Comparison of the Morphological and Electrotonic Properties of Renshaw Cells, Ia Inhibitory Interneurons, and Motoneurons in the Cat

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Bui, T. V., S. Cushing, D. Dewey, R. E. Fyffe, and P. K. Rose. Comparison of the morphological and electrotonic properties of Renshaw cells, Ia inhibitory interneurons, and motoneurons in the cat. J Neurophysiol 90: 2900–2918, 2003. First published July 23, 2003; 10.1152/jn.00533.2003. The morphological and electrotonic properties of 4 motoneurons, 8 Ia inhibitory interneurons, and 4 Renshaw cells were compared. The morphological analysis, based on 3-D reconstructions of the cells, revealed that dendrites of motoneurons are longer and more extensively branched. Renshaw cells have dendrites that are shorter and simpler in structure. Dendrites of Ia inhibitory interneurons could be as long as those of motoneurons but the branching structure resembled that of Renshaw cells. Compartmental models were used to determine the electrotonic properties of the paths from each dendritic terminal to the soma. The attenuations of steady-state voltage changes in motoneurons were 3 and 7 times larger than in Ia inhibitory interneurons and Renshaw cells, respectively. The same relative order was observed for current attenuation and electrotonic length. The dendritic input resistances in Renshaw cells were 2 and 4 times larger than in Ia inhibitory interneurons and motoneurons, respectively. The difference in these electrotonic properties increased during higher synaptic activity as modeled by a decrease of $R_m$. The peak amplitudes of voltage transients at sites of brief, synaptic-like changes in conductance were highly dependent on cell class and were largest in Renshaw cells and smallest in motoneurons. In combination with class-specific differences in the attenuation of transient voltage signals, this led to large differences in the peak amplitudes of somatic voltage transients. Differences in the rise times and half-widths of the voltage transients were observed as well. Thus, based on passive properties, each cell class has a unique set of input/output properties.

INTRODUCTION

Neurons are equipped with a wide assortment of voltage-gated and ligand-gated ion channels that exert important influences on the integration of synaptic inputs (cf. Magee 2000; Migliore and Shepherd 2002; Reyes 2001). However, a comprehensive understanding of the impact of these conductances on the integrative properties of neurons must take into consideration the fundamental computational structure set by the passive properties of the dendritic tree. These electrotonic properties are in part dictated by the morphological features of dendrites, such as their physical length, diameter, and branching pattern (Rall 1977). Together with the passive electrical characteristics of the membrane and cytoplasm, these properties determine the resistance encountered by current flow as it travels axially through the dendritic tree or outwardly through the membrane. In turn, these resistances govern the efficacy of transmission of synaptic current to the soma and the resulting change in somatic membrane potential. A quantitative description of these parameters is thus a prerequisite to understanding how neurons process synaptic input to produce specific output patterns (Ascoli 1999; Bras et al. 1987; Carnevale et al. 1997; Chitwood et al. 1999; Jaffe and Carnevale 1999; Mainen and Sejnowski 1996; Mainen et al. 1996; Zador et al. 1995).

In the present study, we systematically compared the electrotonic properties of spinal motoneurons and two classes of spinal interneurons, Renshaw cells and Ia inhibitory interneurons. Spinal motoneurons are “the final common path” for all neural circuits involved in motor control (Sherrington 1947). Renshaw cells and Ia inhibitory interneurons are, respectively, key components of circuits responsible for recurrent and reciprocal inhibition (Baldissera et al. 1981; Jankowska 1992; Windhorst 1990). The electrotonic characteristics of Renshaw cells and Ia inhibitory interneurons have not previously been described. In contrast, the electrotonic properties of motoneurons, either in terms of electrotonic length, charge transfer, and/or attenuation of voltage signals have been assessed in various contexts (Bras et al. 1987; Burke et al. 1994; Clements and Redman 1989; Edwards and Mulloney 1984; Fleshman et al. 1988; Korogod et al. 2000; Nitzan et al. 1990; Segev et al. 1990; Svirskis et al. 2001; Thurbon et al. 1998; Ulrich et al. 1994). However, descriptions of input resistances, current attenuations, and voltage attenuations for all parts of the dendritic tree for spinal motoneurons are incomplete [see, however, the work of Edwards and Mulloney (1984) on median gastric neurons of the stomatogastric ganglion of the spiny lobster, Bras et al. (1987) and Nitzan et al. (1990) for brainstem motoneurons in the cat and guinea pig, and Korogod et al. (2000) for current transfer for a single cat gastrocnemius motoneuron].

To determine the electrotonic properties of each cell class, we performed a comprehensive morphological analysis of electrophysiologically identified members of the 3 cell
classes, extending the results of previous morphological studies (motoneurons: Cullheim et al. 1987; Kernell and Zwaagstra 1989; Rose et al. 1985; Ulhake and Kellerh 1981; Renshaw cells; Fyffe 1990; Lagerback and Kellerh 1985; Ia inhibitory interneurons: Rastad et al. 1990). With the aid of these anatomical measurements, we constructed compartmental models to determine the transmission of steady-state and transient responses to constant current injections or brief changes in membrane conductance at sites throughout the dendritic tree. Our results indicate that spinal motoneurons, Ia inhibitory interneurons, and Renshaw cells differ in terms of the amplitude of the excitatory postsynaptic potentials (EPSPs) generated by dendritic synapses, as well as the efficacy of transmission of current and voltage signals to the soma. Portions of this work were previously presented in abstract form (Bui et al. 2000).

**Methods**

**Animal preparation**

All cells examined were selected from a collection of feline motoneurons and spinal interneurons stained in previous experiments (Alvarez et al. 1997; Rose and Neuber-Hess 1991; Rose et al. 1995). The experimental protocols were conducted in compliance with approved institutional protocols (Queen’s University Animal Care Committee and Wright State University) and in accordance with Canadian Council of Animal Care and NIH guidelines.

**Electrophysiological identification of cells**

Biventer cervicis and complexus motoneurons were antidromically identified using stimulating electrodes placed on C2 and C3 nerves. Identification of Renshaw cells relied on their characteristic high-frequency discharge after activation of motor axons (Eccles et al. 1954) in the posterior biceps/semitendinosus or triceps surae nerves (see Fyffe 1990, 1991b). Ia inhibitory interneurons were distinguished by their monosynaptic activation after stimulation of dorsal roots L2–S1 at group I strength as well as their susceptibility to recurrent inhibition by Renshaw cells (Hultborn et al. 1971). In addition, they were not antidromically activated after motor axon stimulation (Alvarez et al. 1997; Fyffe 1991a). The morphology, location, and axonal trajectory of the stained cells were subsequently used to confirm the cells’ identities.

**Intracellular staining**

The intracellular staining of motoneurons was performed using beveled electrodes filled with 20% horseradish peroxidase in 0.1–0.5 M Tris/0.2–0.5 M KCl, pH 7.4. The low osmolarity of the solution (0.2 M KCl) was designed to minimize artifacts caused by osmotic stress (Major 2000). The Renshaw cells and Ia inhibitory interneurons were intracellularly stained using beveled electrodes filled with 4–8% neurobiotin (Vector Laboratories, Burlingame, CA) in 0.1 M Tris/0.5 M KCl, pH 7.6.

**Perfusion and tissue processing**

The animals were euthanized with an overdose of Nembutal (about 70 mg/kg) and perfused with saline followed by 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4). Spinal cord blocks were postfixed for 4–8 h at 4°C, and then stored in phosphate buffer with 15% sucrose. A Vibratome was used to obtain serial 50-μm-thick longitudinal sections or coronal sections.

**Cell reconstruction**

The dendritic processes contained in each slice were mapped using a computer-aided neuron tracing system (Eutectic NTS; Sun Technologies, Raleigh, NC) and X63 oil immersion objective (N.A. 1.40) for the motoneurons or a dry 60× objective (N.A. 0.95) for the Renshaw cells and Ia inhibitory interneurons. Tracings of each dendrite were converted into series of data points consisting of the X-, Y-, Z-coordinates and diameters of the processes. A data point was added for every change in direction or change in diameter greater than 0.2 μm. The number of data points needed to describe an entire dendritic tree ranged from 954 (a Renshaw cell) to 13,500 (a motoneuron). To reconstitute an entire dendritic tree, the data from consecutive slices were merged together. Before merging, each section was “dewrinkled” and scaled in the Z-axis to account for possible wrinkling and shrinking of the tissue during fixation and preparation. The dewrinkling process consisted of adjusting the Z-coordinate of all data points such that the cut surfaces of all the dendritic segments located at the top and bottom of the sections were equal to a common “highest” and “lowest” Z-coordinate that corresponded to the Z-coordinates of the highest and lowest dendritic segments of the section, respectively. Subsequently, the data points were scaled such that the difference between the upper and lower Z-coordinates of dendritic segments corresponded to the original thickness of the section. For all 3 cell classes, tissue shrinkage in the plane of section was estimated to be about 5–7%.

**Accuracy of morphological reconstruction**

The validity of our results strongly depends on the accuracy of the neuron reconstructions. Discrepancies between the neuron and its reconstructed image can be introduced at several stages of the reconstruction process. Morphological noise can originate from histological, optical, and operator-linked distortions (Horcholle-Bossavit et al. 2000). Specifically, systematic errors can result from mechanical inadequacies in the acquisition system or from biases in measurements made by the operator. To address this issue, frequency histograms of sampling interval and of dendritic diameter were constructed to identify such biases. Median sampling intervals ranged from about 2 to 8 μm; Renshaw cells and Ia inhibitory interneurons were generally reconstructed at smaller sampling intervals than motoneurons. The small intervals indicate a thorough sampling of the dendritic tree. Furthermore, dendritic diameters were smoothly distributed in a unimodal manner, indicating an approximately continuous and consistent sampling. These observations suggest that operator-based or equipment-based systematic errors were minimal during the reconstruction process.

**Compartmental modeling**

For each cell, a compartmental model was constructed. A prolate spheroid represented the soma, and the dendritic trees were represented by a series of uniform diameter cylinders whose lengths, diameters, and connectivity were dictated by the anatomy of the neurons as captured by the reconstructions. The maximal and minimal diameters of the prolate spheroid representing the soma equaled the maximal and minimal diameters of the largest ellipse that could be fitted within the contour of the cell body drawn at a magnification of ×500. Compartments consisted of successive data points of comparable diameter. The diameter of each compartment was set to the diameter of the first data point that is part of the cylinder. A new cylindrical compartment was added whenever the diameter changed by more than 10% of the diameter of the first data point in the cylinder, a cylinder reached a maximal length of 30 μm, or a dendritic branch bifurcated. An ANSI-C program performed the conversion from data points to cylindrical compartments. Subsequently, the model was transformed into an equiva-
lent electrical representation based on cable theory (Rall 1977). On average, the compartmental models of the motoneurons, Ia inhibitory interneurons, and Renshaw cells consisted of 4.362 ± 670 (±SD), 3.008 ± 2.160, and 710 ± 366 compartments, respectively. The membrane of every compartment, including the soma, was modeled as a parallel resistor-capacitor circuit. Compartments were linked to adjacent proximal and distal compartments by resistors. The values assigned to these resistors and capacitors were determined by the geometry of each compartment and the specific membrane properties using formulae previously described by Rall (1977).

The exact value of specific membrane and cytoplasmic properties continues to undergo revision because of differences in estimation techniques, the physiological conditions under which measurements are taken, as well as species and cell types (Clements and Redman 1989; Major et al. 1994; Roth and Haussner 2001; Stuart and Spruston 1998; Svirskis et al. 2001; Thurbon et al. 1998; Ulrich et al. 1994). The value of the specific resistivity of the cytoplasm ($R_j$) selected for this study, 70 $\Omega \cdot$ cm, is based on calculations for motoneurons (Barrett and Crill 1974) and is close to the value for saline (Hille 2001). This value is comparable to those estimated for other cell types using double whole cell recording (Roth and Haussner 2001; Stuart and Spruston 1998). $R_m$ estimates ranged from 5.3 $\mu$S/cm$^2$ (Thurbon et al. 1998) to 200 $\mu$S/cm$^2$ (Major et al. 1994). In addition to differences in $R_m$ arising from estimation techniques, variations may also arise as a consequence of the amount of background synaptic activity (Bernander et al. 1991; Raastad et al. 1998) and activation state of voltage-gated channels (Migliore and Shepherd 2002; Reyes 2001). Therefore 3 values of specific membrane resistivity ($R_j$), 3,750, 15,000, or 60,000 $\Omega \cdot$ cm$^2$, were used in different simulations. The specific membrane capacitance ($C_m$) was set to the canonical value of 1 $\mu$F/cm$^2$ (Hille 2001).

Data analysis

To study the electrotonic properties of the dendritic trees, simulations were performed using Saber, a mixed-signal simulator software package (Synopsys, Mountain View, CA) (Carnevale et al. 1990). The responses to steady-state current input were characterized in terms of voltage attenuation en route to the soma, current attenuation en route to the soma, and input resistance. The steady-state electrotonic properties of every compartment were calculated by coupling the results from a current injection at the soma and a current injection at every dendritic terminal. The current injection at the terminals provided a means to calculate the conductance looking toward the soma for each compartment, whereas the current injection at the soma allowed us to calculate the conductance looking toward the terminal for each compartment. As described by Bras et al. (1987), the conductance to ground ($G_j$) of each compartment is the sum of the conductance looking toward the soma, the conductance looking toward the terminal, and the conductance through the compartmental membrane. The latter is negligible. The compartment input resistance ($R_j$) is the reciprocal of $G_j$. The attenuation of the current as it travels from the compartment to the soma ($I_{ATT}$) is

$$I_{ATT} = \frac{V_{ATT}}{R_{ATT}} = \frac{V_j}{R_j} R_N$$

where $V_{ATT}$ and $R_{ATT}$ are attenuations of the voltage and dendritic input resistance from the compartment to the soma, $V_j$ and $R_j$ are the voltage change and input resistance at compartment $j$, and $V_N$ and $R_N$ are the voltage change and input resistance at the soma, respectively. The above calculations allow us to determine the input resistance, as well as the voltage attenuation and current attenuation in the somatopetal direction of every compartment without having to simulate a current injection to every compartment. For the purpose of these calculations, $R_j$ was approximated by the input resistance of the first compartment of the primary subtree in which the current was injected. The maximum difference between this input resistance and $R_j$ was found to be 4.8% (motoneuron LVN1-2). The average errors calculated for the 3 classes of neurons were 1.4 ± 1.3 (SD), 1.3 ± 1.6, and 0.4 ± 0.7%.

The electrotonic distance from the soma to each compartment was calculated as the sum of the electrotonic lengths of the intervening compartments. Thus the electrotonic distance $X$ of a compartment $j$ is given as

$$X_j = \sum_{i=1}^{j-1} \frac{R_i d_i}{R_j} = \frac{R_j d_j}{R_j}$$

where $d_i$ is the physical length of compartment $k$ and $R_k$ is its space constant.

To determine the response of the models to single transient events, a time-dependent conductance change was added to each compartment and simulated individually. The conductance change was modeled as an alpha-function (Rall 1967):

$$g(t) = g_{peak} \frac{t}{t_{peak}} \exp\left[1 - \frac{t}{t_{peak}}\right]$$

where the peak conductance $g_{peak}$ was assigned a value of 5 nS and the time-to-peak of the conductance change $t_{peak}$ was assigned a value of 0.20 ms. The 10–90% rise time of this function is 0.12 ms and the half-width is 0.49 ms. The reversal potential of the conductance change was set to 0 mV and the resting membrane potential was set to −70 mV. These values were designed to mimic the conductance change associated with activation of one Ia afferent on spinal motoneurons (Finkel and Redman 1983). Comparable data describing the magnitude and time course of conductance changes in response to single afferents contacting Ia inhibitory interneurons and Renshaw cells are not available. For these cells, the selected parameters of the conductance change provided a “benchmark” synaptic conductance change that allowed direct comparisons of the transmission of transient signals across all cell classes.

For each conductance change, the following characteristics of the voltage response were measured: peak amplitude of the voltage change at the compartment of injection and the resultant voltage change at the soma, the attenuation of the peak voltage from the compartment to the soma, the 10–90% rise time at the compartment of injection and at the soma, the ratio of the 10–90% rise time at the soma to that at the compartment, the half-width at the compartment of injection and at the soma, and finally, the ratio of the half-width at the soma to that at the compartment.

Area weighting

The steady-state and transient electrotonic properties of compartments belonging to each path taken from the soma to each dendritic end were calculated to provide a single measure of each of those electrotonic properties for that path. Specifically, the value of a particular electrotonic property $x$ of a compartment was weighted by its surface area in relation to the total surface area of the path. The area weighting of an electrotonic property (AWx) for a particular path is given as

$$AW_x = \sum_{k=soma}^{end of path} \frac{x_k \text{area}_k}{\sum_{all 	ext{ compartments}} \text{area}}$$

where $x_k$ and area$k$ are the surface area and the electrotonic property measured at compartment $k$, respectively. Area-weighted electrotonic properties invariably have smaller or equal values than the same
properties as measured from the dendritic terminal. As an example, consider the area-weighted electrotonic length of a dendrite divided into 10 compartments. The 5 most proximal compartments have a diameter of 4.0 μm and a length of 200/π μm. The 5 most distal compartments have a diameter of 1.0 μm and a length of 200/π μm. Thus the ratio of the surface areas of the proximal versus distal compartments is 4. Uniform values of ρv and Rv are such that the 5 most proximal compartments will have an electrotonic length of 0.05, whereas the 5 most distal compartments will have an electrotonic length of 0.1. Thus, the electrotonic length at the terminal will be 5(0.05) + 5(0.1) = 0.75. The area-weighted electrotonic length, however, is [4(0.05 + 0.10 + 0.15 + 0.20 + 0.25) + 1(0.35 + 0.45 + 0.55 + 0.65 + 0.75)]/[5(4) + 5(1)] = 0.23. Assuming that synapses are distributed uniformly according to surface area, this value is equivalent to the average electrotonic distance from the soma of all synapses located on this dendrite.

Statistical analysis

Comparisons of various morphological and electrotonic properties between the 3 groups of cells were made using the nonparametric Kruskal–Wallis test. If significant differences were revealed, then pairwise comparisons were performed using the nonparametric Mann–Whitney test. Significance for both tests was taken as a probability of a false positive conclusion of P ≤ 0.05. The symbols >, <, and = were used to indicate whether a class of cells was significantly greater, significantly lesser, or not significantly different to another class of cells, respectively. MN ≈ IaIN ≈ RC indicates that there are no significant differences within the group and none for all pairings.

Because many parameters studied were not normally distributed, all electrotonic and morphological properties of individual dendrites are reported as the medians, along with the upper and lower 95% confidence levels of the median in the following format: median.upper 95% lower 95% confidence levels were obtained using the statistical method of bootstrapping (Efron 1979). Briefly, for each parameter studied, 1,000 additional samples based on the measured sample were created using sampling with replacement. Each new sample consisted of data points selected from the original n-sized sample. The construction of a new sample involved repeatedly resampling from the original sample with each data point being assigned a probability 1/n of being in the new sample. After each resampling, the data point was returned to the original sample for further sampling. This process was performed n times to form a new sample. From the 1,000 new n-sized samples created, medians were calculated for each sample and then ordered. The 25th and 975th largest medians are considered to be the lower and upper 95% confidence levels of the medians. Contrary to the morphological properties of the individual dendrites, the morphological properties of the cells as a whole were reported as the median ± SD because the sample sizes did not warrant an analysis using the bootstrapping method.

To test the hypothesis that a morphological or electrotonic property was significantly larger or smaller than a certain specific value, the nonparametric Wilcoxon signed-rank test was used as a one-sample median test. Each data point was ranked according to the magnitude of the signed difference to the tested value, and the test statistic of the paired-sample Wilcoxon signed-rank test was calculated to determine the validity of the hypothesis (Zar 1996).

Finally, the distributions of the morphological and electrotonic properties are depicted as cumulative histograms (e.g., Fig. 2). Each point represents the value for a single path. All the paths for all neurons belonging to a particular cell class were grouped together.

RESULTS

Morphology

Qualitatively, the morphology of each class of neurons could be readily discerned by the complexity of dendritic branching and the spatial extent of the dendritic tree. Figure 1 depicts a reconstruction of a cell for each class. The dendritic trees of motoneurons (n = 4, Fig. 1A) were larger and more elaborate than Renshaw cells (n = 4, Fig. 1C) were smaller and simpler. The dendrites of the Ia inhibitory interneurons (n = 8, Fig. 1B) approached those of motoneurons in length but not in branching complexity. These observations were verified by a more detailed morphometric analysis, which first considered each cell in its entirety, and then examined components of the dendritic tree, such as paths and branches, separately.

GLOBAL PROPERTIES. Several key characteristics of the dendritic tree of motoneurons, Ia inhibitory interneurons, and Renshaw cells are summarized in Table 1. For all properties analyzed, whether pertaining to size (e.g., length, surface area) or topology (e.g., number of primary subtrees and terminals), motoneurons were greater in magnitude than both of their interneuronal counterparts. The total length of an average motoneuron’s dendrites was 5 times greater than that of the average Ia inhibitory interneuron and 18 times greater than that of the average Renshaw cell. Dendritic surface area followed a similar trend. The dendrites accounted for over 90% of the surface area for the 3 cell classes. The average diameter of dendritic processes showed no difference between motoneurons and Ia inhibitory interneurons. However, the diameter of Renshaw cell dendrites was smaller than the other two. An examination of the branching structure of the dendritic trees revealed that motoneurons consisted of 2 to 3 times as many primary subtrees as Ia inhibitory interneurons and Renshaw cells. Likewise, motoneurons had 4 times as many dendritic terminals as Renshaw cells. The proportional difference in the number of terminals between the 3 classes of neurons was larger than the number of subtrees because of the higher frequency of branching in the dendritic tree of motoneurons. A pairwise statistical analysis confirmed that motoneurons and interneurons (Renshaw cells and Ia inhibitory) were significantly different for all properties studied except average dendritic diameter, whereas Renshaw cells and Ia inhibitory interneurons were different for metric properties but not topological properties (total dendritic length: MN > IaIN > RC; total surface area: MN > IaIN > RC; dendritic percentage of total surface area: MN > IaIN > RC; average diameter: IaIN ≈ MN > RC; number of primary subtrees: MN > IaIN ≈ RC; number of terminals: MN > IaIN ≈ RC).

PATH LENGTHS. The dendritic trees were broken down into their constituent paths (i.e., the dendritic trajectory from soma to terminal). The total path lengths were found to be significantly different between the 3 classes of spinal neurons (MN > IaIN > RC). As illustrated by Fig. 2, paths were longest for motoneurons (1,095 ± 1,059 μm), intermediate for Ia inhibitory interneurons (661 ± 580 μm), and shortest for Renshaw cells (430 ± 372 μm).

BRANCHES. Dendritic paths are composed of a series of branches separated by branchpoints and just like the paths, the branches (Fig. 3) were longer for motoneurons (208 ± 131 μm) than Ia inhibitory interneurons (151 ± 118 μm) and shortest for Renshaw cells (103 ± 78 μm) (MN > IaIN > RC). Branch lengths were also categorized according to their order of branching away from the soma (somatofugal) (Fig. 4A) or away from the terminals (somatopetal) (Fig. 4B). In the somatofugal direction, branch lengths increased with order, peaking...
approximately at the order representing the median terminal order (see Branching) at which point the branches became progressively shorter for higher-order branches. The parabolic relationship between somatofugal order of branching and branch length was consistent for all 3 classes of neurons, but with branch length peaking at different orders for the 3 classes. Only for higher orders were branches significantly different between the 3 cell classes (1st order, 2nd order, and 3rd order: MN ≈ IaIN ≈ RC; 4th order: MN > IaIN > RC; 5th order: MN ≈ IaIN > RC; 6th order: MN ≈ IaIN). In the somatopetal direction, branch length decreased with somatopetal order (Fig. 4B). Branch lengths were different between 2 out of the 3 cell classes for almost all orders in the somatopetal direction, except 2nd-order and 3rd-order branches away from the terminal (terminal branches: MN ≈ IaIN > RC; 2nd order: MN ≈ IaIN ≈ RC; 3rd order: MN ≈ IaIN ≈ RC; 4th order: MN

Table 1. Summary of global morphological properties of three classes of spinal neurons

<table>
<thead>
<tr>
<th></th>
<th>Motoneurons (n = 4)</th>
<th>Ia Inhibitory Interneurons (n = 8)</th>
<th>Renshaw Cells (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dendritic length, μm</td>
<td>80.368 ± 9.013</td>
<td>14.989 ± 7.705</td>
<td>4.290 ± 1.159</td>
</tr>
<tr>
<td>Soma surface area, μm²</td>
<td>6,435.0 ± 481.3</td>
<td>3,113 ± 891.5</td>
<td>1,753.8 ± 597.8</td>
</tr>
<tr>
<td>Total dendritic surface area, μm²</td>
<td>428.682 ± 33.647</td>
<td>81.390 ± 46.141</td>
<td>16.756 ± 8.425</td>
</tr>
<tr>
<td>Dendritic percentage of total surface area, %</td>
<td>98.5 ± 0.2</td>
<td>95.5 ± 2.3</td>
<td>89.9 ± 3.0</td>
</tr>
<tr>
<td>Average dendritic diameter, μm</td>
<td>1.7 ± 0.2</td>
<td>1.8 ± 0.5</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td>Number of primary subtrees</td>
<td>12 ± 1</td>
<td>5 ± 1</td>
<td>4 ± 0</td>
</tr>
<tr>
<td>Number of terminals</td>
<td>137 ± 25</td>
<td>31 ± 13</td>
<td>29 ± 8</td>
</tr>
</tbody>
</table>

Values are means ± SD. The average dendritic diameter was calculated by multiplying each compartment’s diameter by its length. Each product was summed and the sum divided by the total dendritic length of the cell. A primary subtree is the sum of branches that can be traced back to one common first-order branch.
IaIN \approx RC; 5th order: MN > IaIN \approx RC; 6th order: MN > IaIN).

**Branching Structure.** In addition to being composed of longer branches, a higher degree of branching contributed to the longer paths seen in the dendritic trees of motoneurons relative to those of interneurons. As illustrated by Fig. 5, the median somatofugal order of the terminal branches of the motoneurons is higher by one or two orders compared to the terminal branches of the spinal interneurons (motoneurons: 5\text{th}; Ia inhibitory interneurons: 4\text{th}; Renshaw cells: 3\text{rd}). The three classes of neurons were found to be significantly different for this topological property (MN > IaIN > RC). The maximal branching order for motoneurons, Ia inhibitory interneurons, and Renshaw cells was 12, 8, and 6 respectively.

**Branch Diameter.** In addition to physical length and branching, the attenuation of synaptic signals and the input resistance seen by synapses are also influenced by dendritic diameter (Rall 1977). The average diameter of each branch was measured and subsequently arranged according to somatofugal and somatopetal order (Fig. 6). When considering all branches, the medians for motoneurons, Ia inhibitory interneurons and Renshaw cells were 1.51, 1.72, and 1.09 \mu m, respectively. Similar to the average diameters reported in Table 1, the average diameters of branches from Renshaw cells were significantly less than Ia inhibitory interneurons and motoneurons, but the average diameter of the branches of the latter two were not different from each other (IaIN \approx MN > RC). For both types of branch ordering, average branch diameter was found to differ between at least 2 cell classes (except for somatopetal 6th order) and when ordered in the somatopetal direction, motoneuron branches were sometimes smaller in diameter than Ia inhibitory interneurons or Renshaw cells (somatofugal 1st order: MN \approx IaIN > RC; 2nd order: MN > IaIN > RC; 3rd order: MN \approx IaIN > RC; 4th order: MN > IaIN > RC; 5th order: MN > IaIN > RC; 6th order: MN \approx IaIN) (somatopetal Terminal: MN \approx IaIN > RC; 2nd order: IaIN > MN > RC; 3rd order: IaIN > MN > RC; 4th order: IaIN > MN > RC; 5th order: IaIN > RC > MN; 6th order: MN > IaIN).

**Tapering.** Changes in diameter, whether found within a branch or at the juncture between a parent and its 2 sibling branches, also determine the attenuation of synaptic signals (Holmes and Rall 1992; Rall 1977). Both expansion and constriction of dendrites in the distal direction were observed for all 3 classes of neurons; however, the diameter predominantly decreased in the distal direction. The percentage of branch tapering for all 3 cells was found to be significantly greater than 0% (P \leq 0.02) and the medians for motoneurons, Ia inhibitory interneurons, and Renshaw cells were 17_{12}, 17_{22}, and 17_{36}%, respectively. When considering all branches, the tapering was not significantly different between the 3 classes of neurons (MN \approx IaIN \approx RC). No major differences were observed when branches were classified according to somatopetal or somatofugal order (Fig. 7) (somatofugal 1st order: MN \approx IaIN < RC; 2nd, 3rd, 4th, and 5th order: MN \approx IaIN \approx RC; 6th order: MN \approx IaIN) (somatopetal Terminal, 4th order and 5th order away: MN \approx IaIN \approx RC; 2nd order: MN < IaIN \approx RC; 3rd order: MN \approx IaIN < RC; 6th order: MN \approx IaIN).

**Branching Ratio.** A parent branch and its 2 siblings can be regarded as a single continuous cylinder if certain conditions are met (Rall 1977). One of these conditions concerns the diameters of the parent branch and its 2 siblings. A branching ratio (Fig. 8) of 1 is a requirement for electrotonic continuity between a parent branch and its 2 sibling branches. For the 3 cell classes studied, branching ratio was found to be significantly higher than 1.0 (P \leq 0.02). The medians of the branching ratio for motoneurons, Ia inhibitory interneurons, and Renshaw cells were 1.23_{1.27}, 1.07_{1.08}, and 1.45_{1.70}, respectively. Although there was a significant difference of branching ratio between the Ia inhibitory interneuron and the 2 other cell classes, this difference was not significant between motoneurons and Renshaw cells (RC \approx MN > IaIN).

**Electrotonic Properties.**

The morphological analysis demonstrated that motoneurons, Ia inhibitory interneurons, and Renshaw cells differed in terms of branching structure and length. We would expect that these morphological differences translate into different electrotonic structures (Rall 1977). To confirm this, the electrotonic properties of motoneurons, Ia inhibitory interneurons, and Renshaw...
cells were calculated using compartmental models based on detailed anatomical measurements. First, the passive spread of steady-state signals was considered. Subsequently, an analysis of the spread of single transient events was performed.

Steady-state analysis

Four parameters were used to describe the steady-state electrotonic characteristics of each compartment: electrotonic distance from the soma, input resistance, voltage attenuation, and current attenuation. Initial simulations were performed using a value of $R_m$ of $15,000 \, \Omega \cdot \text{cm}^2$. The relationship between the electrotonic properties and the distance from the soma for a dendritic path of an inhibitory interneurons is shown in Fig. 9. For this particular trajectory, voltage attenuation (Fig. 9B) ranged from 1 (indicating no signal attenuation) at the soma to 288.5 at the terminal, whereas current attenuation (Fig. 9D) ranged from 1 at the soma to 1.63 at the terminal. The amplitude of the membrane potential change at the site of injection also varied with distance as indicated by measurements of input resistance (Fig. 9C), which ranged from 14.5 MΩ at the soma to 2,562.8 MΩ at the terminal. Abrupt 10-fold increases in the magnitude of the electrotonic properties such as the one seen at about 650 μm in Fig. 9 were commonly observed at branch points, attributed to large decreases in the diameters of the sibling branches relative to the parent branch. A discontinuity at around 650 μm was also observed for electrotonic length (Fig. 9E).
ELECTROTONEIC PROPERTIES AT TERMINALS. Figure 10 summarizes the distribution of the electrotoneic properties of the dendritic terminals. Voltage attenuation (Fig. 10A), current attenuation (Fig. 10C), and electrotoneic length (Fig. 10D) were greatest for motoneurons (voltage attenuation: 139.6 ± 127.6; current attenuation: 1.78 ± 1.72; electrotoneic length: 1.09 ± 0.66), intermediate for Ia inhibitory interneurons (voltage attenuation: 59.8 ± 41.8; current attenuation: 1.32 ± 0.66; electrotoneic length: 0.72 ± 0.66), and smallest for Renshaw cells (voltage attenuation: 8.8 ± 6.6; current attenuation: 1.20 ± 0.66; electrotoneic length: 0.56 ± 0.50). The order was different with regard to dendritic input resistance (Fig. 10B) where the medians for the motoneurons, Ia inhibitory interneurons, and Renshaw cells were 402.1 ± 368.8, 721.6 ± 592.9, and 623.6 ± 490.7 MΩ, respectively. The 3 classes of cells were significantly different for these electrotoneic properties (for voltage attenuation, current attenuation, and electrotoneic length: MN > IaIN > RC, input resistance: IaIN > RC > MN).

AREA-WEIGHTED ELECTROTONEIC PROPERTIES. In light of the abrupt increases in attenuations and input resistance observed in more distal regions, the electrotoneic properties of the terminal compartments misrepresent the electrotoneic properties seen by more proximal synapses. To take into account the electrotoneic properties of proximal compartments, we calculated for each dendritic path a weighted average with respect to surface area of the electrotoneic properties of every compartment that constitute the path (see METHODS). The resulting measure provides an average of the electrotoneic properties seen by all synapses on each path, assuming that the synapses are distributed uniformly with respect to surface area. The results of this area-weighting procedure when applied to steady-state electrotoneic properties are summarized in Fig. 11. Compared to the parameter values at the terminal, area-weighted values were much smaller (e.g., the area-weighted voltage attenuation for the path depicted in Fig. 9A was 9.8, compared to a voltage attenuation of 288.6 measured at the terminal). However, the overall relationship between the 3 groups of spinal neurons was unaltered, except for input resistance where Renshaw cells showed larger area-weighted values than those of Ia interneurons. There was greater signal loss for inputs to motoneurons than inputs to Ia inhibitory interneurons, and inputs to Renshaw cells suffered from the least attenuation (voltage attenuation, current attenuation, electrotoneic length: MN > IaIN > RC; input resistance: MN < IaIN < RC). The medians of the 4 electrotoneic properties of the 3 cell classes are summarized in Table 2 ($R_{m} = 15,000 \, \Omega \cdot \text{cm}^2$). The area-weighted voltage attenuation of motoneurons was 2.9 times and 7.9 times larger than that of Ia inhibitory interneurons and Renshaw cells.

![Graph A](image1.png)

![Graph B](image2.png)
respectively; the area-weighted current attenuation of motoneurons was 1.15 times and 1.18 times larger than that of Ia inhibitory interneurons and Renshaw cells, respectively; and the area-weighted electrotonic length of motoneurons was 1.5 times and 1.9 times larger than that of Ia inhibitory interneurons and Renshaw cells, respectively. Conversely, the area-weighted input resistance of Renshaw cells was 1.9 times and 4.1 times larger than that of Ia inhibitory interneurons and motoneurons, respectively.

SENSITIVITY TO MEMBRANE RESISTIVITY. Effective $R_m$ depends on the amount of background synaptic activity (Bernander et al. 1991; Raastad et al. 1998) and activation state of voltage-gated channels (Migliore and Shepherd 2002; Reyes 2001). Because input resistance, as well as voltage and current attenuation are dependent on $R_m$ (Rall 1977), simulations were repeated with values of $R_m$ set at 3,750 and 60,000 $\Omega \cdot cm^2$. As seen in Fig. 12, the relative differences in voltage attenuation between the 3 cell classes were not altered by changes of $R_m$. Table 2 summarizes the data for all electrotonic parameters at different values of $R_m$. As expected, higher membrane resistivity decreased the current and voltage attenuation, whereas input resistance increased. Lower...
membrane resistivity produced the converse effects. All differences between the 3 cell classes remained significant (voltage attenuation, current attenuation, electrotonic length at $R_m$ of 3,750 and 60,000 $\Omega \cdot \text{cm}^2$: MN > IaIN > RC; input resistance length at $R_m$ of 3,750 and 60,000 $\Omega \cdot \text{cm}^2$: MN < IaIN < RC). However, the relative differences of voltage and current attenuation between the 3 cell classes were accentuated by lower membrane resistivity and reduced by higher membrane resistivity. For example, at 3,750 $\Omega \cdot \text{cm}^2$, the median of the voltage attenuation of motoneurons was 3.2 times and 11.8 times larger than those of Ia inhibitory interneurons and Renshaw cells, respectively, whereas at 60,000 $\Omega \cdot \text{cm}^2$, the median of the voltage attenuation of motoneurons was 2.2 times and 3.9 times larger than those of Ia inhibitory interneurons and Renshaw cells, respectively.

**Transient analysis**

The analysis of steady-state signals provides a measure of neuronal input/output properties under conditions of constant current injection or sustained high-frequency synaptic activity (Rall and Agmon-Snir 1999). However, inputs to spinal neurons are often transient. Koch et al. (1995) argue that for fast synaptic events, a voltage threshold rather than a current threshold must be exceeded to generate action potentials. Thus we examined the voltage response to an exemplar change in conductance designed to mimic transient activation of a small number of synapses (see methods).

When measured at the compartment where the conductance change was applied, the peak amplitude of the depolarization for Renshaw cells ($9.25^{10.68}$ mV) was about twice as large as for Ia inhibitory interneurons ($5.24^{5.58}$ mV) and motoneurons ($4.06^{4.78}$ mV) (Fig. 13A, MN < IaIN < RC). When the peak amplitude was measured at the soma, the proportional difference between the 3 cell classes increased. EPSPs arriving at the soma ($1.08^{0.97}$ mV) were approximately 3 times larger for Renshaw cells than for Ia inhibitory interneurons ($0.33^{0.30}$ mV) and 10 times larger compared to motoneurons ($0.10^{0.10}$ mV) (Fig. 13B, MN < IaIN < RC). The area-weighted attenuation of the peak amplitude of the transient signals was 7 to 8 times greater than the area-weighted voltage attenuation of steady-state inputs for all 3 cell classes (MN: $103.0^{109.7}$; IaIN: $33.4^{40.4}$; RC: $10.0^{12.4}$; Fig. 13C, MN > IaIN > RC).

The rise time of the voltage change measured at the compartment was slightly shorter for motoneurons ($0.24^{0.24}$ ms) compared to Ia inhibitory interneurons ($0.26^{0.26}$ ms) and Ren-
However, when measured at the soma, EPSPs had longer rise times in motoneurons (1.1 1.1 1.2 ms) than in Ia inhibitory interneurons (0.9 0.9 1.0 ms) and Renshaw cells (0.8 0.8 1.0 ms) (Fig. 14B, MN > IaIN = RC). The half-widths of voltage transients measured at the compartment where the conductance change was applied and that measured at the soma were smaller for motoneurons (at compartment: 1.1 1.1 1.2 ms; at soma: 7.1 7.0 7.4 ms) than for Ia inhibitory interneurons (at compartment: 1.4 1.4 1.5 ms; at soma: 8.2 8.8 8.8 ms) and Renshaw cells (at compartment: 1.6 1.5 1.8 ms; at soma: 9.2 9.0 9.0 ms).

Area-weighted electrotonic properties were calculated as sums of magnitude of properties at each compartment, weighted by surface area of compartment relative to surface area of soma-to-terminal path to which compartment belonged.
The morphology of Renshaw cells and Ia inhibitory interneurons has been previously described (Renshaw cells: Fyffe et al. 1983; Rastad et al. 1990). Overall the morphological properties reported for our sample of Renshaw cells and Ia inhibitory interneurons described in this study appear to be representative of their respective classes. Renshaw cells and Ia inhibitory interneurons described in this study are legitimate substitutes for their counterparts in the lumbar-sacral spinal cord. Equally important, the 4 motoneurons described in this study are typical of a much larger sample of motoneurons described in our other studies.

The morphology of Renshaw cells and Ia inhibitory interneurons has been previously described (Renshaw cells: Fyffe et al. 1990; Lagerback and Kellerth 1985; Ia inhibitory interneurons: Rastad et al. 1990). Overall the morphological properties reported for our sample of Renshaw cells and Ia inhibitory interneurons were comparable to previous studies, although some of the Renshaw cells studied by Lagerback and Kellerth (1985) had up to 3 more primary subtypes than our sample (the average, however, was close to 4) and the dendrites of Ia inhibitory interneurons studied by Rastad et al. (1990) were slightly shorter. Thus, despite the small sample sizes, the Renshaw cells and Ia inhibitory interneurons described in this study appear to be representative of their respective classes.

### Methodological considerations

#### Morphological characteristics

The total dendritic lengths, total dendritic surface areas, number of terminals, and variability of the branching ratio parameter observed for motoneurons in this study were similar to those reported in an earlier analysis of neck motoneurons (Rose et al. 1985). The present study uses neck motoneurons as surrogates for hindlimb spinal motoneurons to compare motoneurons with 2 classes of hindlimb spinal interneurons. Is this valid? The total dendritic length, dendritic surface area, number of terminals, number of primary subtypes, and mean path length of our sample neck motoneurons are comparable, though slightly smaller, to these features reported for hindlimb motoneurons (Cullheim et al. 1987; Kernell and Zwaagstra 1989; Ulfhake and Kellerth 1981). Dendritic diameter profiles of the 2 classes of motoneurons also resemble each other, as Ulfhake and Kellerth (1981) found similar patterns of tapering in relation to branch order with little tapering for branches closer to the soma, and larger amounts of tapering for terminal branches. The branching ratio between parent and daughter branches of hindlimb motoneurons is often greater than 1.0 and variable, like neck motoneurons (Cullheim et al. 1987; Rose et al. 1985; Ulfhake and Kellerth 1981). Thus the neck motoneurons described in the study are legitimate substitutes for their counterparts in the lumbar-sacral spinal cord.

#### Area-weighting

Current and voltage attenuations measured at dendritic terminals have often been used as indices of the overall electrotonic properties of neurons. However, the electrotonic properties at the terminals are not the same as the electrotonic properties of compartments on the path from the terminal to the soma. Attenuations at compart-

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**Table 2. Summary of electrotonic properties of three classes of spinal neurons at different values of $R_m$**

<table>
<thead>
<tr>
<th></th>
<th>Motoneurons (n = 4)</th>
<th>Ia Inhibitory Interneurons (n = 8)</th>
<th>Renshaw Cells (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area-weighted voltage attenuation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_m = 3.750 \Omega \cdot cm^2$</td>
<td>$51.8_{-4.0}^{+4.7}$</td>
<td>$41.2_{-1.3}^{+1.3}$</td>
<td>$4.8_{-0.5}^{+0.5}$</td>
</tr>
<tr>
<td>$R_m = 15.000 \Omega \cdot cm^2$</td>
<td>$14.3_{-1.4}^{+1.4}$</td>
<td>$10.8_{-0.9}^{+0.9}$</td>
<td>$1.8_{-0.6}^{+0.6}$</td>
</tr>
<tr>
<td>$R_m = 60.000 \Omega \cdot cm^2$</td>
<td>$4.7_{-0.5}^{+0.5}$</td>
<td>$2.3_{-0.3}^{+0.3}$</td>
<td>$1.2_{-0.2}^{+0.2}$</td>
</tr>
<tr>
<td>Area-weighted current attenuation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_m = 3.750 \Omega \cdot cm^2$</td>
<td>$2.05_{-0.35}^{+0.24}$</td>
<td>$1.38_{-0.10}^{+0.08}$</td>
<td>$1.28_{-0.31}^{+0.31}$</td>
</tr>
<tr>
<td>$R_m = 15.000 \Omega \cdot cm^2$</td>
<td>$1.26_{-0.24}^{+0.24}$</td>
<td>$1.10_{-0.08}^{+0.08}$</td>
<td>$1.07_{-0.08}^{+0.08}$</td>
</tr>
<tr>
<td>$R_m = 60.000 \Omega \cdot cm^2$</td>
<td>$1.07_{-0.06}^{+0.06}$</td>
<td>$1.02_{-0.02}^{+0.02}$</td>
<td>$1.02_{-0.02}^{+0.02}$</td>
</tr>
<tr>
<td>Area-weighted input resistance (MΩ)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_m = 3.750 \Omega \cdot cm^2$</td>
<td>$3.18_{-0.30}^{+0.28}$</td>
<td>$50.9_{-0.6}^{+0.6}$</td>
<td>$96.2_{-0.4}^{+0.4}$</td>
</tr>
<tr>
<td>$R_m = 15.000 \Omega \cdot cm^2$</td>
<td>$4.53_{-0.49}^{+0.49}$</td>
<td>$100.3_{-0.6}^{+0.6}$</td>
<td>$191.4_{-0.6}^{+0.6}$</td>
</tr>
<tr>
<td>$R_m = 60.000 \Omega \cdot cm^2$</td>
<td>$65.4_{-6.2}^{+6.2}$</td>
<td>$148.6_{-13.7}^{+13.7}$</td>
<td>$542.2_{-36.2}^{+36.2}$</td>
</tr>
<tr>
<td>Area-weighted electrotoneic length</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_m = 3.750 \Omega \cdot cm^2$</td>
<td>$0.68_{-0.05}^{+0.05}$</td>
<td>$0.43_{-0.05}^{+0.05}$</td>
<td>$0.36_{-0.05}^{+0.05}$</td>
</tr>
<tr>
<td>$R_m = 15.000 \Omega \cdot cm^2$</td>
<td>$0.34_{-0.02}^{+0.02}$</td>
<td>$0.24_{-0.02}^{+0.02}$</td>
<td>$0.18_{-0.02}^{+0.02}$</td>
</tr>
<tr>
<td>$R_m = 60.000 \Omega \cdot cm^2$</td>
<td>$0.17_{-0.01}^{+0.01}$</td>
<td>$0.11_{-0.01}^{+0.01}$</td>
<td>$0.05_{-0.01}^{+0.01}$</td>
</tr>
</tbody>
</table>

Values are median, where superscript represents the upper 95% confidence interval of median and the subscript represents the lower 95% confidence interval of median.
ments en route to the soma will be smaller. Moreover, because of their larger diameter, more proximal dendritic segments are likely to receive more synapses than distal dendritic regions. Thus, the electrotonic properties seen by a synapse at a dendritic terminal is not representative of the electrotonic properties seen by most synapses. This study introduces an alternative to measuring the electrotonic properties at the terminal as a means of quantifying the electrotonic properties of a neuron on a per-path basis. For each path from a dendritic terminal to the soma, electrotonic properties of each constituent compartment were measured and subsequently weighted according to the compartment’s surface area relative to the total surface area of the path. By taking into account the electrotonic properties of proximal segments, area-weighted electrotonic properties represent a more accurate index of the attenuation of signals generated by synapses distributed throughout the dendritic tree.

Although area-weighting provides a precise measure of the electrotonic properties of each path from dendritic terminal to the soma, this method is not without its flaws. When considering the electrotonic properties of the dendritic tree as a whole, our path-by-path analysis using area-weighting introduces a bias. The influence of proximal sections in our analysis will be exaggerated given that the same proximal zones are part of a larger number of paths than more distal regions. This means that for motoneurons, which have more branching, the low-attenuation proximal sections have larger weighting in the calculation of their electrotonic properties than in the case of Renshaw cells and Ia inhibitory interneurons. As a consequence, the differences of electrotonic properties between the 3 cell classes, when considered on a cell-by-cell basis rather than a path-by-path basis, will be greater than reported in this study. Although a cell-by-cell analysis is an attractive option, we...
FIG. 13. Cumulative histogram of area-weighted voltage response to transient conductance change. A: peak amplitude (mV) at compartment where conductance change was applied. B: peak membrane potential (mV) at soma. C: attenuation of peak amplitude.

FIG. 14. Cumulative histogram of area-weighted 10–90% rise time of voltage response to transient conductance change. A: rise time (ms) measured at compartment where conductance change was applied. B: rise time (ms) measured at soma. C: ratio of rise time measured at soma over rise time measured at compartment where conductance was applied.
chose the path-by-path strategy because of the small number of cells in each cell class and the large number of paths.

SELECTION OF PASSIVE MEMBRANE PROPERTIES. We showed that the relative differences in the electrotonic properties between motoneurons, Ia inhibitory interneurons, and Renshaw cells were similar for different values of membrane resistivity. This assumes that the membrane properties of the 3 cell classes are the same. Judging from the large range of reported estimates of $R_m$, $R_i$, and $C_m$ obtained from different cell classes, this assumption may be invalid (Clements and Redman 1989; Major et al. 1994; Roth and Hausser 2001; Stuart and Spruston 1998; Svirskis et al. 2001; Thurbon et al. 1998; Ulrich et al. 1994). It is possible that motoneurons, Ia inhibitory interneurons, and Renshaw cells have different membrane properties that result in similar electrotonic properties for the 3 cell classes studied. Of the 3 cell classes, passive membrane properties have been reported only for motoneurons (Barrett and Crill 1974; Burke et al. 1994; Clements and Redman 1989; Fleshman et al. 1988; Rose and Vanner 1988; Svirskis et al. 2001; Thurbon et al. 1998; Ulrich et al. 1994). In fact, $R_m$ has been found to vary in motoneurons depending on the motor unit type to which they belong (Burke et al. 1982). However, in a study of the membrane properties of ventral horn neurons found in rat spinal cord slices, the passive properties estimated for putative interneurons were not different from those of putative motoneurons (Thurbon et al. 1998). Nonetheless, if the membrane properties of the 3 cell classes differ, the membrane property that is most likely to differ between the 3 cell classes is $R_m$, based on the large range of reported values of this membrane property. Let us assume that the value of $R_m$ for motoneurons is 15,000 $\Omega \cdot cm^2$. The data in Table 1 provide a means of estimating the required values of $R_m$ for the other 2 cell classes that would make their electrotonic properties match those of the motoneurons. Because the electrotonic length is proportional to the square root of $R_m$, the $R_m$ of Ia inhibitory interneurons must be about 6,280 $\Omega \cdot cm^2$ and that of Renshaw cells must be about 4,204 $\Omega \cdot cm^2$ for all 3 cell classes to have a median area-weighted electrotonic length of 0.34. Based on the data in Table 1, the other electrotonic properties of Ia inhibitory interneurons will be close to the electrotonic properties of motoneurons with an $R_m$ of 15,000 $\Omega \cdot cm^2$. However, the area-weighted voltage attenuation and input resistance of Renshaw cells, based on their values at an $R_m$ of 3,750 $\Omega \cdot cm^2$, are not equivalent to corresponding parameters of motoneurons with $R_m$ fixed at 15,000 $\Omega \cdot cm^2$. In fact, the $R_m$ of Renshaw cells would have to be less than 3,750 $\Omega \cdot cm^2$. Thus it is not possible to transform a Renshaw cell into a motoneuron by simply scaling the value of $R_m$.

Nevertheless, we cannot rule out the possibility that scaling other passive membrane properties or specific nonuniformities in $R_m$ [e.g., a somatic shunt (see Durand et al. 1984) or distal decreases in $R_m$ (see London et al. 1999)] might result in equivalent electrotonic properties for motoneurons and Renshaw cells. However such “solutions” would likely have a short time course, given the dynamic regulation of effective $R_m$ by tonic synaptic activity (Bernander et al. 1991) and voltage-gated channels (Migliore and Shepherd 2002; Reyes 2001).

TRANSIENT ANALYSIS. The extrapolation of the results of the steady-state studies to the transmission of transient signals is uncertain because of the filtering caused by the capacitance of...
the membrane (Rall 1977). We therefore examined the transmission of voltage signals generated by an exemplar conductance change that was based on data reported by Finkel and Redman (1983). The details of this conductance change (i.e., $g_{\text{peak}}$ and $t_{\text{peak}}$) are less important than the fact that this conductance change represents a typical fast synaptic connection to spinal neurons. We recognize that EPSPs or IPSPs generated by other conductances with different time courses will not follow the precise changes in time course and magnitude reported in this study (Chitwood et al. 1999; Larkum et al. 1998; Magee and Cook 2000; Roth and Hauser 2001; Williams and Stuart 2002). However, our method provided a means to systematically compare the impact of membrane capacitance on the transmission of EPSPs along the dendrites of motoneurons, Ia inhibitory interneurons, and Renshaw cells.

**Physiological implications**

**PASSIVE PROPERTIES.** All of the simulations conducted in this study were constrained by the assignment of passive membrane properties. This constraint may appear to be arbitrary, or worse, invalid, given the growing body of evidence for the widespread distribution of voltage-dependent channels on dendrites (cf. Migliore and Shepherd 2002; Reyes 2001). However, as stated elegantly by Carnevale et al. (1997) as well as by Segev and London (2000), in the absence of a quantitative description of the delivery of current and/or voltage signals to the soma under passive conditions, it is much more difficult to understand the influence of voltage-dependent channels (Bernander et al. 1994; Migliore and Shepherd 2002; Reyes 2001), the consequences of synaptic location (Carnevale et al. 1997; London and Segev 2001; Magee and Cook 2000; Williams and Stuart 2003), and the local interactions that occur between synapses (Koch et al. 1983; Mainen et al. 1996). Thus, a comprehensive description of the underlying integrative structure imposed by the passive properties of these cells is a critical step in the interpretations of the role of active properties and the distributions of synaptic inputs.

**SIGNAL BOOSTING IN MOTONEURONS.** This study shows that synaptic inputs to motoneurons suffer from relatively larger voltage and current attenuation. A recent modeling study showed that in the absence of active processes, the loss of current attributed to cable properties, in conjunction with a reduced synaptic current delivery attributed to driving potential saturation, could limit the amount of current reaching the soma to levels insufficient to drive most motoneurons to discharge in a physiological range of firing activity (Rose and Cushing 1999). However, a number of mechanisms have been investigated that may overcome this predisposition of motoneurons toward large signal loss. The hyperpolarization-activated inward current $I_h$ has been found to act as a depolarizing leak current in neonatal rat spinal motoneurons (Kiethn et al. 2000). A fast persistent sodium current is believed to be essential for rhythmic firing (Lee and Heckman 1999). Monoamines such as serotonin and noradrenaline facilitate a different persistent inward current likely generated by the L-type calcium channels (Bennett et al. 1998; Carlin et al. 2000; Lee and Heckman 2000; Lee et al. 2003; Svirskis et al. 2001). In trigeminal and hypoglossal motoneurons, inward depolarizing currents from N- and P-type calcium channels, along with a TTX-sensitive current, have been identified as additional sources of depolarizing currents along with the L-type calcium current (Hsiao et al. 1998; Powers and Binder 2003). Some of these depolarizing currents originate from the dendritic tree (Bennett et al. 1998; Carlin et al. 2000; Lee et al. 2003; Powers and Binder 2003).

**EFFICIENCY OF SIGNAL PROPAGATION IN DENDRITES OF RENSHAW CELLS.** In the somatopetal direction, there is relatively negligible attenuation of tonic synaptic inputs (measured in terms of current or voltage loss) in the dendrites of Renshaw cells. Furthermore, the attenuation of transient voltage signals is comparatively small. Combined with larger EPSPs at dendritic synapses, this suggests that from the standpoint of signal transmission, there would be little need for dendritic signal boosting mechanisms. Despite evidence of persistent inward currents in other spinal neurons (Derjean et al. 2003; Hounsgaard and Kjaerulff 1992; Russo and Hounsgaard 1996), no evidence of such currents has been found in Renshaw cells. An immunohistochemical study found on average, 4 serotoninergic boutons on cat Renshaw cells (Carr et al. 1999), confirming earlier reports that unlike for motoneurons, serotonin has a weak effect on Renshaw cells. Moreover, serotonin acts to inhibit Renshaw cells (Jordan and McCrea 1976). At present, voltage-gated channels have not been identified on the dendrites of Renshaw cells. This does not imply that voltage-gated channels are absent in the dendrites of Renshaw cells; rather it would suggest that they may serve other purposes than signal boosting such as the selective dampening of signals (Bernander et al. 1994; Hoffman et al. 1997), modulation of discharge patterns (Schwindt and Crill 1999; Williams and Stuart 1999), activation of second-messenger systems through Ca$^{2+}$ influx (Helmchen 1999), or other local computational processes (Reyes et al. 2001).

Conversely, powerful hyperpolarizing mechanisms may be necessary to dampen excitatory inputs. Although capable of firing at high frequencies, Renshaw cells fire at low rates during certain types of fictive locomotion (McCrea et al. 1980). Putative glycinergic inputs to Renshaw cells have been found to be located primarily on the soma and proximal dendrites (Alvarez et al. 1997). Furthermore, the serotonergic innervation on Renshaw cells is also juxtasomatic (Carr et al. 1999). This juxtasomatic distribution is strategically positioned to counteract excitatory influences more effectively (Alvarez et al. 1997; Koch et al. 1983).

**HETEROGENEITY WITHIN IA INHIBITORY INTERNEURONS AND FUNCTIONAL CONSEQUENCES.** Ia inhibitory interneurons shared morphological features of large principal neurons like motoneurons and small interneurons like Renshaw cells. For example, some dendrites of Ia inhibitory interneurons approached the length of the longest dendrites of motoneurons and others were as short as the shortest dendrites of Renshaw cells. This heterogeneity was reflected in the electrotonic properties measured. The cumulative histograms describing the distribution of area-weighted electrotonic properties show that the values for the Ia inhibitory interneurons were uniformly distributed across a range that spanned the smallest to the largest values of the combined data from Renshaw cells and motoneurons. This result may be a consequence of 2 sources of variability: 1) our sample of 8 Ia inhibitory interneurons may be composed of a heterogeneous population of cells. Some are small and simple like Renshaw cells. Others are larger and more complex, like motoneurons. Finally, others lie midway between Renshaw...
cells and motoneurons in term of their dendritic structure. Or 2) Ia inhibitory interneurons are a homogeneous population with all cells possessing dendritic trees that are composed of dendrites that vary widely in their structural dimensions, and the wide distribution in the cumulative histogram data is typical of individual cells. The data from Rastad et al. (1990) suggest that the former scenario may be the main source of the variability. Our small sample size of Ia inhibitory interneurons precluded a systematic analysis of these alternatives. Nevertheless, our results emphasize the need to consider the consequences of the structural variability of Ia inhibitory interneurons in the context of input/output properties. Ia inhibitory interneurons, despite their common name, may be composed of a functionally diverse population of cells, distinguished by dissimilar input/output properties.

TIME WINDOW FOR INTEGRATION. Transient events at large electrotonic distances are brief as current going to other regions of the dendritic tree, rather than through the membrane, dominates the flow of current going away from the site of injection (Agmon-Snir and Segev 1993; Jack et al. 1975; Rall 1977; Williams and Stuart 2003). Thus, for motoneurons, transient events at the site of input are more likely to be brief as a consequence of their longer and more elaborate dendritic trees. Indeed, the rise times and the half-widths measured at the sites of conductance change are smallest for motoneurons, and therefore the window for temporal integration of dendritic events is shorter for motoneurons than for their interneuronal counterparts.

As transient events propagate from the site of injection to the soma, the rise time and the half-width of the signal increase (Agmon-Snir and Segev 1993; Jack et al. 1975; Rall 1977; Williams and Stuart 2003). Theoretical studies have demonstrated that the extent of the broadening of the signal is influenced by the electrotonic distance traveled (Jack et al. 1975; Rall 1977) and the complexity of the dendritic morphology between the site of the injection and the destination (Agmon-Snir and Segev 1993). Because the 3 cell classes had differences in morphological complexity and electrotonic length, one would expect the broadening of the signal to be different as well. In particular, the change in the rise times and the half-widths of the voltage responses as they propagate to the soma should be considerably larger in motoneurons, considering the longer electrotonic length and the larger complexity of their dendritic processes. Unexpectedly, our simulation results show that the differences in the change in rise times and half-widths between the 3 classes are small. In fact, contrary to what one would expect, the change in half-widths is smallest for motoneurons. This suggests that the unique dendritic structure of these 3 cell classes normalizes the half-widths. Although the events arising from distal synapses of the 3 cell classes, when observed at the soma, may differ significantly in terms of time course, the average synapse will not, whether it is placed on a motoneuron, a Ia inhibitory interneuron, or a Renshaw cell. Thus, assuming similar membrane properties, differences in the average time window of integration for these 3 cell classes are small.

FLUCTUATIONS OF BACKGROUND SYNAPTIC ACTIVITY. Our transient analysis also revealed that transient inputs to Ia inhibitory interneurons and Renshaw cells when compared to motoneurons, have larger amplitudes when seen at the soma. Furthermore, the rise times of EPSPs arriving at the soma of these cells are faster than in motoneurons. Thus, the fluctuations in membrane potential caused by background synaptic activity will have larger peak-to-peak variations. This has implications for the input/output properties of these cells. Fluctuations in somatic voltage transients attributed to random background synaptic activity have been shown to increase the responsiveness of neocortical pyramidar neurons to synaptic inputs (Ho and Destexhe 2000; Stacey and Durand 2000) and the predictability of trial-to-trial spiking activity of rat cerebral cortex neuron (Mainen and Sejnowski 1995). However, the combination of large voltage fluctuations and shunting that result from background synaptic activity leads to divisive effects on the relation between frequency of action potential firing and synaptic input (Chance et al. 2002; Prescott and De Koninck 2003). Thus the input/output properties of Renshaw cells and Ia inhibitory interneurons may be more susceptible to gain modulation than motoneurons as a result of their passive properties.

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