron deafferentation by using cats with both chronic L5 transection and L7-S1 rhizotomy also found an increased calculated threshold voltage (Gustafsson et al., 1982). This same study, the only previous attempt to address membrane electrotonic structure, found a significant reduction in L without a change in τ_m, suggesting perhaps that motoneurons shrink when deprived of a fraction of their afferent input.

The present study offers the most complete assessment of electrical properties in chronic spinal animals and employs the most rigid criteria for cell health. It is the first study to document an increase in measured threshold voltage (V_{Th}) as well as altered subthreshold voltage-dependent conductances as shown by the increased incidence of SAG and probably

anomalous rectification in chronic spinal motoneurons.

VI. Relation of membrane properties to Ia EPSPs

Following 6 week chronic spinal cord transection, mean Ia composite EPSPs in ankle extensor motoneurons tend to become larger with significant reductions in EPSP risetime and half-width (Table 1). In view of the possibility that these motoneurons may alter their electrotonic structure to promote such changes (eg. Gustafsson et al., 1982), the membrane properties of these motoneurons were presently determined. Since L was found to be unchanged, the increased composite Ia EPSP amplitude in motoneurons from chronic spinal preparations is unlikely to be attributable to a change in the passive membrane properties of motoneurons. Further, the finding of a decrease in τ_m may contribute to (eg., see Rall et al., 1967; Gustafsson and Pinter, 1984e) but not fully account for (Hochman et al., 1987) the decreases in risetime and half-width. A preliminary examination that incorporated the mean passive membrane properties of both preparations into a 10-compartment Rall model of the motoneuron showed that the mean Ia synaptic location would have to move closer to the soma compartment and increase its conductance (Hochman et al., 1987) to account for the recorded EPSP differences in chronic spinal preparations. It is crucial that studies relating membrane electrical properties and EPSP shape be continued with motoneuron modelling in an attempt to estimate the shift in Ia synapses required to explain experimental findings.

Section C

Relating Changes in Ia EPSPs to Membrane Electrical Properties

I. Summary

The results of Section C suggest that chronic spinalization results in changes in composite Ia EPSPs and motoneuron electrical properties that are related to motor-unit type. Mean "homonymous" EPSP risetime and half-width from presumed FR motoneurons undergo highly significant decreases concomitant with, and partly related to, large increases in "homonymous" EPSP amplitude. Changes in the shape index plot of EPSPs from presumed FR motoneurons (Fig. 17b) are consistent with the appearance of composite Ia EPSPs in motoneurons having "mean" synaptic locations relatively closer to the soma. These changes in the chronic spinal preparation could enhance Ia-reflex recruitment of motoneurons as shown by the increased ratio of EPSP amplitude to threshold voltage (amp/V_{Th}). Mean motoneuron membrane properties for presumed FR motoneurons, however, are completely unaltered.

In contrast, EPSPs recorded in presumed FF motoneurons are practically unchanged after chronic spinalization, yet these motoneurons have membrane electrical properties that are significantly altered. These motoneurons appear to "shrink" (as evidence by changes in T_{Cap}) possibly to maintain a similar electrotonic length (L) in the face of a decreased membrane resistivity (τ_m). A decrease in the mean CV of presumed FF motoneurons is in general agreement with previous findings (Mayer et al., 1984; Munson et al., 1986) and may relate to the decreased motoneuron surface area as would be predicted by the size principle (Henneman et al., 1965). Finally, AHP duration is decreased in presumed FF motoneurons from chronic spinal preparations, which would suggest a change in their firing properties.

Presumed S motoneurons from chronic spinals undergo "homonymous" EPSP shape and amplitude changes similar to, though less dramatic than, thise in presumed FR motoneurons. Also, presumed S motoneuron membrane properties are changed in a manner similar to presumed FF motoneurons (e.g. decreased τ_m and T_{Cap} with unchanged L). Finally, it appears that EPSPs and motoneuron membrane properties from motoneurons of "homonymous" mixed muscle presumed S seem to be affected differently than soleus motoneurons after chronic spinalization since only SOL motoneurons have large amp/V_{Th} increases (suggestive of an increased potential for reflex motoneuron recruitment).

II. Division of motoneurons into presumed type

The present classification scheme relied on the use of rheobase and R_{in} to subdivide motoneurons into 3 populations of motor-unit type. It has previously been shown to be 91% accurate (Zengel et al., 1985). While others have used this method of motoneuron division (Gustafsson and Pinter, 1984a,b,c; Hultborn et al., 1989; Heckman and Binder, 1989), caution must be used in its application. First, membrane injury resulting from electrode impalement can alter R_{in} and rheobase. For example, Section B has shown that "healthy" motoneurons have greater rheobase/R_{in} ratios (compare Table 3 to Table 5). Since the present population of motoneurons are "healthier" than those from which the accuracy of such a classification criterion was originally inferred (Zengel et al., 1985) it is possible that application of the previously defined rheobase/R_{in} ratio results in an overestimate of the number of FF motor-unit types and an underestimate of the number of S's in the present sample. The inclusion of τ_m and AHP half decay time as other membrane parameters to help subdivide motoneurons into motor-unit types has been shown to increase the accuracy of typing to 97% (see Zengel et al., 1985) but use of these parameters would have greatly reduced our sample size and afforded only

a 6% increase in accuracy and they were therefore not employed. Another consideration concerns the fact that "electrical" typing of motoneurons has only been established in MG and may not accurately reflect type in LG or PL motoneurons.

Munson et al. (1986) have shown that use of the rheobase and R_{in} classification scheme in chronic spinal animals is less accurate. As compared to the unlesioned preparation, more FR motoneurons are improperly classified (most as FF) while FI units (a small number of units with intermediate fatigability between FF and FR) most normally electrically classified as FF (70%; Zengel et al., 1985) become more frequently classified as FR (50%; Munson et al., 1986). It is therefore possible that the present changes in "presumed" FR motoneurons may be influenced by an increased percentage of FI motoneurons in this category. Note however that FI motoneurons represent only a small percentage of the motor-unit types in both unlesioned (4%) and chronic spinal (9%) preparations (Munson et al., 1986). Clearly, mechanical typing experiments need to be done. For example, the present finding of an increased percentage of presumed FF's in the chronic spinal preparation probably coincides with an increased percentage of both FF and FI motor-unit types as reported previously with use of mechanical typing (Mayer et al., 1984; Munson et al., 1986).

Thus there is a need for great caution in relating the present "presumed" type classification to actual changes in motor-unit type. Nonetheless, in support of the accuracy of this classification criterion, the present proportion of motor-unit type in unlesioned cats agree well with previous estimates utilizing the mechanical typing method of Burke et al. (1973) for MG and PL (Burke et al., 1973; Proske and Waite, 1974; Mayer et al., 1984; Zengel et al., 1985; Munson et al., 1986; Emonet-Dénand et al., 1988) when FI motor-units are electrically classified as FF (Zengel et al., 1985). Although the distribution of mechanically typed

motoneurons in LG remains largely unexplored, the present proportions in the unlesioned preparation agree well with the muscle fibre type distribution for this muscle (Ariano et al., 1973). Further, Ia EPSP size and shape as well as membrane properties in the present sample varied among the 3 presumed types in both unlesioned and chronic spinal preparations as they do in mechanically typed motoneurons (Burke, 1968; Burke, Rymer, and Walsh, 1976; Zengel et al., 1983; Fleshman et al., 1981; Mayer et al, 1984; Munson et al., 1986). Therefore, it is thought that the present subdivision of motoneurons is capable of adequately detecting changes in the different motoneuron types.

Finally, regardless of accuracy to motoneuron type, the present division separates motoneurons into 3 groups which differ in threshold current excitability (rheobase). (Rheobase is inversely related to R_{in} so that use of R_{in} in rheobase/R_{in} for motoneuron subdivision does not detract from viewing the 3 populations as differing in rheobase values.) Thus, motoneurons of low and particularly midrange rheobase values appear to undergo the greatest changes in EPSPs after transection while motoneurons with midrange rheobase values represent the only motoneuron subpopulation whose membrane properties are unaltered after chronic spinalization.

III. Both motoneuron species and type help dictate Ia EPSP shape and amplitude

Mean homonymous Ia EPSP risetime and amplitude vary with motor-unit type, both tending to decrease in the order S > FR > FF (Burke, 1968; Fleshman et al., 1981; Mayer et al., 1984; Munson et al., 1986). It is therefore possible that the reported EPSP differences among motoneuron species (in both the unlesioned and chronic spinal preparations; see Results Section A) may arise from differences in the proportion of motor-unit types between the species. For instance, as compared to the other

ankle extensor motoneuron species, EPSPs in MG motoneurons have the shortest mean risetimes (Table 1) which would be expected from having a greater percentage of FF motoneuron types (Emonet-Dénand et al., 1988). Also, the mixed muscle PL has a long mean EPSP risetime comparable to that of the exclusively slow SOL (Burke et al., 1974) (see Table 1) which relates to the unusually large number of slow motoneurons within the PL pool (Emonet-Dénand et al., 1988). Nonetheless, LG and MG motoneuron species have the same approximate proportion of motor-unit types (Ariano et al., 1973) yet their EPSP shapes differ (Table 1) suggesting that type distribution differences alone can not solely account for EPSP shape differences among motoneuron species.

If differences in EPSP risetime, half-width and amplitude among the motoneuron species (in both types of preparations; Section A, Table 1) were due simply to different percentage distributions of motor-unit types (Table 6) then one should be able to calculate the mean EPSP value for each motoneuron species by knowing both the percentage of each motor-unit type (Table 6) and the mean EPSP value for each motor-unit type (Table 7). Table 10 attempts to do this for EPSP amplitude, risetime and half-width. It can be seen that the mean EPSP value recorded from motoneurons of each species (as reported in Table 1), are similar to mean EPSPs calculated from the summed products of mean EPSP values for each motor-unit type and their proportion within a species. For instance, as with actual values given previously (Section A, Table 1) Table 10 shows that calculated MG EPSP risetime is shorter than those of LG and PL, and calculated LG half-width and risetime undergo the greatest percentage change after chronic spinalization. These comparisons support the notion that part of the variation in EPSPs recorded in different ankle extensor motoneuron species is due to changes in the proportions of the different motor-unit types.

However, as shown in Table 11, the mean EPSP value in each presumed

motor-unit type differ between motoneuron species. For instance, regardless of type, MG motor-units have the shortest mean risetime of all the species, particularly within presumed S motoneurons where mean MG EPSP risetime at 0.56 ms is 30% lower than the next lowest mean value (PL's at 0.80 ms). Further, mean EPSP risetime, half-width and amplitude in LG always undergo the greatest relative changes after chronic spinalization in all presumed types.

In conclusion, it is clear that both type- and species-related differences help govern the shape of composite Ia EPSPs. The greatest changes in EPSPs after chronic spinalization appear to occur preferentially in presumed FR motoneurons supplying LG motoneurons.

IV. Assessment of EPSP changes in the 3 presumed types

As discussed in Section A, the shape index plot can be used as a relative measure of synaptic location (Rall et al., 1967; Tsukahara, 1985). The present plots would suggest that "mean" synaptic input is closer to the soma for presumed FR motoneurons in the chronic spinal preparation as compared to the unlesioned state (17B), especially since mean passive membrane properties which influence EPSP shape (Rall et al., 1967; Gustafsson and Pinter, 1984c) are unchanged in this group. It is tempting to suggest that, for presumed S motoneurons, the chronic spinal preparation is characterized by a relative absence of motoneurons having "mean" synaptic locations farther from the soma (17C); however, in view of the significant decrease in τ_m for these motoneurons, the observed changes are likely due to a changed τ_m. This is shown in the normalized shape index plot of Figure 19.

Mean "homonymous" EPSP risetime and half-width were shortened while amplitude was elevated in both presumed FR and S motoneuron types in

chronic spinal animals. If Ia synaptic conductance remained the same in both preparations and "mean" synaptic location moved closer to the soma, the aforementioned experimental findings would be expected, with shortened risetime and half-width values associated with larger EPSP amplitude in single motoneurons from the chronic spinal preparation. In general agreement, there is a tendency for EPSPs with shorter risetime values to have increased amplitudes (Section A, Figure 7). Further, when risetime and amplitude are compared in both presumed FR and S motoneurons, amplitude increases are greater in short risetime EPSPs from chronic spinal animals. It would appear that the mechanisms governing amplitude increases are at least partly related to the overall changes in EPSP shape.

Heteronymous EPSP risetime decreases and amplitude increases are not selective for either motoneuron species (Section A, Table 2) or presumed motor-unit types (Table 7) after chronic spinalization. In contrast, "homonymous" effects are both presumed type- (Table 7) and species- (Section A, Table 1) related, with the greatest changes occurring in EPSPs from presumed FR and LG motoneurons while there are no changes in EPSPs from presumed FF or MG motoneurons. There is no obvious explanation for the differences in specificity of changes after chronic spinalization between heteronymous and "homonymous" EPSPs of both motoneuron species and presumed motor-unit type.

Gustafsson and Pinter (1984c) have used Rall neuronal modelling to show that differences in membrane resistivity and geometry account for the range of EPSP risetime and half-width that exists between "fast" and "slow" motoneuron types. In other words, they believe that passive membrane electrical properties can account for the range of EPSP shapes seen. Further, Gustafsson et al. (1982) suggest on theoretical grounds that, after 3 weeks spinalization and dorsal rhizotomy, the altered

motoneuron membrane properties would result in an increased amplitude synaptic input. In short, both studies emphasize the importance of postsynaptic membrane properties on EPSP shape and amplitude. However, in the present population of presumed FR motoneurons, changes in EPSP shape after chronic spinalization cannot be attributed to postsynaptic membrane properties, which are unchanged, but rather support a presynaptic proximal shift in Ia synaptic input. These findings may relate to the "unmasking" of short risetime, large amplitude unitary EPSPs found to emerge in MG motoneurons following both acute (Cope et al., 1980) and long term spinal cord transection (Nelson and Mendell, 1979).

V. Contribution of EPSP amplitude increases to potential motoneuron recruitment

Do the reported changes in mean Ia EPSP shape and amplitude in chronic spinal cats bring about reported increased reflexes? One approach is to associate the increased EPSP amplitude in individual motoneurons with their threshold excitability. For instance, increased EPSP amplitudes may be matched with a decreased threshold excitability (eg. increased rheobase or V_{Th}) in individual motoneurons, the net effect being a lack of change in Ia monosynaptic reflex excitability. In fact, in the present sample of motoneurons, an overall 22% increase in "homonymous" EPSP amplitude is coupled to a 15% increase in rheobase and a 16% increase in VTh, suggesting that motoneuron membrane excitability changes counter EPSP amplitude increases and prevent hyperreflexia. However, as shown in Table 7, it appears that presumed FR motoneurons from chronic spinal preparations undergo a net 62% increase in potential Ia reflex recruitment as assessed by the ratio amp/V_{Th}. Soleus motoneurons may also increase their reflex excitability even though the mean presumed S motoneuron amp/V_{Th} value is unchanged. It thus appears that the mechanisms subserving increased reflexes are both type- and species- related. Further, the

results from presumed S motoneurons show that significant EPSP amplitude increases do not necessarily imply an increased likliehood of recruitment and that motoneuron membrane properties can counter an increased EPSP amplitude by having an increased V_{Th}.

In the absence of a change in EPSP amplitude, increased Ia reflexes have been associated with an increased rate of rise of composite Ia EPSPs (Decima et al., 1986) after chronic dorsal column section; possibly by increasing the firing probability of motoneurons (Gustafsson and McCrea, 1984; Fetz and Gustafsson, 1983; Cope et al., 1987). In the present sample of motoneurons, presumed FR and S underwent significant risetime decreases that alone may produce increased reflex responses.

VI. Motoneuron membrane properties

Whereas EPSPs in presumed FR motoneurons underwent the greatest relative change after chronic spinalization (Table 7), membrane properties of presumed FF motoneurons underwent the greatest changes in membrane properties (Table 8). These differences strengthen the hypothesis that chronic spinalization produces changes in Ia EPSP and membrane electrical properties in ankle extensor motoneurons that relate to motor-unit type. Both presumed FF and S motoneuron types underwent a change in passive membrane properties after chronic spinalization. In both FF and S motoneuron groups chronic spinalization resulted in a 15% reduction in τ_m. A reduced τ_m with an unchanged L and R_{in} supports an equivalent cylinder surface area (T_{Cap}) decreased as shown in Table 8. The decrease in τ_m would contribute to the mean decrease seen in EPSP half-width without substantially affecting EPSP risetime or amplitude (McCrea and Schefchyk, 1989). Because presumed FR motoneuron passive membrane properties are unchanged in chronic spinal animals, EPSP shape and size changes in FR cannot be accounted for changes in membrane properties alone. This is

probably true for presumed S motoneuron as well since a preliminary investigation employing Rall compartment modelling and simulating Ia synaptic conductances (Hochman et al., 1987) supports a synaptic plasticity.

Presumed FF motoneurons from chronic spinal animals also undergo changes in active membrane properties. A reduction in AHP duration might suggest that these are the motoneurons which increase their incidence of SAG in the chronic spinal population (see Results Section B). However the incidence of SAG elicited from 500μs duration current pulses is increased similarly in all 3 presumed types to an incidence of ≈20% in motoneurons from chronic spinal animals. Since AHP duration partly determines motoneuron firing properties, motoneuron firing frequency verses injected current (their F-I curves) should be investigated in the future.

It is interesting that, regardless of the reported changes in passive membrane properties after chronic spinalization, motoneuron electrotonic length (L) was unchanged. Section B of Results suggests that in order for L to remain unchanged after chronic spinalization while τ_m decreased, the motoneuron dendritic architecture is altered (Fig. 12) and cell surface area decreased (see Table 3). The regulation of L may be sensitive to the extent of deafferentation, or require peripheral afferent input since spinal transection with rhizotomy causes L to decrease (Gustafsson et al., 1982).

General considerations of the possible events contributing to Ia EPSP and motoneuron plasticity:

At this point, it may be useful to consider the events associated with chronic spinal cord transection that might help account for the present

observations.

Complete L1-L2 spinal cord transection severs all supraspinal and long propriospinal synaptic input supplied to motoneurons (either directly, or indirectly through interposed interneurons). Naturally, the activity of the remaining segmental circuitry will depend entirely on peripheral afferent input (assuming the absence of spontaneous or resonant spinal neural activity). There is no reason to believe that the organization of the remaining segmental circuitry undergoes changes since reflexes present in the unlesioned acute spinal cat can be elicited in the chronic spinal cat without the emergence of novel synaptic connections (personal observations; McCrea et al., 1985). The only obvious difference in synaptic transmission between the acute and chronic spinal cat is a sharpening and enlargement of synaptic responses suggestive of a more efficient transmission through some reflex pathways (McCrea et al., 1985).

I. Loss of descending input

In the cat, both propriospinal and supraspinal descending systems have monosynaptic connections onto motoneurons (Grillner et al., 1970, 1971; Baldiserra et al., 1981; Shapovalov et al., 1967; Hongo et al., 1969; Jankowska et al., 1974) and it is conceivable that a loss of these synapses on the motoneuron membrane surface would create an environment conducive to a strengthening of the surviving synapses, including synapses from interneurons and monosynaptic group Ia and II afferents. Tsukahara (1985) has shown that, in the red nucleus, the removal of a portion of the known afferent connections is sufficient to cause a sprouting of the remaining afferent systems so as to occupy the vacant space left by the degenerating afferents. If the descending monosynaptic boutons were located relatively closer to the soma than the mean location of Ia boutons, a preferential proximal sprouting of Ia boutons might be

expected, producing an overall decrease in EPSP risetime and half-width while increasing EPSP amplitude as seen experimentally. There are descending monosynaptic EPSPs from Deiter's nucleus and reticulospinal nuclei which appear to have EPSP shapes suggestive of more proximal synaptic input than Ia afferents (Grillner et al., 1970, 1971; Baldiserra et al., 1981; Shapovalov et al., 1967). Monosynaptic EPSPs from the red nucleus have also been reported (Hongo et al., 1969) but occur very infrequently in ankle extensor motoneurons. Further, anatomical labelling studies in the rat have revealed proximal dendritic monosynaptic boutons from coeruleospinal, raphespinal, and reticulospinal nuclei (Holstege and Kuypers, 1987). A substantial portion of motoneurons also receive propriospinal monosynaptic input (Jankowska et al., 1974) but their EPSP shape has not been examined. In all, only ≈30% of hindlimb motoneurons do not receive monosynaptic EPSPs from either supra- or propriospinal origin while 34% of these motoneurons receive EPSPs from both sources (Jankowska et al., 1974). It is tempting to suggest a differential incidence of descending monosynaptic EPSPs related to motoneuron type, those motoneurons not receiving descending connections being the FF motoneuron types, with FR motoneurons having the greatest degree of descending connections. These differences would support the differences in EPSP plasticity following chronic spinal lesions. One could also hypothesize that aside from type-related connectivity differences, MG motoneurons might receive fewer descending monosynaptic connections than the other ankle extensor motoneuron species. Clearly, the relation between descending monosynaptic connections and motoneuron species as well as motoneuron type would provide the results to support or refute this hypothesis. Considering that rubrospinal oligosynaptic effects in MG motoneurons are related to motor-unit type (Burke et al., 1970), a type-related descending organization is an attractive hypothesis.

An alternative explanation is if the descending monosynaptic

connections end, on average, distal to the Ia afferent termination sites in FF and MG motoneurons but not in FR or LG motoneurons, less of a shift to more proximal Ia EPSPs might be expected in the former motoneurons.

II. Effects of partial axotomy

Axon collaterals from Ia afferents ascend in the dorsal column and exit to terminate in and around Clarke's column between L3 and T12 (Lloyd and McIntyre, 1950). The present L1-L2 level of spinal transection would then cut the ascending axons of an unknown percentage of Ia afferents. Lower lumbar dorsal column lesions (L3) thought to produce a nearly complete axotomy of these ascending axons result in an increased monosynaptic reflex as well as an increased post-tetanic potentiation in hindlimb motoneurons (Decima and Morales, 1983). This condition of "partial axotomy" is thought to increase the diameter of the undamaged axon collaterals and increase the potency of their synapses (Decima and Morales, 1983). However, upon intracellular examination of heteronymous EPSPs, there were no amplitude increases but a greater rate of rise for the potentiated or unpotentiated EPSP amplitude (Decima et al., 1986) supporting the suggestion that EPSPs with a greater rate of rise are more likely to recruit motoneurons (Gustafsson and McCrea, 1984; Fetz and Gustafsson, 1983; Cope et al., 1987). The extent to which "partial axotomy" of Ia afferent collaterals contributes to the present series of observations is unknown; however, it is clear that "partial axotomy" alone cannot account for an increased EPSP amplitude, most pronounced in heteronymous connections. However, Nelson (in Mendell, 1988) showed that unitary EPSPs were moderately enhanced after dorsal column lesions.

III. Recruitment order

Both the increased amplitude and decreased risetime of composite Ia EPSPs would contribute to an increased reflex excitability in motoneurons. However, this tells nothing about changes in the characteristics of recruitment evoked by stretch stimuli. It has been convincingly established that motoneuron recruitment from stimuli that activate synergic ankle extensor Ia muscle spindle afferents is strictly type-related with motoneuron recruitment occurring in the order S > FR > FI > FF (Burke et al., 1976; Fleshman et al., 1981b; Harrison and Taylor, 1981; Zajac and Faden, 1985). The present demonstration of an increased likelihood of reflex recruitment in presumed FR motoneurons after chronic spinalization may result in an altered recruitment order among motoneurons. Thus stretch stimuli that predominantly recruit postural type S motor-units (Zajac and Faden, 1985) might recruit a larger proportion of type FR motor-units in the chronic spinal state which produce greater tensions at faster contraction times (see Burke, 1981) characteristic of the EMG changes seen (Brothers et al., 1983). This is an important consideration which requires further investigation with mechanical typing of motoneurons to establish definitively whether FR motoneuron types are easier to recruit reflexly.

IV. Increased expression of relatively "silent" synapses

The reported mean amplitude increases and risetime decreases of composite Ia EPSPs after chronic spinalization do not necessarily require a growth of new synapses. There is strong evidence to support the existence of Ia synapses which are relatively "silent" (Nelson and Mendell, 1979) but become "unmasked" after post-tetanic potentiation (Hirst et al., 1981), decreases in presynaptic inhibition (Clements et al., 1987), acute spinal transection (Nelson et al., 1979), or acute transection rostral to a prior chronic transection (Cope et al., 1980). Such "unmasking" is probably brought about by an increased probability of

synaptic transmission at boutons with previously low transmission probability (Hirst et al., 1981; Redman and Walmseley, 1983b; Clements et al., 1987) and may be responsible for observations of an increased projection frequency (Nelson et al., 1979; Cope et al., 1980). Increased transmission probability has been theoretically ascribed to a decrease in branch point failure (Henneman et al., 1984). For several other central connections it has similarly been shown that "ineffective" afferent synapses becoming expressed after certain lesions (for reviews, see Mendell, 1984; Wall, 1988).

There are contrasting reports of unmasking of silent synapses in the chronic spinal animal. Evidence in favor of an "unmasking" effect after chronic spinal injuries is the persistence of an elevated projection frequency at 3 months with the appearance of short risetime large amplitude unitary EPSPs (Nelson and Mendell, 1979) and a decreased presynaptic inhibition (Naftchi et al., 1980). However, Munson et al. (1986) found no evidence of an increased projection frequency after chronic spinal transection. Further, after chronic spinal hemisection there appeared to be an increase in presynaptic inhibition in the cat (Hultborn & Malmsten, 1983) and no change in post-tetanic potentiation in the rat (Malmsten, 1983).

Are these silent synapses preferentially proximal, distal or random? Mendell and collaborators (Mendell and Nelson, 1979; Nelson et al., 1979; Cope et al., 1980) would suggest that these "silent" synapses are more proximal by virtue of the appearance of short-risetime large amplitude unitary EPSPs after acute and chronic spinal cord transection. The expression of previously silent proximal synapses would support the present findings on composite Ia EPSPs.

V. Activity dependency

There is a dramatic decrease in soleus muscle activity after chronic spinalization (Czéh et al., 1978; Alaimo et al., 1984). Together with the finding of a change in the pattern of activity of the mixed muscle LG, there is strong suggestive evidence that changes in the activity of motoneurons after chronic spinalization are type related (Alaimo et al., 1984). Kuno and collaborators have shown that a decrease in muscle activity shortens AHP in soleus motoneurons after spinal transection (Czéh et al., 1978), peripheral nerve conduction block (Czéh et al., 1978), or leg immobilization in a shortened position (Gallego et al., 1979a). These results are not associated with afferent activity and suggest that factors related to muscle activity can alter motoneuron membrane properties. In order to explain the present findings of changes in FF and S motoneuron properties, both presumed S and FF muscle fibres would have to undergo the greatest reduction in activity.

Prolonged disuse of muscle afferent transmission enhances monosynaptic reflexes (for references see Gallego et al., 1979b) and produces larger Ia EPSPs (Gallego et al., 1979b). Immobilization of MG in a stretched position, which should result in increased muscle spindle impulse activity, produces a decrease in EPSP amplitude (Mayer et al., 1984b). After chronic spinal transection, muscle inactivity is likely to result in a decrease in muscle afferent activity, which if similar to disuse, might promote the increase in EPSP amplitude. For afferent inactivity to explain the present findings, one would expect to find the greatest relative decrease in activity from both fatigue-resistant motor-unit types (FR and S) while FF remain unchanged. Since Ia afferent fibres have a greater projection frequency to FR and S motoneurons (Fleshman et al., 1981a) it is likely that their activity will have undergone the greatest relative decrease.

VI. Trophic influence

A retrograde trophic influence of muscle on motoneurons was firmly established by the investigations of Kuno and collaborators on soleus motoneurons (Czéh et al., 1978; Gallego et al., 1979). They showed that AHP duration decreases evoked by events causing muscle inactivity (eg. spinal cord transection, peripheral nerve conduction block using a TTX nerve cuff, immobilization of ankle muscles in shortened position) could be prevented by events that caused muscle contraction or stretch but did not require motoneuron activation (eg. stimulation distal to peripheral nerve block, immobilization of ankle muscles in stretched position). For a trophic influence to explain the observed membrane property changes, it would also have to be influenced differently for the different motor-unit types after chronic spinalization.

VII. Conclusions

As explored above, possible mechanisms subserving increased monosynaptic reflexes after chronic spinal cord transection are numerous. Interestingly, all of the aforementioned mechanisms of synaptic plasticity would be predicted to act in accordance with the reported Ia composite EPSP changes after chronic spinalization. The degenerating descending monosynaptic connections are probably closer to the motoneuron soma than Ia synapses creating an environment conducive to proximal collateral sprouting. The existence of "silent" Ia synapses also appear to occur more proximally. Together with the size-enhancing effects of disuse (supersensitivity), all elements contribute to an increased EPSP amplitude with decreased risetimes and half-widths.

In accordance with Purves' trophic theory of neural connections (Purves, 1984) where neurons release trophic factors retrogradely, it is

not unlikely that retro-trophic factor(s) from motoneurons help influence Ia synaptic potency just as muscle fibre type helps determine motoneuron properties. Type-related differences in Ia EPSP amplitude are relevant to motoneuron recruitment and it is likely that type-related differences in motor-unit firing patterns (Hennig and Lømo, 1985; Eken and Gundersen, 1988) help maintain this relation and are partly responsible for EPSP changes after transection. The decrease in muscle activity following chronic spinal transection also has a retrograde trophic effect on motoneuron membrane properties which appears to affect the motoneuron types differently.

Chronic spinal transection alters the firing patterns of fast and slow twitch muscles, as well as changing the proportion of motor-unit types in each muscle (Roy et al., 1984; Mayer et al., 1984a; Munson et al., 1986; present observations). It appears that it is the change in motor-unit firing which alters muscle contractile properties since characteristic EMG activity patterns can maintain fast or slow denervated muscle contractile properties while a foreign firing pattern (resembling either fast or slow units) can alter muscle contractile properties (towards fast or slow units) (Eken and Gundersen, 1988). In regard to the chronic spinal animal, the reduced activity is conducive to an alteration towards faster motor-unit types.

A proposed scheme of the events causing synaptic and motoneuron plasticity is as follows. Chronic spinalization reduces motoneuron firing (Alaimo et al., 1984). The reduced firing reduces muscle activity and produces changes in the properties of muscle fibres altering the proportion of motor-unit types (Roy et al., 1984; Mayer et al., 1984a; Munson et al., 1986). Reduced muscle activity reduces sensory afferent activity which enhances Ia synaptic efficacy (supersensitivity) (Gallego et al., 1978). Reduced muscle activity also retrogradely affects

motoneuron membrane properties (Czéh et al., 1978). The change in the properties of motoneurons matches the muscle mechanical properties towards an increase in faster motor-unit types (present observations; Mayer et al., 1984a; Munson et al., 1986). At the same time, degeneration of descending monosynaptic boutons onto motoneurons creates an environment conducive to proximal collateral sprouting (Tsukahara, 1985). The motoneuron membrane supersensitivity evoked by a reduced afferent activity helps promote sprouting mechanisms, as does a partial axotomy of ascending Ia axon branches (Decima and Morales, 1983). The Ia EPSP changes are type- and species-related with each motoneuron type and species having different amounts of descending monosynaptic connections, FR and LG motoneurons having the greatest percentage of descending connections. The changes in motoneuron membrane properties are type- related since each motor-unit type undergoes a different degree of activity alteration after chronic spinalization with FF and S undergoing the greatest relative change while FR unit activity is relatively unchanged.

Summary of Results

An electrophysiological analysis of composite Ia EPSPs and motoneuron membrane properties in 6 week (L1-L2) chronic spinal cats has been undertaken in an attempt to explore possible "plastic" intracellular events that might relate to increased stretch reflexes.

Figure 20 presents a schematic summary of the changes seen in the mean amplitude and shape of composite Ia EPSPs of ankle extensor motoneuron species (20A) as well as in the 3 motoneuron groups that approximate actual motor-unit types (20B). With the exception of homonymous effects in MG and presumed FF motoneurons, all other composite EPSPs were significantly larger (shown by thickened lines). Mean composite Ia EPSP risetime was also shortened in motoneurons from chronic spinals with the

exception of presumed FF motoneuron types (shown by a relatively reduced distance from pointed end of pentagon).

A motoneuron model (see Rall et al., 1967; Rall, 1964, 1967, 1977) was used in an attempt to assess the degree of synaptic "plasticity" required to account for the Ia composite EPSP amplitude increases and the risetime and half-width decreases seen in motoneurons after chronic spinalization (Hochman et al., 1987). The 10 compartment neuron models in Figure 21 utilize mean passive motoneuron membrane properties to create "Rall" compartment parameters (i.e. compartment conductance and capacitance, coupling conductance). Therefore, any change in EPSPs arising from changes in membrane passive properties is accounted for by the model. Each compartment has equivalent electrical properties and represents a progressively greater electrotonic distance from compartment 1 (i.e., the soma). One can then incorporate a distribution of excitatory conductances that would produce voltage waveforms in compartment 1 similar to the mean composite Ia EPSP shape found experimentally (compare experimental EPSP risetime and half-width values to modelled values in Fig. 21A,B). By varying the conductance magnitude (assuming no change in conductance duration) one can further model the relative conductance increase required to account for the increased EPSP amplitudes seen in motoneurons from chronic spinals.

Figure 21A shows that in order to simulate the EPSP changes after chronic spinalization for combined LG, PL, and SOL motoneurons, the modelled synaptic conductance would have to shift 2 compartments proximally and increase overall conductance by 20% (to account for the experimental mean EPSP amplitude increase of 73%). For presumed FR motoneurons, the modelled synaptic conductance would have to move 2 compartments more proximal and increase overall conductance by 60% (to account for the experimental mean EPSP amplitude increase of 144%).

Thus, a change in Ia EPSP size and shape after chronic spinalization is not attributable to the changes in passive membrane properties described in Section B. Rather, an "apparent" synaptic plasticity has occurred which can be simulated with a neuron model as having a mean synaptic input relatively closer to the soma as well as an increased conductance magnitude. The increased conductance magnitude would relate to an increased synaptic transmission, be it by the increased expression of relatively "silent" proximal synapses or by a preferential proximal collateral sprouting to replace degenerated descending boutons.

Overall, the changes in Ia EPSP and motoneuron membrane properties following chronic spinalization would support increased reflexes. Although an increased threshold voltage would suggest that motoneurons have a decreased probability of recruitment after chronic spinalization, it is apparent that subthreshold conductances are modified (e.g. increased anomalous rectification) which minimize the effects of threshold differences. Further, threshold voltage is unchanged in presumed FR motoneurons and their increased Ia EPSP amplitude after chronic spinalization would contribute to increased reflexes as shown by their increased ratio of EPSP amplitude to threshold voltage. This is probably the case for SOL motoneurons as well. Finally, considering that shorter EPSP risetimes are associated with an increased probability of motoneuron firing (Gustafsson and McCrea, 1984; Fetz and Gustafsson, 1983; Cope et al., 1987) and increased reflex responses (Decima et al., 1986), the present reductions in EPSP risetime found in motoneurons from chronic spinal preparations would also contribute to the increased reflexes found in these animals.

Future investigations should be aimed at evoking monosynaptic Ia and II EPSPs by muscle stretch to simulate better the increased stretch

reflexes evoked by tendon tap after spinalization. Also, a detailed investigation of the altered membrane conductances and firing properties of chronic spinal motoneurons would enhance the introductory findings of a decreased AHP duration, increased incidence of SAG, and change in subthreshold conductances.

Table 1: All entries represent mean values ± standard deviation in unlesioned (unles.) and 6 week chronic spinal (spinal) preparations. Numbers in brackets are the number of observations. The level of statistical significance of the difference between unlesioned and chronic spinal values (Student's t-test) is given beside the chronic spinal value (ns, $p > .1$). NT, not tested. See text for further details.

Table 1 Amplitudes, risetimes, and half-widths of "homonymous" EPSPs

	amplitude (mV)		risetime (ms)		half-width (ms)	
All Motoneurons						
A						
1.1T						
unles.	0.99 ±.78 (87)		.79 ±.25 (74)		6.13 ±2.34 (74)	
spinal	1.43 ±.89 (102)	.001	.56 ±.19 (102)	.001	4.10 ±1.73 (97)	.001
1.2T						
unles.	1.53 ±1.21 (149)		.71 ±.30 (136)		5.66 ±2.10 (134)	
spinal	1.95 ±1.27 (157)	.001	.56 ±.19 (157)	.001	3.89 ±2.10 (144)	.001
1.4T						
unles.	2.18 ±1.14 (77)		.69 ±.27 (76)		5.49 ±1.85 (72)	
spinal	2.76 ±1.85 (89)	.01	.54 ±.16 (89)	.001	3.35 ±1.77 (81)	.001
MG						
B						
1.1T						
unles.	1.01 ±.66 (29)		.65 ±.20 (28)		5.45 ±2.57 (28)	
spinal	1.22 ±.78 (36)	ns	.51 ±.20 (36)	.01	3.97 ±1.65 (34)	.001
1.2T						
unles.	1.50 ±.98 (58)		.57 ±.24 (58)		5.16 ±1.85 (58)	
spinal	1.57 ±.86 (62)	ns	.48 ±.15 (62)	.01	3.95 ±1.42 (57)	.001
1.4T						
unles.	2.27 ±1.29 (36)		.55 ±.21 (35)		4.90 ±1.47 (33)	
spinal	2.42 ±1.14 (46)	ns	.52 ±.13 (46)	ns	3.68 ±1.40 (41)	.001
LG						
C						
1.1T						
unles.	0.81 ±.81 (27)		.76 ±.28 (15)		6.28 ±2.66 (15)	
spinal	1.05 ±.60 (24)	ns	.51 ±.15 (24)	.001	3.42 ±1.20 (24)	.001
1.2T						
unles.	1.23 ±1.15 (48)		.74 ±.31 (35)		5.42 ±2.19 (35)	
spinal	1.80 ±1.24 (42)	.01	.54 ±.17 (42)	.001	2.93 ±1.71 (40)	.001
1.4T						
unles.	2.02 ±1.23 (14)		.79 ±.32 (14)		4.81 ±1.44 (13)	
spinal	3.27 ±2.41 (29)	.05	.51 ±.12 (29)	.001	2.26 ±0.95 (29)	.001
SOL						
D						
1.1T						
unles.	1.02 ±.56 (13)		.89 ±.18 (13)		6.77 ±1.93 (13)	
spinal	1.72 ±.90 (13)	.025	.68 ±.17 (13)	.01	4.93 ±2.10 (12)	.025
1.2T						
unles.	2.07 ±1.21 (15)		.95 ±.29 (15)		7.19 ±1.85 (15)	
spinal	2.54 ±1.59 (18)	ns	.69 ±.18 (18)	.01	4.99 ±2.88 (16)	.01
1.4T						
unles.	2.23 ±0.57 (9)		.94 ±.14 (9)		7.56 ±1.97 (9)	
spinal	2.84 ±2.74 (4)	NT	.75 ±.25 (4)	NT	7.00 ±3.54 (4)	NT
PL						
E						
1.1T						
unles.	1.18 ±1.02 (18)		.95 ±.22 (18)		6.58 ±1.80 (18)	
spinal	1.88 ±.99 (29)	.025	.62 ±.18 (29)	.001	4.52 ±1.89 (27)	.001
1.2T						
unles.	1.91 ±1.59 (28)		.85 ±.28 (28)		6.22 ±2.22 (26)	
spinal	2.51 ±1.47 (35)	.1	.66 ±.22 (35)	.01	4.42 ±2.50 (31)	.01
1.4T						
unles.	2.08 ±1.03 (18)		.78 ±.22 (18)		6.05 ±1.87 (17)	
spinal	2.82 ±2.24 (10)	ns	.68 ±.23 (10)	ns	3.89 ±1.57 (7)	NT

Table 2 **Amplitudes and risetimes of heteronymous EPSPs**

	amplitude (mV)		risetime (ms)	
Triceps				
unles.	*1.46 ±1.05 (38)		.70 ±.16 (31)	
spinal	2.67 ±1.93 (33)	.01	.53 ±.14 (30)	.001
LGS to MG				
unles.	**1.36 ±1.01 (18)		.76 ±.16 (12)	
spinal	2.58 ±1.50 (13)	.01	.51 ±.20 (11)	.01
MG to LG				
unles.	***1.55 ±1.10 (20)		.67 ±.16 (19)	
spinal	2.73 ±2.19 (20)	.025	.54 ±.10 (19)	.01

Amplitude and risetime measurements for heteronymous Ia composite EPSPs.

Table 2: (*) four, (**) one, and (***) three amplitudes ≤ 200 μV not included in calculation of mean in unlesioned preparations.

Table 3. Electrical properties of motoneurons with action potential heights ≥ 80 mV.

		Unlesioned			Chronic Spinal			
A								
A.P.	mV	88.2	±6.05	(87)	88.3	±6.10	(108)	ns
Em	mV	69.5	±6.5	(41)	69.7	±6.34	(28)	ns
B								
R_{inS}	MΩ	1.07	±0.51	(65)	0.97	±0.44	(82)	ns
R_{inL}	MΩ	1.09	±0.57	(83)	0.96	±0.50	(101)	ns
τ_m	ms	5.54	±1.80	(71)	4.61	±1.45	(91)	.001
τ_1	ms	0.92	±0.27	(66)	0.76	±0.25	(91)	.001
L		1.41	±0.16	(66)	1.41	±0.13	(91)	ns
T_{cap}	nF	9.4	±3.2	(64)	8.4	±2.8	(89)	.05
C								
SPCT	nA	37.7	±17.1	(79)	48.4	±17.6	(103)	.001
Rheo	nA	13.4	±7.9	(79)	15.3	±8.2	(101)	ns
V_{Th}	mV	11.6	±3.4	(69)	13.3	±4.5	(89)	.01
R_{inL}*Rheo	mV	11.2	±4.4	(77)	11.9	±4.9	(96)	ns
Rheo/R_{inL}	mV	18.7	±16.5	(77)	22.9	±16.7	(98)	.1
D								
AHP	ms	86.3	±26.7	(71)	76.6	±25.1	(91)	.05
AHPhd	ms	22.1	±8.5	(67)	20.3	±7.6	(83)	.05
AHPmV	mV	3.27	±1.53	(52)	3.67	±1.49	(63)	ns

Abbreviations: A.P., action potential height; Em, resting membrane potential; R_{inS}, input resistance from brief (.5ms) current pulse; R_{inL}, input resistance from long (50ms) current pulse; τ_m, membrane time constant; τ_1, equalization phase time constant; L, electrotonic length; T_{Cap}, total cell capacitance; V_{Th}, threshold voltage; SPCT, short pulse current threshold; Rheo, rheobase; R_{inL}*Rheo, calculated threshold voltage; V_{Th}/R_{inL}, calculated rheobase current; Rheo/R_{inL}, ratio of rheobase to input resistance; AHP, afterhyperpolarization duration; AHPhd, duration of AHP from peak voltage to half-decay; AHPmV, AHP peak voltage deflection.

Table 4. Membrane electrical properties of separate motoneuron species.

		MG		LG		SOL		PL	
τ_m	UL	5.71 ±1.67 (32)		5.00 ±1.76 (26)		7.23 ±2.39 (6)		5.41 ±1.22 (6)	
	CS	4.61 ±1.49 (32)	.01	4.17 ±1.16 (24)	.1	5.22 ±1.48 (6)	NT	4.79 ±1.01 (26)	ns
τ_1	UL	0.89 ±0.21 (31)		0.85 ±.19 (22)		1.31 ±.51 (6)		0.96 ±.18 (6)	
	CS	0.75 ±.24 (32)	.05	0.73 ±.20 (24)	.05	0.87 ±.28 (6)	NT	0.79 ±.28 (26)	ns
R_{InL}	UL	1.01 ±0.43 (38)		0.97 ±0.55 (30)		1.77 ±0.57 (6)		1.41 ±0.86 (8)	
	CS	0.84 ±0.42 (36)	.1	0.81 ±0.41 (27)	ns	1.59 ±0.40 (6)	NT	1.07 ±0.57 (29)	ns
L	UL	1.36 ±0.13 (31)		1.45 ±0.18 (22)		1.48 ±0.15 (6)		1.48 ±0.18 (6)	
	CS	1.38 ±0.13 (32)	ns	1.45 ±0.09 (24)	ns	1.41 ±0.15 (6)	NT	1.39 ±0.15 (26)	ns
T_{Cap}	UL	9.9 ±2.9 (29)		10.2 ±3.3 (22)		7.2 ±3.1 (6)		6.8 ±2.3 (6)	
	CS	9.4 ±2.7 (31)	ns	9.0 ±2.6 (24)	ns	5.2 ±1.7 (5)	NT	7.6 +2.4 (26)	ns
AHP	UL	82.4 ±21.2 (30)		84.5 ±31.2 (27)		119.4 ±23.7 (6)		83.9 ±15.4 (7)	
	CS	73.5 ±24.7 (31)	ns	72.1 ±21.6 (26)	.1	98.7 ±16.5 (5)	NT	78.7 ±28.5 (26)	ns
SPCT	UL	38.7 ±17.9 (37)		42.5 ±16.1 (28)		19.0 ±10.3 (5)		26.9 ±8.5 (8)	
	CS	52.4 ±16.0 (35)	.01	49.9 ±14.5 (29)	.1	22.2 ±9.2 (8)	NT	48.5 ±19.0 (27)	.005
Rheo	UL	14.0 ±7.4 (35)		16.1 ±8.1 (29)		4.6 ±2.0 (6)		7.4 ±4.0 (8)	
	CS	16.0 ±6.9 (35)	ns	18.4 ±8.7 (27)	ns	5.5 ±2.4 (7)	NT	13.9 ±8.3 (28)	.05
V_{Th}	UL	11.6 ±3.8 (30)		11.9 ±3.3 (26)		10.0 ±3.9 (4)		11.0 ±1.9 (8)	
	CS	13.9 ±3.6 (31)	.01	13.4 ±4.0 (23)	ns	10.1 ±6.3 (7)	NT	13.1 ±4.8 (25)	ns
Rh/R_{InL}	UL	18.8 ±13.1 (33)		25.2 ±19.9 (29)		2.8 ±1.6 (6)		7.5 ±5.9 (8)	
	CS	24.4 ±14.3 (35)	ns	29.1 ±16.6 (26)	ns	4.3 ±3.5 (5)	NT	20.2 ±18.6 (28)	.1

Abbreviations as in Table 3 except: NT, not tested.

Table 5. Electrical properties of motoneurons with action potentials of 60-79 mV. Abbreviations as in Table 3.

		Unlesioned			Chronic Spinal			
A.P.	mV	71.1	±5.4	(65)	71.6	±5.3	(63)	ns
Em	mV	57.4	±3.3	(9)	56.5	±5.6	(10)	ns
R_{inS}	MΩ	1.02	±0.77	(14)	.85	±0.45	(23)	ns
R_{inL}	MΩ	1.23	±0.85	(58)	1.05	±1.02	(52)	ns
τ_m	ms	5.15	±2.12	(18)	5.07	±2.14	(23)	ns
L		1.44	±0.14	(17)	1.41	±0.14	(22)	ns
T_{cap}	nF	10.4	±11.2	(16)	11.9	±11.8	(22)	ns
Rheobase	nA	10.1	±7.2	(50)	9.9	±6.0	(45)	ns
V_{Th}	mV	7.6	±3.0	(42)	7.9	±3.5	(41)	ns
SPCT	nA	25.0	±15.5	(49)	25.3	±13.3	(50)	ns
R_{inL}*Rheo	mV	8.5	±6.4	(39)	7.6	±7.0	(39)	ns
Rheo/R_{inL}	mV	15.1	±15.4	(47)	17.0	±17.0	(43)	ns
AHP	ms	95.0	±29.0	(43)	90.0	±25.0	(35)	ns
AHPhd	ms	25.9	±9.3	(41)	24.0	±8.0	(34)	ns
AHPmV	mV	3.9	±2.3	(22)	4.1	±2.0	(25)	ns

Table 6. Percentage distribution of motoneuron species into presumed motor unit types.

		FF		FR		S	
		%	n	%	n	%	n
all	UL	42	(45)	26	(29)	32	(35)
	CS	51	(64)	23	(39)	18	(23)
LG	UL	54	(21)	18	(7)	28	(11)
	CS	58	(22)	29	(11)	13	(5)
PL	UL	14	(3)	33	(7)	52	(11)
	CS	33	(11)	39	(13)	27	(9)
MG	UL	43	(21)	31	(15)	27	(13)
	CS	56	(31)	27	(15)	16	(9)
Munson et al. (1986)							
MG	UL	52	(FF & FI)	23		25	
	CS	70		10		19	
Mayer et al. (1984)							
MG	UL	52	(FF & FI)	23		25	
	CS	65		18		18	

Abbreviations: FF, presumed fast fatigable motoneurons; FR, presumed fast fatigue-resistant motoneurons; S, presumed slow motoneurons; LG, lateral gastrocnemius; PL, plantaris; MG, medial gastrocnemius; UL, unlesioned; CS, 6 week chronic spinal; (FF & FI), mechanically typed fast fatigable and fast intermediate-fatigable motoneurons combined.

Table 7. Mean "homonymous" EPSP risetime, half-width, and amplitude at 1.2T; heteronymous EPSP risetime and amplitude at 2T; and, ratio of "homonymous" amplitude to threshold voltage (amp/V_{Th}) for the three presumed motoneuron types.

		FF				FR				S			
HOMONYMOUS													
risetime	UL	0.51	±0.18	(38)		0.69	±0.15	(25)		0.79	±0.26	(37)	
	CS	0.50	±0.18	(55)	ns	0.52	±0.17	(34)	.0001	0.67	±0.19	(28)	.05
half-width	UL	3.68	±1.19	(34)		4.92	±0.78	(23)		6.59	±1.94	(36)	
	CS	3.03	±1.38	(51)	.05	3.40	±1.34	(33)	.0001	5.03	±2.02	(25)	.01
amplitude	UL	1.40	±1.09	(46)		1.21	±0.75	(27)		2.15	±1.26	(39)	
	*UL	1.65		(39)		1.31		(25)		2.26		(37)	
	CS	1.64	±1.08	(56)	ns	2.04	±1.21	(34)	.01	2.96	±1.98	(29)	.05
	*CS	1.67		(55)		2.04		(34)		3.06		(28)	
HETERONYMOUS													
risetime	UL	0.68	±0.21	(12)		0.72	±0.06	(6)		0.75	±0.16	(9)	
	CS	0.50	±0.14	(12)	.01	0.51	±0.08	(6)	.001	0.60	±0.18	(5)	.05
amplitude	UL	1.18	±0.77	(16)		1.66	±0.85	(6)		2.09	±1.15	(9)	
	CS	2.20	±1.32	(13)	.01	3.09	±2.59	(6)	ns	4.28	±2.41	(6)	.05
EXCITABILITY													
amp/V_{Th}	UL	0.17		(31)		0.13		(23)		0.32		(31)	
	CS	0.16		(49)	ns	0.21		(29)	.01	0.36		(26)	ns

* - ≤ 200 μV EPSPs not included

Values are given as mean ± standard deviation with sample number in brackets. All statistical tests using student's t-test with .05, .01, .001, and .0001 representing levels of probability; ns, not significant;

Table 8. Mean motoneuron membrane properties for the three presumed motoneuron types.

		FF				FR				S			
A.P. (mV)	UL	82.9	±8.3	(48)		81.8	± 9.3	(31)		81.3	±10.5	(45)	
	CS	85.7	±7.3	(65)	ns	80.7	±10.1	(41)	ns	84.8	± 9.9	(35)	ns
τ_m (ms)	UL	4.47	±0.91	(37)		5.14	±1.10	(16)		7.02	±2.08	(25)	
	CS	3.81	±0.89	(53)	.001	5.02	±1.55	(26)	ns	5.93	±1.23	(25)	.05
R_{In} (MΩ)	UL	0.62	±0.15	(48)		0.91	±0.21	(31)		1.77	±0.70	(45)	
	CS	0.60	±0.15	(65)	ns	0.86	±0.21	(41)	ns	1.63	±0.43	(32)	ns
L	UL	1.46	±0.14	(35)		1.40	±0.14	(15)		1.37	±0.17	(22)	
	CS	1.43	±0.12	(52)	ns	1.40	±0.12	(26)	ns	1.38	±0.15	(25)	ns
T_{Cap}	UL	12.10	±2.70	(35)		8.87	±2.18	(15)		6.81	±2.14	(22)	
	CS	10.35	±3.24	(52)	.01	9.48	±2.91	(26)	ns	5.42	±1.43	(25)	.01
rheobase(nA)	UL	19.7	±5.1	(48)		11.6	±3.1	(31)		4.3	±2.5	(45)	
	CS	20.6	±5.4	(65)	ns	10.5	±3.2	(41)	ns	4.7	±2.2	(32)	ns
V_{Th} (mV)	UL	11.6	±3.7	(39)		10.4	±3.1	(28)		8.6	±3.7	(39)	
	CS	13.2	±4.3	(57)	ns	11.2	±4.0	(36)	ns	9.9	±5.9	(32)	ns
SPCT (nA)	UL	47.4	±14.2	(47)		31.3	±12.0	(30)		18.3	± 9.6	(36)	
	CS	54.2	±15.9	(63)	.05	35.6	±15.5	(39)	ns	23.3	±15.0	(32)	ns
AHP (ms)	UL	79.5	±21.4	(43)		81.9	±17.1	(27)		110.5	±31.5	(35)	
	CS	69.0	±16.9	(59)	.01	79.1	±24.6	(32)	ns	104.5	±27.4	(28)	ns
AHP_{mV} (mV)	UL	2.36	±0.97	(28)		3.13	±1.15	(18)		4.84	±2.01	(24)	
	CS	2.99	±1.12	(38)	.05	3.60	±1.03	(26)	ns	5.70	±1.50	(19)	ns
CV (m/s)	UL	88.8	±11.5	(30)		81.9	± 8.6	(14)		74.5	±14.2	(20)	
	CS	81.6	± 8.6	(56)	.005	79.7	±10.1	(27)	ns	75.0	± 8.7	(21)	ns

Table 9. Percentage distribution of motoneuron species for each presumed unit type.

		MG	LG	PL	S
UL	FF	48%	46%	7%	0%
CS	FF	49%	33%	17%	0%
UL	FR	50%	23%	27%	0%
CS	FR	38%	26%	33%	3%
UL	S	28%	26%	26%	21%
CS	S	29%	16%	29%	26%

Table 10. Comparison of calculated mean EPSP values verses experimental mean EPSP values.

		FF		FR		S		Actual
EPSP amplitude								
MG								
	UL	1.40(.45)	+	1.21(.31)	+	2.15(.24)	= 1.52mV	1.50mV
	CS	1.64(.56)	+	2.04(.27)	+	2.96(.16)	= 1.94mV	1.57mV
LG								
	UL	1.40(.54)	+	1.21(.18)	+	2.15(.28)	= 1.58	1.23
	CS	1.64(.58)	+	2.04(.28)	+	2.96(.14)	= 1.94	1.80
PL								
	UL	1.40(.14)	+	1.21(.36)	+	2.15(.50)	= 1.71	1.91
	CS	1.64(.33)	+	2.04(.39)	+	2.96(.27)	= 2.14	2.51
EPSP risetime								
MG								
	UL	.51(.45)	+	.69(.31)	+	.79(.24)	= .63ms	.57ms
	CS	.50(.56)	+	.52(.27)	+	.67(.16)	= .53	.48
LG								
	UL	.51(.54)	+	.69(.18)	+	.79(.28)	= .63	.76
	CS	.50(.58)	+	.52(.28)	+	.67(.14)	= .53	.51
PL								
	UL	.51(.14)	+	.69(.36)	+	.79(.50)	= .71	.85
	CS	.50(.33)	+	.52(.39)	+	.67(.27)	= .55	.66
EPSP half-width								
MG								
	UL	3.68(.45)	+	4.92(.31)	+	6.59(.24)	= 4.76ms	5.45ms
	CS	3.03(.56)	+	3.40(.27)	+	5.03(.16)	= 3.42	3.97
LG								
	UL	3.68(.54)	+	4.92(.18)	+	6.59(.28)	= 4.72	5.42
	CS	3.03(.58)	+	3.40(.28)	+	5.03(.14)	= 3.41	2.93
PL								
	UL	3.68(.14)	+	4.92(.36)	+	6.59(.50)	= 5.58	6.22
	CS	3.03(.33)	+	3.40(.39)	+	5.03(.27)	= 3.68	4.42

Table 11. Mean "homonymous" EPSP values between ankle extensor motoneuron species for the 3 presumed unit types.

Presumed FF

		MG	LG	PL
rt	UL	.47 (21)	.55 (13)	.62 (3)
	CS	.48 (29)	.48 (17)	.66 (9)
hw	UL	3.91 (19)	3.37 (13)	3.32 (1)
	CS	3.42 (27)	2.44 (17)	2.76 (7)
amp	UL	1.67 (21)	1.19 (20)	1.61 (3)
	CS	1.56 (29)	1.68 (17)	1.66 (10)

Presumed FR

		MG	LG	PL
rt	UL	.63 (12)	.76 (5)	.71 (7)
	CS	.44 (14)	.58 (9)	.58 (9)
hw	UL	4.86 (11)	5.29 (5)	4.73 (6)
	CS	3.67 (13)	3.04 (9)	3.54 (9)
amp	UL	1.59 (12)	1.02 (7)	0.86 (7)
	CS	2.07 (14)	1.82 (9)	2.15 (9)

Presumed S

		MG	LG	PL	SOL
rt	UL	.56 (9)	.94 (8)	.80 (9)	.89 (10)
	CS	.53 (7)	.68 (5)	.74 (5)	.69 (8)
hw	UL	6.10 (9)	7.10 (8)	5.00 (8)	7.72 (10)
	CS	4.57 (6)	4.13 (4)	5.65 (4)	5.49 (8)
amp	UL	2.05 (9)	2.21 (10)	2.52 (9)	1.97 (10)
	CS	2.21 (7)	3.77 (5)	2.77 (6)	3.18 (8)

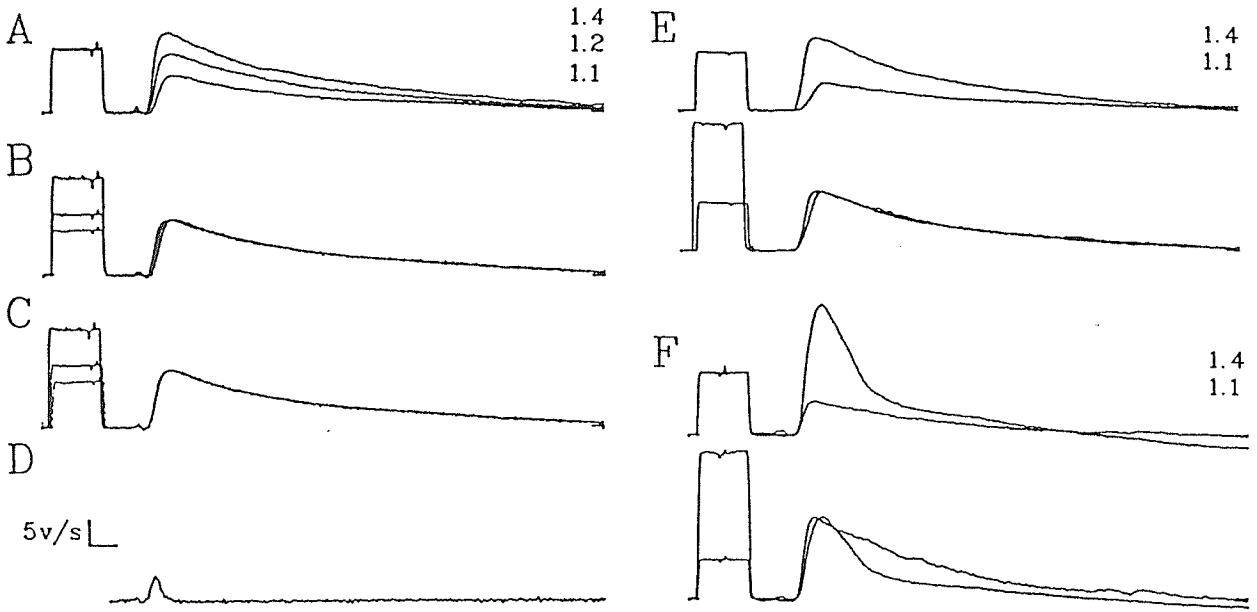


Figure 1.

Examples of composite Ia EPSPs evoked by different strengths of nerve stimulation (T, times threshold) . Records in A-D are from an MG motoneuron, in E from another MG and in F from an LG motoneuron; all traces are the averages of 32 sweeps digitized at 40μs per point. The calibration pulse is 2 mV, 2 ms in all panels. EPSPs were amplitude-normalized in B, C, and the lower traces in E and F. In C and the lower traces in E and F, normalized EPSPs were shifted horizontally in order to align the initial rising phases of the EPSPs. The trace in D is the derivative of the EPSP evoked at 1.2T in panel A.

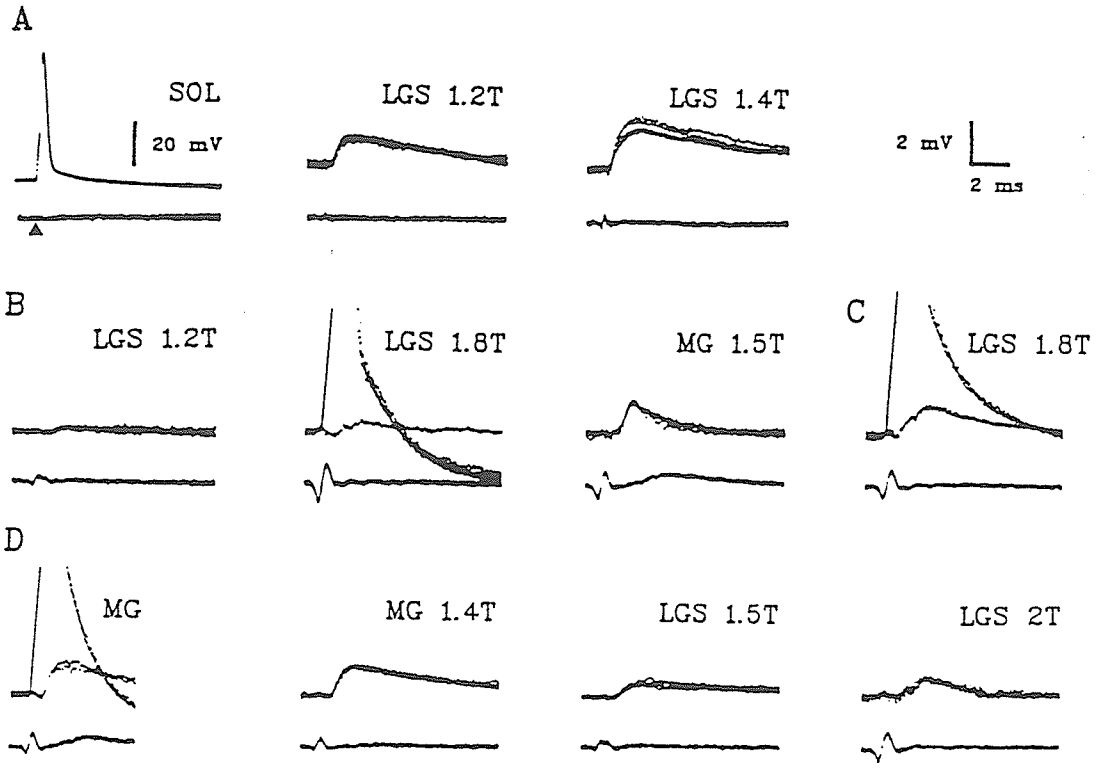
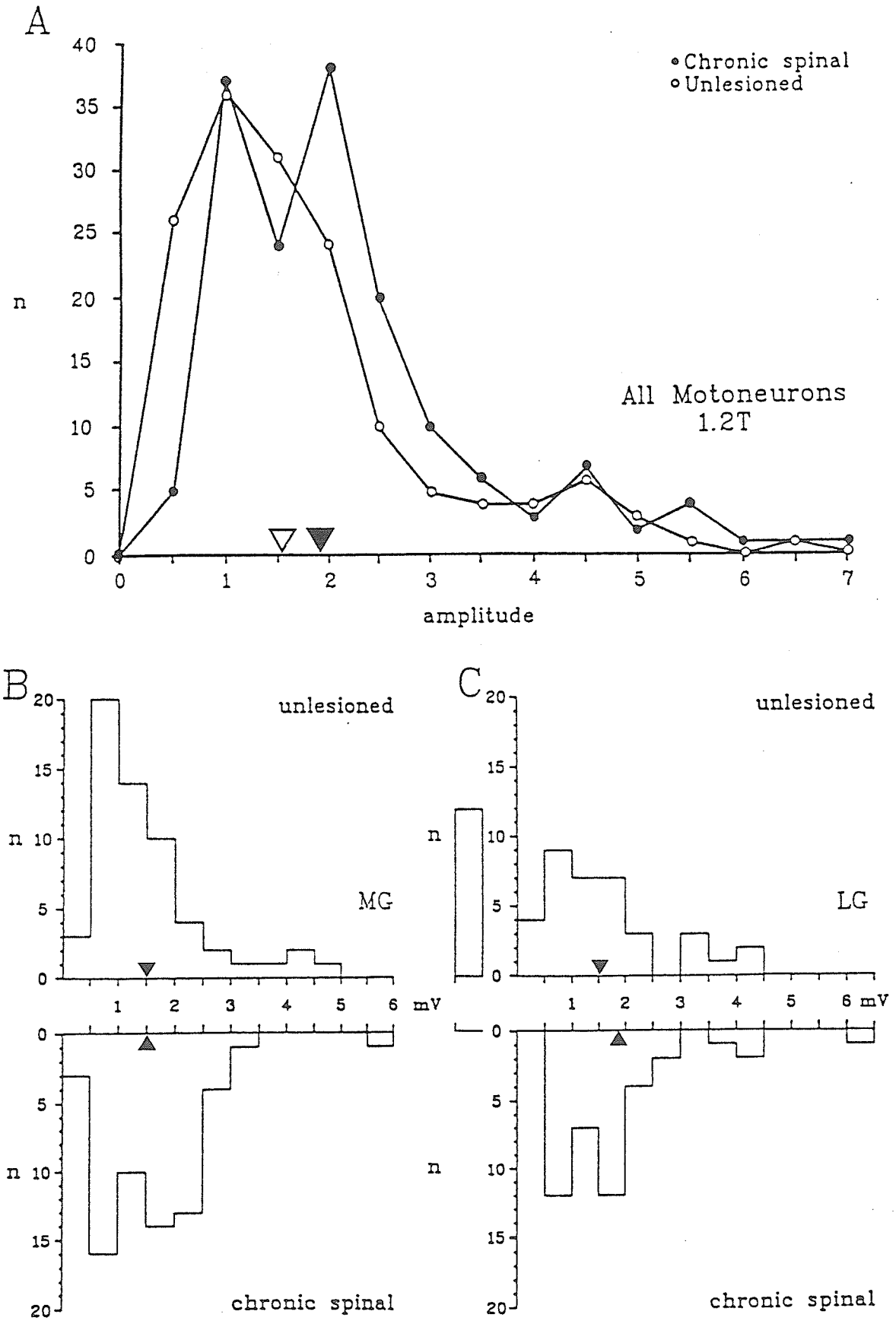


Figure 2.

Composite EPSPs recorded from a SOL (panel A), two LG (B and C) and a MG (D) motoneuron in the same experiment. This figure shows an example of a minimal amplitude EPSP in an LG motoneuron from an unlesioned preparation in the leftmost set of records in panel B. Each set of records consists of 4 superimposed traces with the intracellular records displayed above the cord dorsum recording. The arrow in the left panel in A indicates the arrival of the nerve volley at the cord dorsum. Note that the gain of the cord dorsum recording in panel A is lower than in panels B-D. The voltage calibration applies to the intracellular records only. Stimulation of the LGS nerve produced substantial EPSPs in the SOL motoneuron in panel A and the MG motoneuron in D. The LG motoneuron in B received substantially larger EPSPs from the heteronymous MG nerve than from stimulation of the combined homonymous and heteronymous LGS nerve. LGS effects in this cell failed to grow appreciably even at 1.8T, the antidromic threshold. The next two cells penetrated, an LG (panel C) and an MG (D), received larger EPSPs from the same nerve. The rising phases of the action potentials in B-D have been retouched for illustration.

Fig. 3.

Amplitudes of Ia composite "homonymous" EPSPs evoked at 1.2T. Panel A shows the amplitudes of 1.2T EPSPs in the pooled sample of MG, LG, SOL and PL motoneurons with the unlesioned values in open and chronic spinal values in filled circles. In the histograms in B and C and Figures 4 and 6, data from unlesioned preparations are plotted above and those from 6 week chronic spinal preparations below. Panel B contains homonymous 1.2T EPSP amplitudes recorded in MG motoneurons and C contains mixed 1.2T EPSP amplitudes in LG motoneurons. The histogram bars to the left of the ordinate in C show the incidence of EPSPs recorded in LG that were undetectable or clearly less than 200 μV. All EPSPs in chronic spinal LG were greater than 500 μV. The arrows indicate mean values for the sample. Note the increased mean in the chronic spinal preparation in the pooled data (A) and in LG motoneurons (C). The mean unlesioned value indicated in C was calculated with EPSPs smaller than 200 μV omitted.


A
Chronic spinal
Unlesioned
All Motoneurons
1.2T
n
amplitude
B
unlesioned
MG
chronic spinal
C
unlesioned
LG
chronic spinal
mV

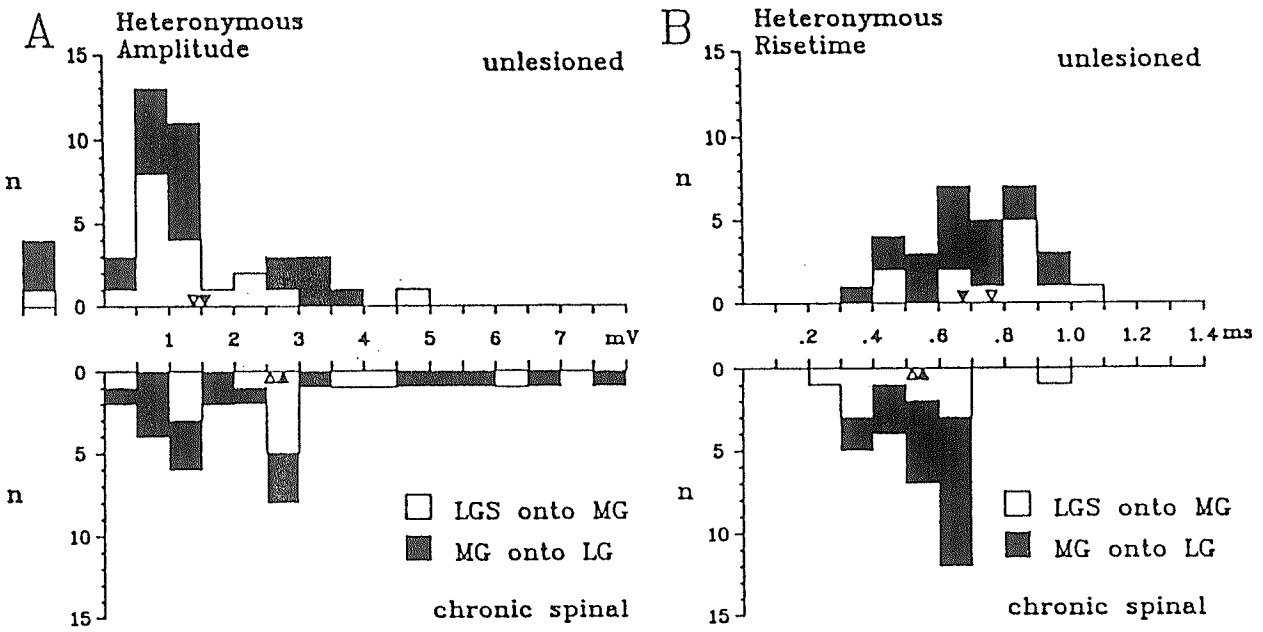


Figure 4.

Amplitudes (panel A) and 10 - 90% risetime (panel B) of heteronymous Ia EPSPs in unlesioned (upper histograms) and 6 week chronic spinal animals (lower histograms). Open squares represent EPSPs evoked by stimulating the LGS nerve and recording in MG motoneurons while filled squares are EPSPs recorded in LG motoneurons from stimulation of the MG nerve. The open and filled arrows indicate the corresponding mean values. Nerves were stimulated at 2T. The histogram bar to the left of the ordinate in A indicates the incidence of motoneurons with undetectable heteronymous EPSPs.

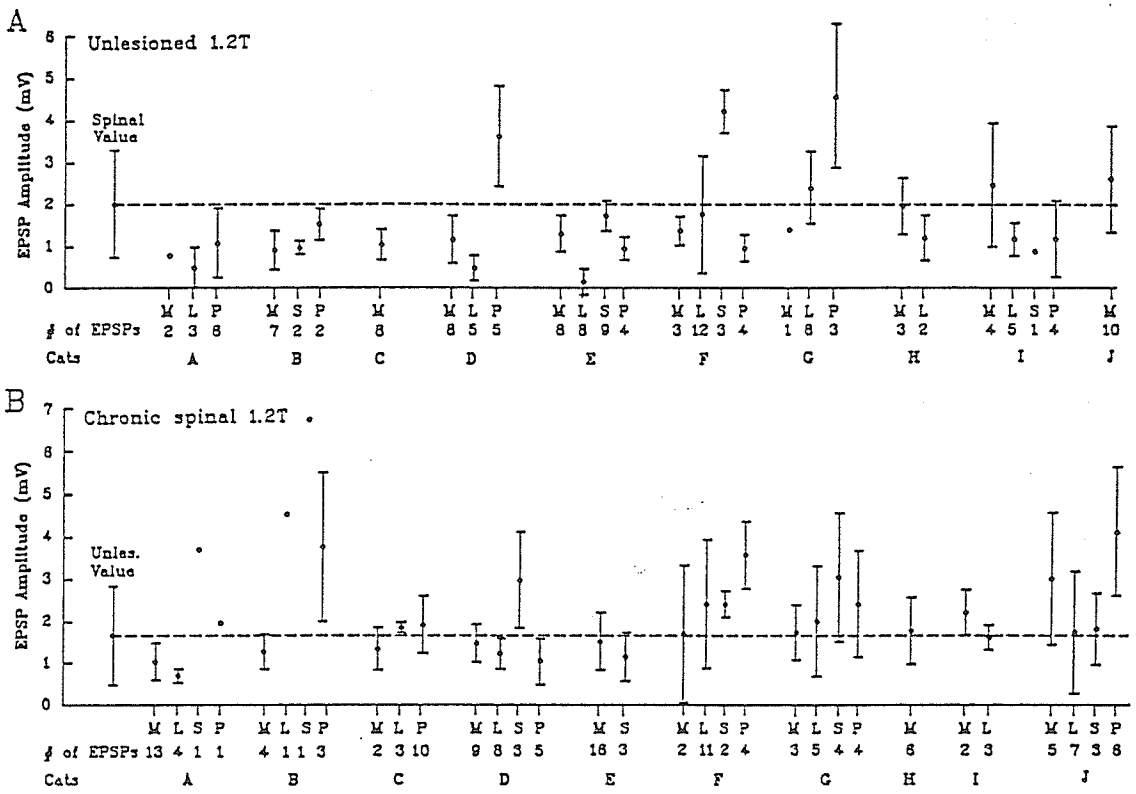


Figure 5.

Amplitude variability among several experiments in unlesioned (A) and chronic spinal (B) preparations. Individual experiments are represented by a letter (A-J). Within each experiment, amplitudes (mean ± S.D.) of 1.2T EPSPs in individual motoneuron species are plotted above a letter corresponding to the motoneuron species (M=MG, L=LG, S=SOL, P=PL). Below each letter, the number of motoneurons from which the mean EPSP amplitude is calculated is given. For example, the leftmost the dashed horizontal line and the vertical bar represent the pooled mean amplitude ± S.D. for chronic spinal (A) and unlesioned (B) amplitudes. Note that some unlesioned cats had EPSP amplitudes greater than the overall spinal mean value. Conversely, there were spinal experiments with EPSPs smaller than the overall mean unlesioned amplitude.

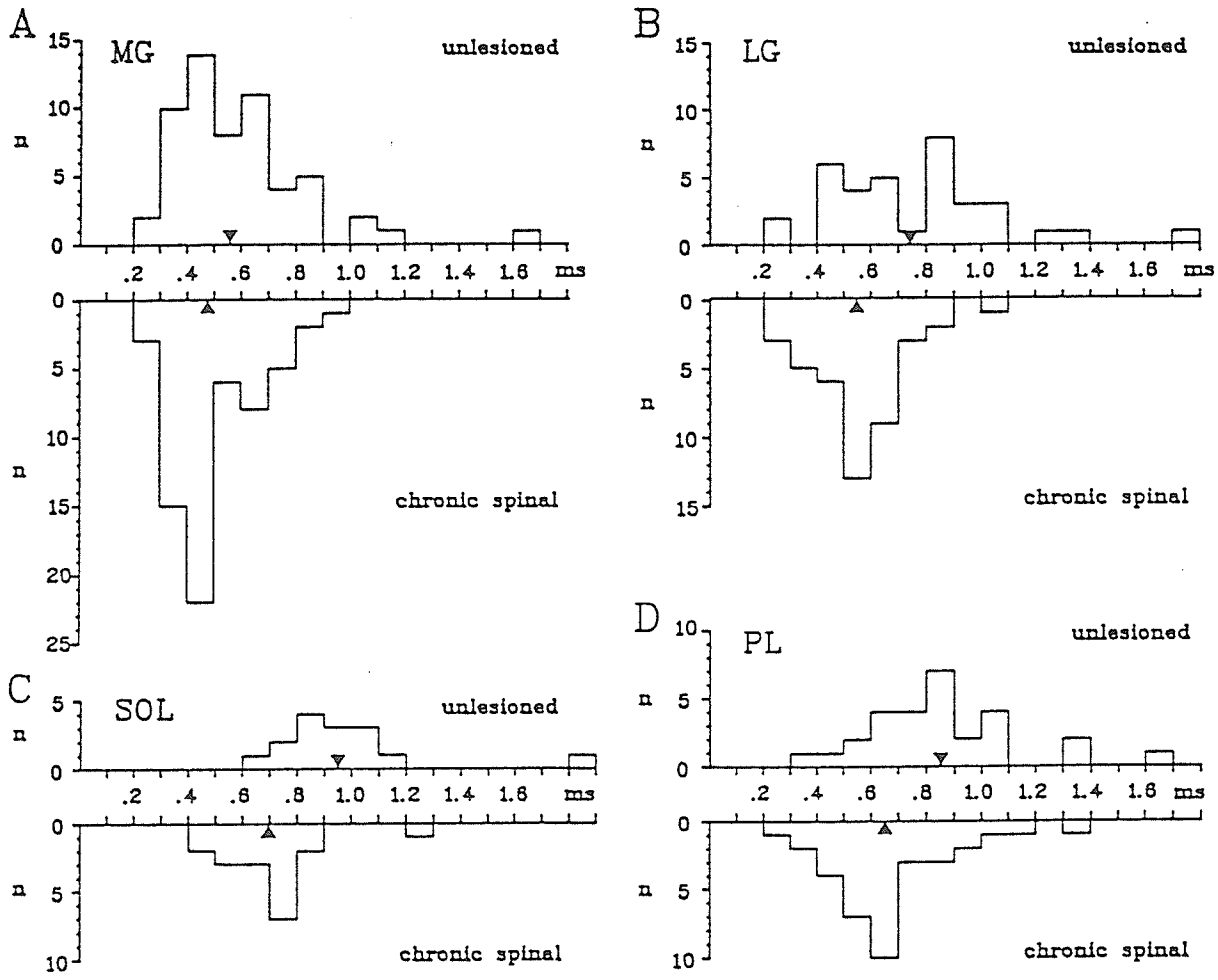


Fig. 6.

Risetime of "homonymous" Ia composite EPSPs evoked at 1.2T in MG, LG, SOL and PL motoneurons (panels A-D respectively). Note the decreased mean 10 - 90% risetime in the chronic spinal preparation in all four motoneuron species.

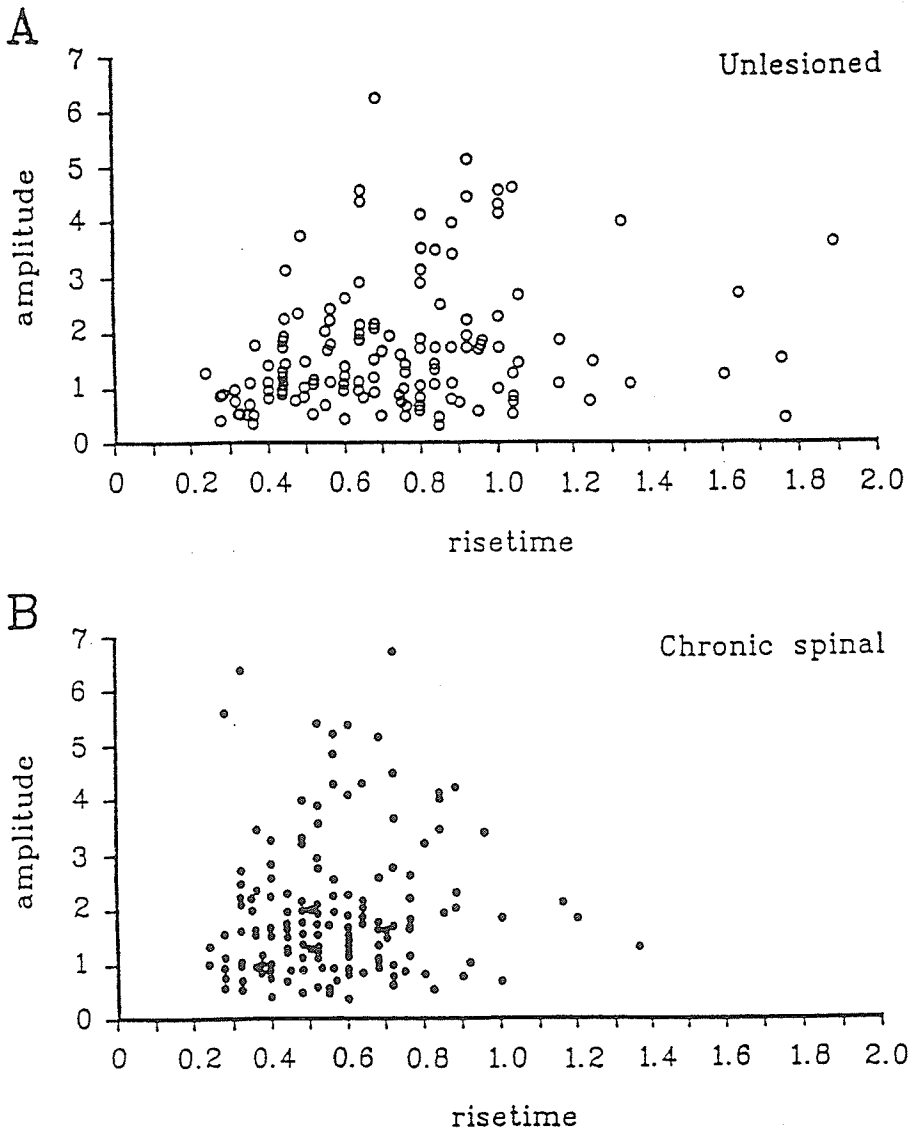


Fig. 7.

The risetimes of 1.2T "homonymous" EPSPs are plotted against their amplitudes in unlesioned (A) and chronic spinal (B) preparations using pooled data from all four motoneuron species. Note the increased incidence of large-amplitude, short-risetime EPSPs in the 6 week chronic spinal preparation.

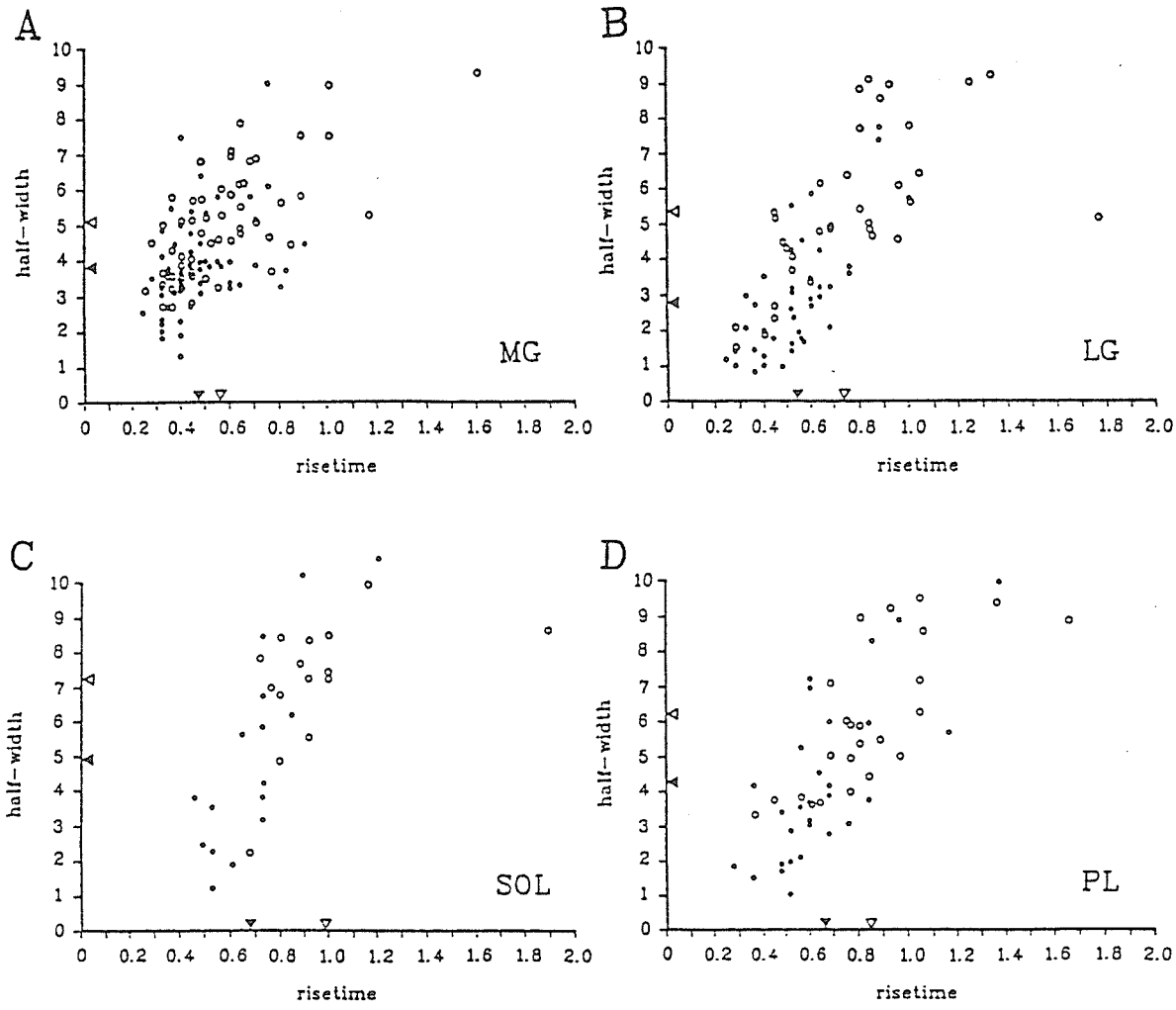
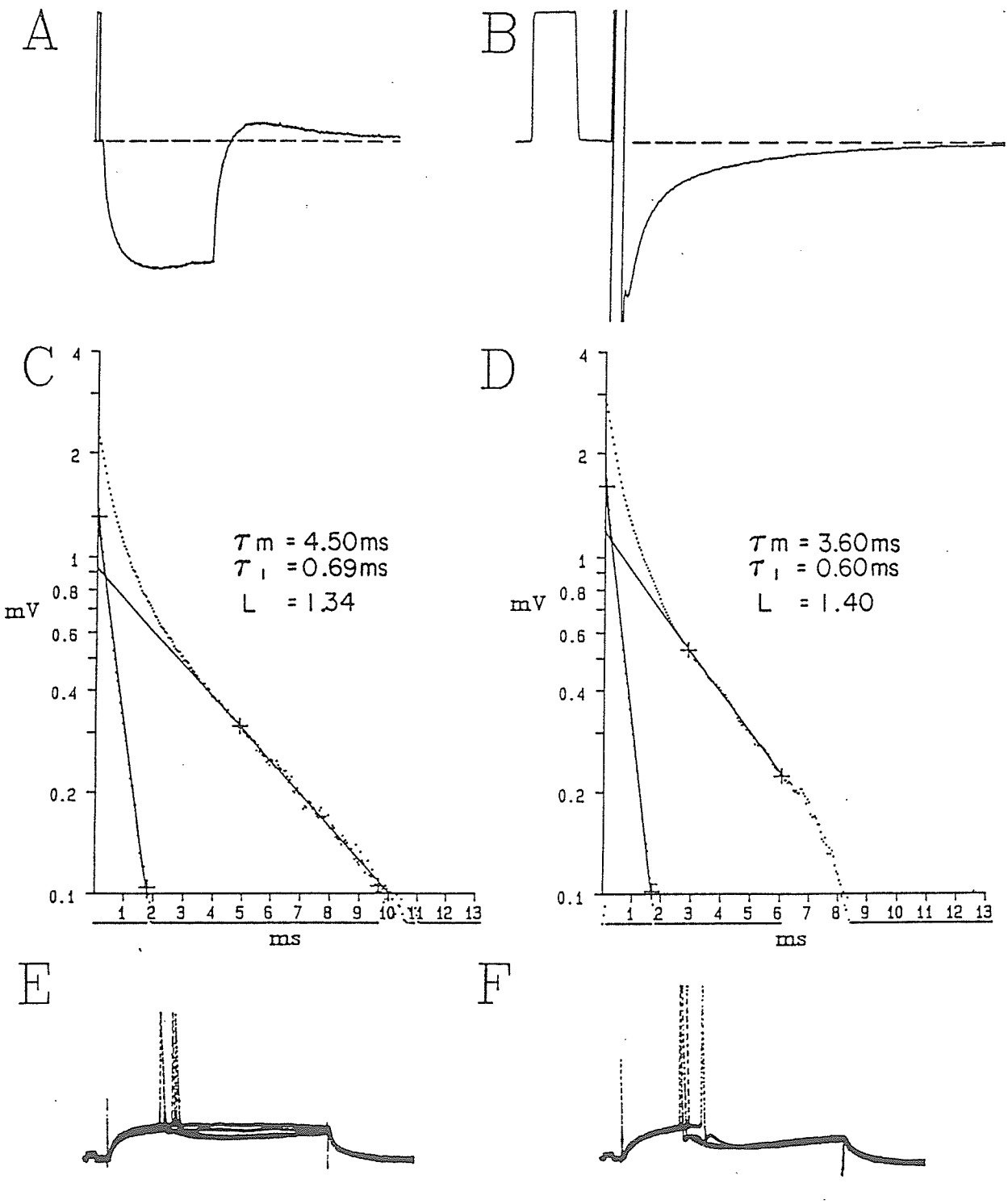


Fig. 8.

Shape index plots (half-width vs. risetime) for "homonymous" composite Ia EPSPs evoked at 1.2T in MG (A), LG (B), SOL (C), & PL (D) motoneurons. The open circles and dots represent EPSP shape measurements from unlesioned and chronic spinal animals respectively.

Figure 9.

Methods for estimating some membrane electrical properties. A: Averaged intracellular record (64 sweeps) of the voltage response to a 2 nA hyperpolarizing current pulse (50 ms). Note the slight "sag" developing about halfway through the voltage response. The dotted line represents baseline to help distinguish the overshoot following current pulse termination. R_{inL} was determined from the peak voltage deflection occurring shortly after current onset. B: The averaged voltage transient (256 sweeps) from a brief (.5 ms) hyperpolarizing current pulse (15 nA) in the same cell as A is used to estimate passive membrane properties (τ_m, L, and R_{inS}). Stimulus artefact contaminates the rising phase of the voltage transient. Note that the transient decays without an overshoot. C: A semilogarithmic plot of the voltage transient in B to illustrate the linear regression "peel" procedure used to estimate τ_m, and τ_1, and calculate L. D: semilogarithmic plot of decaying voltage transient from another motoneuron displaying an obvious increase in slope occurring at ≈6 ms, which is considered to be due to the activation of a SAG process. E,F: Four superimposed sweeps of an oscilloscope tracing of the voltage deflection at rheobase of 2 motoneurons requiring large currents (32 nA in E; 17 nA in F). Note that in both cases the electrode is well balanced at the make and break points confirming an absence of electrode polarization; this ensures an accurate measurement of thresold voltage (V_{Th}) obtained from simultaneous photographs from a second oscilloscope with higher gain (not shown). In A,B,E, and F, the calibration pulse is 2 mV, 2 ms.


A
B
C
D
E
F
τm = 4.50ms
τ1 = 0.69ms
L = 1.34
τm = 3.60ms
τ1 = 0.60ms
L = 1.40
mV
ms
4
2
1
0.8
0.6
0.4
0.2
0.1
1 2 3 4 5 6 7 8 9 10 11 12 13

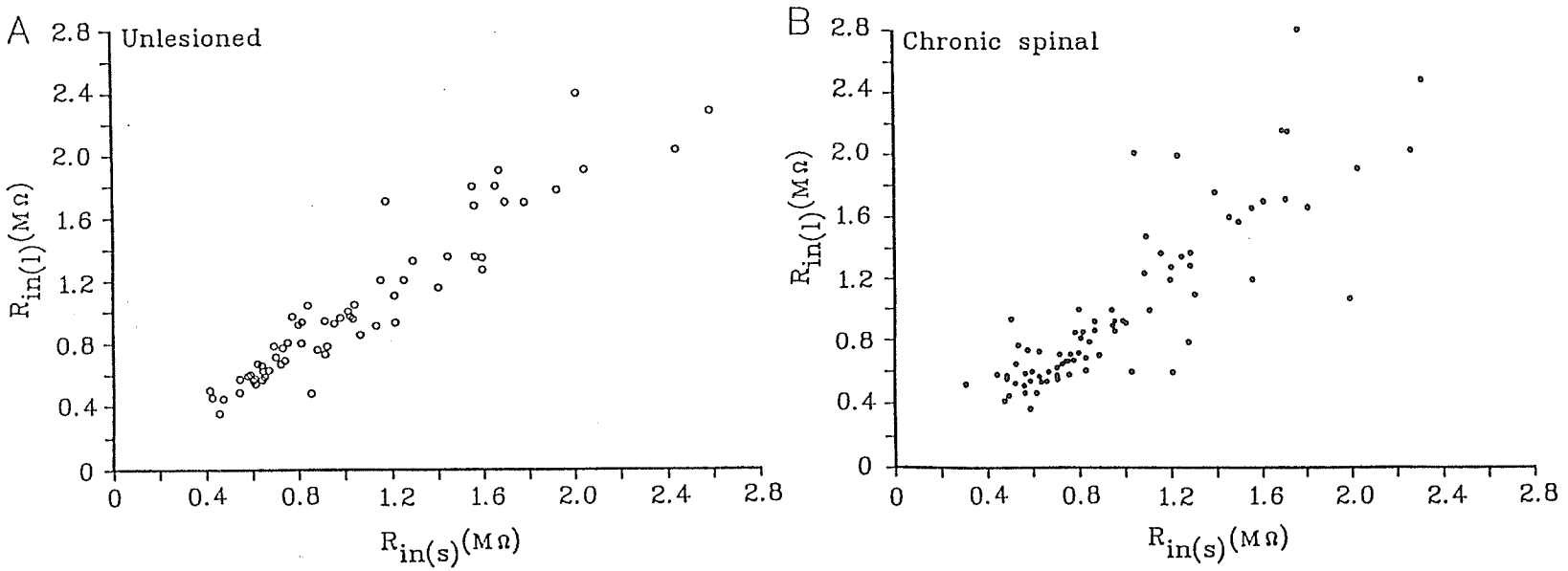


Figure 10.

Scatterplot of input resistance estimated by integration of the voltage transient produced by 0.5ms current pulses (R_{inS}) and input resistance measured from the peak deflection of a 50ms current pulses (R_{inL}) in unlesioned (A) and chronic spinal preparations (B). For A, r = 0.95; for B, r = 0.86.

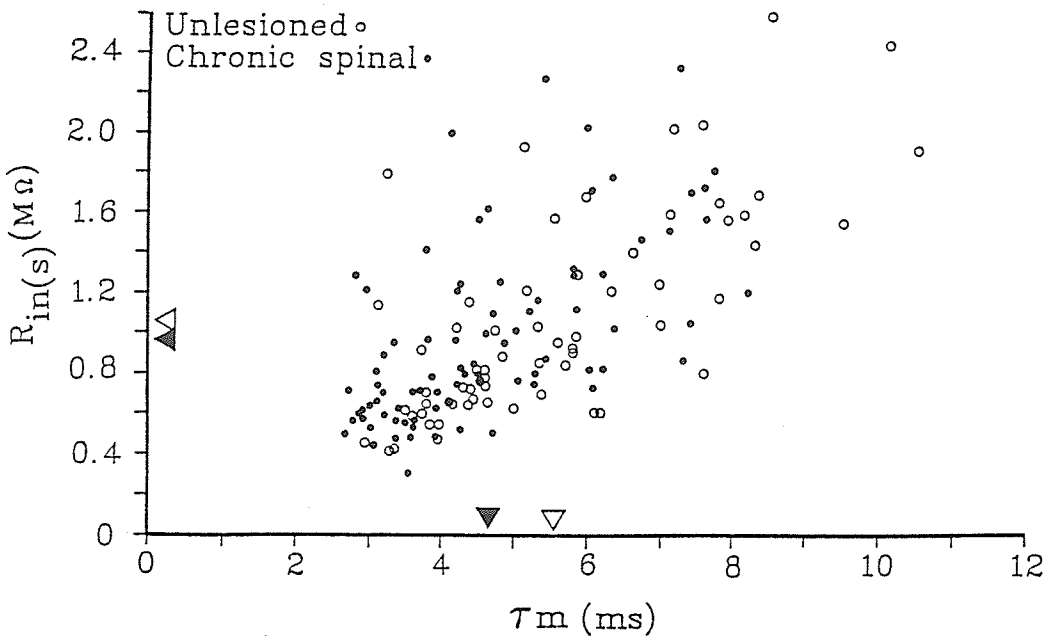


Figure 11.

Scatterplot of membrane time constant (τ_m) and input resistance (R_{inS}) in unlesioned (open circles; r = 0.69) and chronic spinal (dots; r = 0.68) preparations. Triangles on axes represent mean values in unlesioned (open triangles) and chronic spinal (closed triangles) preparations.

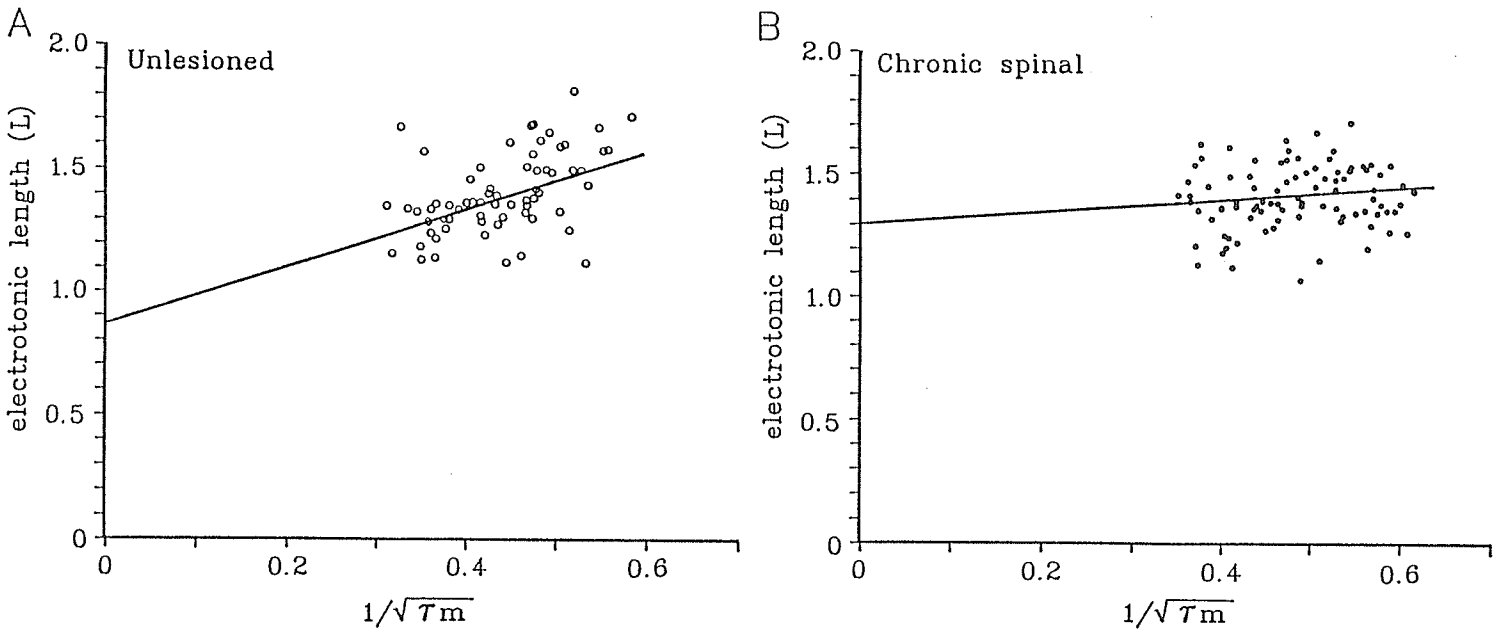


Figure 12.

Scatterplot of $1/\sqrt{\tau_m}$ and electrotonic length (L) in unlesioned (A) and chronic spinal (B) preparations. The solid line represents the best fit linear regression interpolated to the Y-intercept. For A, r = 0.50; for B, r = 0.13.

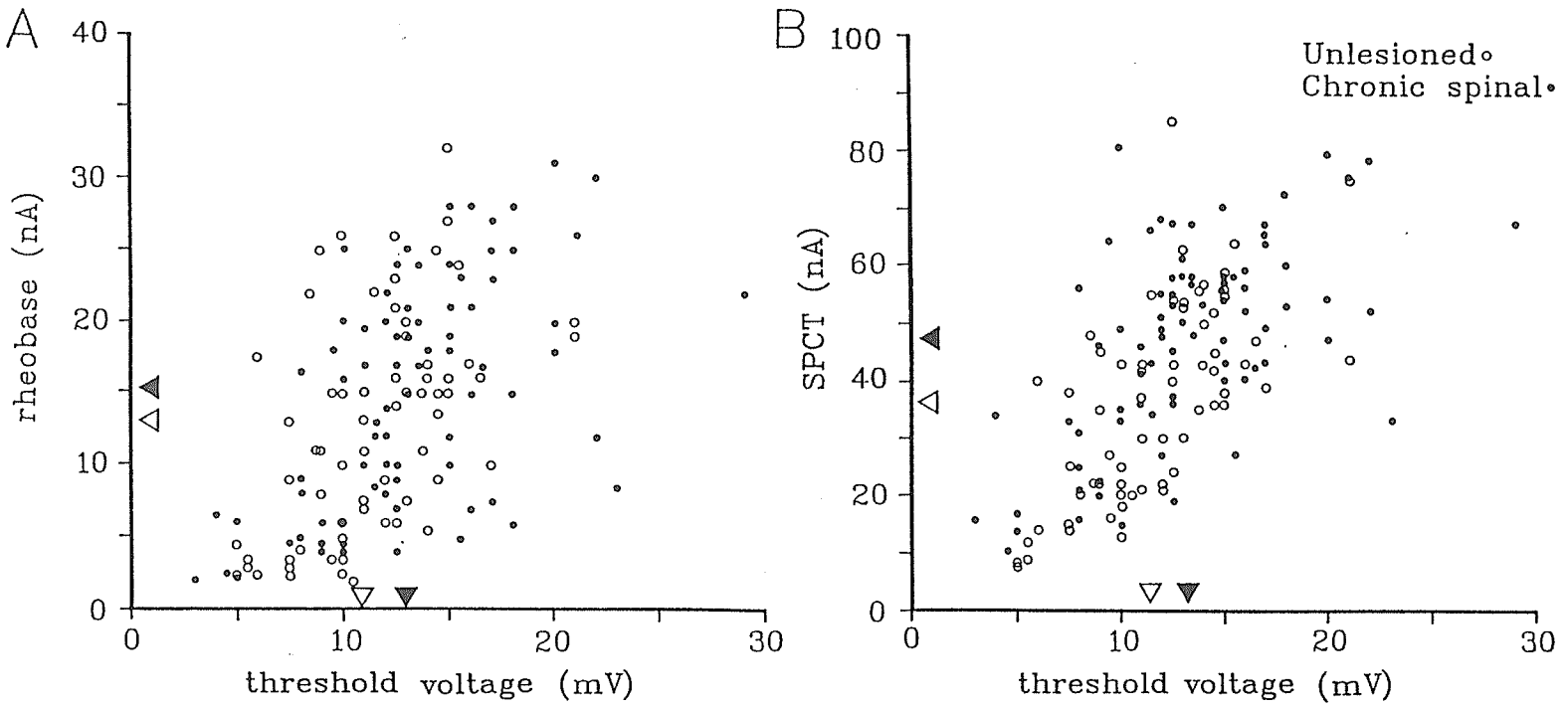


Figure 13.

Scatterplot of threshold voltage (V_{Th}) and rheobase (A) or short pulse current threshold (SPCT) (B). Symbols as in Figure 3. For A, r = 0.52 in unlesioned and 0.54 in chronic spinal preparations. For B, r = 0.67 in unlesioned and 0.61 in chronic spinal preparations.

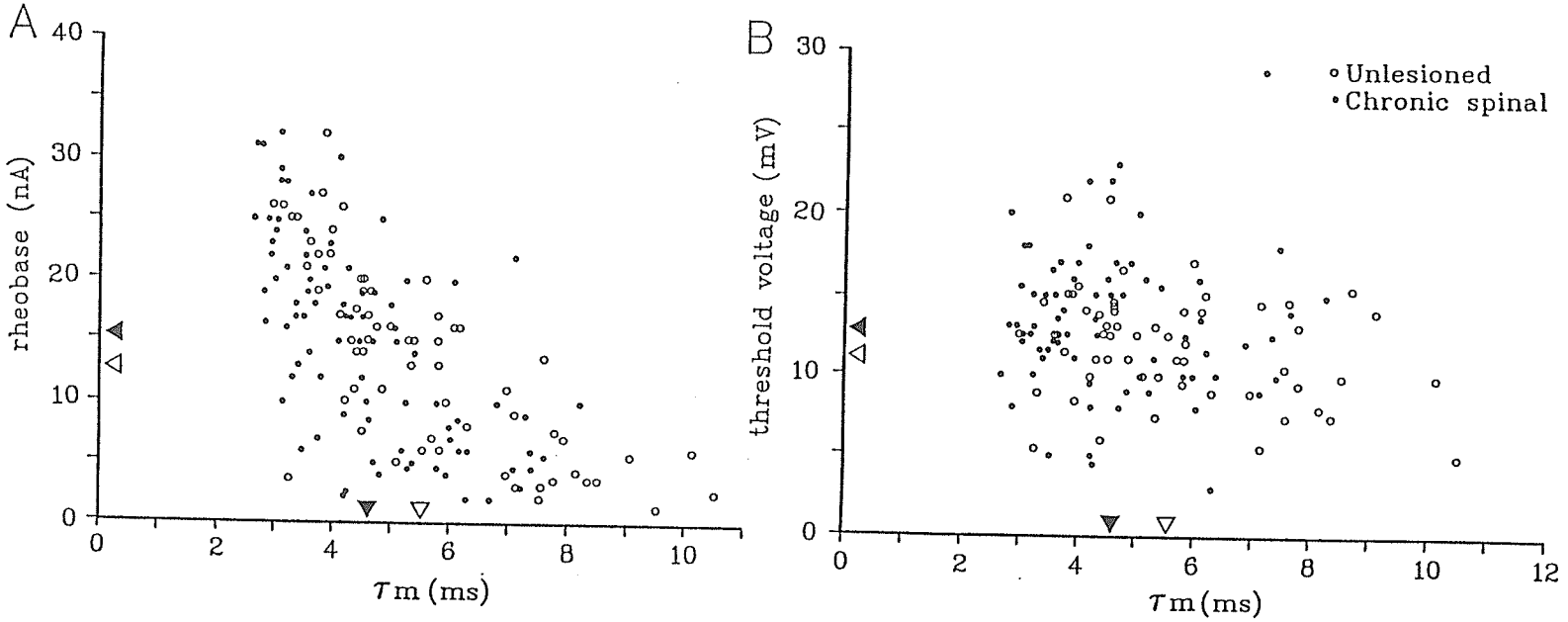


Figure 14.

Scatterplot of membrane time constant (τ_m) and rheobase (A) or threshold voltage (V_{Th}) (B). Symbols as in Fig 3. For A, r = -0.76 in unlesioned and -0.64 in chronic spinal preparations. For B, r = -0.33 in unlesioned and 0.00 in chronic spinal preparations.

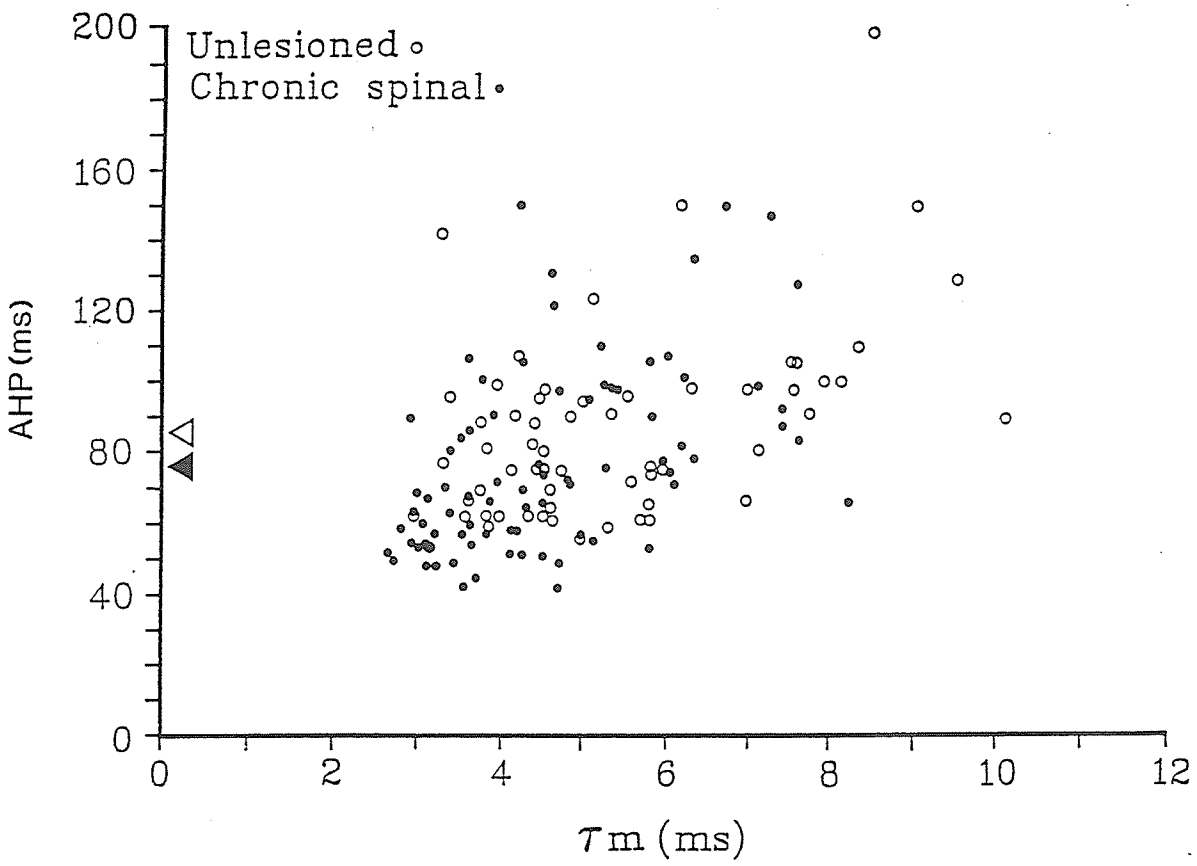


Figure 15.

Scatterplot of membrane time constant (τ_m) and AHP duration. For unlesioned, r = 0.49; for chronic spinal r = 0.51.

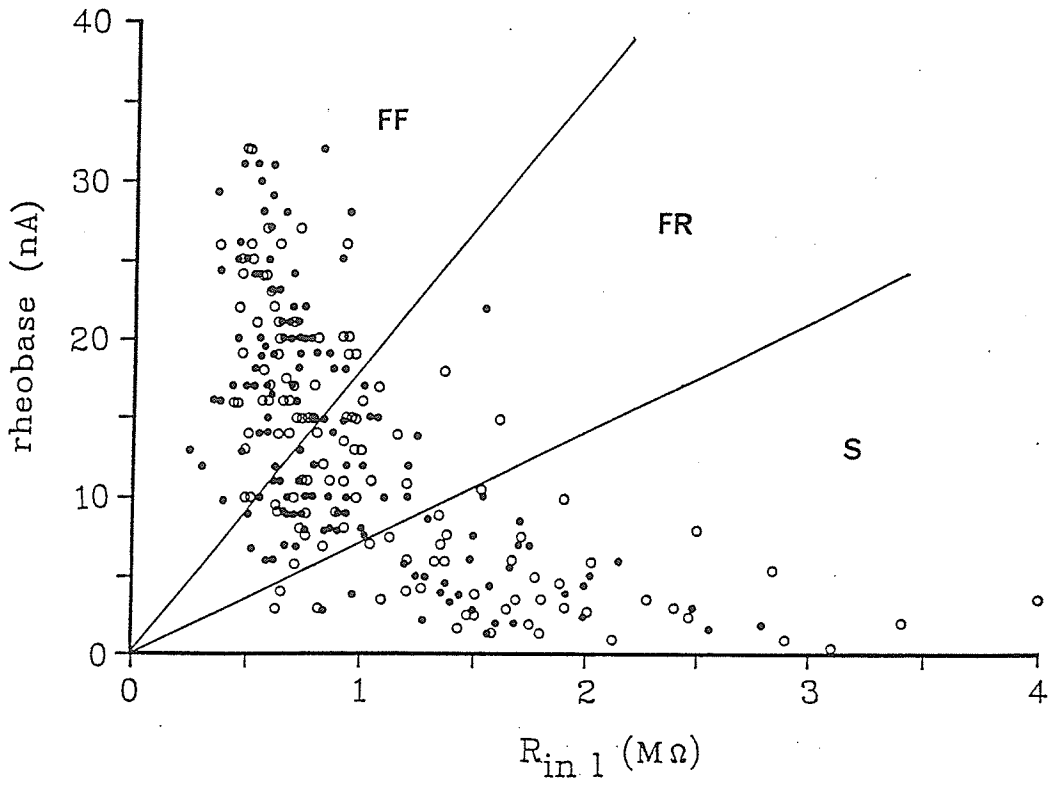


Figure 16.

Scatterplot of input resistance (R_{in}) and rheobase. The two lines extending from the origin represent slopes of 7 and 18 nA/MΩ that approximately divide motoneurons into the 3 major catogories of unit type according to Zengel et al., 1985. The open circles represent data from unlesioned animals and the dots are from chronic spinal animals.

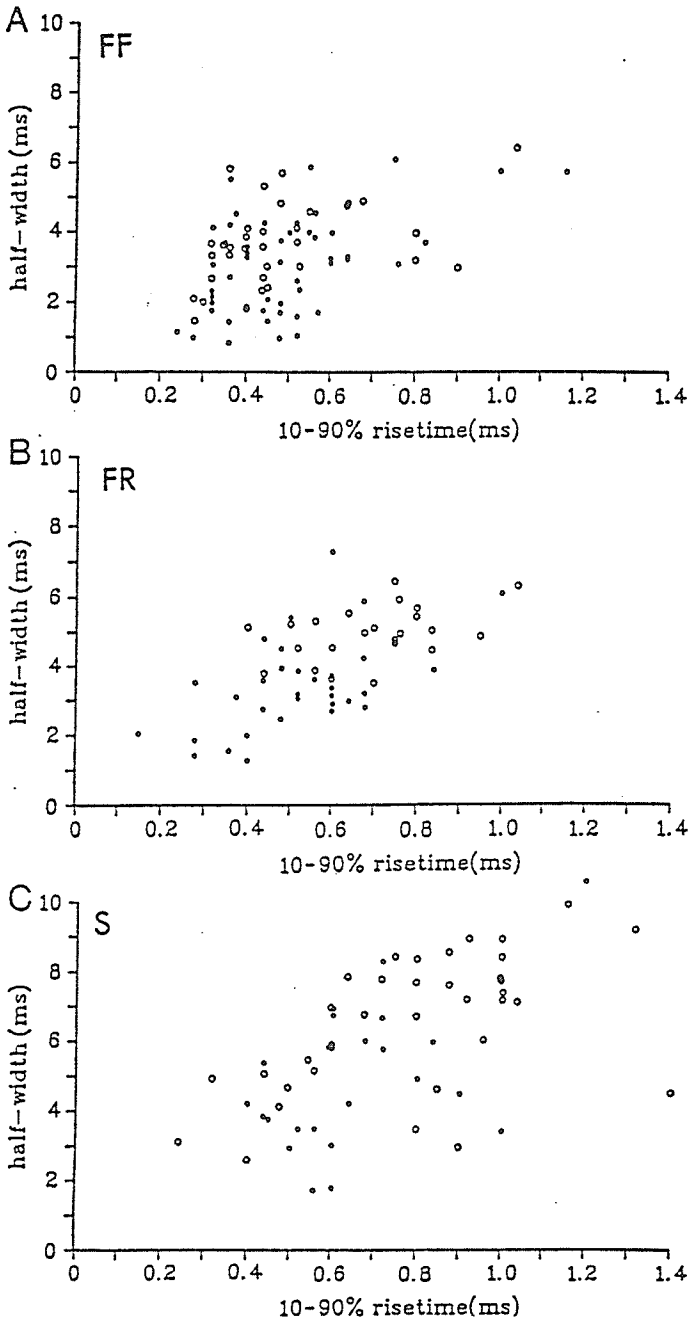


Figure 17.

Scatterplots of "homonymous" Ia EPSP 10-90% risetime and half-width for the 3 presumed unit types in unlesioned (open circles) and chronic spinal (dots) preparations. The correlation coefficients for presumed FF (A) are 0.45 and 0.51 for unlesioned and chronic spinal preparations respectively. For presumed FR (B) these values are 0.41 and 0.51; for presumed S (C), 0.54 and 0.51.

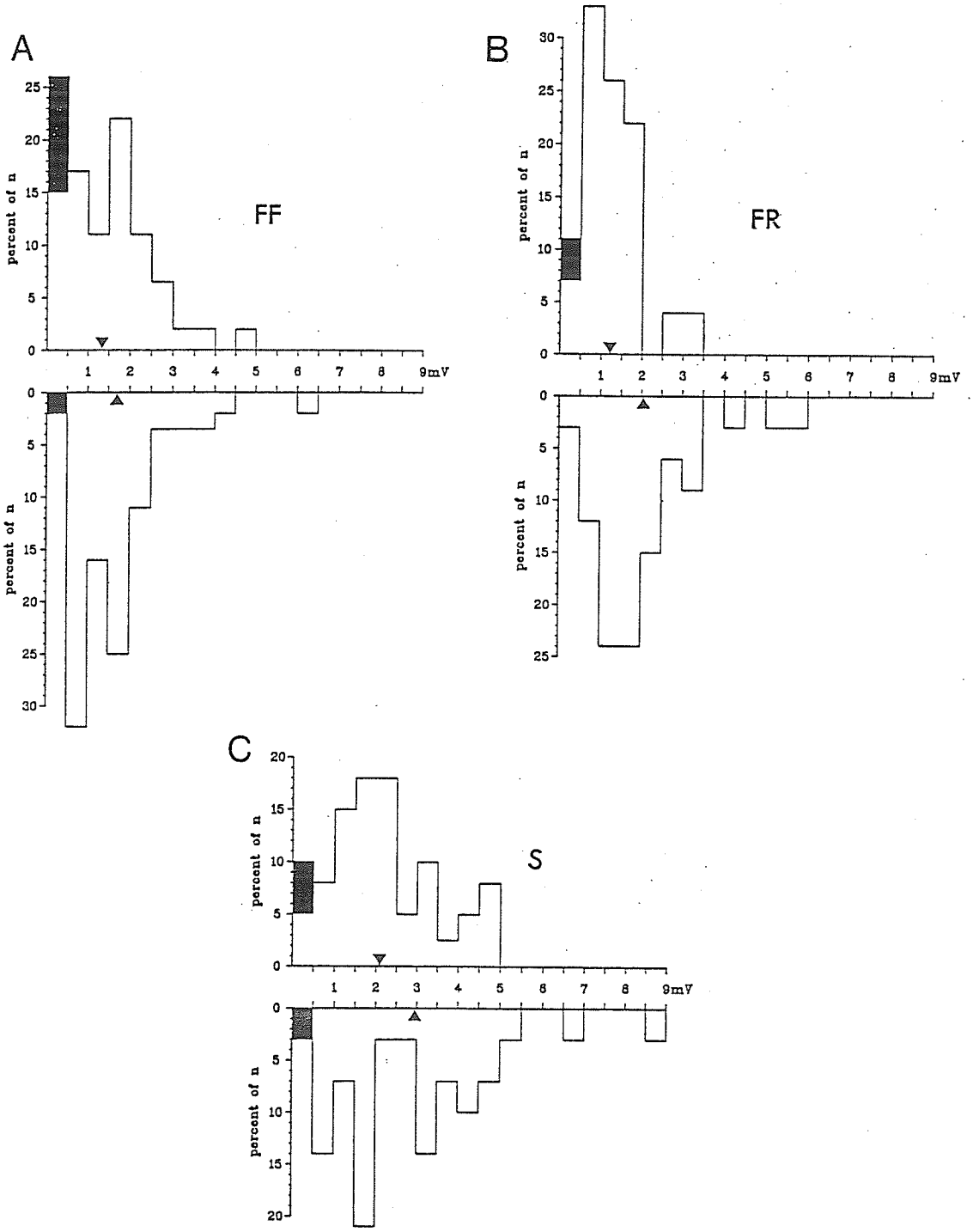


Figure 18.

Histograms of the percentage distribution of "homonymous" EPSP amplitude for presumed FF (A), presumed FR (B), and presumed S (C) in unlesioned (upper) and chronic spinal (lower) preparations. The closed triangles along the axes represent mean values. The shaded areas represent motoneurons with negligible EPSP amplitude values (≤ 200μV).

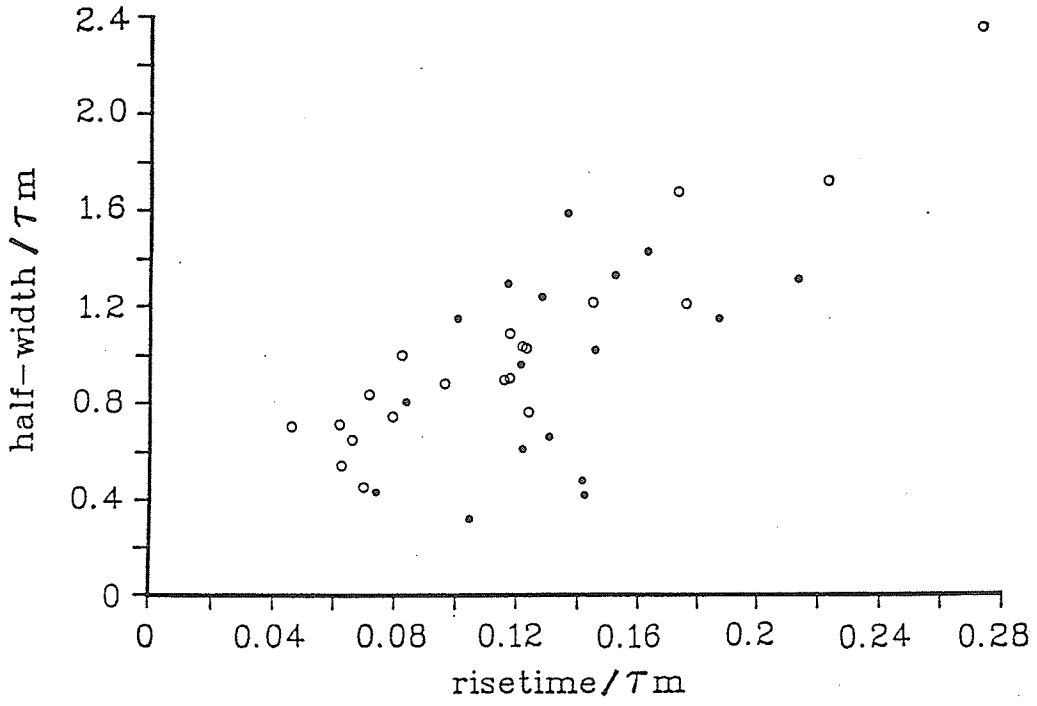


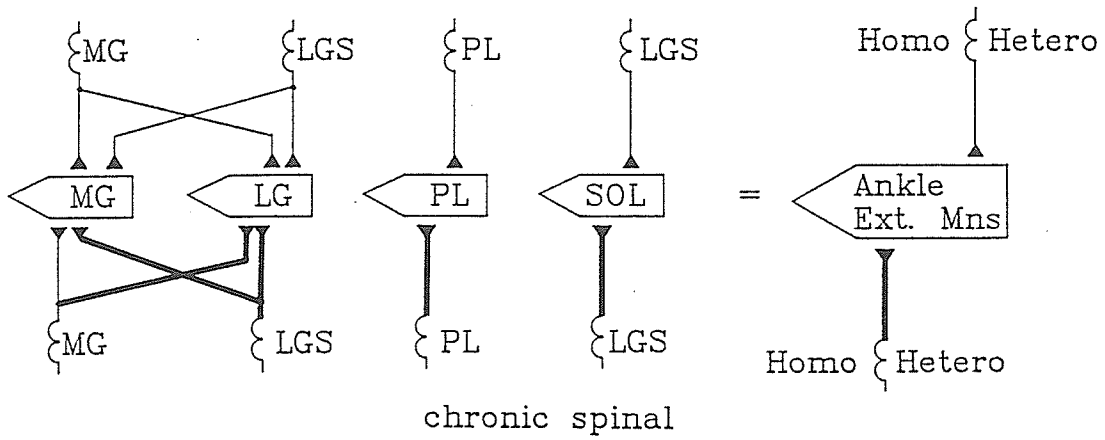
Figure 19.

Normalized EPSP shape index for presumed S motoneurons in unlesioned and chronic spinal preparations to show that differences in EPSP shape between the two preparations (Figure 2C) can be largely accounted for by differences in membrane time constant (τ_m).

Fig. 20.

A & B. Summary diagrams of the principal changes in Ia composite EPSPs in 6 week chronic spinal preparations. The "springs" represent Ia stretch receptors with their afferents (lines) making synaptic contacts (filled triangles) with the motoneurons (pentagons). Decreased risetimes are indicated by a shift to the left (compare upper and lower portions of each figure) of the position of the Ia afferent contact on the motoneurons. The leftward shift of synaptic contacts onto motoneurons in the chronic spinal preparation represents the theoretical notion that these synapses are electrically closer to the soma. An increased EPSP amplitude is indicated by thicker lines in the lower part of each figure. Figure A represents the recorded EPSP differences in the four ankle extensor species examined, the overall result (shown on the right hand side) being a decreased risetime and increased amplitude of composite Ia EPSPs in chronic spinal animals. Figure B represents the EPSP changes associated with the 3 motoneuron types showing that the FR motoneurons undergo the greatest EPSP amplitude increases and risetime decreases. Abbreviations as in text.

A


unlesioned
MG
LGS
PL
LGS
Homo
Hetero
MG
LG
PL
SOL
=
Ankle
Ext. Mns
MG
LGS
PL
LGS
Homo
Hetero
chronic spinal

B

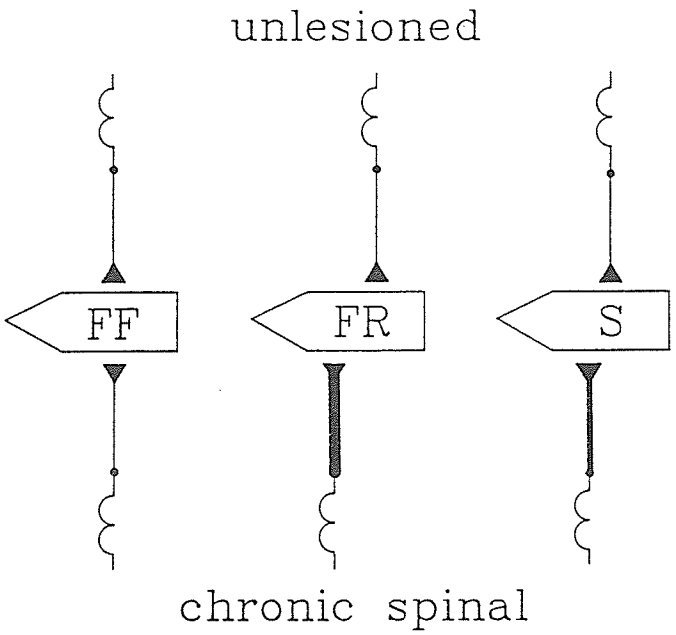

unlesioned
FF
FR
S
chronic spinal

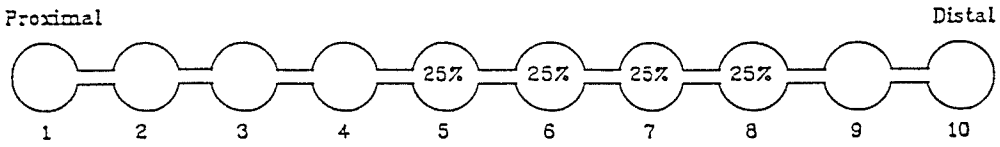
Figure 21.

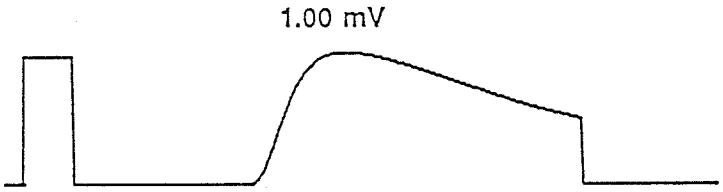
The mean experimental values in this figure are from a subset population of combined LG, PL, and SOL motoneurons (A) and presumed FR motoneurons (B) presented previously (Hochman et al., 1987). Mean R_{in}, τ_m, and L values from chronic spinal and unlesioned preparations were converted to "Rall" parameters for the motoneuron model (compartmental conductance and capacitance; coupling conductance). Each circle represents 1 of 10 compartments with equal conductance and capacitance; each connection between compartments having an equivalent coupling conductance. Proceeding distally, each compartment represents progressively greater electrotonic distances from the soma (first proximal compartment). Modelled EPSPs that best fit the experimental data were generated using the percentage distribution of conductances specified within the labelled compartments. In modelling the compartmental location and conductance magnitude of EPSPs, it can be seen that both LG-PL-SOL and presumed FR motoneuron models from the chronic spinal preparation required increased coonductances at more proximal locations to account for the observed mean EPSP paramters seen experimentally.

A 1 UNLESIONED

Combined LG, PL, and SOL mean experimental values:

EPSPs		Passive Membrane Properties	
amplitude	= 1.21 mV	R_{in}	= 1.31 MΩ
risetime	= 0.93 ms	τ_m	= 5.63 ms
half-width	= 6.41 ms	L	= 1.42



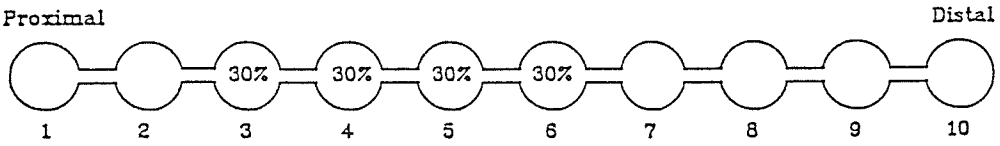


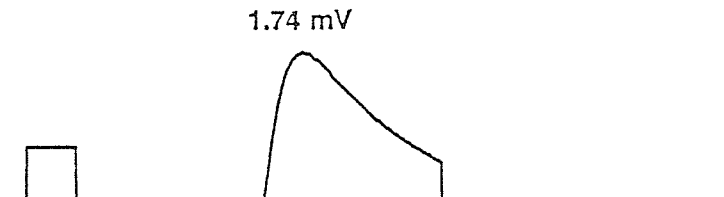
rt. = 0.99 ms hw. = 5.99 ms

2 CHRONIC SPINAL

Combined LG, PL, and SOL mean experimental values:

EPSPs		Passive Membrane Properties	
amplitude	= 2.10 mV (73% ↑)	R_{in}	= 1.01 MΩ
risetime	= 0.58 ms	τ_m	= 4.82 ms
half-width	= 4.06 ms	L	= 1.43



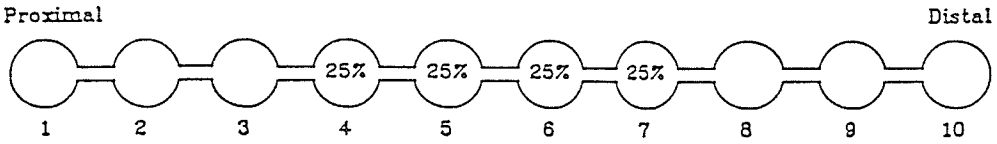


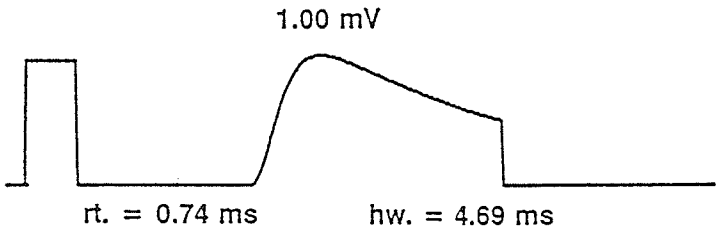
rt. = .61 ms hw. = 3.46 ms

B 1. UNLESIONED

Presumed FR mean experimental values:

EPSPs		Passive Membrane Properties	
amplitude	= 0.81 mV	R_{in}	= 0.96 MΩ
risetime	= 0.75 ms	τ_m	= 5.26 ms
half-width	= 5.24 ms	L	= 1.36

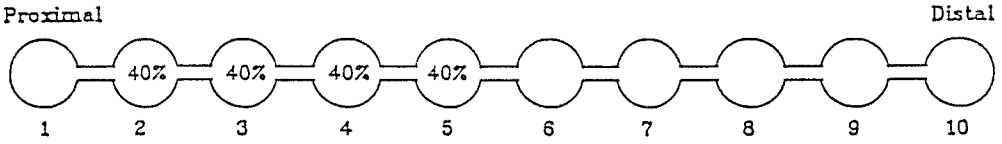


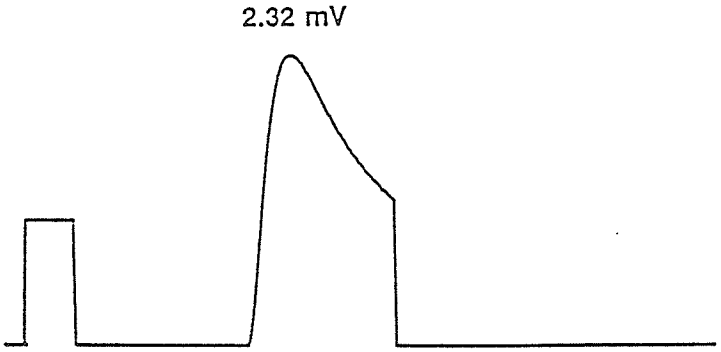


2 CHRONIC SPINAL

Presumed FR mean experimental values:

EPSPs		Passive Membrane Properties	
amplitude	= 1.98 mV(144% ↑)	R_{in}	= 0.76 MΩ
risetime	= 0.54 ms	τ_m	= 3.34 ms
half-width	= 3.34 ms	L	= 1.41





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