Frequency sensitivity in interneurons in the cricket cercal sensory system: the role of synaptic and biophysical mechanisms

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Abstract

We use biophysically-based models of interneurons from the cricket cercal system to examine the effects of membrane properties on interneuron processing of dynamic sensory input. Our models incorporate five different ion channel types formulated during previous studies. Model sensory inputs are based on experimental recordings from afferent neurons in response to air current stimuli. We use these models to demonstrate the role of resonant membrane properties, synaptic input patterns, and synaptic integration in determining the response properties of primary sensory interneurons.

Introduction

The cricket cercal system is a mechanosensory system involved in behaviors such as mate detection and predator evasion (Hoyle, 1958; Kamper and Dambach, 1985; Gnatzy and Hustert, 1989). The cricket cerci are covered with filiform hairs of varying lengths that selectively respond to near-field air current stimuli (Roddey and Jacobs, 1996). The movement of each hair initiates an increase or decrease in the firing rate of a single associated afferent neuron, thereby encoding sensory information. These receptor

neurons synapse onto primary sensory interneurons in the terminal ganglion. Understanding the biophysical mechanisms used by interneurons to gather, process, and relay information about the dynamics of air current stimuli is crucial to our understanding of this model sensory system. In particular, our goal in this work is to understand the role of biophysical membrane properties in determining the frequency filtering of interneurons. In previous work, we used compartmental models to show that the passive electrotonic structure of the dendritic arbor and the dynamic sensitivity of the spike-initiation zone play a large role in determining frequency sensitivity in interneurons (Crook, et al, 2002). In this work, we use reduced models to allow for a mathematical analysis of channel kinetics and interactions and a better understanding of how membrane properties contribute to interneuron processing of dynamic sensory stimuli. We also use more realistic models of synaptic input in order to examine the contributions of synaptic input patterns and synaptic integration.

Methods

In previous studies, we used electrophysiology data and parameter search techniques to construct Hodgkin-Huxley type models for several different ionic channels known to be present in the primary sensory interneurons of the cricket cercal system (Hodgkin and Huxley, 1952). Ensembles of these different ion channel types were used to construct models for several different primary sensory interneurons (Cummins et al, 2002; Eaton et al, submitted). By varying the ion channel densities and kinetic parameters, we were able to match spike shape and other observed response characteristics such as spike frequency adaptation (Kanou and Shimozawa, 1984; Miller

et al, 1991; Clague et al, 1997).

In this work, electrophysiology data from afferents are used to create realistic sensory input to the interneuron models. Intracellular recordings were obtained from afferents during the presentation of air current stimuli. Spike-times from multiple trials were used to create post-stimulus time histograms. Calculations to identify periods of elevated rates of firing along with the reliability and precision of those events across stimulus frequencies are used to quantify how sensory information is transmitted to the interneurons in the terminal ganglion.

We model postsynaptic currents using the standard expression $I_{syn}=g_{syn}s(V_{syn}-v)$ where v is a variable representing the membrane potential, V_{syn} is the synaptic reversal potential (0 mV), g_{syn} is the maximal conductance, and s is a variable taking values between 0 and 1 that represents the normalized conductance change due to synaptic events. The form of the differential equation governing the behavior of s is chosen so that the resulting postsynaptic potentials fit experimentally observed potentials (Davis and Murphey, 1993). Spike times driving synaptic events were obtained from a probabilistic model of afferent neuron spike events developed using the afferent data outlined above.

Previously, morphologically-based compartmental models for these interneurons have used one model synapse in each compartment where each model synapse represents multiple biological synapses (Crook et al, 2002) or used more realistic synaptic input with 1000 different model synapses where each represents an individual biological synapse with an independent sequence of synaptic events (Cummins et al, 2003). In this work, we examine the response characteristics of the reduced model interneuron for varying numbers and patterns of synaptic inputs in order to demonstrate the effects of

synaptic timing and integration.

Summary of Results

Damped oscillations will always occur in a type II neuron where the dynamics of the transition to repetitive firing can be modeled with a Hopf bifurcation (Kuznetsov, 1995). These subthreshold oscillations contribute to the frequency preferences seen in neurons; that is, these neurons prefer inputs near 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). Previous analysis of our interneuron models reveals a type II mechanism in the underlying mathematical structure (Eaton et al, submitted). In this work, we examine the frequency preferences of our model neuron in different parameter regimes and demonstrate the dependence of resonant characteristics on the parameters and gating variable functions. In particular, we show that frequency preferences are determined by the relationship between the reversal potential and associated activation and/or inactivation curve and by the time constant/voltage relationship for several different channel types including a sustained potassium channel.

When presented with an air current stimulus with a sine wave velocity profile of fixed frequency at the preferred stimulus direction, an afferent neuron responds with a several spikes where the event is phase-locked to the stimulus. When the direction is sufficiently far from the peak direction, the firing rate decreases and the response is no longer phase-locked. The responses of afferents associated with long and medium length filiform hairs (Roddey and Jacobs, 1996) maintain a constant phase difference across

frequencies although the phase lag relative to the stimulus varies in a systematic way. We demonstrate the effects of these phase differences in synaptic inputs on the response properties of model interneurons for different parameter regimes corresponding to different filtering properties. We also demonstrate the effects of the precision of these phase-locked synaptic events on interneuron response characteristics and how the frequency selectivity and processing of synaptic inputs depends on the membrane potential. These results reveal the potential contributions of ionic channels and membrane properties in determining the frequency selectivity of interneurons.

Previous modeling studies of several directionally-selective interneurons in the cercal system showed that the anatomical distribution of synaptic inputs is an important factor in determining an interneuron's directional selectivity (Cummins et al, 2003). In those studies, morphologically-based compartmental models with passive dendrites were used. However, it is known that some interneurons in the cercal system have dendrites with voltage-dependent channels. It has been shown that active dendrites with certain voltage-dependent properties can reduce or eliminate the location-dependent variability of synaptic input (Cook and Johnston, 1997; Cook and Johnston, 1999). Due to the use of reduced models in this work, we are unable to examine the effects of the structure of the dendritic arbor on the processing of synaptic inputs and interneuron frequency selectivity. Future studies using morphologically-based models with active dendrites will address these issues.

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