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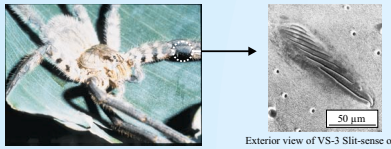
A MODEL OF EXCITABILITY IN SPIDER MECHANORECEPTOR NEURONS CONFIRMS THAT SODIUM INACTIVATION CONTROLS THEIR RAPID ADAPTATION

Päivi H. Torkkeli and Andrew S. French Department of Physiology and Biophysics, Dalhousie University, Halifax, Nova Scotia, Canada

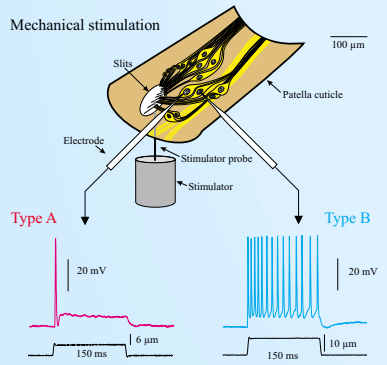
1. Introduction

Rapid sensory adaptation, in which the response to a step input decays to silence after a short time, is found in a range of vertebrate and invertebrate mechanoreceptors. Although mechanical components, and the transduction channels themselves, may contribute to adaptation, voltage- and calcium-activated ionic currents seem to dominate the behavior in many rapidly adapting receptors. Here, we show that differences in the inactivation properties of voltage-activated sodium channels can explain the strongly different adaptation patterns seen in paired mechanoreceptor neurons of a spider slit-sense organ.



Exterior view of VS-3 Slit-sense organ

The lyriform slit-sense organ VS-3 in the patella of the spider, *Cupiennius salei*, has 7-8 slits that are each innervated by a pair of morphologically similar bipolar mechanosensory neurons. Both neurons in each pair respond to sustained stimulation with a rapidly adapting burst of action potentials, but one member of each pair (Type A) adapts much faster, usually producing only one or two action potentials. In contrast, Type B neurons produce a burst of action potentials that can last for more than 100 ms. These different dynamic properties are dominated by the action potential encoding mechanisms, because similar dynamic responses are seen with either mechanical or intracellular electrical stimulation.

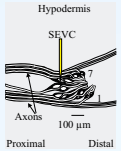


2. Active Currents

Active currents in theVS-3 neural somata have been investigated using single electrode voltage clamp (SEVC) in a preparation where the hypodermis containing the VS-3 neurons is removed from the patella and the surrounding axons are crushed to improve the space clamp. Four major voltage-activated currents have been characterized:

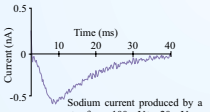
- A non-inactivating potassium current that repolarizes the action potential (delayed rectifier)
- A rapidly inactivating potassium current that does not require hyperpolarization but activates at relatively depolarized potentials
- A rapidly inactivating sodium current that causes the leading edge of the action potential
- A low-voltage-activated calcium current

Removal of either the rapidly inactivating potassium current or the calcium current does not significantly change the adaptation properties of the neurons.
(Sekizawa et al., 1999; 2000; Torkkeli et al. 2001)



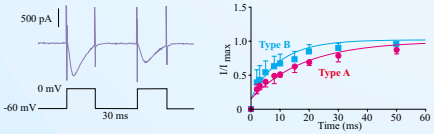
3. Sodium Currents in Type A and Type B Neurons

Sodium currents were difficult to study by single electrode voltage clamp through high resistance electrodes (40-80 MΩ). The extracellular sodium concentration was reduced from the normal 223 mM to 100 mM to obtain a reliable clamp. Potassium currents could not be completely eliminated pharmacologically, so sodium currents were studied by subtracting recordings with and without 1 µM TTX in the bath.



The major differences between the active currents in Type A and Type B neurons are in the inactivation properties of the voltage-activated sodium currents. Sodium inactivation in Type B neurons has a more gradually sloping Boltmann function and recovers more quickly under a wide range of conditions (Torkkeli et al., 2001). The figures below show recovery from inactivation at one holding potential and test pulse width.

Recovery from inactivation. Holding potential -60 mV, 30 ms test pulses to 0 mV



4. The Model

Boltzmann equations described the infinite values of the activation and inactivation states, m_∞, $m_{3\infty}$ and h_∞ versus voltage:

$$g / g_{max} = \frac{1}{1 + e^{(V - V_{50})/s}} \qquad \text{Equation (1)}$$

where g is membrane conductance, V is membrane potential, V_{50} is the membrane potential at half-maximal activation or inactivation, and s is the slope factor.

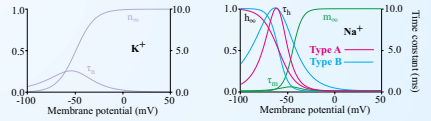
The time constants of activation, inactivation and recovery from inactivation were represented by functions of membrane potential:

$$\tau = \tau_{max} \frac{e^{\delta(V - V_{50})/s}}{(1 + e^{(V - V_{50})/s})^2} \quad 0 < \delta < 1 \qquad \text{Equation (2)}$$

where τ is a time constant of activation, inactivation or recovery from inactivation, τ_{max} is the maximum value of τ, and δ is a constant. We further simplified the model by using the same values of V_{50} and s in Equations (1) and (2) for each activation or inactivation variable. This reduced the number of kinetic parameters for each gate to four (V_{50}, s, τ_{max} and δ) and simplified the inclusion of a different time constant of recovery from inactivation in the model, which was achieved by changing the value of τ_{max} between two values, depending on the direction of movement along the Boltzmann curve during each step.

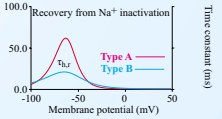
The differential equations were integrated by the exponential Euler method (MacGregor 1987) with a step size of 20 µs. The software was constructed as a C++ class library, similar to the Conical simulation system (Strout 1996) but restricted to a single isopotential spherical cell. All simulations were performed on an IBM-compatible personal computer.

Passive membrane parameters for Type A and Type B neurons were taken from Sekizawa et al. (1999). Only two active currents were used: an inactivating sodium current and a non-inactivating potassium current. Parameters for the two currents were based on voltage clamp and current clamp data (Sekizawa et al., 1999; 2000; Torkkeli et al., 2001; French et al., 2001). Identical parameters were used for activation and inactivation of currents in both Type A and Type B neurons, except for inactivation slope and recovery from inactivation:

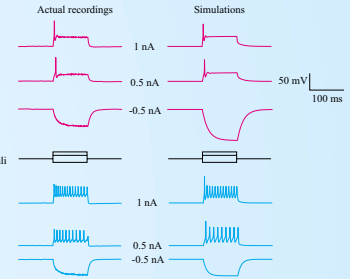


Differences between Type A and Type B

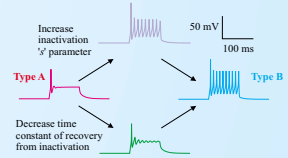
Different parameters were used for the inactivation slope parameter, s, and the time constant of recovery from sodium inactivation in Type A and Type B neurons models.



5. Results



6. Converting Type A to Type B



Increasing the 's' parameter led to a burst with higher threshold and smaller action potentials than Type B. Decreasing the time constant of recovery from inactivation led to membrane oscillations. Both changes were needed to convert Type A to Type B or Type B to Type A.

7. References

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8. Conclusions

- The firing properties of the spider VS-3 neurons can be well-approximated by a model that contains only two active currents, sodium and potassium.
- The different adaptation properties of the Type A and Type B neurons can be explained by changes in the inactivation properties of the sodium current.
- Two changes in sodium inactivation are required: a change in the slope of the h_∞ curve and a change in the time constant of recovery from inactivation.
- The passive properties of the cell membranes of Type A and Type B neurons are significantly different, but this difference is not needed to explain the different firing properties.

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