Role of Physics in Nerve Conduction; Electrochemistry; Future Prospects

Raghottam Manoj Sattigeri¹, Dr. Bhagya Manoj Sattigeri²

¹TY BSc (Hons) Physics, Dept. Of Physics, Faculty of Science, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat
²Professor and Head, Dept. Of Pharmacology, Sumandeep Vidyapeeth’s, SBKS Medical Institute and Research Centre, Piparia, Vadodara, Gujarat

Abstract: The most important and vital structure of the human body is the nervous system which is complex and elaborate. A blur idea existed in the scientific community for more than 2000 years that, there exists a mode of communication between our brain and our body, but by the ground breaking work of Luig Galvani changed our perception about the nerve conduction. Contributions from the great Physicists like Hermann von Helmholtz, Erwin Neher, Bert Sakmann, Hodgkin and Huxley has helped us understand the basic functioning of the nerve cell, the correlation between the transmission of an electrical impulse and nerve signal transmission. Various experimental studies conducted by these Noble Laureates has today enabled us to understand the reasons behind neurological disorders and has also helped us advance in the management of the neurological disorders.

Keywords: Biophysics, Nerve cell, Nerve signalling, Neurotransmitter, Neurological disorder, Neurophysics, Physics

1. Introduction

The most important and vital structure of the human body is the nervous system which is complex and elaborate. The nervous system includes the Central Nervous System (CNS) and the Peripheral Nervous System (PNS), which co-ordinate and function together to regulate different processes of the human body. The signal (stimuli such as pain, pressure, temperature) of various types are sensed and transmitted to the CNS, in turn the brain interprets the data received by it and responds to the stimuli by conduction of an impulse through the PNS to the site of origin of impulse in the form of response. The entire process of response to stimuli by conduction of an impulse through the CNS happens in fractions of seconds [1], [2].

A blur idea existed in the scientific community for more than 2000 years that, there exists a mode of communication between our brain and our body, but by the ground breaking work of Luig Galvani (who conducted experiments on frogs with the help of galvanometer to understand the nerve function, in the late 18th century) successfully established that the electric currents are necessary for the conduction of impulse across neuron [3].

2. The Structure of the Nerve Cell

Neuron is the functional unit of the nervous system which consists of the cell body (which contains nucleus, mitochondria, and cell organelles), the dendrites (which function as a receiver/transducer) and the axon (similar to the electric cables) which functions as a transmitter (Fig-1). These axons are surrounded by a membrane called myelin sheath which plays a major role in the rate of electric transmission. Those axons with myelin sheath are the myelinated fibres and those without myelin sheath are called as the unmyelinated fibres. However, in the myelinated fibres there are interruptions present which are called as the node of ranvier [4], [5].

3. Conduction of an Impulse

The neurons respond to the stimuli and conduct impulses because of a membrane potential that is established across the cell membrane which can be explained by a voltmeter with one electrode placed inside the neuron and the other outside.

Figure 1: Figure indicates the structure of Neuron

Figure 2: Difference in Membrane Potential Using Voltmeter
There exists negativity inside the neuron as compared to the outside of the neuron. This difference is referred to as the resting membrane potential of a neuron. The resting membrane potential is expressed as -70 mV, which is observed when the membrane is not stimulated or conducting impulses \([2], [3]\). The ions responsible for the membrane potential are sodium \((Na^+\)\) and potassium \((K^+\)\). Nernst and Planck in collaboration gave an equation that directly relates the membrane potential with the concentration of the ions at the either side of the membrane.

\[
V \text{(in mV)} = \frac{RT[C]}{F[C^*]}
\]

Where,
- \(V\) is the membrane potential (measured in mV).
- \(R\) is Rydberg constant.
- \(T\) is Absolute Temperature.
- \(C\) and \(C^*\) are the concentrations of the ions outside and inside the membrane respectively \([6], [7], [8],[9]\).

### 4. Ion Gates/Channels - Action Potential

The nerve cell membranes contain special passage ways for the two ions sodium \((Na^+\)\) and potassium \((K^+\)\), which are called the ion gates or ion channels. These are the passages through which these ions diffuse, that occur on the arrival of stimulus, ultimately giving rise to the Action Potential generation \([10], [11]\).

The dendrites receive stimuli which trigger the opening of the \(Na^+\) channels, this results into increase of the potential from -70mV to -55mV \((\text{Step -1, Fig -4})\). If the opening of the \(Na^+\) channel is wide enough then the process continues, else it dies out. Once the potential reaches action/gate threshold limit more and more \(Na^+\) channels open up and increase the potential to +33mV \((\text{Step -2, Fig -4})\). This potential is a peak value and the process to reach this peak value is called depolarization. Followed by which the \(K^+\) channels open \((\text{Step -3, Fig -4})\) which leads to the process of repolarization. Since the opening is slower in the case of \(K^+\) channels the \(Na^+\) channels do not close immediately and ensure that the process is one-way. As time elapses the \(Na^+\) channels close completely and the \(K^+\) influx decreases the potential from +33mV to -90mV, which thus overshoots the resting membrane potential \((-70mV\)\). The process of repolarization \((\text{Step -4, Fig -4})\) is followed by a hyperpolarization state \((\text{when the potential is }< -70mV i.e., -90mV\)\) \((\text{Step -5, Fig -4})\). Again the continuous process of the \(K^+\) and \(Na^+\) pump brings the potential back to -70mV \((\text{resting membrane potential})\) \((\text{Step -6, Fig -4})\). Thus an Action Potential is generated and the signal is transmitted.

The equations relating impulse propagation to the ion permeability changes were presented by Hodgkin and Huxley Theory \((1952\)\) by voltage clamp experiments for which they received Nobel Prize in Medicine \((1963\)\). The patch clamp technique allowed the study of single/multiple ion channels in the cells, which was used to explain the flow \((\text{current})\) of ions and the fundamental cell processes such as action potential by Erwin Neher & Bert Sakmann in late 1970 who were awarded with Nobel Prize in Physiology and Medicine \((1991\)\) \([3]\). Hodgkin and Huxley used their results from the voltage clamp experiments to define sodium and potassium conductivities during action potential \([13]\). For example the conductivity of the sodium ion is given by:

\[
J_{\text{Na}} = (V - V_{\text{Na}}) g_{\text{Na}}
\]

Where,
- \(J_{\text{Na}}\) = Sodium Current Density;
- \(g_{\text{Na}}\) = Sodium Conductivity;
- \(V_{\text{Na}}\) = Sodium Nernst Potential;
- \(V\) = Transmembrane Potential.

(A similar equation can be obtained for potassium ion.)

These definitions are nevertheless arbitrary. Studies conducted by Hodgkin and Huxley explain that the membranes respond to smaller electric signals. This explains that propagation of an electric signal in an axon is similar to the propagation of a signal in a cable as shown in Fig-5. This was explained by the Resistance–Capacitance (RC) model, which is a landmark in medical science.
The impulses travel at a speed of presence/absence of myelin and resistances and is influenced by the 19th century excitatory. The latter diffuses across the synaptic cleft, as the impulse conduction than those without myelin [6].

Movement of the action potential along a nerve cell is called as the impulse conduction. The impulses travel at a speed of anywhere from 1m/s to 120m/s and is influenced by the diameter of the fibre and the presence/absence of myelin sheath. Neurons with myelin (myelinated neurons) are fast in impulse conduction than those without myelin [6].

In a myelinated neuron, action potentials only occur along the nodes and therefore the impulses jump over the areas of myelin going from node to node and this is called as saltatory conduction of impulse (Latin saltate - jump) as depicted in Fig 6 b.

Hermann von Helmholtz and Cremer in early 20th century developed cable theory for the neuronal fibres which was explained by modelling dendrites and axons as cylinders composed of segments with capacitances $C_m$ and resistances $R_m$ combined in parallel with the resistance along the fibre $R_t$ due to axoplasm as shown in Fig-7 [14].

Later in 1950 with improvement in technique, cable theory became important for analysing data collected from microelectrode recordings and for analysing the electrical properties of neuronal dendrites.

6. Synapse: Impulse Transmission at Synapse

These are the junctions that occur between presynaptic neuron and dendrite or cell body of a postsynaptic neuron. At synapse the end of the axon is referred to as synaptic knob, with a lot of synaptic vesicles in them that contain the neurotransmitters and mitochondria; hence the impulse is transmitted by the release of neurotransmitters. The neurotransmitters are of two types; excitatory neurotransmitters which stimulate the postsynaptic membrane for example: Glutamate, and inhibitory neurotransmitters which inhibit transmission of an impulse for example: Gamma Amino Butyric Acid (GABA)[15], [16], [17].

The action potential travels down the presynaptic axon towards the synapse. This activates the voltage gated calcium (Ca) channels, leading to calcium influx that triggers release of the neurotransmitter from the storage vesicles. The released neurotransmitter diffuses across the synaptic cleft, binds to the postsynaptic receptors and activates them, to cause a physiological response which may be excitatory or inhibitory.
7. Conclusions

Physics and Biology are intertwined, Erwin Schrödinger a quantum physicist, said that, “most of the biological phenomena’s observe the thermodynamic laws of nature” [18]. We thus observe that the signal transmission in a nerve cell can also be explained by the laws of diffusion of ions. Knowledge of the molecular structure of the ion channels explain the occurrence of various genetic disorders affecting nerve conduction particularly the cardiac disorders [19]. Therefore, importance of the nerve conduction study is that it aids to diagnosis of many of the medical conditions such as Carpel Tunnel Syndrome, Cubital Tunnel Syndrome, Guillaine Barre Syndrome, Peripheral Neuropathy, Peroneal Neuropathy, Spinal Disc Herniation, Tarsal Tunnel Syndrome, and Ulnar neuropathy [20], [21]. Further, it has been proved that role of physics is important in the management of various neurological disorders.

8. Future Prospects

This article is an effort to strengthen the understanding of relation between the principles of physics and neurobiology. Numerous efforts are being made in the field of Neurophysics. All these studies suggest that investigation and treatment of diseases such as; Alzheimer’s, Parkinsonism, Muscle atrophy, motor neuron disease etc… can be improved by further research in Neurophysics. The areas of further research can be as follows:

- Application of external electrical stimuli in the paralysed rats showed that the rats could walk and climb stairs. The same can be extended in the treatment of paralysed human beings [22].
- Wearable sensor network for health monitoring in Parkinsonism [24].
- Stem cell physics, multiple laser beam treatment of Parkinson disease [23].
- Use of complex realities of signal transduction in Alzheimer disease and in several nerve muscle conduction disorders [25].
- Understanding the organisation of brain matter in terms of sub-atomic particles (Quantum Mechanics) which may help increase the capacity of the brain matter in memory and cognition [25].
- Laser regenerative medicine for the treatment of neurological diseases [23].

At this moment it seems long way to go before the biophysics becomes a focused area of interdisciplinary research.

References

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Authors Profile

Raghottam M Sattigeri, a third year BSc (Hons) Physics student at The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat. Who has been scoring 8.6 CGPA. He has received two Criterion Recognition Awards from NASA for his literary work in 2013. He is interested in pursuing his research in the field of Solid State Physics and its applications to Biology, especially to Neuro-biology.