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A New Dynamic Electronic Model of Neuron's Membrane

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Abstract— Neural system consists of billions of neurons that naturally do control the bio-physical system. A typical neuron basically consists of soma which is the functional body of neuron, axon, dendrites and synapses. An action potential is generated across the neuron's membrane and conducted to the axonal terminals through which the next neighboring neuron/neurons are excited. The action potential is generated via ionic discharge of membrane in the format of none or all. In this particular study a new electronic integrate and fire model of neuron possessing dynamic properties of a real neuron is introduced. The circuit developed here is inspired from the well known Hodgkin Huxley model with addition of dynamic voltage controlled ionic gates and channels. The model stays in the resting state unless it is triggered through anywhere/dendrite on the membrane. In accordance with the increase of power range of excitation applied to the neuron the frequency of action potentials generated by electronic cell model increases. The generated pulse very quickly propagates to the axon terminals and triggers the next cell, and accordingly repeats the action potential with the same format as in the previous cell. With carrying out some specific tests on this electrical model it is aimed to further understand the electrical and molecular interaction/communication made over a real neuronal network.

Keywords : *Neuron, action potential, integrate and fire electronic model.*

1. Introduction

Organisms have their particular forms of information generators and transceivers on cellular scale to communicate and control their organic structures. Understanding the basic principles of this amazing control system and/or subsystems is always a matter of wonder for scientists. In this direction many studies have been and is being conducted in variety of basis, such as experimental biology [1], systematic [2-7] and electronic models [8] However, the well developed techniques used in digital communication technologies are still not compatible with miraculous biological cellular communication system. Therefore studies performed toward understanding the communication between neurons are still very challenging.

From the historical perspective, Hodgkin and Huxley [9] through conduction of a set of experiments on the giant axon of the squid had showed that it is feasible to model the ionic current transport through cell membrane with three different types of ionic currents, Sodium (Na^+), Potassium (K^+) and a leakage current that mainly of Chlorine (Cl^-) ions. They also showed that ionic sodium and potassium exchange between intracellular and extracellular precincts depends on specific voltage-dependent ion channels. During resting state the voltage from internal to external of membrane had been measured to be about -70mV, and for any excitation over the threshold (about -40mV) the cell had been shown to produce a spiky potential called Action Potential (AP). The action potentials mainly had manifested a discharge,

recharge and refractory phases. From this basic information they had introduced an electrical model for cell membrane at resting state as shown in Figure 1 [9].

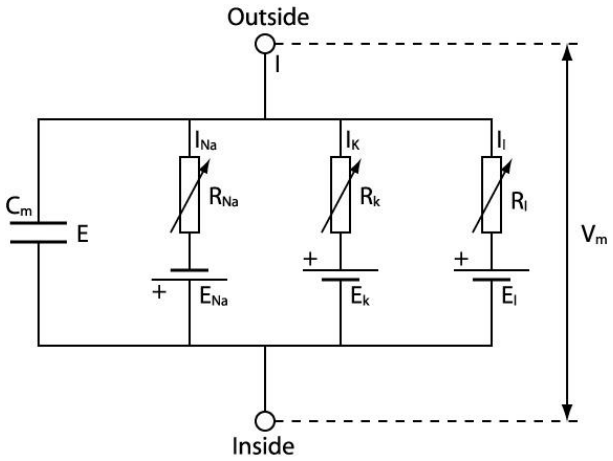

Figure 1. Hodgkin-Huxley electrical model for cell membrane at resting state [REF]

A biological neuronal network or system through which the inter-organ interactive message exchange is being realized is configured from billions of neuronal cells that has a functional body (soma) , axon and dendrites with synapses. As an action potential is generated by the cell it is conducted to the neighboring cells through synaptic mechanism on the pre synaptic axonal ends and post synaptic dendrites. Beside of electrical signaling, the inter-space medium between cells called cleft transmits the message in the format of molecular transportation via diffusion. This transport characterizes the cells on the pathway of signaling to uniquely repeat the message signal organized in terms of action potentials' codes.

The AP is generated through the ionic discharge of cell's membrane in the manner none or all. The membrane is considered to operate in the format of integrate and fire. In this particular study an electronic integrate and fire model possessing properties of a real neuron is introduced. The circuit developed here is an active electronic model of cell membrane which stays in the resting state unless it is triggered through anywhere/dendrites on the membrane. According to the power range of excitation applied to the neuron the frequency of APs generated by electric cell model alters, and hence it behaves as a convertor of voltage to pulsates frequency. The generated pulse very quickly propagates to the axon terminals and triggers the next cell, and accordingly repeats the action potential with the same format of the previous cell. With carrying out some specific tests on this electrical model it is aimed to further understand the electro-chemical communication that is made throughout the real neuronal network.

1. De**sign of the Electronic Model**,

From the biophysical point of view an AP consists of four fundamental phases as shown in Figure 2 (a). At resting state cell's membrane potential measured between external and internal media is about -70 to -90 mV, depending on the cell type. As membrane voltage reaches to a certain threshold level (usually about -40mV) the membrane depolarizes and its voltage immediately raises to a positive level (mainly around 20 to 40 mV) and then re-polarizes back toward its resting state via ionic transport through membrane and then after a refractory period the membrane potential turns back to its resting state as shown in Figure 2 (a). Most dominantly the ionic particles crossover cell's membrane through voltage dependent gates or voltage controlled channels. During refractory period, sometimes the cell turns into hyper polarization state. It should be noted that during the re-polarization phase new APs cannot be generated.

Considering the complex biological mechanism and function of a neuron, an electronic circuit was designed to model a segment of the cell membrane as shown in Figure 2 (b). The model is a simple circuit consisting of a membrane voltage, resistance and capacitance and a voltage gated mechanism designed with a uni-junction transistor (UJT) [10] serially connected to a bipolar junction transistor (BJT). Here the uni-junction transistor simulates the threshold level of the ions' gate and the bipolar transistor simulates the nonlinear ion transportation phenomenon through the membrane (encircled with the dashed line in the Figure). The voltage across the membrane is introduced for simulating the mean resting state membrane voltage resulted from the difference in potassium (K^+), sodium (Na^+) and Chlorine (Cl^-) ionic concentrations in extracellular and intracellular media. The resistance (Ry) that serially connected to the voltage source through emitter of the bipolar junction transistor simulates the base resistance, while the BJT simulates the ionic concentration dependent resistance of the membrane. The capacitance (C_1) connected in parallel to the bipolar junction is added to the circuit to simulate the refractory phase of the action potential when it discharges. The voltage variable resistive component (VRs) is integrated to the circuit to simulate any dendrite of the cell which may be affected from any external or internal excitation or energy source. As the resistance value of this component is altered in accordance with the stimulation voltage fed to the dendrite the cell membrane starts to generate action potentials. The electronic model also obeys none or all law while generating the action potentials. As the level of stimulus increases, the repetition rate of APs increases accordingly, and vice versa. Figure 3 shows the generated action potentials across the model (membrane) in accordance with the applied sinusoidal voltage as a stimulator. Therefore as in real biological case the stream of APs generated by the model can be modulated with the stimulus' format.

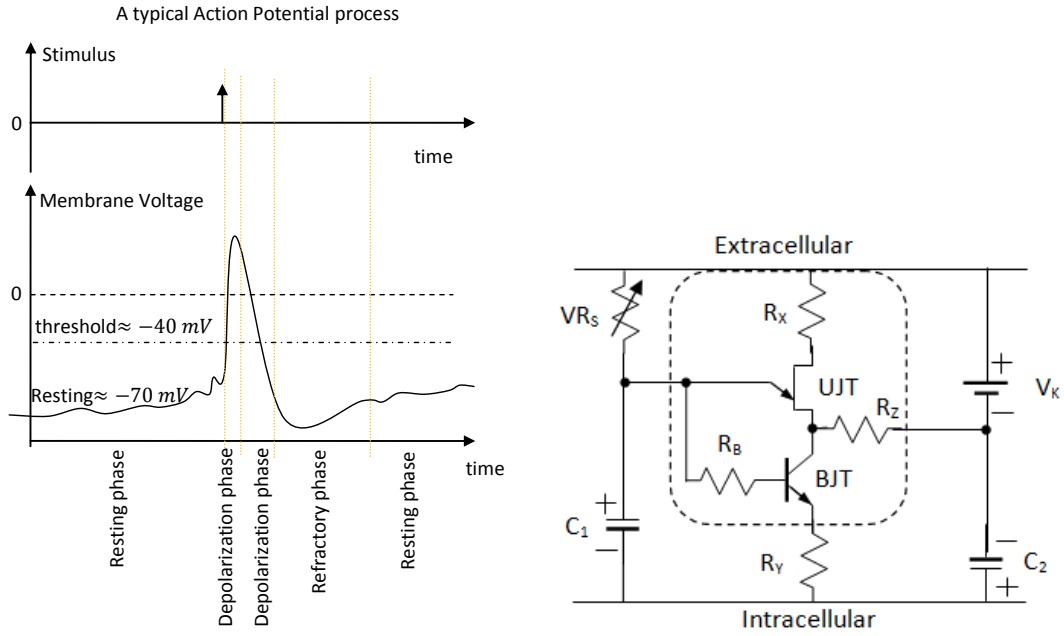

Figure 2 (a) A schematic representation of an Action potential. (b) The electronic model designed to represent cell membrane

Here, the designed circuit may be considered as the active model for soma. The axonal part of the membrane may be modeled similar to passive current carrying cables. In this case, the axon can be modeled with an LC circuits connected in the ladder fashion.

The transient voltage across capacitor (C_1) that simulating the membrane capacitance can be formulated as

$$V(t) = V_f + (V_f - V_i)\exp(t/\tau) \quad (1)$$

Where $V_f = \frac{V_{DC}C_2}{C_1+C_2}$ is the final voltage value, V_i=0 is the initial value of the membrane voltage and the integration time constant across cell's membrane is $\tau = VR_S\frac{C_1C_2}{C_1+C_2}$. At the activation point the capacitive voltage can be calculated as

$$E = V(t_p) = V_f + (V_f - V_i)\exp(t_p/\tau) \quad (2)$$

Where E is the turn on voltage level of the UJT. Similar to the ionic voltage dependent channels, as the UJT becomes ON the electronic channel between extracellular and intracellular turns on and the current through membrane becomes maximum and creates an impulse across the membrane electronic model. when the UJT becomes ON the BJT Transistor also operates in active region and controls and shape of the electronic/ionic current flowing through the channel. After the UJT turns OFF the BJT remains in active region due to the voltage stored on C_2 for a short time to simulate the refractory period of the cell's membrane. After BJT turns off the integrating phase starts again just similar to the real cell's characteristics. Here the parameters of the proposed electronic model shown in Figure 2 (b) are optimized to be: Rx = 2.2 K Ω; Ry = 100 Ω; Rz = 10 Ω; Rs = 100 KΩ; C_1= 10μF; : C_1= 2.2μF; V_k = 11V; VRs =Voltage variable resistance (10K-30K, in this circuit). However this values can relatively be increased or decreased to much exactly show membrane's parameter values.

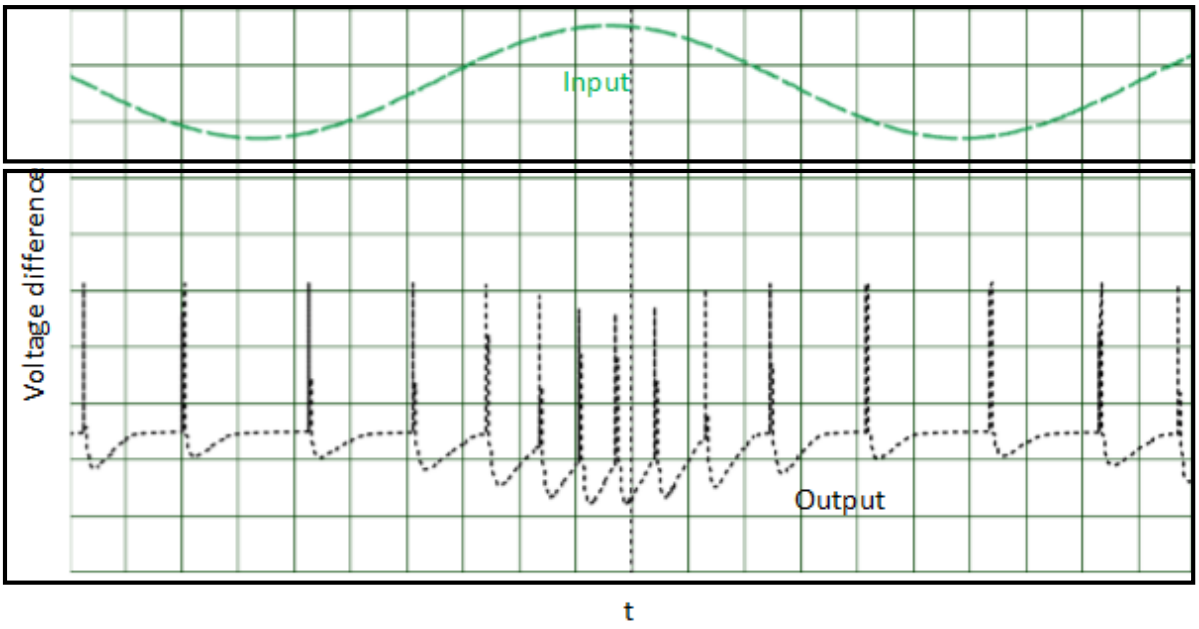

Figure 3. Input and output signals of the proposed model for neuron's membrane

2. Propagation of Action Potential along with Axon

The axon of a neuronal cell can be about one meter long with a cross section of a few nanometer. when a neuron is stimulated the voltage-dependent ionic gates open and consequently Na^+ ions transported from extracellular to intracellular region while K^+ ions transported form intracellular region to extracellular region. As a result of this depolarization process the Action Potential propagates along with the axon as shown in Figure 4.

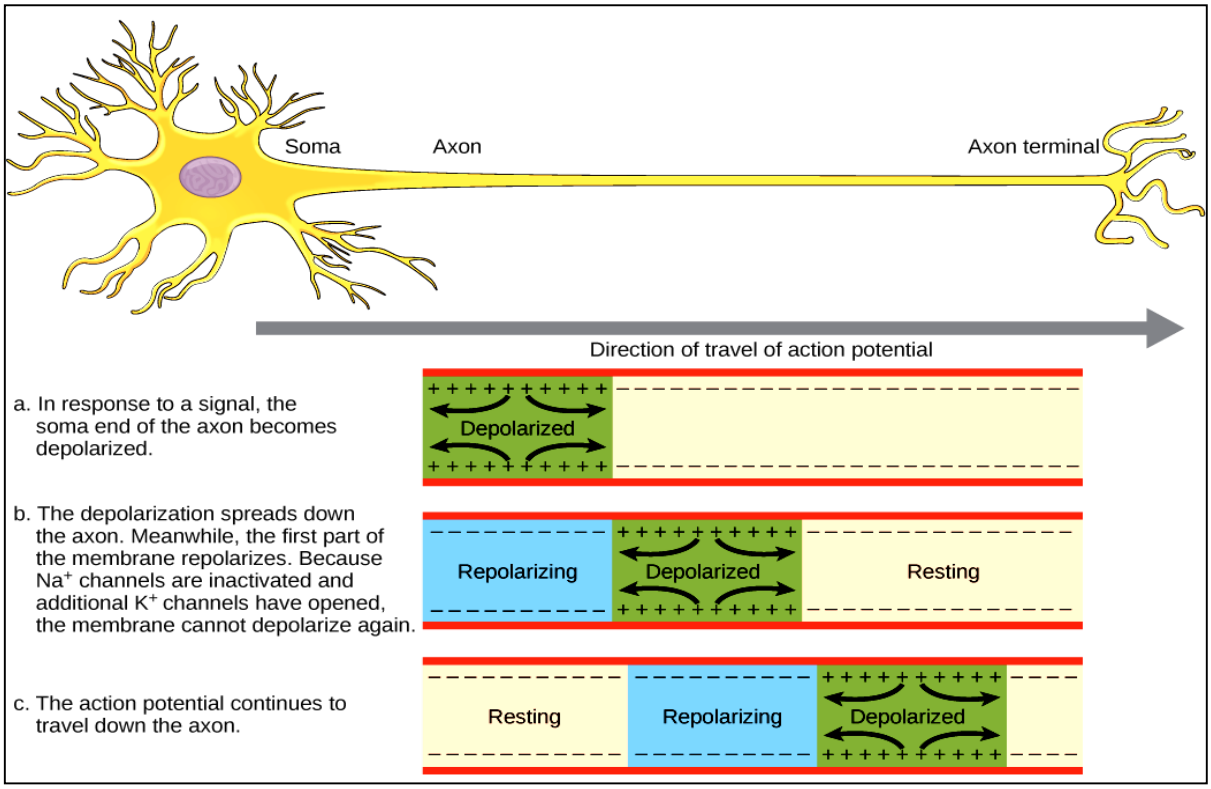

Figure 4. shows the schematic representation of propagation of AP. Adapted from OpenStax College, Biology (CC BY 3.0) [11]

3. Conclussion

In order to simulate the neuronal cell a new electronic model was designed. A UJT and BJT transistor in serial configuration was used to realize the voltage dependent gate circuit through which electronic charges are passed similar to the passage of ionic particles through cell's membrane. The DC voltage was used to simulate the average ionic voltage measured across membrane. The integrate and fire models available in the literature, for example [5], are mostly have a complex configuration but not possess all of the biological properties of neurons and synapses. The results obtained with operation of the circuit showed that the designed circuit well suited to the real neuronal cell and exhibits almost the same characteristics of the neuron as simulating all phases of an AP. The electronic current flowing through the circuit resembles the ionic current flowing through membrane of the cell. With the design of the circuit and the obtained results it is understood that on chip semiconductor neuron models can be developed. Also, with the advanced technology perhaps the design of biology inspired neuronal networks can be possible. As mentioned previously the frequency of the APs can be controlled by the input voltage given to the VCR which means that the information given to the circuit is converted into APs stream whose frequency linearly related to the information processed. Therefore we believe that any information can be processed through a neuronal network designed in this way.

VI. Acknowledgements

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