We investigated the kinetic properties of the hyperpolarization-activated inward current ($I_h$) of thalamocortical (TC) neurons. Recently, it was shown that this current is characterized by different time constants of activation and inactivation, which was in apparent conflict with the single-exponential time course of the current. We introduce here a model of $I_h$, based on the cooperation of a slow and a fast activation variable and show that this kinetic scheme accounts for these apparently conflicting experimental data. We also report that following the combination of such a current with other currents seen in TC cells, one observes several types of oscillating behavior, similar to the slow oscillations and the spindle-like oscillations seen in vitro.

Keywords: Thalamus; Sleep; Lateral geniculate nucleus; Biophysical model; Hodgkin-Huxley formalism; Slow oscillations; Spindle-like oscillations; Low-threshold calcium

A model of the inward current $I_h$ and its possible role in thalamocortical oscillations

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\[ \frac{dF}{dt} = \frac{(H_x(V) - F)}{\tau_f(V)} \]  

Comparison between single and double precision results showed that single precision is sufficient for integration of equations 1-4.

All numerical integrations were performed using

\[ \frac{dS}{dt} = \frac{(H_x(V) - S)}{\tau_f(V)} \]
cells. Moreover, for cat TC cells, spindle-like oscillations have also been found when enhancing $I_{h}$.

In this case, while increasing $I_{h}$ strength, the following sequence of modes were observed: a hyperpolarized resting state when $I_{h}$ is blocked, slow oscillations for weak values of $I_{h}$, spindle-like oscillations for higher values of $I_{h}$, and finally, a depolarized resting state for a further increase in the value of $I_{h}$. This sequence was reversed by gradually decreasing the strength of $I_{h}$.

A similar sequence of oscillatory modes can be seen in the model as the maximal conductance of $I_{h}$ is decreased. As shown in Figure 2, for the highest values of $g_{h}$, the membrane lies in a depolarized resting state close to $-60$ mV. Decreasing $g_{h}$ leads to spindle-like oscillations (intraspindle frequency of 10—14 Hz and a period of approximately 9 s). As $g_{h}$ is decreased further, one observes oscillations of a lower frequency around 1.1 Hz. Finally, for the weakest values of $g_{h}$, the membrane switches to a hyperpolarized resting state, close to $-80$ mV.

FIG. 1. Simulation of voltage clamp protocols on the double activation model of $I_{h}$. Activation of $I_{h}$ with an initial potential of $-80$ mV and the...
oscillating and resting states, as seen experimentally by the experiments of Soltesz et al.\textsuperscript{16} The transition between these modes is achieved by increasing the maximal conductance of $I_v$. The model therefore produces several modes, similar to those seen in TC cells.