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RESEARCH ARTICLE

NEURONAL STRUCTURE AND NEED FOR IMPROVED ACTION POTENTIAL PROPAGATION MODELING

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ABSTRACT

The nervous system is made up of a large number of interacting neurons or nerve cells. Neuron is an electrically excitable cell that processes and transmits information through electrical and chemical signals. A typical neuron possesses a cell body or (soma), dendrites, and an axon. In neurons, action potentials play a central role in cell-to-cell communication. Once an action potential is initiated at one point in the nerve cell, it propagates through the axon to the synaptic terminal region and from there signal is transmitted to next neuron. Propagation and generation of action potentials have so far been studies by treating the whole system as consisting of electric circuit having conductance and resistances. However (from cell biology) we know that lot more is happening while action potential is being propagated through axon. Additionally with the advent of computers, now, we can afford to undertake more complicated modelling and analysis of action potential propagation. This will lead to improved understanding and better ability to improve neuronal performance. We therefore propose the possibility of modeling action potential propagation using Fluid equations and Maxwell equations.

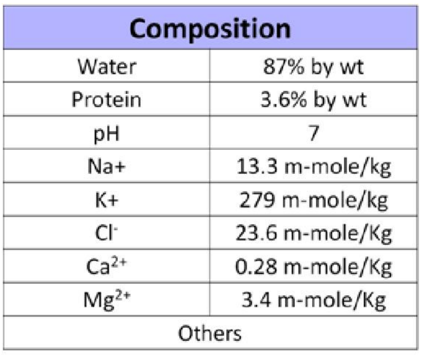
INTRODUCTION

(Kandel *et al*., 2000; Byrne, 1997; Sabry *et al*., 1995, Hodgkin and Huxley, 1952; Audesirk *et al*., 2004; Luby-Phelps *et al*., 2000; Dyann and Abott, 2001; Byrne, 1997; Gerstner and Kistler, 2002; Sterratt *et al*., 2011) Neurons are cells that are integral part of the nervous system. They are like other cells in the human beings and animals in many ways, however, there is one important difference between neurons and other cells i.e. they are specialized in transmitting information throughout the body. These transmit information in both chemical and electrical forms. There are several different types of neurons responsible for different tasks. For example, Interneurons are responsible for communicating information between different neurons. Motor neurons transmit information from the brain to the muscles. And, sensory neurons carry information from the sensory receptor cells throughout the body to the brain. Proper functioning of neuron is absolutely essential for all the parts of the body. Their malfunction can lead to several neuronal diseases. It is for this reason that despite its complexity, scientific community has put tremendous effort in understanding the neuron and its structure during past century. In line with the scientific community of this field, in this paper, we propose to expand the scope of modeling action potential propagation.

Neuron Structure

(Kandel *et al*., 2000; Byrne, 1997; Sabry *et al*., 1995, Hodgkin and Huxley, 1952; Audesirk *et al*., 2004).

Table 1. Typical Axoplasm composition in squid gaint axon (Gilbert, 1975; Keochlin, 1955)



Composition	
Water	87% by wt
Protein	3.6% by wt
pH	7
Na+	13.3 m-mole/kg
K+	279 m-mole/kg
Cl^-	23.6 m-mole/Kg
Ca^{2+}	0.28 m-mole/Kg
Mg^{2+}	3.4 m-mole/Kg
Others	

There are three basic parts of a neuron: the dendrites, the cell body and the axon (Table 1 shows the typical composition of cytoplasm (fluid inside neuron). The cytoplasm inside axon is called as axoplasm) All neurons differ in size, shape, and other characteristics depending on their function. Some neurons have long axons while others can be quite short. Some are highly branched in order to receive a great deal of information while others have few dendritic branches. The axon is a key component of nerve cells over which information is transmitted from one part of the neuron to the terminal regions. Axons can be very long extending up to a meter or so in some

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of the human cells. The synapse is the terminal region of the axon and it is here where one neuron forms a connection with another and conveys information through the process of synaptic transmission. Dendrites are signal receivers. The cell body (called as soma) contains the nucleus and the other organelles necessary for its functioning. The cytoplasm comprises of cytosol (the gel-like substance enclosed within the cell membrane) and the organelles (the cell's internal sub-structures). Axoplasm is the cytoplasm within the axon of a neuron.

Action potential

(Beilby 2007; Hodgkin *et al*., 1952; Dyann and Abott, 2001; Byrne, 1997; Gerstner and Kistler, 2002). An action potential is a short-lasting event in which the membrane potential of a neuron rapidly rises and then falls. Action potentials in neurons are also known as *spikes*, and the sequence of action potentials generated by a neuron is called its spike train. Once an action potential is initiated at one point in the nerve cell, it propagates through the axon to the synaptic terminal region and from there signal is transmitted to next neuron. Specific types of voltage controlled ion channels embedded in a cell's membrane generate action potentials. These channels are closed when the membrane potential is close to the resting potential, but they quickly begin to open if the membrane potential increases to a threshold value. When these channels open, they permit an inward flow of sodium ions, which increases the membrane potential. This in turn causes more channels to open, producing a greater electric current across the cell membrane, and so on. This process proceeds rapidly until all of the local ion channels are open, resulting in a large increase in the membrane potential. Thereafter, the ion channels rapidly inactivate. As the sodium channels close, sodium ions can no longer enter the neuron, and they are actively transported out of the membrane. Then the Potassium channels are activated, which leads to outward current of potassium ions, returning the membrane to the resting state. After an action potential has occurred, there is a transient negative shift, due to additional potassium flow. This is the mechanism that actually prevents an action potential from traveling back the way it just came from. Many types of action potential exist in cell and are determined by the types of leak channels, voltage-gated channels, ionic concentrations, channel distributions, membrane temperature, capacitance etc. Literature on action potential is vast and we suggest further reading (Dyann and Abott 2001; Gerstner and Kistler, 2002; Sterratt *et al*., 2011) for better understanding and for more details.

Existing Models for Action Potential propagation

(Dyann and Abott, 2001; Byrne, 1997; Gerstner and Kistler, 2002; Sterratt *et al.,* 2011) Including the famous Hodgkin-Huxley and the Cable equation, scientists have proposed various models for modeling action propagation and initiation. Some of them are listed below:

Integrate-and-Fire Model

This is probably one of the most used and well-known example of a formal spiking neuron model. Its basic model is also known as leaky-integrate-and-fire. Here, the membrane is understood to be leaky due to ion channels.

Spike Response Model

In this model the state of neuron is described by a single state variable. If this variable reaches a threshold value then a spike is generated.

Hodgkin-Huxley Model

This model is a classic description of conductance model. This model was developed based on experiments with the squid giant axon. It has three types of ionic i.e. potassium (K), sodium (Na), and leak currents. Potassium (K) and sodium (Na) currents are controlled by voltage dependent ion channels. Leak current takes care of other channels (and it mainly consists of Cl^-).

Morris-Lecar Model

This 2D model describes oscillations in a barnacle giant muscle fiber. This is modelled by equations where expression for the membrane potential and for the potassium gating variable is considered.

Hindmarsh-Rose Model

The general form of the Hindmarsh-Rose model is given by equations, where specific functions are correctly chosen to produce the desired results. The model exhibits its properties depending on the choice of specific functions.

FitzHugh-Nagumo Model

This model is obtained by reducing four equations of the Hodgkin-Huxley model to a system of two equations. And, likewise, there are many more models, however, the primary disadvantage of all these models is that they only model in terms of electric circuit hence they are very limited in providing in-depth understanding.

Conclusion and Recommendations for future

Based on the above observations and disadvantage of existing action potential models we recommend the inclusion of following in action potential modeling:

a) Fluid equations, namely

(Patankar 1980; Katta *et al*., 1994; Roquemore and Katta 2000; Roubíček 2006; Qian and Sejnowski 1988; Murthy and Mathur 1988; Weisstein 2014 Navier-stokes equations; Landau and Lifschitz 1987; Zwillinger 1977; Weisstein 2014 Convective operator; Cengel and Cimbala 2010; Rathore 2006)

1) Continuity equation for mass conservation.
2) Momentum equations (take care of forces and velocities)
2.1 In axial direction.
2.2 In radial direction.

2.3 In angular direction.

3) One Species Equation for each species – takes species transport and species conservation.
4) Energy equation.

b) Magnetic field generated due to movement of charge (Maxwell's equations (Gambhir *et al*., 1993; Jackson 1998; Weisstein 1996)).
c) Effect of extracellular fluid (they will also generate electric and magnetic field).
d) Axon may not be assumed to be a perfect cylinder. Inclusion of above will help us in better understanding of physical phenomena happening inside the axon. Additionally, optimized values of many unknown properties inside neuron can be obtained (which are otherwise difficult to obtain using experiments). Also, effect of varying various parameters (temperature, diffusion, fluid velocity etc) can be studies. On the whole, this will help us in improving neuronal performance in many situations.

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