Week 2 – part 5: Detailed Biophysical Models

Neuronal Dynamics:
Computational Neuroscience of Single Neurons

Week 2 – Biophysical modeling:
The Hodgkin-Huxley model

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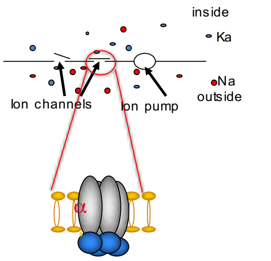
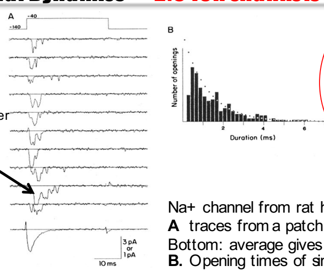
- 2.1 Biophysics of neurons
  - Overview
- 2.2 Reversal potential
  - Nernst equation
- 2.3 Hodgin-Huxley Model
- 2.4 Threshold in the Hodgkin-Huxley Model
  - where is the firing threshold?
- 2.5. Detailed biophysical models
  - the zoo of ion channels

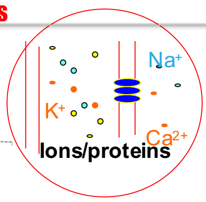
Neuronal Dynamics – 2.5 Biophysical models



Neuronal Dynamics – 2.5 Ion channels

Steps:
Different number of channels





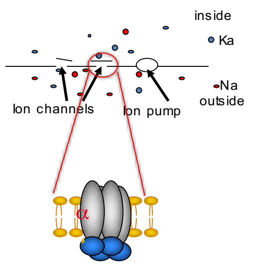
Na+ channel from rat heart (*Patlak and Ortiz 1985*)
A traces from a patch containing several channels.
Bottom: average gives current time course.
B. Opening times of single channel events

Neuronal Dynamics – 2.5 Biophysical models

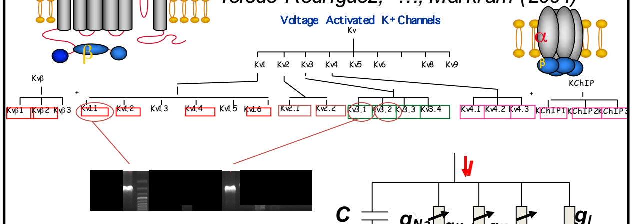
There are about 200 identified ion channels

http://channelpedia.epfl.ch/

How can we know which ones are present in a given neuron?

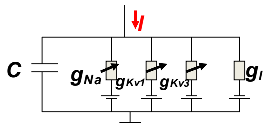


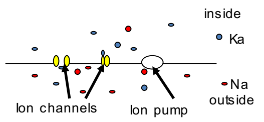
Ion Channels investigated in the study of *Toledo-Rodriguez, …, Markram (2004)*



schematic mRNA
Expression profile

Model of a hypothetical neuron





stimulus

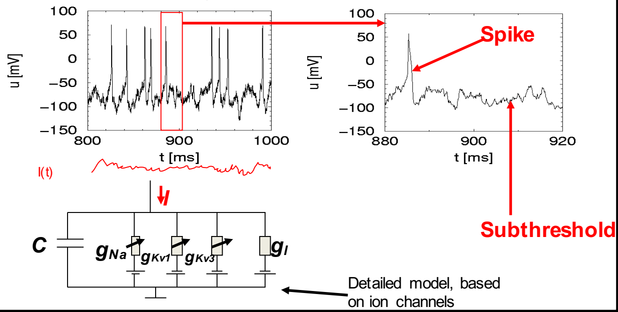
$$C\frac{du}{dt} = -\underbrace{g_{Na}m^3h(u-E_{Na})}_{I_{Na}} - \underbrace{g_{Kv1}n_{Kv1}^4(u-E_K) - g_{Kv3}n_{Kv3}^2(u-E_K)}_{I_K} - \underbrace{g_l(u-E_l)}_{I_{leak}} + I(t)$$

How many parameters per channel?

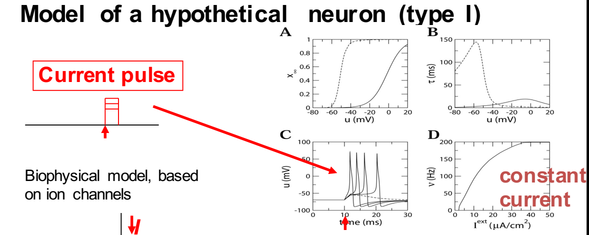
$$\frac{dm}{dt} = -\frac{m-m_0(u)}{\tau_m(u)} \qquad \frac{dh}{dt} = -\frac{h-h_0(u)}{\tau_h(u)} \qquad \frac{dn_3}{dt} = -\frac{n_1-n_{0,3}(u)}{\tau_{n,3}(u)}$$

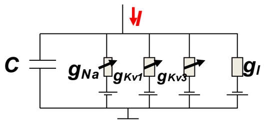
Erisir et al, 1999
Hodgkin and Huxley, 1952

Model of a hypothetical neuron



Model of a hypothetical neuron (type I)





- Delayed AP initiation
- Smooth *f-I* curve

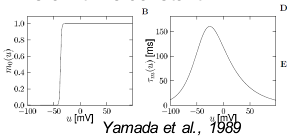
type I neuron

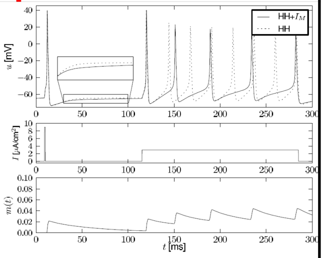
Neuronal Dynamics – 2.5 Adaptation

Functional roles of channels?
- Example: adaptation

Neuronal Dynamics – 2.5 Adaptation: I_M-current

M current: $I_M = g_M m \; (u - E_K)$
- Potassium current
- Kv7 subunits
- slow time constant



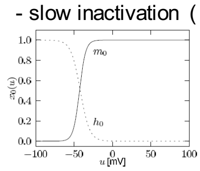


Yamada et al., 1989

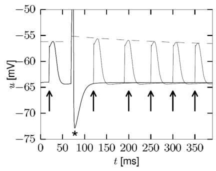
I_M current is one of many potential sources of adaptation

Neuronal Dynamics – 2.5 Adaptation – I_{NaP} current

current: $I_{NaP} = g_{NaP} m \; h \; (u - E_{Na})$
- persistent sodium current
- fast activation time constant
- slow inactivation (~ 1s)

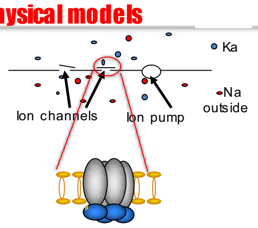


Aracri et al., 2006



I_{NaP} current
- increases firing threshold
- source of adaptation

Neuronal Dynamics – 2.5 Biophysical models



Hodgkin-Huxley model provides flexible framework

Hodgkin&Huxley (1952)
Nobel Prize 1963

Exercise – 2. 5. Hodgkin-Huxley model – gating dynamics

A) Often the gating dynamics is formulated as

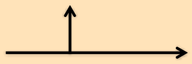
$$\frac{dm}{dt} = \alpha_m(u)(1-m) - \beta_m(u)m \qquad \frac{dm}{dt} = -\frac{m - m_0(u)}{\tau_m(u)}$$

Calculate $m_0(u)$ *and* $\tau_m(u)$

B) Assume a form $\alpha_m(u) = \beta_m(u) = \frac{1}{1 - \exp[-(u+a)/b]}$

How are *a* and *b* related to γ and θ in the equations

$$\frac{dm}{dt} = -\frac{m - m_0(u)}{\tau_m(u)}$$



$$m_0(u) = 0.5\{1 + \tanh[\gamma(u - \theta)]\}$$

C) What is the time constant $\tau_m(u)$?

Neuronal Dynamics – References and Suggested Reading

- Hodgkin, A. L. and Huxley, A. F. (1952). *A quantitative description of membrane current and its application to conduction and excitation in nerve.* J Physiol, 117(4):500-544.
-Ranjan, R.,et al. (2011*). Channelpedia: an integrative and interactive database for ion channels*. Front Neuroinform, 5:36.
-Toledo-Rodriguez, M., Blumenfeld, B., Wu, C., Luo, J., Attali, B., Goodman, P., and Markram, H. (2004). *Correlation maps allow neuronal electrical properties to be predicted from single-cell gene expression profiles in rat neocortex*. Cerebral Cortex, 14:1310-1327.
-Yamada, W. M., Koch, C., and Adams, P. R. (1989). *Multiple channels and calcium dynamics*. In Koch, C. and Segev, I., editors, *Methods in neuronal modeling*, MIT Press.
- Aracri, P., et al. (2006*). Layer-specic properties of the persistent sodium current in sensorimotor cortex*. Journal of Neurophysiol., 95(6):3460-3468.

Reading: W. Gerstner, W.M. Kistler, R. Naud and L. Paninski, *Neuronal Dynamics: from single neurons to networks and models of cognition.* Chapter 2*: The Hodgkin-Huxley Model,* Cambridge Univ. Press, 2014
OR W. Gerstner and W. M. Kistler, Spiking Neuron Models, Chapter 2, Cambridge, 2002