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Huber-Braun neuron dynamics

Dinámicas neuronales Huber-Braun

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ABSTRACT

We study a physiologically realistic implementation of internal stochasticity in a four dimensional Hodgkin-Huxley (HH) type model of cold receptors. We show that in a deterministically tonic-firing regime, changing the parameters can drive the neuron into a state of complex bursting behavior. An explanation of the mechanism behind this effect is given in terms of a bifurcation diagram of inter-spike interval (ISI) as the temperature and external current are altered.

RESUMEN

Se estudia una implementación fisiológica realística interna en un modelo neuronal de cuatro dimensiones tipo Hodgkin-Huxley (HH) de receptores fríos. Se demuestra que en un régimen determinista de disparo tónico, cambiando los parámetros temperatura corriente, se puede conducir a la neurona en un estado de comportamiento de estallido complejo. Una explicación del mecanismo detrás de este efecto se da en términos del diagrama de bifurcación de los inter-pulsos (ISI, por sus siglas en inglés) en función de la temperatura y corriente externa son cambiados.

INTRODUCTION

Neurons transmit information via electrical signals. When the cell membrane is at its resting membrane potential, the activation gates of the voltage-gated sodium ion (Na+) channels are closed and the inactive gates are open, while voltage-gated potassium ion (K+) channels are closed. Depolarization is initiated by a stimulus which makes the membrane potential positive, opening the voltage-gated sodium ion channels. Under stimulations, the membrane potential becomes positive and the sodium channels are open. Sodium ions diffuse across the membrane causing depolarization and the voltage-gated potassium ion channels also begin to open, but more slowly. As the membrane potential approaches maximum depolarization, the inactivation gates of the voltage-gated sodium ion channels begin to close causing a decrease of the diffusion of sodium ions. Since the potassium ion channels remain open, potassium ions continue to diffuse out of the cell. The extra efflux of potassium ions causes the membrane potential to become slightly more negative than the resting value. After the voltage-gated potassium ion channels close, the active transport of sodium and potassium ions reestablish the resting membrane potential (Braun, Huber, Anthes, Voigt, Neiman, Pei & Moss, 2000).

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Neuron; dynamics; spike; bursts; chaos; tonic-firing; inter-spike interval (ISI).

Palabras clave:
Neurona; dinámica; pulso; ráfagas; caos; intérvalo inter-pulso (ISI).

Huber-Braun model

The Huber-Braun model was originally developed from the Hodgkin-Huxley (HH) model to mimic temperature dependent alterations of static impul-

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se patterns of peripheral cold receptors in the skin (Braun *et al.*, 2000; Braun, Huber, Anthes Neiman, Pei & Moss, 2001; Finke, Postnova, Rosa, Freund, Huber & Feudel, 2010):

$$C_M \frac{dV}{dt} = -I_l - I_d - I_r - I_{sd} - I_{sr} - I_{ext}, \quad (1)$$

$$I_\mu = \rho . g_\mu . a_\mu (V - V_0) \quad \text{where } \mu = d, r, sd, sr, \quad (2)$$

$$\frac{da_\mu}{dt} = \phi(T) \frac{(a_{\mu\infty} - a_\mu)}{\tau_\mu} \quad \text{for } \mu = r, sd, \quad (3)$$

$$\frac{da_{sr}}{dt} = \phi(T) \frac{(-\eta I_{sd} - k a_{sr})}{\tau_{sr}}; \quad ad = ad_\infty, \quad (4)$$

$$a_{\mu\infty} = \frac{1}{1 + exp(-s_\infty (V - Vo_\infty))}, \quad (5)$$

$$\rho = 1.3^{(T-T_0)/10^\circ C}; \quad \phi = 3^{(T-T_0)/10^\circ C} \quad (6)$$

Where: C_M is the membrane capacitance and $I_l = g_l \cdot (V - V1)$ is a passive leak current. I_μ the subscripts *d* and *sd* label depolarizing and slow depolarizing sodium currents, while *r* and *sr* label repolarizing and slow repolarizing potassium currents, g_μ are the maximum conductances, and V_μ are the equilibrium potentials. a_μ are the activation kinetics of the ion channels. $a_{\mu\infty}$ are the steady-state activation curves; ρ and ϕ are the temperature dependences. The numerical parameter values are as follows, equilibrium potentials: VL = -60, VNa = VNap = 50 (in mV); ionic conductances: gL = 0.1, gNa = 1.5, gK = 2.0, gNap = 0.25 (in mS/cm^2); and membrane capacitance: C_M = 1 (in lF/cm^2), τr = 2 ms, τsd = 10 ms, τsr = 20 ms; $sd = sr$ = 0.25, ssd = 0.09; $V_0 d = V_0 r$ = -25 mV, $V_0 sd$ = -40mV; η = 0.012, k = 0.17; T_0 = 25 ºC see figure 1.

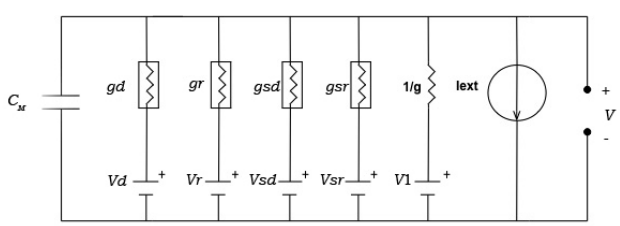

Figure 1. Huber-Braun neuron as an electrical circuit.
Source: Authors own elaboration.

Neuron dynamics

When the temperature and current are varied, different dynamical regimes can be distinguished (Braun *et al.*, 2001; Finke *et al.*, 2010). Sub-threshold: For very low temperature or small current, the membrane potential is below a threshold (-45 mV) and the neuron is not active. Tonic-firing: For higher temperature or current, the membrane potential exceeds the threshold and the neuron produces periodic spikes. Period-doubling bifurcations: As the temperature or current increases, the neuron undergoes period-doubling bifurcations in the inter-spike interval (ISI). Burst discharges: As the temperature or current further increases, many spikes appear in each burst and the number of the spikes depends on the temperature. The typical time series is shown in figure 2. Period-adding bifurcations: For high temperature or current, the number of spikes in each burst decreases (increases) in the backward (forward) period-adding bifurcation as the temperature (current) increases.

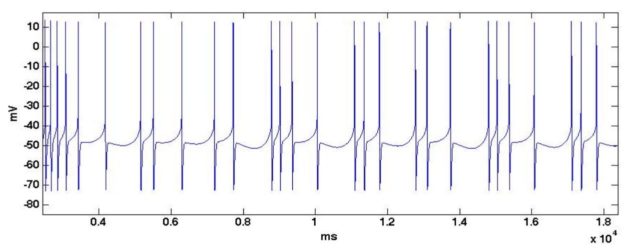

Figure 2. Time series of membrane potential for T = 8 ºC.
Source: Authors own elaboration.

Figures 3 and 4 shows the bifurcation diagrams of ISI with the temperature and current as control parameters.

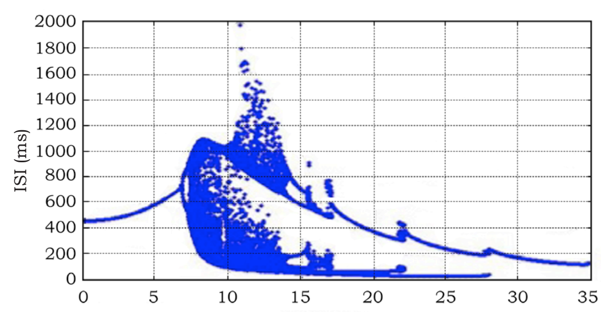

Figure 3. Bifurcation diagrams of ISI with temperature.
Source: Authors own elaboration.

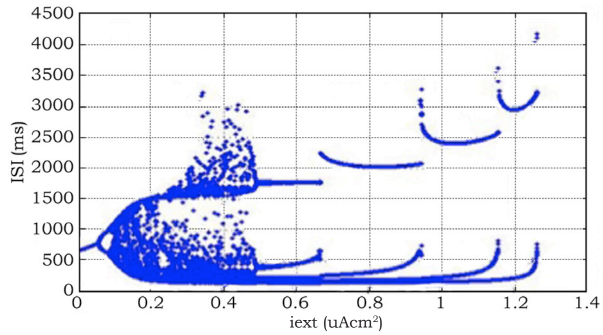

Figure 4. Bifurcation diagrams of ISI with Iext.
Source: Authors own elaboration.

CONCLUSION

The Huber-Braun neuron model produces very rich dynamics including periodic spikes, bursts of spikes, period-doubling and period-adding bifurcations, and chaos. Using the temperature and current as control parameters, different dynamical regimes have been found. The bifurcation diagrams of ISI have been constructed with respect to the temperature and current.

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