COMPARTMENTAL MODELS OF ELECTROTONIC STRUCTURE AND SYNAPTIC INTEGRATION IN AN IDENTIFIED NEURONE

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SUMMARY

1. A three-compartment model of the electrotonic structure of an identified motoneurone, the median gastric (m.g.) neurone of the stomatogastric ganglion of the spiny lobster (Panulirus interruptus) was constructed, based on the passive response of the cell to a step of injected current. While its structure is only remotely related to that of the cell, the model is able to predict the passive response of the cell to any waveform of injected current.

2. The shape of the m.g. neurone provided the basis for the development of a multicompartment model of the cell from the simple compartment model. Unlike the three-compartment model, the multicompartment model has a structure that corresponds closely to that of the cell while it retains the ability to predict the passive response of the cell to any waveform of injected current.

3. The multicompartment model was used to analyse the electrotonic structure and synaptic integration of the cell. The axon acts as a current sink, causing steady-state, voltage attenuation, between the tips of different dendrites and the integrating segment to range between 20 and 80%. Steady-state voltage attenuation in the distal direction is 2%, or less.

4. Synaptic inhibition of m.g. by interneurone 1 was simulated with simultaneously activated conductance-increase synapses located on all dendritic end-compartments of the model. Inhibitory post-synaptic potential (i.p.s.p.) waveform recorded in the cell soma was duplicated in the soma compartment when the synaptic conductance change in each of the twenty-eight end-compartments was set equal to 5 nS for 8 ms. I.p.s.p. waveform forms in dendritic end-compartments were 30% larger than in the soma compartment i.p.s.p., while i.p.s.p.s in the integrating segment compartments were intermediate in size.

5. Charge from a 92 mV, 1 ms action potential in the model axon was passively conducted from axonal compartments to the soma compartment of the model, where it reproduced the attenuated, broadened voltage waveform of action potentials recorded in the cell soma. Passive spread of charge from an axonal action potential to terminal dendritic compartments evoked potentials there that were 30% larger and faster than the corresponding soma compartment potential.

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INTRODUCTION

The electronic structure of a neuron is the foundation on which the integration of all its synaptic currents and active responses rests. The electronic structure also determines what electrical events can be recorded from a given site in a neuron, and how effectively the membrane potential of the cell can be controlled from that site. Most recent attempts to describe the electronic structure of particular neurons (Jack & Redman, 1971; Jensek & Redman, 1973; Barrett & Crill, 1974; Christianson & Trebl, 1970; Tumer & Schwartzkroin, 1980; Brown, Perkel, Norris & Peacock, 1981) have used allite's application of cable theory to the flow of current in neurons (Rall, 1969, 1977). This theory assumes that membrane voltage varies continuously throughout the neuron, and describes how voltage changes everywhere in the cell in response to currents that flow within it. The partial differential equations that describe current flow in a cable model become very difficult to solve, however, when the model represents the structure of a cell that has either a complex shape or non-uniform specific membrane properties.

An alternative approach describes the electronic structure of a neuron as a set of unidirectional compartments linked by ohmic resistances (Rall, 1962, 1964; Perkel & Mulloney, 1978; Perkel, Mulloney & Badiali, 1981). Each compartment corresponds to a single region of the cell, as the cell is subdivided into more regions, the corresponding compartmental model more closely approximates a cable-theoretical description of the cell. A compartmental description gives up the assumption that membrane voltage varies continuously throughout the cell, but since current flow in the model is described by a set of coupled, first-order, ordinary linear differential equations (Perkel & Mulloney, 1978), voltage transients can readily be calculated numerically or analytically (Perkel et al., 1981).

We have used these techniques to describe the electronic structure of the median gastric (m.g.) neuron, a unique, identifiable motoneuron in the stomatogastric ganglion of the spiny lobster, Pandurus interruptus. We have first used the passive response of the cell to a step injection of current to construct a simple three-compartment model of the cell's electronic structure. This model indicates that, seen from the cell soma, the cell is electrically quite extensive. We have then created a multicomartment model of the cell by combining an anatomical description of the same cell, obtained from intracellular dye injection, with the three-compartment model. We have used the multicomartment model to study synaptic integration in the m.g. neuron, which is of interest because the cell functions both as an interneuron and as a motoneuron. The cell's dendrites are both presynaptic and post-synaptic to other neurons, allowing it to help mediate the gastric rhythm of the lobster's stomach, while spines in its axon excite the OM9 muscle, which pulls apart the lateral teeth of the stomach (Mulloney & Selverston, 1974). The model of the m.g. neuron indicates that the cell's axon acts as a current sink for dendritic inputs, necessitating considerable spatial and temporal summation of dendritic inputs to achieve the synaptic potential amplitude recorded in the cell soma. In addition, electrical events in the integrating segment and nearby axon are found to exert a strong and equal influence on the membrane potential in the tips of the cell's dendrites.
Experimental procedure

We used anaesthetized gastrectomized lobsters Panulirus interruptus from its attachments to the animal’s stomach and debrided it to expose neuronal cell bodies (Miiller & Solleveld, 1974). We bathed the ganglion and associated nerves in aerated, oxygenated saline (Miiller & Solleveld, 1974; Murder, 1976) kept close to 15°C.

Measurement of the response to injected current

We identified the soma of the m.g. motoneuron (Swanson & Mulloney, 1975) in each of six animals and penetrated it with our 30 MQ micropipette filled with 2.5 mM KCl. When the electrode was outside the cell (connected to bath ground) its voltage response to applied current (< 400mA, rise time of 100 ms after the capacity compensation of the amplifier (Gating Instruments, Iowa City, IA) was adjusted. If a stable membrane potential of at least – 60 mV was obtained, we injected a small step of current (usually less than – 3 nA, with a rise time of 100 ms) into the cell through the micro-electrode. We used the response recorded from that same electrode to determine the membrane time constant of the cell by plotting that response semilogarithmically and measuring the slope of the terminal linear portion of the curve (Jack, Nodle & Town, 1975). The time constant of the m.g. was 4.7 ms, which is more than 25 log units greater than the time constant of the electrode time constant.

We penetrated the cell soma with a second electrode that contained a 5% solution of Lucifer Yellow in 1 mM NaCl (Stewart, 1975, 1981). The resistance of this dye-filled electrode was typically 100 MQ. A third, low-conductance electrode (about 3 MQ) was placed immediately outside the soma of the cell. To minimize the effects of electrode capacitance, we lowered the level of the saline so that only the final 200-250 μm of the electrodes were in the bath. Additional capacitance compensation was achieved electronically. We injected steps or pulses of current into the cell soma through the second electrode, while the first electrode recorded the intracellular response and the third electrode recorded the extracellular response. The membrane potential of the soma was recorded as the difference between these voltages.

An initial negative voltage deflection was frequently recorded in response to a hyperpolarizing current step injected by the second electrode (Fig. 1). That deflection is due to an initial surge of capacitive current that flows through the electrode capacitance and the small extracellular resistance to ground. The brief negative potential created by current flow through the extracellular resistance is recorded by both the intracellular and extracellular electrodes. A small part of the negative deflection remains after subtraction of these records because the extracellular electrode does not detect the entire extracellular potential. The points taken from this trace to analyze the cell’s response omitted the first 0.5 ms of the response when the negative deflection took place.

The recorded voltages were amplified by a.c.-coupled pre-amplifiers (Gating Instruments, Iowa City, IA) and displayed and photographed on a cathode ray tube (c.r.t.). The injected current was measured with a current-to-voltage converter placed between the bath and system ground. Injected current had a 0-100 ms rise time of less than 200 μs. We accepted the voltage responses if, first, the membrane time constant measured from those responses matched that measured with the micro-electrode before the second electrode was introduced, and if, secondly, the input resistance of the cell was linear over the voltage range traversed by the step response. We obtained one hundred points from the c.r.t. photograph of each pulse or step response with the help of a “HI-PAD” digitizing pad (1041) from resolution (Houston Instrument, Houston, Texas). These points which were evenly spaced along the length of the photographed response curve, were stored in the computer for later analysis.

Cell shape

Following measurement of the step and pulse response, we intracellularly injected Lucifer Yellow dye into the cell with 10 nA pulses of hyperpolarizing current applied through the second electrode (Stewart, 1975, 1981). The pulses were 0.5 ms long and applied at 1 Hz for 1 h. We examined the filled cell with a Fluorescence compound microscope (Zeiss), and those areas of the cell that could be seen clearly, such as the cell soma and major processes, were drawn using a camera lucida.

The tissue was then fixed in buffered formalin (10% formalin in 0.1 M sodium-phosphate buffer) for 10 min, placed in a solution of 10% formalin in methyl formaldehyde for 1 h, dehydrated in 100% ethanol and
clears in methyl salicylate. We drew the three-dimensional shape of the cell in the cleared tissue using a camera lucida. The post-fixation drawings of the cell and ganglion made it possible to calibrate the shrinkage of the cell produced by fixation and dehydration. We found this shrinkage to be approximately 40% for the diameters of cell processes and 20%, for the heights of processes and the same diameter.

Simulation and simulations

The analysis of data and the construction of three-compartment models were performed by a Nippe computer (Nordstar Computer, Berkeley, CA). One set of programs written in BASIC facilitated 'peeling' exponential decay terms from the step response (Fig 2), while another program used these decay terms and a set of formulas presented in the Appendix (eqns. 1-2, 5-21) to calculate parameter values for a three-compartment model of the cell. We obtained responses of the multicompartment model of the cell (Figs. 6, 8 and 9) from FORTRAN programs that calculated the eigenfunction expansion (Vedel et al. 1981) on a Univac 90/80 computer at Georgia State University.

Fig. 1. Response of cell to hyperpolarizing current step. Top: injected current, low sweep speed. Middle: transmembrane potential of soma, high sweep speed. Bottom: transmembrane potential of soma, low sweep speed. The initial negative deflection in the middle and bottom traces is due to capacitive current from the electrode (see text).

RESULTS

Analysis of the passive response of a stomatogastric motorneurone

To determine the electrotonic structure of the m.g. neurone we recorded the response of the cell at its soma to steps of hyperpolarizing current injected there. Fig. 1 presents a record of the 3 nA step of hyperpolarizing current that was injected through one intracellular electrode, and the transmembrane potential of the soma, which was recorded with two additional electrodes (see Methods).

The initial negative deflection on the voltage traces in Fig. 1 is due to the surge of capacitive current that flows at the onset of the current step through the electrode capacitance and the small extracellular resistance to ground (see Methods). The points taken from this trace to analyse the cell's response constituted the first 0.75 ms of the response when the negative deflection took place.

The step response of the cell soma can be fitted by the sum of a constant and three exponential decay terms. The constant is the asymptotic response, which equals the product of the current amplitude and the input resistance (Rh). After subtracting this constant from the data, we 'peeled' exponential terms from the difference curve to determine their coefficients and time constants (Raib, 1999). First we plotted the difference curve semilogarithmically, and identified a terminal straight line portion on that plot. Then we determined the equation of the line which had the best least-squares fit to that linear portion; the analog of that equation provided the first exponential term; difference curve to more obtain tw within the experim the asymptotic value v(t)

\[ v(t) = -14.366 + 1.24(t - t_0) \]

for \( t > 0 \). Time is in s in Fig. 3 along with

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To determine w provide a better fit to one equation with a

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and

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As can be seen, there is good agreement between the curve described by eqn. (1) and the recorded step response. The root-mean-square of the differences between points on the transient curve and points at corresponding times calculated from eqn. (1) is 0.11 mV, which is within the noise of the oscilloscope trace.

To determine whether an equation with a different final time constant could provide a better fit to the data than eqn. (1), we 'peeled' the data twice more to obtain one equation with a longer (1a) and one with a shorter (1b) long time constant than exp. (1). These equations are:

\[ V(t) = -14.36 + 4.10 \exp(-t/35.4) + 7.15 \exp(-t/17.4) + 3.15 \exp(-t/0.83) \]  
(1a)

\[ V(t) = -14.36 + 8.24 \exp(-t/35.4) + 2.90 \exp(-t/9.8) + 3.26 \exp(-t/0.67) \]  
(1b)
A three-compartment model.

Besides providing a basis for the data, eqn. (1) is also an expression of the three-compartment model of a neuron. The circuit represents the structure of the cell, and the equation describes the time course of the membrane potential in response to a current stimulus. The model assumes that the current is applied to a single compartment, and the membrane potential is given by eqn. (1). The parameters in the model are: 

\[ V = \frac{1}{C_m} \frac{dQ}{dt} \]

where \( V \) is the membrane potential, \( C_m \) is the membrane capacitance, and \( Q \) is the charge on the membrane.

The responses of the cell were also recorded for current steps between \(-5 \) and \(5 \) nA applied to the soma; the responses are linear when the somatic membrane potential is between \(20 \) mV hyperpolarized and \(7 \) mV depolarized. Depolarizations of \(7 \) mV evoke axonal impulses that appear greatly attenuated and prolonged in the soma (Fig. 9.4).

The input resistance of the neurone equals \(4-78 \) MΩ, while the longest time constant of the charging curve is \(4-78 \) ms. We measured somatic responses to similar current injections in m.g. neurones of five other animals. The input resistances of these cells varied between \(4 \) and \(5 \) MΩ, while their longest time constants varied between \(36 \) and \(63 \) ms.

The three-compartment model represents the step response of a current step. The model is also able to replicate the data when the cell is driven by a burst of current (Fig. 9.4).
A three-compartment model of the m.g. neurone

Besides providing a good description of the response of the cell to a current step, eqn. (1) is also an exact description of the voltage response at one of the nodes of a three-compartment circuit (Fig. 4) to a step of current applied at the same node. This circuit may provide an initial, approximate description of the electrososic structure of the cell because eqn. (1) describes the step response of both the cell and the circuit. Since the voltage response is recorded in the soma of a monopolar neurone to a current step injected there, an end-compartment of the circuit can provide a description of the isopotential soma. Because of the branching structure of the rest of the cell, it is not possible to assign the other two compartments unambiguously to a pair of serially connected isopotential regions of the cell. Instead, the two compartments can represent the effective input impedance of the rest of the cell, as seen from the soma. This circuit can then be used to predict the passive response of the cell, recorded in the soma, to any wave form of current injected there.

To obtain values for the resistances and capacities of the circuit that would enable it to mimic the response of the cell, we derived a set of formulae that express these values in terms of the coefficients and time constants of the step response. These formulae are presented as eqns. (A 2)-(A 21) in the Appendix. The derivation assumed that the coefficients and time constants characterized the step response that occurs in an end-compartment of the circuit to current injected there. Consequently, an end-compartment of the circuit, compartment I, represents the isopotential soma, so that the capacitance of that compartment represents the total capacitance of the soma. (If it were assumed that the injection site in the cell could be represented best by a middle compartment of the circuit, the formulae that express the circuit parameters in terms of the time constants and coefficients would be different.)

Eqn. (A 7) (see Appendix) gives the value of the capacitance of the first (soma) compartment of the circuit in terms of the coefficients and time constants (inverse time constants) of the step response. That capacitance is 652 μF. The capacitance of the second compartment is free to be chosen between an upper limit of 600 nF and a lower limit of 331 nF; these limits are set by inequality (A 18). If it is assumed that the membrane of the cell is uniform in its passive properties, then eqn. (A 20) will hold, where τₐ, the membrane time constant, equals 4.7 ms, the longest time constant of eqn. (1). The value of C₂ will then be 656 nF, which is at the upper end of its range, and C₃ will equal 13-15 nF. The values of the resistances and capacitances in the three-compartment model for the m.g. neurone are presented in Table 1.

The response of the model and the cell to applied current

The three-compartment model was created from eqn. (1), which closely approximates the step response of the cell (Fig. 3). The response of the model to a −3 nA current step is also given by eqn. (1), and so there is no question that the model can replicate the data used to make it. Since the model is linear and time-invariant, it will also be able to predict the linear, time-invariant responses of the cell to other wave forms of current.
Predictions of the three-compartment model

The first compartment of the model can represent the soma of a unipolar cell like the m.g. neurone; it is not possible to correlate the other two compartments with particular regions of the cell. Rather the second compartment may be taken to represent regions that are electrically near the soma, while the third compartment represents regions that are more distant. As such, the model can indicate how those regions of the cell would respond to current or voltage wave forms applied at the soma.

Table 1. Values of resistances (MO) and capacities (nF) in the three-compartment model of m.g. neurone

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<th>1</th>
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<tbody>
<tr>
<td>$R_1$</td>
<td>64.2</td>
<td>1.51</td>
<td>6.34</td>
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<tr>
<td>$C_1$</td>
<td>0.002</td>
<td>0.58</td>
<td>0.00</td>
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<tr>
<td>$R_2$</td>
<td>9.99</td>
<td>3.16</td>
<td>0.00</td>
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<td>$C_2$</td>
<td>5.63</td>
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<td>Voltage transfer ratio between compartments of model.</td>
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<td>1-2</td>
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Column number represents compartment of current injection.

This could be useful in assessing the value of the reversal potential of synaptic inputs occurring at some distance from the soma, or in assessing the effects of a voltage clamp applied at the soma on other regions of the cell. For instance, when a steady-state voltage or current is applied to the first (soma) compartment, the steady-state voltage obtained in the second compartment is calculated to be 71% of the soma compartment voltage, while the final voltage in the third compartment is 20% of the soma compartment voltage. Steady-state voltage transfer ratios for all pairs of compartments are presented in Table 1. These results indicate that the electrical structure of the cell is extensive, and that a voltage clamp imposed in the soma cannot control membrane potential elsewhere in the cell.

A multicompartiment model of the m.g. neurone

We determined the shape of the m.g. neurone by filling it with the intracellular dye Lucifer Yellow (Stewart, 1981). We used a description of this shape, together with the three-compartment model, to construct a multicompartiment model of the electrophoretic structure of the cell. Like the simple model, this multicompartiment model is able to mimic the response of the cell to currents injected into the soma. The model also describes the passive spread of current from an injection site anywhere in the cell into all the major structures of the cell. We have used these descriptions to demonstrate the effect of dendritic synapses on the soma, where recordings were made, and on other regions of the cell.

Compartmentalization of the cell's structure

We drew the cell's structure from the whole-mount preparation using a camera lucida attachment to a Zeiss fluorescent microscope. That drawing, which is uncorrected for tissue shrinkage, is presented in Fig. 5A. The numbers next to the...
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Fig. 5. Structure of cell and multicompartment model. A: camera lucida drawing of the
stained m.g. neuron. Numbers refer to the vertical distance, in micrometers, dorsal (+) or
vestral (−) to the equatorial plane of the ok body. These numbers and the calibration
bar refer to the fixed, dehydrated and cleared tissue. Shrinkage of process diameters was
approximately 40%, shrinkage of length and soma diameter was approximately 30%. A,
axon; D1–D8, the major dendrites; IS, integrating segment; S, soma. B: compartments
of the multicompartment model. Abbreviations as in A; the eight major dendrites are
indicated by the first digit of the compartmental label (e.g. 11 refers to the first
compartment of the first dendrite). The axon is represented by three compartments. (See
Tables 2 and 3.)
major processes refer to the distance, in micrometres, dorsal (+) or ventral (−) to the equatorial plane of the cell body. Measurements of the three-dimensional lengths and diameters of the processes of the m.g. neurone were obtained from the stained cell and corrected for tissue shrinkage (see Methods).

We used these corrected measurements of the lengths and diameters of processes of the m.g. neurone, together with the parameter values of the three-compartment model, to construct a multicompartment model of the cell. In that model, the cell soma was represented by a single compartment that was identical to the first compartment of the three-compartment model. Similarly, the first coupling resistance of the three-compartment model, \( R_{ij} \), provided an estimate of the coupling resistance between the soma and the rest of the cell.

The rest of the cell was compartmentalized by first identifying what we wished to call the 'nodal points' of the cell's structure. Nodal points are defined as being either the branch points of processes, the end-points of processes, or points along the length of a long, unbranching process. A single compartment in the model represents the region of the cell in the immediate neighbourhood of a nodal point. The membrane area of a region represented by a compartment is calculated from the lengths and diameters of all the processes that intersect at the nodal point, according to the formula

\[
A_j = \sum_i \left( \pi \times D_{ij} \times L_{ij} / 2 \right).
\]

where \( A_j \) is the area of the \( j \)th region, and the nodes \( j \) are those that are directly coupled to node \( i \) by a segment of length \( L_{ij} \) and diameter \( D_{ij} \). The formula assumes that these processes are cylindrical over half the length of a single segment, which they appear to be. Only half the length of each segment is included in \( A_j \); the other half is considered to be part of the adjacent region.

The compartmental capacitance, \( C_m \), is the product of the membrane area of the region, \( A_j \), and the specific membrane capacitance, \( C_m \), which we assume to be 1 \( \mu F/cm^2 \) (Cole, 1968; Brown, et al. 1981). Similarly, the \( \kappa \)-compartmental resistance, \( R_{ij} \), is defined to be the quotient of the specific membrane resistance, \( R_m \), and the same membrane area. The value of \( R_m \) is assumed to be equal to 1/\( \kappa C_m \), or 41.7 \( \Omega \) cm for the m.g. neurone. The coupling resistance that links two compartments, \( R_{ij} \), represents the series resistance of the cytoplasm in the process that connects two nodes of the cell. As the processes in the stained, living m.g. neurone appear cylindrical, the capacitance can be described by

\[
R_{ij} = 4R_m L_{ij} / (\pi D_{ij}^2).
\]

\( R_{ij} \) is the resistivity of the cytoplasm, which in lobster nerve is about 60 \( \Omega \) cm (Katz, 1966).

The axon of the m.g. neurone can be represented best by a terminated cable; in order to facilitate computation, however, we have chosen to represent the axon as a set of three serially connected compartments that has approximately the same input impedance as the cable. The soma is represented by a single compartment as in the three-compartment model. Assuming that the soma membrane is characterized by a capacitance of 1 \( \mu F/cm^2 \) (Cole, 1968; Gorman & Mirollo, 1972; Brown, et al. 1981), the value of the lumped capacitance gives an effective somatic membrane area of...


| Table 2: Compartmental resistances (Ω) in the model of the m. g. neurone. The compartmental labels are the same as in Fig. 3.B. S, soma; D, dendrite (e.g. D14 refers to compartment 11 in Fig. 3.B); IS, integrating segment; A, axon. |
|---|---|---|---|---|---|
| S | IS1: | IS2: | IS3: | D14: | D15: |
| 612 | 1647 | 3384 | 1102 | 1902 | 14196 |
| D11: | 1014 | 247 | 425 | 441 | 1902 |
| D12: | 1885 | 580 | 2311 | 2942 | 1902 |
| D13: | 1762 | 1327 | 3487 | 243 | 14196 |
| D14: | 2600 | 6804 | 10090 | 244 | 7429 |
| D15: | 746 | 1968 | 292 | 244 | 14196 |
| D16: | 1736 | 10887 | 1166 | 13345 |
| D17: | 1348 | 2169 | 5770 | 14196 |
| D18: | 8733 | 510 | 856 | D71: | 1423 |
| D19: | 469 | 662 | 999 | D72: | 24234 |
| D20: | 1960 | 1077 | 2839 | 6800 |
| D21: | 2448 | 1337 | 2839 |
| D22: | 1354 | 1356 | A1: | 368 |
| D23: | 3231 | 3142 | A2: | 368 |
| D24: | 1363 | 207 | 24 |
| D25: | 2533 | 1546 |
| D26: | 7459 | 7553 |
| D27: | 3384 | 2830 |
| D28: | 3862 | 12254 |
| D29: | 3034 |
| D30: | 8779 |
| D31: | 6096 |
| D32: | 6096 |

| Table 3: Inter-compartmental coupling resistances (Ω). Compartmental labels are the same as in Fig. 3.B (e.g. D11 refers to compartment 11 in Fig. 3.B) |
|---|---|---|---|---|---|
| S-IS1: | IS1-IS2: | IS2-IS3: | IS1-IS1: | IS1-IS2: | IS1-IS3: |
| 0.27 | 0.23 | 1.73 | 0.27 | 0.23 |
| D11-D12: | 0.81 | D22-D23: | 0.90 | D32-D33: |
| D13-D14: | 2.3 | D23-D24: | 1.35 | D33-D34: |
| D15-D16: | 0.29 | D24-D25: | 0.45 | D34-D35: |
| D16-D17: | 2.2 | D25-D26: | 1.95 | D35-D36: |
| D17-D18: | 2.90 | D26-D27: | 1.28 | D36-D37: |
| D18-D19: | 0.48 | D27-D28: | 0.04 | D37-D38: |
| D19-D20: | 0.25 | D28-D29: | 0.50 | D38-D39: |
| D20-D21: | 0.94 | D29-D30: | 2.86 | D39-D40: |
| D21-D22: | 0.27 | D30-D31: | 1.29 | D40-D41: |
| D22-D23: | 0.29 | D31-D32: | 1.29 | D41-D42: |
| D23-D24: | 0.42 | D32-D33: | 1.40 | D42-D43: |
| D24-D25: | 1.02 | D33-D34: | 0.04 | D43-D44: |
| D25-D26: | 0.04 | D34-D35: | 0.04 | D44-D45: |
| D26-D27: | 0.09 | D35-D36: | 0.04 | D45-D46: |
| D27-D28: | 1.90 | D36-D37: | 0.04 | D46-D47: |
| D28-D29: | 1.29 | D37-D38: | 0.04 | D47-D48: |
| D29-D30: | 3.01 | D38-D39: | 0.04 | D48-D49: |
| D30-D31: | 2.49 | D39-D40: | 0.04 | D49-D50: |
| D31-D32: | 0.82 |
| D32-D33: | 0.37 |
| D33-D34: | 0.37 |
| D34-D35: | 0.37 |
| D35-D36: | 0.37 |
| D36-D37: | 0.37 |
| D37-D38: | 0.37 |
| D38-D39: | 0.37 |
| D39-D40: | 0.37 |

Note: All resistances are given in Ω.

About 90 Ω cm (Katz, a terminated cable; in D23 represent the axon as diametrically the same input compartment as in the axon is characterized by FT2; Brown et al., 1981).
68180 μm², which is close to the value of 68810 μm² calculated from the dye-filled cell.

The arrangement of compartments in the multicompartment model of the m.g. neuron is shown in Fig. 5B. The values of the compartmental resistances and intercompartmental coupling resistances are given in Tables 2 and 3, respectively. The value of each compartmental capacitance is given by the ratio of the membrane time constant, τm, to the compartmental resistance.

![Graph showing the step response of the m.g. neuron and the multicompartment model](image)

**Fig. 6. Step responses of the m.g. neuron and the multicompartment model.** The responses of the soma (dots) and soma compartment (continuous curve) to -3 nA injected there. *Same experimental data as in Figs. 2 and 3.*

**Step response of the multicompartment model**

We calculated the voltage response of the soma compartment to a -3 nA current step applied there to see whether the multicompartment model could reproduce the step response of the m.g. neuron. This calculation is presented in Fig. 6 superimposed on a plot of the experimental points. The good agreement between the responses of the model and the cell to this input supports the use of the model as a description of the neuron's electrotonic structure.

**Electrotonic structure of the m.g. neuron**

**Input resistances of different parts of the model.** The flow of current within the m.g. neuron depends in large part on the input resistance which each part of the cell presents to neighboring parts (Rall & Rinzel, 1973). In particular, current flow depends on the input resistance that each of the major branches (dendrites, axon, soma) presents to the integrating segment where they all join (Fig. 5d). We obtained estimates of those cellular input resistances from input resistances calculated for corresponding parts of the model. The input resistances presented by the six major model dendrites to integrating segment compartment ISI (Fig. 5B) have an average value of 354 MO (range: 122-1071 MO). The input resistance of the soma compartment

**Table 4. Intraspinal v. end-compartment voltage transfer ratio.**

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Transfer Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>D12</td>
<td>0.74</td>
</tr>
<tr>
<td>D14</td>
<td>0.95</td>
</tr>
<tr>
<td>D16</td>
<td>0.38</td>
</tr>
<tr>
<td>D18</td>
<td>0.11</td>
</tr>
<tr>
<td>D63</td>
<td>0.48</td>
</tr>
<tr>
<td>D66</td>
<td>0.36</td>
</tr>
<tr>
<td>D67</td>
<td>0.42</td>
</tr>
<tr>
<td>D69</td>
<td>0.55</td>
</tr>
<tr>
<td>D611</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Steady-state voltage input resistance**

The model input resistance is significantly greater from the dendritic compartment 5B onwards (B in the soma and dorsal to ISI) than in ISI1. From the soma to the axon, the input resistance is presented to a single end-compartment, the steady-state voltage recorded in 1.4. The voltage transfer ratio between the steady-state voltage of the soma to the second compartment is calculated.

From these calculations, the voltage applied at the soma is reduced to the axonal compartment by 17% (at the soma) and 19% (at the axon).
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seen from IS1 is 623 MΩ, while that of the branch that leads to the axonal compartments is 50 MΩ. This last value is nearly entirely due to the low input resistance of the axonal compartments themselves, which is 50 MΩ. The low input resistance of the axonal branch indicates that the axon is a current sink for the cell. Steady-state currents that arose in any of the dendrites would converge on the integrating segment and then flow into the axon before leaving the cell.

Table 4: Centripetal voltage transfer ratio between dendritic end-compartment and IS1. A voltage transfer ratio gives the voltage in IS1 when 1 V is maintained in the dendritic end-compartment.

<table>
<thead>
<tr>
<th>D12</th>
<th>D24</th>
<th>0.53</th>
<th>D34</th>
<th>0.56</th>
<th>D43</th>
<th>0.45</th>
<th>D54</th>
<th>0.31</th>
</tr>
</thead>
<tbody>
<tr>
<td>D44</td>
<td>0.66</td>
<td>D26</td>
<td>0.53</td>
<td>D36</td>
<td>0.25</td>
<td>D45</td>
<td>0.45</td>
<td>D55</td>
</tr>
<tr>
<td>D66</td>
<td>0.24</td>
<td>D76</td>
<td>0.82</td>
<td>D87</td>
<td>0.33</td>
<td>D98</td>
<td>0.36</td>
<td>D101</td>
</tr>
<tr>
<td>D112</td>
<td>0.48</td>
<td>D12</td>
<td>0.50</td>
<td>D182</td>
<td>0.41</td>
<td>81</td>
<td>0.79</td>
<td>A1</td>
</tr>
<tr>
<td>D166</td>
<td>0.35</td>
<td>D176</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D167</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D169</td>
<td>0.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D160</td>
<td>0.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Steady-state attenuation between different parts of the model. The low axonal input resistance suggests that steady-state voltage attenuation within the cell is greater from the dendritic tips to the integrating segment than from the integrating segment outwards (Rall & Rinzel, 1972). This suggestion is supported by calculations of steady-state voltage transfer ratio between different compartments of the model. The voltage attenuation from the central integrating segment compartment IS1 (Fig. 3.5E) outward to the soma and dendritic tips is very small: the steady-state voltage in the soma and dendritic end-compartment n about 99% of a maintained voltage in IS1. From the soma and end-compartment into IS1 the steady-state voltage attenuation is much greater: a voltage applied at the soma is reduced to 79% of its value at IS1, while a voltage applied to an end-dendritic compartment is reduced to between 11 and 74% of its value at IS1. Table 4 presents the calculated voltage transfer ratios between end-compartment and IS1. Each of these values is the ratio of the steady-state voltage in compartment IS1 to the steady-state voltage applied to a single end-compartment. Because the model axon is a current sink, considerable steady-state voltage attenuation also occurs from IS1 to the further axonal compartments: the transfer ratio from IS1 to the first axonal compartment is 0.97, while the ratios to the second and third axonal compartments are 0.71 and 0.21, respectively.

From these calculated voltage transfer ratios it is apparent that a steady-state voltage applied at the soma would be significantly reduced within the dendritic tree and along the axon. A steady-state voltage applied at the soma compartment of the model is reduced at the dendritic tip compartments to 78% of its original value, while at the axonal compartments it is reduced to between 77% (at the first compartment) and 17% (at the third) of that value.
neurons: inhibition from another animal by recording the soma response to a step of hyperpolarizing current injected there while the cell was inhibited by a burst of spikes in Int. 1 (Fig. 7 B). The change in somatic membrane potential reached a final value of $-21 \text{ mV}$ in response to $-5.5 \text{ nA}$ of current (Fig. 7 C), which yields an input resistance of $3.8 \text{ M}\Omega$. This is a reduction of more than $20\%$ from the resting value of the cell's input resistance ($48 \text{ M}\Omega$). Similarly, the longest time constant of the step response was about $36 \text{ ms}$, which is a reduction of $18\%$ from the resting value ($44 \text{ ms}$). These measurements from another cell are useful because the two m.g. neurons happened to have nearly identical electrical properties in the resting state; they had the same resting somatic input resistance ($48 \text{ M}\Omega$) and the same reversal potential for i.p.s.p.s from Int. 1 ($-14 \text{ mV}$ from rest), as well as very similar resting membrane time constants ($417 \text{ ms}$ and $44 \text{ ms}$).

Simulation of synaptic inputs to the m.g. neuron

To simulate the response of the m.g. neuron at a post-synaptic site, we modified the corresponding compartment in the model according to Fig. 8 A: the serial combination of a synaptic resistance, a synaptic driving potential and a switch was placed in parallel with the compartmental resistance and capacitance. The switch was closed to simulate the change in post-synaptic conductance that occurs following post-synaptic transmitter release, and was open at other times. The resulting square-waveform of the change in compartmental post-synaptic conductance made the computation of the post-synaptic response tractable.

In his study of the distribution of synaptic contacts among stomatogastric neurons, King (1976a, b) found that chemical synaptic interactions between two neurons occur at a number of separate synaptic contacts widely distributed over both of the neurons. To simulate the response of m.g. to synaptic input from Int. 1, we examined the case where the tips of all m.g. dendrites receive simultaneous inputs from Int. 1. Consequently, we describe all twenty-eight terminal dendritic compartments (Fig. 8 B) with the circuit of Fig. 8 A. We calculated that if the synaptic resistances in the terminal dendritic compartments were set equal to $200 \text{ M}\Omega$, the input resistance of the model would be $36 \text{ M}\Omega$ when the synaptic switches were all closed. This input resistance is quite close to the value of $36 \text{ M}\Omega$ measured in the m.g. neuron during Int. 1 input. Moreover, when the switches are closed, current flow in the model is described by a new series of time constants, the longest of which is $356 \text{ ms}$, which is close to the measured value of $36 \text{ ms}$.

With the synaptic resistances set equal to $200 \text{ M}\Omega$, we estimated the synaptic driving potential from the measured synaptic reversal potential and the calculated steady-state voltage transfer ratios. When the synaptic switches are closed, the transfer ratio between the soma and dendritic end-compartment drops from 0.78 to 0.70. By setting the synaptic driving potential equal to $-10 \text{ mV}$ from rest, we found that the new transfer ratio would cause the synaptic reversal potential at the soma to equal the measured value of $-14 \text{ mV}$ from rest.

With the synaptic driving potential and resistances set equal to $-10 \text{ mV}$ and $200 \text{ M}\Omega$, respectively, we found that if the synaptic switches in all dendritic end-compartment were closed for $8 \text{ ms}$, the calculated potential change in the soma compartment (Fig. 8 B) was quite similar to the recorded somatic i.p.s.p. caused by
input from Int. 1 (Fig. 7.2). The closing of the switch for this time also evoked a response in compartment 37 (Fig. 8B) that is typical of the responses of most dendritic end-compartments: it rose faster than the soma compartment's response to an amplitude that was about 30% larger, and fell along a curve that was quite similar to the soma compartment's response. The responses of other end-compartments range from 15 to 30% larger than the soma response. The potentials in the integrating segment compartment 181 rose more quickly than the soma potential and less quickly than dendritic compartment potentials; similarly, its peak amplitude was intermediate between the two.

If the synaptic inputs are restricted to the end-compartments of only one of the major dendrites (e.g., D6, which has five end-compartments), the response of the soma compartment is at least 75% smaller (Rinzel & Hall, 1974). To make the soma response to inputs at a single dendrite comparable to the response of Fig. 8B, it is necessary to decrease the synaptic resistances of the compartments in that dendrite by more than a factor of 5. A fast synaptic current flows to the summed currents at the maximum that is to number of contacts each conductance must.
by more than a factor of 4. This larger synaptic conductance means that the initial synaptic current flowing at each of these contact sites is greater than 0.25 nA; these summed currents cause the potential change in the affected dendrite to reach a maximum that is twice as large as that of the other dendrites and soma. If the reduced number of contacts is distributed among all the major dendrites, then the synaptic conductances must be similarly increased if the response of the soma compartment

![Graph showing spikes in the cell and model, A, attenuated spikes recorded in the m.g. soma in response to three k-rhe of depolarizing current injected through. Top trace: 15 nA; middle trace: 14 nA; bottom trace: 13 nA. The cell's input resistance remained constant during the two smaller current injections. B, response of soma compartment S, integrating segment compartment B1 and a dendrite-end compartment 25 to a 82 mV, 1 ms action potential wave form created in the first axon compartment A. The 100 mV vertical scale refers to curve A; the 10 mV scale refers to all the other curves.]

is to remain the same. In this instance, however, the responses of all the dendrites will be similar. Finally, we found that under all of these conditions changes in the duration of synaptic switch closure caused roughly proportional changes in the rise time of the post-synaptic potential (p.s.p.) in the soma compartment, 8 ms closure times yielded some compartment p.s.p. with rise times most similar to those recorded in the m.g. soma (Fig. 7A).
The passive spread of impulses into dendrites

The dendrites of the m.g. neurone not only receive inhibition from Int. 1, they also mediate m.g.'s inhibition of Int. 1. The impulses in the m.g. neurone that produce this inhibition presumably originate in or near the soma, and propagate passively into the soma and dendrites. This is suggested by the similar attenuated impulses recorded in the soma during gastric oscillation (Fig. 7B) and in response to current injection in the soma (Fig. 9A). In both instances the appearance of impulses in the soma coincides with their appearance in the axon; there is no indication of more than one impulse initiation zone (Mulloney & Selverston, 1974). Moreover, injections of just-subthreshold currents into the soma had no measurable effect on the cell's input resistance measured there (Fig. 9A); this suggests that the conductance changes which accompany impulse initiation are electrically remote from the soma.

We used the model to determine first whether the charge produced by an axonal action potential can spread passively to the soma to create the potentials recorded there, and second how that passive spread of charge affects dendritic potentials. We applied a time-varying voltage to the proximal axonal compartment to re-create a 92 mV, 1 ms action potential there, and then calculated the responses of the integrating segment compartment, the soma compartment and the dendritic end-compartments to the passive flow of charge from that axonal compartment. The wave form of the action potential in the axonal compartment and the passive responses of the other compartments are presented in Fig. 9B. The response of the soma compartment is similar to that of the impulse recorded in the m.g. soma. The impulses in the end-compartments of all dendrites are similar, and are about 30%, larger and 30%, faster than the soma impulse. If the tip of each dendrite is presynaptic as well as post-synaptic to Int. 1, as King (1974a, b) suggests, then these dendrites will be activated synchronously and uniformly by each m.g. impulse.

**Discussion**

The three-compartment model

In the absence of anatomical information concerning the structure of a neurone, it is still possible to obtain some understanding of the electrotonic structure of the cell by analyzing its response to pulses or steps of injected current (Ball, 1969; Jack et al., 1975). We used the formula provided in the Appendix to calculate values for the resistances and capacitances of a three-compartment model from the step response of the cell. The model makes it possible to predict the linear responses of the cell to injected currents while avoiding specific assumptions about neuronal shape. These predictions are only useful when current is applied to the compartment that corresponds to the injected region of the cell, which in this instance is the cell soma. The responses of that compartment predict the responses of the soma, while the responses of the second and third compartments predict the responses of regions of the cell that are at increasing distances from the soma. The small voltage transfer ratio between the first (soma) and third compartments, 0.20, indicates that the latter compartment represents a region of the cell that is electrically quite distant from the soma.
The identity of those distant regions can be discovered by comparing voltage transfer ratios in the three-compartment model with those of the multicompartment model. The voltage transfer ratio between the first and second compartments of the three-compartment model of m.g. is 0.71, which is close to the transfer ratio of 0.77 between the soma and first axonal compartment of the multicompartment model. The transfer ratio of 0.26 between the first and third compartments of the three-compartment model is within the range of the transfer ratios between the soma and second and third axonal compartments of the larger model. It is apparent then, that while the first compartment of the three-compartment model can predict the linear response of the m.g. soma to current injected there, the response of the second compartment will predict the linear response of the proximal portion of the axon to that current, and the response of the third compartment will predict the response of a more distant region of the axon.

The multicompartment model

Knowledge of the structure of the cell makes it possible to transcend the limitations of simple compartmental models by constructing a multicompartment model that describes the flow of current in all parts of the cell (Barrett & Crill, 1974a). We used the multicompartment model of the m.g. neuron to examine both steady-state voltage attenuation and synaptic integration in the cell. The multicompartment model indicates that while little voltage attenuation occurs for signals passing from the integrating segment out each dendrite, much greater attenuation occurs for a signal passing into the integrating segment from a dendritic tip. This latter attenuation occurs because the axon is a sink for current, which is apparent from the low input resistance of the set of axonal compartments, seen from the integrating segments compartment (Rall & Rinzel, 1973).

In constructing the multicompartment model we made several assumptions, of which two of the most important are: (a) the dendritic processes are cylindrical over short segments, and that the cell membrane has uniform specific membrane resistivity and capacitance. (b) the structure of a neuron is not a simple cylinder but has a branched, intricately branched structure of the current (Rall, 1969; Jack 1975) to calculate values for the linear response of the soma relative to itself. The linear responses of portions of the neuron is the cell soma, of the soma, while the linear responses of regions of the small voltage transfer 0.6, indicates that the latter are quite distant from the vicinity of the soma.
Synaptic integration in the m.g. neurone

The major dendrites of the m.g. neurone all branch from the same point on the integrating segment and end in fine processes in the neuropil. Contacts between somatogastric neurones occur on neuropil processes distributed over several branches of the pre-end post-synaptic neurones (King, 1976a). This distribution of contacts avoids problems of non-linear summation at the post-synaptic membrane which arise when locally summed synaptic conductance changes bring the local membrane potential close to the synaptic reversal potential (Martin, 1966; Barrett & Grilli, 1974a). This could be a particularly serious problem for inhibition of m.g. by Int. 1, as the inhibitory driving potential is only -10 mV from rest. This problem is illustrated by the difference in the peak amplitude of the c.p.s.p. in the synaptic end-compartmental distribution that results when the input is dispersed to all the dendrites (Fig. 8 B) and when the input is confined to a single dendrite. The distributed input results in a peak voltage of 19 ± 0.6 mV (mean ± s.e. d. for twenty-eight end-compartmental, while the input that is confined to a single dendrite, and results in the same soma potential, yields a peak voltage in the synaptic end-compartmental of 3.2 ± 0.6 mV (five end-compartmental of dendrite 6). These potentials would be due to a single impulse in the presynaptic neurone. During gastric oscillation, intervals between Int. 1 impulses may as short as 20 ms. A series of Int. 1 impulses at short intervals will drive the membrane potential to the synaptic reversal potential more quickly in the dendrite that receives at the synaptic inputs than in a dendrite that shares the inputs with other parts of the cell. This will limit the synaptic current that can be produced by a dendrite that receives all the contacts, which in turn may limit the response of its cell to high-frequency inputs.

Passive propagation of impulses into the dendrites

Since the tips of the dendrites are presynaptic as well as post-synaptic elements, the wave form of the impulse that passes into those tips is of considerable interest. This wave form was calculated with the model under two assumptions: (1) that the membrane of the soma, dendrites and integrating segment is passive and characterized by the specific membrane resistivity and capacitance used to create the model; (2) that charge flows passively into those areas of the cell from active membrane in the axon. The bases of these assumptions are that action potentials are greatly attenuated and prolonged in the soma (Fig. 9 A), that the cell has one impulse initiation zone that projects impulses into the axon, and that the input resistance at the soma remains constant even at impulse initiation threshold. This last result indicates that at impulse threshold the membrane conductance changes that mediate impulses generation are far enough from the soma not to allow the soma's steady-state response to current injection.

To simulate the effect of axonal impulse on the passive dendritic tree and soma, an action potential wave form was imposed on the first axonal compartment, and the passive responses of other compartments in the model were calculated. The similarity of the soma compartment's response (Fig. 9 B) to the impulses recorded in the soma (Fig. 5 4) provides support for the assumptions described above. The responses in dendritic end-compartment (Fig. 9 B) suggest that the dendrite impulse is 30% larger in early synaptic integration, suggesting that this occurs in all dendrites. The axon impulse, however, occur in the dendrite oscillation. This makes the model much more realistic (Fig. 9 B).

Interaction of presynaptic impulses

The dendro-dendritic synapses included in the model (Wullich & Dowling, 1974). During the normal 1 frq. alternating input to one cell will elicit a pulse of m.g. to suprare the m.g. neuron during the transmission to another neuron corresponding on dendrites, which will inactivate the presynaptic end-compartmental of dendro-dendritic synapses of predictive models.

Model and identification

The development of Jack & R. et al. 1974, the number of question associated with neuronal cells and in each such question asks for some electrical behaviour addressed here for the role of the active properties during gastric oscillation. The description of these active segment model. The model responses during gastric oscillation between the cell's axon and synaptic properties of an ideal one parameter, such as membrane r...
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is 30% larger and faster than the somatic impulse, which is quite small (3-8 mV). The model also indicates that the responses of all the dendrites are very much alike, suggesting that the presynaptic release of transmitter will have a similar time course in all dendrites. The duration of the dendritic impulse is much longer than that of the axon impulse. This suggests that considerable temporal summation of charge can occur in the dendrites when the cell produces a burst of impulses during the gastric oscillation. This summation could cause the depolarization of the dendritic tips to become much larger than the transient value achieved in response to one axonal impulse (Fig. 9B).

Interaction of presynaptic impulses and post-synaptic inhibition at the dendritic tips

The dendro-dendritic interactions of Int. 1 and m.g. provide a valuable opportunity to study a type of interaction which is found in several vertebrate systems, including the mammalian olfactory bulb (Shepherd, 1971), the vertebrate retina (Werblin & Bowling, 1969) and the geniculate body of the Vahamus (Morest, 1971). During the normal production of the gastric motor pattern, in which m.g. and Int. 1 fire alternating bursts of impulses that last several seconds, the burst of impulses in one cell will strongly depolarize that cell’s dendritic tips, because each impulse will contribute a pulse of depolarization to the voltage accumulated there. It is reasonable to suppose that the presynaptic depolarization that accumulates in dendrites of the m.g. neurone during a gastric burst will cause a summed pulsatile and graded synaptic transmission to post-synaptic dendrites of Int. 1. This transmission will produce a corresponding conductance change and hyperpolarization in the post-synaptic dendrites, which will shunt any residual depolarization there and prevent any immediate reciprocal inhibition of the m.g. neurone by Int. 1. This qualitative picture of dendro-dendritic inhibition must be refined both experimentally and with the help of predictive models of the two neurones and their interactions.

Models and identified neurones

The development of neuronal modelling techniques (Ball, 1969; Barrett & Crill, 1974a; Jack et al. 1975; Ball, 1977; Perkel et al. 1981) makes it possible to ask a number of questions about the relation of structure to function in single, identifiable neurones and in circuits of identifiable neurones. At the level of the single cell, one such question asks how the cell’s shape and membrane properties contribute to the electrical behaviour that it exhibits in its neural circuit. This question has been addressed here for the passive responses of the m.g. neurone. To complete the answer, the active properties of the cell, which mediate the burst of impulses that occurs during gastric oscillation, must be measured and localized within the cell. A description of these active properties can then be incorporated into the multi-compartment model. The model should then be able to mimic the major features of the cell’s responses during gastric oscillation, as well as providing insight into the interactions between the cell’s active responses and its inhibitory synaptic inputs and outputs.

A corollary to this question asks what kinds of variability in the shape and electrical properties of an identifiable neurone in different animals is allowed; is variability in one parameter, such as the shape of the cell, compensated for by change in another, such as membrane resistivity? In the instance of the m.g. neurone, the cell’s high

...
membrane resistivity would seem to allow some variability in its shape in different animals, without affecting the general manner in which it regulates synaptic inputs and outputs (unpublished observations). At the level of neural circuit function, quantitative, predictive descriptions of each of the identifiable elements makes possible a more detailed understanding of their interactions. Static "ball and stick" diagrams of neural circuits may be replaced with dynamic descriptions that can both relate what is already known and predict new phenomena.

**APPENDIX**

The expression

\[ V(t) = R_0 + A_0 \exp(-t/t_0) + A_1 \exp(-t/t_1) + A_2 \exp(-t/t_2), \]  
(A1)

can describe the step response of a three-compartment circuit (Fig. 4) as well as the step response of a neuron. To obtain values for the resistances and capacitances of the circuit that will enable it to mimic the response of the cell, we have derived a set of formulae that express those values in terms of the coefficients and time constants of the step response. These formulae describe a circuit model of those cells in which it can be assumed that the site of current injection corresponds to an end compartment and not the middle compartment, of the circuit. The formulae are:

\[ R_1 = \frac{1}{\alpha_1 C_1 + \sqrt{(\alpha_1 \alpha_2 C_1 C_2)}}, \]  
(A2)

\[ R_2 = \frac{1}{\sqrt{(\alpha_2 \alpha_3 C_2 C_3)}}, \]  
(A3)

\[ R_2 = \frac{1}{\sqrt{(\alpha_2 \alpha_3 C_2 C_3)}}. \]  
(A4)

\[ R_4 = \frac{1}{\sqrt{(\alpha_2 \alpha_3 C_2 C_3)}}, \]  
(A5)

\[ C_1 = \frac{1}{\alpha_1 \alpha_3 + \alpha_2 \alpha_3 + \alpha_2 \alpha_3}. \]  
(A6)

while \( C_1 \) and \( C_2 \) remain undetermined, \( t_0, t_1 \), and \( t_2 \) are rate constants that are the negative inverses of the time constants \( \tau_0, \tau_1 \), and \( \tau_2 \), respectively; \( \alpha_1, \alpha_2, \alpha_3, \) and the products \( \alpha_1 \alpha_2, \alpha_2 \alpha_3, \) and \( \alpha_1 \alpha_3 \) are constant coefficients and are given by

\[ \alpha_1 = \frac{t_0 + \tau_0 + \tau_0 + \tau_0}{t_0 + \tau_0 + \tau_0 + \tau_0}, \]  
(A7)

\[ \alpha_2 = \frac{t_2 + \tau_2 + \tau_2 + \tau_2}{t_2 + \tau_2 + \tau_2 + \tau_2}. \]  
(A8)

\[ \alpha_3 = \frac{t_3 + \tau_3 + \tau_3 + \tau_3}{t_3 + \tau_3 + \tau_3 + \tau_3}. \]  
(A9)

Any values chosen for the resistance values of

The capacitance

while \( b_1, b_2 \), and \( b_3 \) are

while and

The capacitance

depends solely on the step response. If a capacitance \( C_3 \) to \( C_3 \) is restricted to the steady-state membrane of \( C_1 \) and \( C_2 \) to

and

Any value chosen for the resistance values of

As each choice of a model of the cell, a predict the response in the compartments.

A unique model of the membrane resistance is the product of the should equal the same constant in the expression this constraint, the

\[ R_1 \] can be determined.
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\[ a_{11} a_{12} = \frac{P - \alpha_{11} (a_{12} + a_{11})\alpha_{12}}{a_{12}} \]  
\[ a_{21} a_{22} = \frac{P - \alpha_{22} (a_{22} + a_{21})\alpha_{22}}{a_{22}} \]  

\( b_1, b_2 \) and \( b_3 \) are constants that are defined to be

\( b_1 = (r_y - \alpha_{11}) r_y a_{12} \)  
\( b_2 = (r_y - \alpha_{11}) r_y a_{12} \)  
\( b_3 = (r_y - \alpha_{11}) r_y a_{22} \)  

while

\[ P' = a_1 r_y + r_1 r_2 + r_1 r_y \]  
\[ P = r_1 r_2 + r_y \]  

The capacitance of the first compartment, \( C_1 \), is the only circuit parameter that depends solely on the values of the coefficients and time constants that describe the step response. Values of the other circuit elements depend on the values of the capacitances \( C_1 \) and \( C_2 \), which remain to be specified. The choice of values for \( C_1 \) and \( C_2 \) is restricted by the physical requirement that the coupling resistances and steady-state membrane resistances of the circuit be positive. This forces the values of \( C_1 \) and \( C_2 \) to lie between the limits given by the inequalities:

\[ \frac{a_{11} a_{12}}{a_{12}} > C_1 > \frac{(a_{11} a_{12} + a_{11})\alpha_{12}}{(a_{22} a_{22} + a_{22})\alpha_{22}} \]  
\[ \frac{(a_{11} a_{12} + a_{11})\alpha_{12}}{(a_{22} a_{22} + a_{22})\alpha_{22}} > C_2 > \frac{a_{22} a_{22}}{a_{22}} \]  

Any values chosen for \( C_1 \) and \( C_2 \) that lie between these limits will allow all the resistance values of a three-compartment model of the injected cell to be calculated. As each choice of a pair of values for \( C_1 \) and \( C_2 \) will create a different compartmental model of the cell, additional information is needed to choose the model that can best predict the response of the cell in the region that correspond to all three compartments.

A unique model of the cell can be obtained if the membrane capacitance and resting membrane resistance are assumed to be the same everywhere in the cell. In this case, the product of the resistance and capacitance of each compartment in the model should equal the same value, the membrane time constant, which is the longest time constant in the exponential series that describes the step response of the cell. Under this constraint, then,

\[ R_1 C_1 = R_2 C_2 = R_3 C_3 = T_0 = -1/\tau_y \]  

\[ R_1 \] can be determined by rearranging eqn. (A 20):

\[ R_1 = \frac{-1}{\tau_y C_1} \]
Similar manipulations of eqns. (A20) and (A2)-(A6) will allow values to be calculated for all the elements of the compartmental model.

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REFERENCES


Dear Colleague:

I have recently discovered two typographical errors in the equation in the appendix of my paper "Compartmental models of electrotocin struct and synaptic integration in an identified neuron", with Brian Muloney, published in the Journal of Physiology, 148, 89-113. As I recently sent you a reprint of the paper, I would like to correct these errors for you.

In equation A8, the subscript "1" is missing from the middle \( r \) variable in the denominator. The equation should read:

\[
a_{11} = \frac{A_0}{A_0 + A_1 + A_2} \quad \text{(A8)}
\]

In equation A11, a minus sign is missing from in front of the anti expression on the right hand side, and the first \( a_{33} \) in the numerator should be \( a_{11} \).

\[
a_{12} a_{21} = -\frac{a_{11} (P_1 a_{11} a_{22} - a_{11} a_{33})}{a_{33} - a_{11}} \quad \text{(A11)}
\]

Thank you for your interest in our work.