Project plan

Thermal effects on the propagation of action potential in neurons using the Hodgkin-Huxley model

Group 4: Mark Bebawy, Lucas Riedstra, Jim Wagemans

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1 Scientific question

Introduction Neurons are cells which can conduct an electrical impulse. The *axon* transfers such a signal from the cell body to another neuron.

When a signal is received, the membrane potential first rises, then falls, and then restabilises. This event is called an *action potential* or *spike*. The spike propagates as a wave along the axon.

The Hodgkin-Huxley model contains several differential equations that describe the membrane potential during an action potential as function of time. This model describes a neuron as a simple electrical circuit.

Using appropriate simplifications, a spatial component can be added to this model to study the propagation of a spike along the axon.

Research question We want to use the Hodgkin-Huxley model to determine how the temperature affects the duration of a spike and the speed of propagation of a spike. More specifically, we want to study the effect of temperature on

(a) the time it takes for an action potential to complete in one neuron (time from stimulus to first moment that the neuron returns to resting potential);

(b) the speed of the propagation of a spike through the axon.

Hence, our research question is:
What is the effect of temperature on the time it takes for an action potential to complete in one neuron and on the speed of propagation through the axon?

Hypotheses Biological processes are generally known to get faster as temperature increases. This does not continue indefinitely as eventually proteins break down. To see if this would also be the case with neurons, we looked at some scientific papers regarding this topic. In 2014 Georgiev et al. concluded that at high temperature the gates open at a faster rate and hence the time it takes until the action potential finishes is less [1].

In 2007 Kuang et al. also looked at thermal influences on the HH-model and they concluded that there is an environmental temperature range where the speed of action potentials is maximal [2].

Based on these papers our hypothesis is that as temperature increases, initially the time of a spike will decrease and the speed of propagation will increase, until a temperature that is higher than room temperature, after which the time will increase and the speed will decrease.

2 Numerical method

We require a numerical method to approximate solutions to (partial) differential equations. For this we use

- Finite difference (Runge-Kutta 4);
- Finite element method.

We will try to validate our model by comparing our approximation of the action potential to the theoretical action potential curve. Specifically our approximation should go through phases we expect it to go through (depolarization, repolarization and hyperpolarization).

Our model should also satisfy the all-or-nothing principle. The strength of the cell's response (our approximation of the action potential) should only depend on whether or not the stimulus is greater than a certain threshold.

3 Provisioned tools

We plan to implement our model in Python 3. For visualisation we will use matplotlib.pyplot and perhaps other software (to be determined). Of course we will use Github for version control.

4 Plan for division of work

- Mark:
  Implement numerical methods (RK4 and FEM) and implementation of HH equations for one neuron. Work with Jim on graphical interface where variables can be adapted and some kind of visualisation.
- Lucas:
  Research the biological aspects of wave propagation for a theoretical description of model. Extension of model to include spatial component and implementation. Also research different possible extensions of model (see last section).

- Jim:
  Generation of figures for report. Final presentation and poster. Validation of approximations.

5 Timeline

Week:

1. Peer review and starting with implementation of the model (implementation of AP for one neuron).
2. Finish programming model, implement propagation through axon.
3. Running experiments and generating figures, writing report. If time allows, extend model (see next section).
4. Finalizing report, work on poster and presentation.

6 If time allows

Should we find ourselves with extra time on our hands, we could implement a model described in [3]. This model uses discrete ion channel populations represented as a Markov process. We could compare the estimated action potential of

We could also study propagation of the action potential signal through different neurons in different types of networks. However, this seems to be quite difficult as this would require combining different models.

References

[1] George Georgiev et al. "Simulating Influence of Channel Kinetics and Temperature on Hodgkin-Huxley Threshold Dynamics". In: *Procedia Computer Science* 36 (2014). Complex Adaptive Systems Philadelphia, PA November 3-5, 2014, pp. 464–469. ISSN: 1877-0509. DOI: https://doi.org/10.1016/j.procs.2014.09.022. URL: http://www.sciencedirect.com/science/article/pii/S187705091401271X.

[2] Shenbing Kuang et al. "Thermal Impact on Spiking Properties in Hodgkin-Huxley Neuron with Synaptic Stimulus". In: *Pramana* 70 (Mar. 2007). DOI: 10.1007/s12043-008-0016-1.

[3] Adam F. Strassberg and Louis J. DeFelice. "Limitations of the Hodgkin-Huxley Formalism: Effects of Single Channel Kinetics on Transmembrane Voltage Dynamics". In: *Neural Computation* 5.6 (1993), pp. 843–855. DOI: 10.1162/neco.1993.5.6.843. eprint: https://doi.org/10.1162/neco.1993.5.6.843. URL: https://doi.org/10.1162/neco.1993.5.6.843.