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Electrical Modelling of Neuron System for Deep Brain Stimulation Microelectrode

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Abstract

The neurons exhibit electrical behaviour and look like a circuit network The electrical modelling of neuron is presented for the development of suitable microelectrode. The neuron size is of the order of 1250 µm2 with diameter of 20 µm, for this study. The. variation in neuron capacitance is simulated for injected current varying from 0.1 nA – 0.3 nA. The capacitance of the neuron for different conductance, lower to higher, is measured and presented. This study includes the variation of membrane capacitances of neurons with same size but with different conductivity. Neurons may show excitation or inhabitation and this effect is simulated for 0.1 nA current. The results are useful for learning the response of neurons under external stimulating current. According to this paper suitable value for current is necessary for effective deep brain stimulation treatment.

Keywords: Neurons, microelectrode, membrane capacitance, deep brain stimulation, stimulus current

Introduction

The effect of electrical signals on the human being is known before the invention of electricity. Scientists have postulated that the human mind is similar to the network of electrical wires. The neurons can have electrical equivalent models. There are few diseases which deteriorate the quality of life of the patients. Parkinsonian is a state where motor control of the body is lost. Early stage Parkinson is treated through medication but advanced stage is not curable. At this point alternate therapy is sought; and stimulation of brain tissues through electrical signal was proposed. Such systems are called deep brain stimulation (DBS)[1]–[4]. The subthalamic nucleus of the brain is excited through electrical pulses with the help of an implanted microelectrode. This microelectrode provided necessary electrical pulses to the target area. The patient has shown the relief. In DBS system, the electronic pulse is provided to the microelectrode and the microelectrode acts as a transducer. This ionic pulse is converted into bionic signals inside the brain. The microelectrode develops an interface with the surrounding medium. To analyze such interface complex physical phenomena, have to explain [5]–[7]. The overall success of DBS is dependent on the associated electronic circuitry. The electronic circuits perform specific tasks for the success of the DBS system. DBS system has low power devices for the longevity of the implanted battery[3], [6]. The human brain is complex part of the body and performs vital functions. It can be divided into several parts depending upon the functionality such as motory functions, controlling functions, thinking functions and memory.

It should remain healthy and functional all the time. The four major lobes are indicated in the Figure 1**.** The cerebral cortex consists of lobes; Temporal, Occipital, Parietal, Frontal. Each lobe has specific function to perform. In this paper deep part of the brain is suitable for microstimulation.

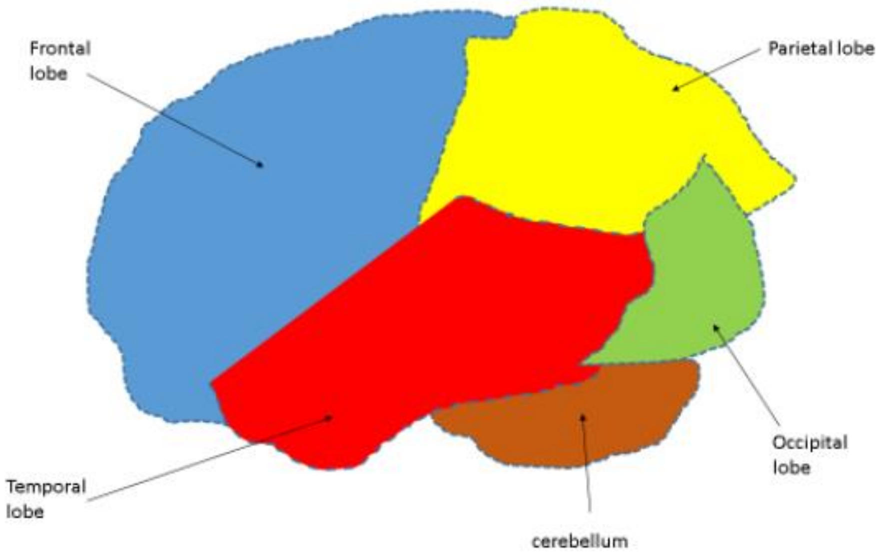

Fig. 1 Brain structure

It is reported that the structure of the cerebral cortex is convoluted for human brain and has ridges (gyri) and grooves (sulci) which divide the brain in different regions[6], [8]. The major effect of convoluted structure is to provide increased volume while maintaining the thickness of the brain. Central sulcus divides the frontal and parietal part of lobes. The frontal lobe is larger and helps to execute higher order functions including personality and behavioral related decisions. The occipital lobes are responsible for visualization related activity. In summary, the human brain is broadly classified into two parts; cerebral hemisphere -1 and cerebral-2. It has several subcortical sections as if basal ganglia, thalamus and cerebellum, and nerve fibers are responsible to connect different cortical areas. The cortex is a covering substance having a thickness around 1.4 to 4.1 mm. Its color is gray, and is often called as gray matter; while, white part in the brain is due to connecting nerve fibres. The grayness of the cortex is akin to presence of large number of neurons.

BASICS OF NEURONS

Neurons are fundamental components of the CNS. These are highly specialized compartment and perform the processing of the information inside the brain. The communication between body part and the brain happens via neurons. With reference to Figure 2, a neuron has cell body, axon, dendrite, and synapse. The cell body (also referred as “soma”) comprises nuclei. The main function of cell body is to provide nourishment to the neuron. The dendrites are dense in construction. The input signal enters through dendrites and action potential is created at Axon Hillock. The Axon Hillock is thicker and connects axon with the soma [9]. The action potentials are sent over the entire axon and at the end of the neuron are decoded into a chemical signal. The terminal branches of neurons have synapses. The action potentials are transferred to other neurons through these synapses[9]–[11].

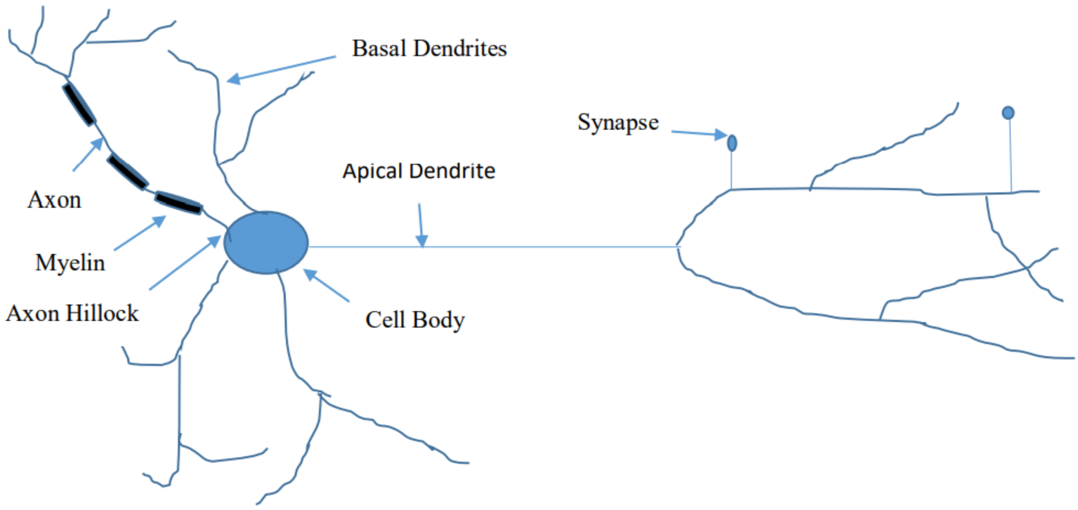

Fig. 2 A basic neuron structure

The size of the axons varies from 0.1 millimetres to 3 feet. The larger axons transmit faster information. Certain axons are enclosed with fatty materials. It is myelin and acts as an insulator. The effect of myelin is fast propagation of information and protection of axon. The neurons inside the brain form an electrical network and bionic current flows through them. The electrical nature of brain neurons was postulated long time back and this information was used to treat basic nerve related disease. Since, neurons are basic components of the brain and it behaves like electrical network; knowledge about its electrical behaviour was main goal for

researchers and scientists. With the development of new analysis tool, it became easier to analyse complex circuits like brain. The brain consists of billions of neurons which interact with each other. The interacting entity is synapses. The neurons exhibit mechanical, chemical and electrical properties. The property of interest, in this paper is electrical nature of the neurons. When electrical current is injected inside the brain through an implanted microelectrode, it interacts with the stimulating current. The transfer of external current into bionic current is done by the microelectrode[2], [12].

MATHEMATICAL MODELLING

The membrane has a lipid region, which is hydrophilic. The ions cannot penetrate and directly pass-through it. The ions use hydrophilic specialized channel proteins. These channels proteins act as a tunnel across the membrane. Some channels are open in resting neurons and others are closed. The closed channels are open only in response to a signal. Two main ion channels are potassium channels, and sodium channels. In neurons, the resting membrane potential depends on movement of $K+$ through potassium leak channels. The opening and closing ion channels alter the membrane potential. The movement of ions across the membrane gives rise to mathematical analysis of the membrane. Hodgkin-Huxley model is electrical model of the membrane[13]. It uses electrical elements to explain the electrical behavior of the ion channels (Figure 3). The properties of the channels are voltage and time-dependent.

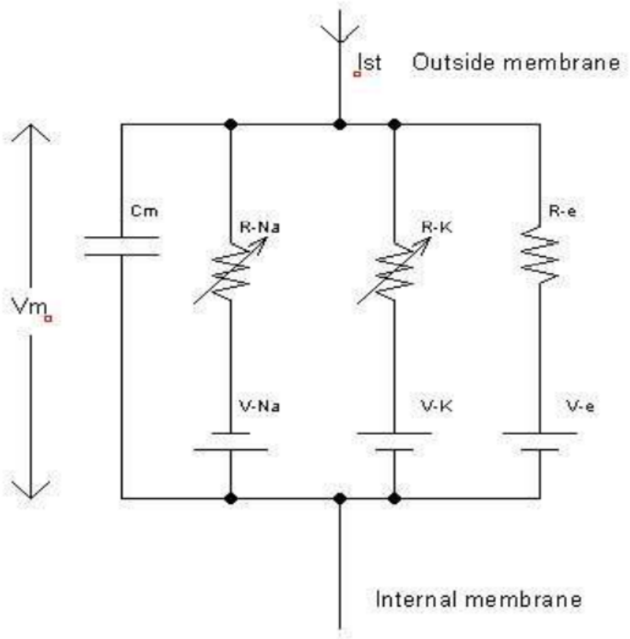

Fig. 3 Hodgkin-Huxley Model

The cell membrane has charge storage capacity represented by a capacitor (Cm). The various kind of ion channels are exhibited by resistors and batteries are used to symbolize electrochemical potentials. Voltage-gated ion channels are exhibited by R-Na and R-K and dependent on time and voltage. The leak channel (R-e) is linear and does not depend on voltage and time. A flow of ions needs potential source to sustain. These voltage sources are compensated by V-Na, V-K and V-e. The electrochemical potentials are developed due to different ion concentrations. The membrane is stimulated using current (Ist). In the equivalent circuit, the current through the membrane has two components, associated capacitive current and resistive ion currents[11], [14], [15].

The capacitive current (Ic) through lipid bilayer is proportional to time derivative of membrane potential (Em)

$$Ic = Cm\frac{dEm}{dt} \qquad (1)$$

The channel current (Ich) is product as follow

$$Ich = g_{r(Em-Er)} \qquad (2)$$

where Er, gr is reversal potential; and conductance of the channel, respectively. The total current (I) across the membrane is the sum of these currents:

$$I = Cm\frac{dEm}{dt} + g_{r(Em-Er)} \qquad (3)$$

In terms of sodium, potassium channels, “I” becomes:

$$I = Cm\frac{dEm}{dt} + g_{Na}(Em - E_{Na}) + g_K(E_m - E_K) + g_e(Em - Ee) \qquad (4)$$

where I is the total membrane current/area, Cm is the membrane capacitance/area, gk and g_{Na} are the potassium and sodium conductance/area, respectively, ENa and EK are the sodium and potassium reversal potentials, respectively, and ge and Ee are the leak conductance per unit area and leak reversal potential, respectively.

PROPOSED SIMULATION MODEL

The neurons are distributed throughout the brain and develops a complex electrical network. The neurons have various shapes and sizes. In this work, neurons are assumed to be spherical for simulation work. The neuron is as shown in Figure 3 has distribution of K+, Na+ and organic anions. The size of the neuron is 20 µm with surface area 1250 μm^2. The concentration of ions is shown in Table 1.

Table 1: Concentration of ions for neuron

Na+ (mM)		K+ (mM)		Cl^- (mM)		Organic anions (mM)
Inner	Outer	Inner	Outer	Inner	Outer	
11	140	150	5	3	115	95

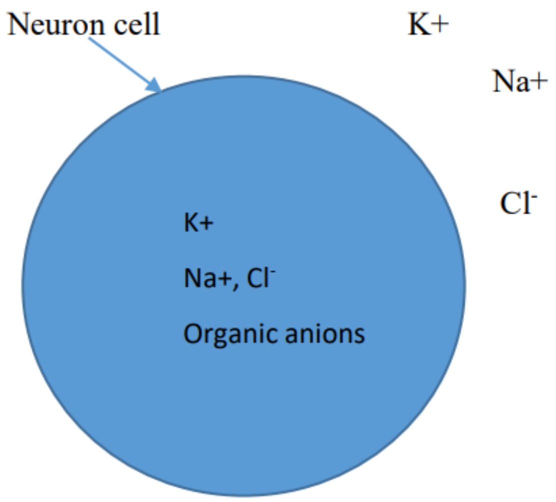

Fig. 4 Spherical Neuron cell

The membrane cell has a potential difference across the body; it is a polarized cell. If the membrane potential rises and becomes more positive than its resting potential, the membrane is depolarized. However, if the membrane potential becomes more negative, the membrane is hyperpolarized. Both conditions are temporary and membrane achieves resting potential after sometime. The above discussion highlights the fact that a living cell will have definite potential due to capacitance of the membrane.

RESULTS AND DISCUSSION

The membrane potential depends on the applied current to the neuron. The membrane potential is plotted under applied current of magnitude 0.1nA. The applied pulse current produces a voltage which follows the capacitor behaviour. As can be

seen in Figure 5, the response of the neuron membrane is capacitive in nature. It rises and falls following time delay. This result also explains that the human body can store charges. As discussed earlier, the potential across the membrane is originated due to difference in concentration of the ions. For example, the concentration of Sodium and Potassium are different inside and outside of the membrane. When electric current is injected inside the brain it affects the ion channels. The ion channels are voltage dependent. So the application of external signal causes the movement of ions through the channels. The equilibrium is disturbed. Again voltage dependent channels adjust themselves to adjust the equilibrium concentration levels.

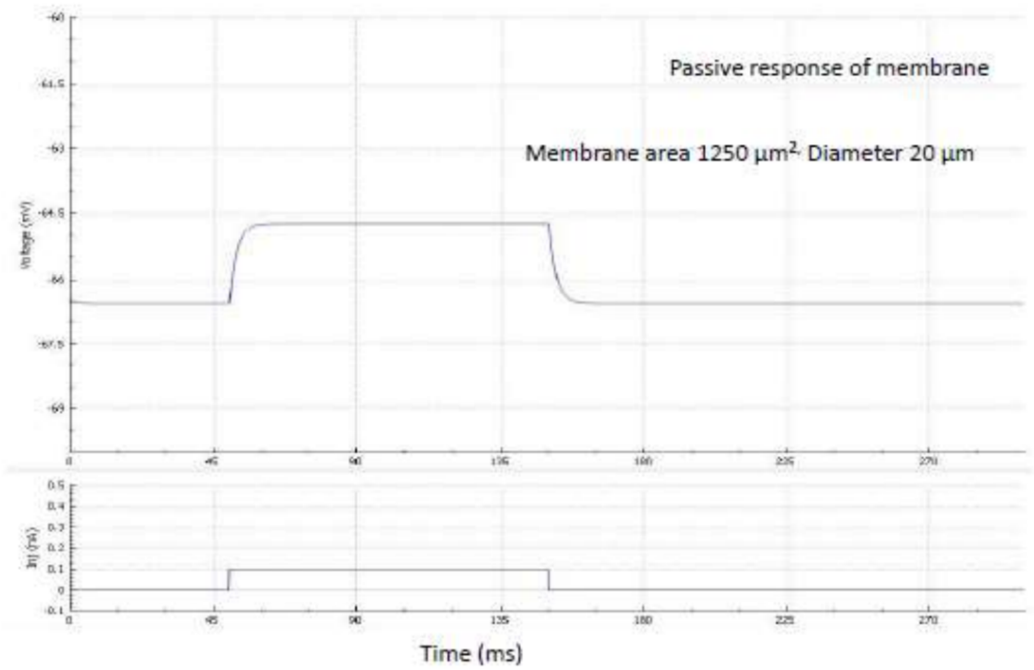

Fig. 5 Measurement of membrane potential under current

The membrane potential depends on the magnitude of stimulating current. In Figure 6, the membrane potential is plotted for varying stimulating current. It is observed that membrane potential is larger for rising current pulses. The amplitude of stimulating current varies from 0.1 - 0.3 nA.

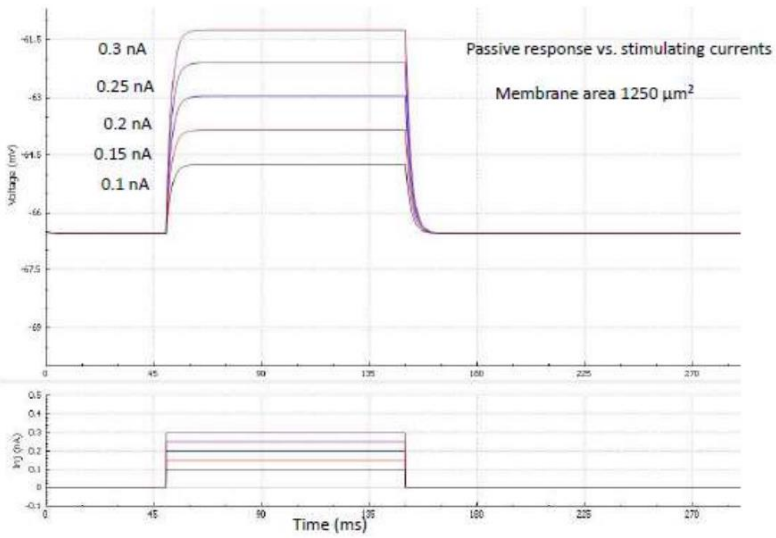

Fig. 6 Measurement of membrane potential for varying stimulating current

The membrane potential depends on the conductance of the neurons. In Figure 7, potential is plotted for various conductance values of Neuron (lower K means higher conductance). The conductance parameter is represented by K which changes from 0.3-0.5. It can be seen from the figure that potential rises for lower conductance value.

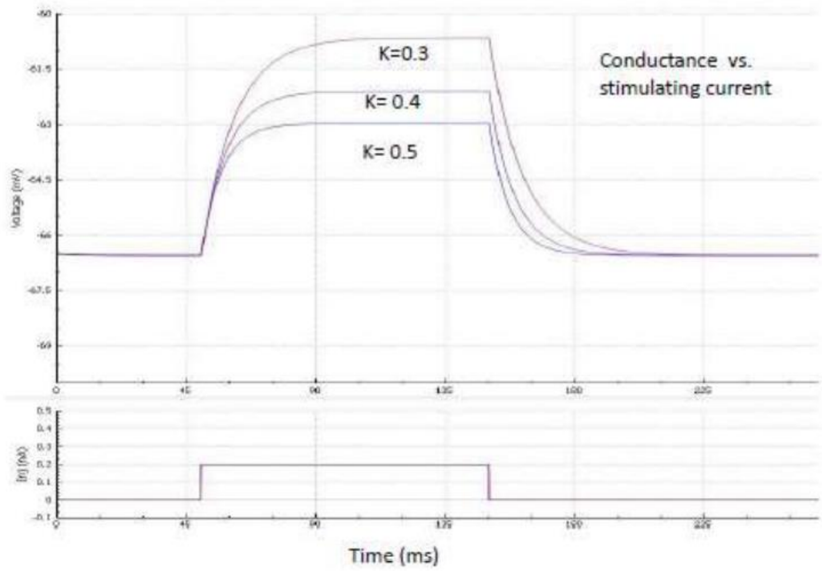

Fig. 7 Measurement of membrane potential for different neuron conductance

The membrane potential may be excitation or inhibition depending on the stimulating current pulses as shown in Figure 8. When positive pulse is applied, it excites the neuron and when the pulse is negative the response of the neuron is inhibition. This information is useful because over excitation of neuron brings brain diseases. To treat such diseases over excitation needs to be reduced.

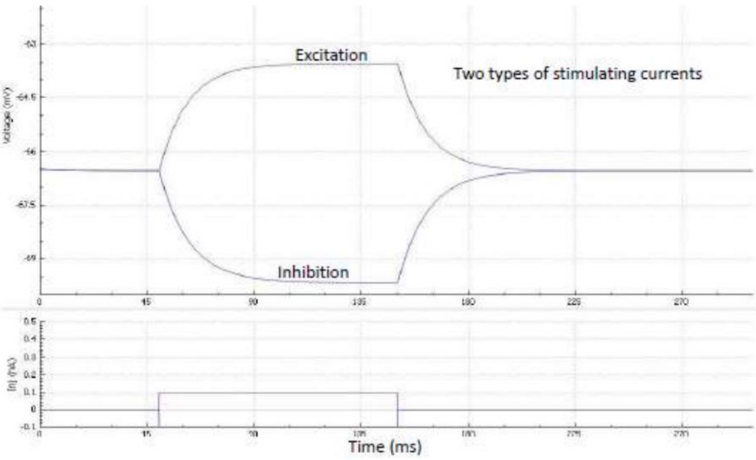

Fig. 8 Excitation and inhibition response of the membrane

CONCLUSION

A working electrical model for neuron is proposed. This model is simulated to measure the effect of current on the membrane potential. The membrane potential depends on the intensity polarity and time duration of current. The crucial design parameter for the microelectrode is to provide safety of the surrounding neurons. The results show that the neuron responses under injected electrical current. The structure of neuron is chemical but it behaves as electrical network. The membrane potential is positive for a living cell and zero for a dead cell. The membrane potential varies as the amplitude of the stimulating current is varied. Depending on the intensity of the stimulating current it may be larger. The result shows that the neurons store electrical charges. A larger storage of charge on the neurons may harm the cell. The damage thus caused may be permanent. The microelectrode should be designed to accommodate safety inside the brain.

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