

# **Modeling ion channels from the cricket cercal sensory system**

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## **Abstract**

We are interested in the representation and processing of information about the dynamics of air current stimuli in the primary sensory interneurons of the cricket cercal system.

Past modeling studies have used two ion channels, a transient sodium channel and delayed-rectifier type potassium channel, to model the spike-producing mechanism in these cells. In this work, we develop channel models based on physiology data obtained by Kloppenburg and Hörner (1998), use the channels to construct a model neuron, and provide an analysis of the underlying mathematical structure. We also examine the frequency sensitivity of the model neuron and its dependence on channel dynamics. This study provides a first step toward developing more accurate models of primary sensory interneurons.

## **Introduction**

The cercal system of the cricket gathers information about the direction and dynamics of low-velocity air movements in the animal's immediate environment (Miller et al, 1991).

In cricket and many other orthopteran insects, the cercal system is involved in behaviors such as oriented escape and mate location (Gnatzy and Hustert 1989; Hoyle 1985;

Kamper and Dambach, 1985). The receptor organs for this modality are the cerci, two appendages covered with mechanoreceptor hairs that are sensitive to air current displacement. Afferent input is relayed to primary sensory interneurons in the terminal

ganglion which project to higher centers of the nervous system (Jacobs and Murphey, 1987). We are interested in how information about the direction and dynamics of air current stimuli is represented and processed in these primary sensory interneurons.

Past modeling studies of primary sensory interneurons in the cricket, *Acheta domestica*, have used two ion channels – a transient sodium channel and delayed-rectifier type potassium channel – to model the spike-producing mechanism in these cells (Crook et al., 2002; Cummins et al., in press). The spatial structure of these compartmental models is based on morphological data, and the parameters for the Hodgkin-Huxley type equations for ionic currents were chosen in order to match the shape of simulated action potentials to physiological data. However, other ion channels are known to be present in these cells. Recent work by Kloppenburg and Hörner (1998) isolated and characterized four voltage-activated currents in two types of cultured primary sensory interneurons, LGI and MGI from the terminal ganglion of crickets, *Gryllus bimaculatus*. In this work, we develop channel models based on the physiology data obtained by Kloppenburg and Hörner (1998), use the channels to construct a model neuron, and provide an analysis of the underlying mathematical structure of the excitable. We also examine the frequency sensitivity of the model neuron and determine how the channel dynamics affect the response to stimuli at different frequencies. This study provides a first step toward developing biophysically-based models of primary sensory interneurons with more accurate channel dynamics.

## Modeling ionic currents

Our model neuron uses Hodgkin-Huxley type equations (Hodgkin and Huxley, 1952) to represent changes in membrane potential due to four different voltage-activated ion channel types. Two potassium channels - an A-type transient potassium channel and a sustained potassium channel - make the clearest contribution to outward currents. We also incorporate inward currents via a transient sodium channel and a sustained calcium channel. For each channel type, the parameters and curves used to describe the dynamics of the gating variables were constrained by the experimental data provided by Kloppenburg and Hörner (1998).

The kinetic equations for the gating variables for each current have the form  $\dot{y}(v) = (y_{\infty}(v) - y(v)) / \tau_y(v)$  where  $y_{\infty}(v)$  is the steady-state activation or inactivation function determined by fitting experimentally-derived curves to a first order Boltzmann equation.  $\tau_y(v)$  provides the time constant/voltage relationship for the activation or inactivation of the current. If the change was too fast for reliable fitting of  $\tau_y(v)$  as described in Kloppenburg and Hörner (1998), we used the steady-state curve in place of the gating variable. Reversal potentials were determined experimentally; however, the values of the maximal conductances for the various currents in different locations of the primary sensory interneurons, including the spike initiation zone, are unknown. For this study, we chose parameter values that caused a transition from a stable rest state to repetitive spiking as a current is applied as shown in Figure 1. Mathematical analysis shows that our model is a type two model; that is, the transition occurs due to a

Hopf bifurcation as described in Rinzel and Ermentrout (1998). Parameters and equations are provided in the Appendix.

Damped oscillations will always occur when the dynamics of a neuron are near a Hopf bifurcation (Kuznetsov, 1995). These subthreshold oscillations contribute to the frequency preferences seen in neurons; that is, neurons prefer inputs at the frequency of the subthreshold oscillation (Izhikevich, 2002). This property of selective response to inputs at preferred frequencies is often referred to as resonance (Hutcheon and Yarom, 2000). Characterizing the biophysical mechanisms that determine the resonant properties of neurons can help us understand the neural properties that are involved in coordinating network activity at certain frequencies. We are interested in determining how the current dynamics might contribute to the different frequency preferences seen in different primary sensory interneurons (Miller et al, 1991; Crook et al., 2002). We examine the frequency preferences of our model neuron in different parameter regimes and study how resonance depends on the relationships among the parameters and gating variable functions. In our model, frequency preferences are affected by the relationship between the reversal potential and associated activation or inactivation curve and by the time constant/voltage relationship for the sustained potassium channel.

## **Future Work**

Future models of interneurons will use parameter searching techniques to select values that reproduce spike shape and other response characteristics for specific primary sensory interneurons of interest. It is likely that accurate representation of these complex response

characteristics will require the inclusion of additional currents known to exist in these interneurons. For example, in some experimental regimes Kloppenburg and Hörner (1998) found that hyperpolarization revealed a 'sag' trajectory which often occurred in conjunction with post-inhibitory rebound. This suggests the presence of a slow inward current activated by hyperpolarization. Additional data suggests the presence of calcium-dependent potassium currents that may contribute to the spike frequency adaptation seen in some primary sensory interneurons (Claque et al., 1997).

## Appendix

### Current Balance Equation

$$C_m \frac{dV}{dt} = I_{app} - I_A - I_K - I_{Na} - I_{Ca} - I_{lk}$$

### Ionic Currents

$$I_A = \bar{g}_A p_\infty j(V - V_A)$$

$$I_K = \bar{g}_K n(V - V_K)$$

$$I_{Na} = \bar{g}_{Na} m_\infty h(V - V_{Na})$$

$$I_{Ca} = \bar{g}_{Ca} q_\infty f(V - V_{Ca})$$

$$I_{lk} = g_{lk}(V - V_{lk})$$

### Kinetic Equations

$$p_\infty(V) = 1/(1 + e^{(V+3.6)/-13.2})$$

$$j_\infty(V) = 1/(1 + e^{(V+40.8)/12.3})$$

$$\tau_j(V) = 5 + e^{(-0.1V+2.99)}$$

$$n_\infty(V) = 1/(1 + e^{(V-23.3)/-21.4})$$

$$\tau_n(V) = 7.3063e^{-0.0254V}$$

$$m_\infty(V) = 1/(1 + e^{V/-8})$$

$$h_\infty(V) = 1/(1 + e^{(V+40.4)/8})$$

$$\tau_h(V) = 0.6632e^{-0.0188V}$$

$$q_{\infty}(V) = 1/(1 + e^{(V+25)/-2.5})$$

$$f_{\infty}(V) = 1/(1 + e^{(V+55)/9})$$

$$\tau_f(V) = 6.632e^{-0.0188V}$$

## Model Parameters

$$V_K = V_A = -91.6 \text{ mV}$$

$$V_{Na} = 68 \text{ mV}$$

$$V_{Ca} = 50 \text{ mV}$$

$$V_{lk} = -60 \text{ mV}$$

## Acknowledgements

We gratefully acknowledge the support of the National Science Foundation (IBN-0091117).

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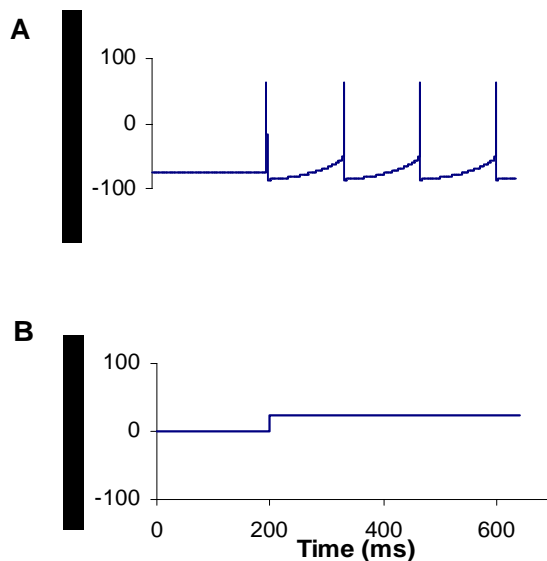


Figure 1. Model response to injected current showing repetitive firing of action potentials.