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Communication mechanism between living cells

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ABSTRACT

This article discusses the biology and physics of electrical system of living body that controls all body functions. Electrochemical potentials in the nerve cells are the source of billions of electrical signals, which propagate from all parts of body to the brain via neurotransmitters in the living body whose measurements allow obtaining useful clinical information. The propagation of electrical pulses in the living body is like transmission of pulses in a cable. The living cell membrane offers resistance and capacitance that form a complex net of electrical circuit. The ratio of space constant between cells to the time constant of neural resistance and capacitance define the speed of nerve impulses from one cell to other cell.

Key words: Neuron; nerve impulse; cell membrane; membrane potential; resistance.

INTRODUCTION

We experience and react accordingly when pricked by a thorn, any finger is cut or hit, an insect bites or moves on any part of the body and even on hair, any part of the body suffers any problem, bombardment of any kind of energy of sound, light, heat on the body, different tastes, danger, etc. We are not the only beings that feel but also do animals, birds, insects, etc. i.e. almost all living organisms experience any type of the disturbances that occur in their surrounding environment and react. Different parts of the organism sense the disturbances to react and then communicate the information to the brain to analyze them to take remedial measures. If there is no proper coordination between brain and specialized sensory receptors for the communication, serious problems occur.

Neurons, the basic building blocks of the nervous system, are the specialized cells, which possess the unique property of converting various forms of stimuli into electrical impulses for the communication of information in living organisms viz. human, animal, bird, insect, etc. They receive information from sense organs or from other adjacent neurons, carry them to the central nervous system CNS (brain and spinal cord), and bring motor information from the

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central nervous system to the motor organs (muscles and glands). Best scientific estimate is 86,000,000,000 neurons and each neuron is connected with nearly 10^5 other neurons, which gives nearly 10^{16} connections in the human nervous system. These neurons are spread all over the body of an organism like a net and provide different communication channels in the form of nerves fibers that have their two inherent properties of excitability to response to stimuli and the conduction of excitation in the form of nerve impulses.[1] They are of many types and vary considerably in shape, size, chemical composition, and function. Despite these differences, neurons consist of the three main parts *viz.* a) soma or cell body, b) an axon, and c) dendrites. Figure 1 shows the structure of a neuron. The soma or cell body is the main body of the nerve cell that contains the nucleus of the cell as well as other structures common to living cells of all types. The genetic material of the neuron is stored inside the nucleus and it becomes actively engaged during cell reproduction and protein synthesis. The soma also contains most of the cell fluid i.e. cytoplasm of the neuron. Dendrites are the branchlike specialized structures emanating from the soma. They are the receiving ends of a neuron. Their function is to receive the incoming neural impulses from adjacent neurons or directly from the sense organs. On dendrites, there are the specialized receptors, which become active when a signal arrives in electrochemical or biochemical form. The received signals are passed on to soma and then to axon so that the information is relayed to another neuron or to muscles. The axon conducts the information along its length, which can be several feet in the spinal cord and less than a millimeter in the brain. At the terminal point, the axon branches into small structures known as the terminal buttons. These buttons have the capability for transmitting information to another neuron, gland and muscles.

Neurons generally conduct information in one direction, that is, from the dendrites through soma and axon to the terminal buttons. The conduction of information from one place to another in the nervous system is done through projections of the nerves, which are bundles of axons. The longest axon in human is of diameter 10-20 μm and length ~1 m that extends from the brain to low in spinal cord or from spinal

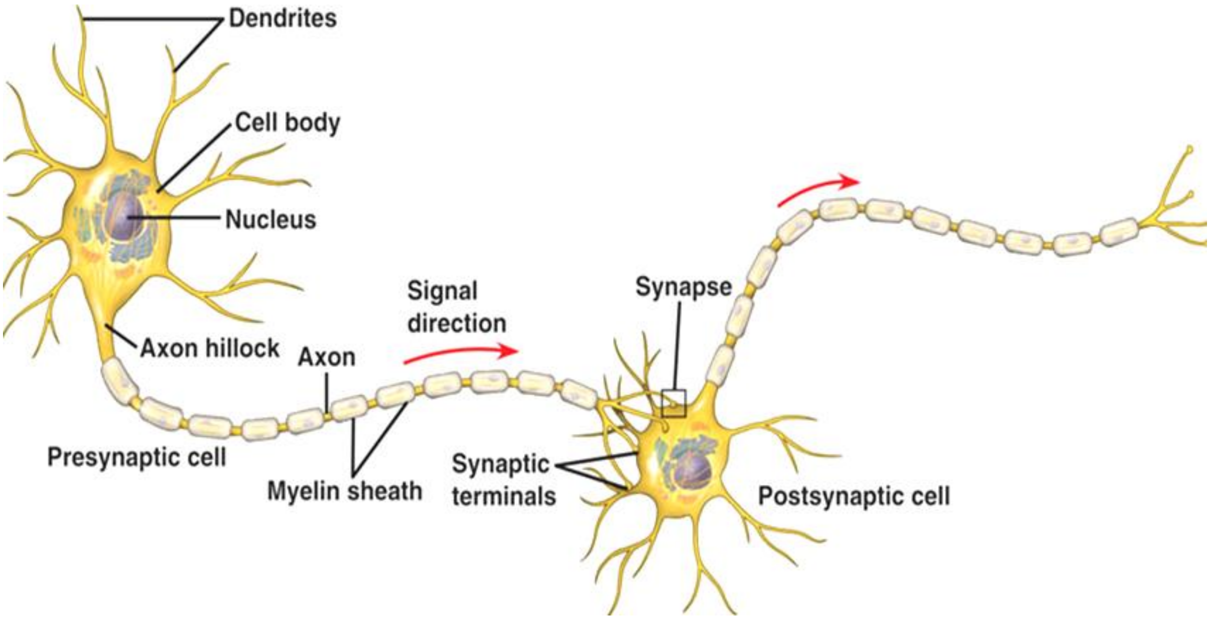


Figure 1. Neuron structure.

cord to fingers, etc. Neuron cells are mainly of two types: *sensory* and *motor*. Sensory nerves, also called afferent nerves, carry information from sense organs to central nervous system. On the other hand, motor nerves, also called efferent nerves, carry information from central nervous system to muscles or glands. A motor nerve conducts neural commands, which direct, control, and regulates our movements and other responses. There are some mixed nerves also, but sensory and motor fibers in these nerves are separate. Dendrites carry information towards the cell body, whereas axons carry information away from it. Thus, in a sense, neurons are one-way channels of communication. Information usually moves from dendrites or the cell body towards the axon and then outward along the structure of neuron. Fatty material, called myelin sheath, produced by glial cells within the nervous system covers each axon. Glial cells surround, support, and protect neurons. Each axon ends with axon terminals that contain neurotransmitters. A region of gap where the axon of one neuron approaches closely other neuron or the cell membrane of other types of cells such as muscle cells is usually termed as synapse. The axon tips of a preceding neuron do make direct connections but form synaptic cleft.

There are two types of communications i.e. communication within neurons and between neurons that take place in all organisms.

COMMUNICATION WITHIN NEURONS

Information travels within the nervous system in the form of a nerve impulse. When stimulus energy exposes the receptors, electrical changes in the nerve potential occurs. Nerve potential is a sudden change in the electrical potential of the surface of a neuron. When the stimulus energy is relatively weak, the electrical changes are so small that the nerve impulse is not generated, and we do not feel that stimulus. If the stimulus energy is relatively strong, electrical impulses are generated and conducted towards the central nervous system.[2] The strength of the nerve impulse, however, does not depend on the strength of the stimulus that caused the impulse. The nerve fibers work according to the all or none principle, which means that they either respond completely or do not respond at all. The strength of the nerve impulse remains constant along the nerve fiber.

Electrical potential of a neuronal membrane is due to chemical ions. Several types of ions e.g. Na^+ and K^+ exist in their different concentrations. A relaxed neuronal cell membrane, so called resting membrane, shows higher permeability for small Na^+ ions and poor permeability for large K^+ ions on one hand. While it behaves like a sodium pump on the other hand that actively pumps Na^+ ions out from cytoplasm to the ECF and transfers less K^+ ions in exchange from the ECF to the cytoplasm. These happen due to different diffusion rates depending on the concentration. There are other factors such as H^+ pumps, uniporters and cotransportes resulting in a higher cationic concentration outside than inside the cell membrane and thus, inner side of cell membrane becomes relatively electronegative to its outer side. As a result, cytoplasm of each cell acquires slight large negative charge inside relative to its outside extra cellular fluid that provides negative potential known as the resting membrane potential RMP of approximately -70mV across the cell membrane of a neuron at rest (Fig. 2). The state of resting membrane at RMP is the polarized state or readiness state of the cell membrane. The RMP undergoes a change under the effective stimulus termed as the action potential.[3] The Figure 3 shows a systematic diagram for the measurement of action potential.[4]

Various forms of physical energy including light, heat, sound, and smell bombard incessantly the organism body and specialized sensory receptors located in eyes, ears, nose, tongue, and skin sense them that change the action potential and thus, the physical energy is converted into electrical signals i.e. neural impulses. Only that physical energy, which is equal or greater than the threshold energy i.e. minimum energy changes into action potential and then converts into the neural impulses. The

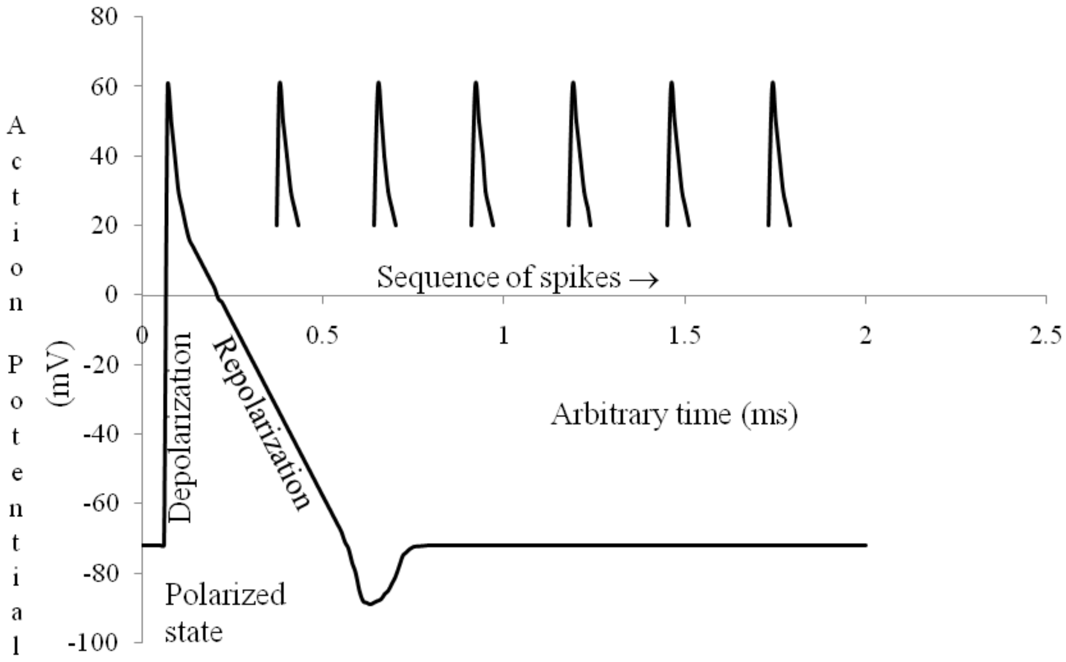
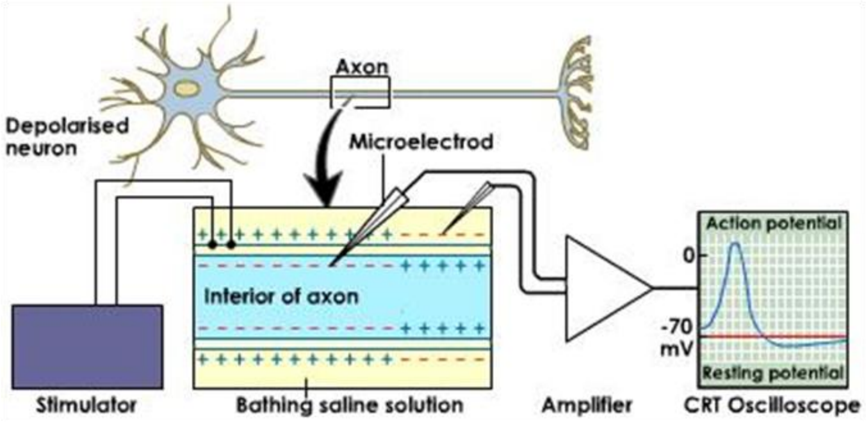


Figure 2. Spikes potential formation

Figure 3. Measurement of action potential.



brain receives these neural impulses via nerves and thus, an organism collects various information signals from its different specialized sensory receptors.

Another basic category of signals within neurons, called graded potentials, results from the external stimulus of the dendrite or cell body. Unlike the all-or-nothing nature of the action potential, the magnitude of a graded potential varies in proportion to the size of the stimulus that produced it. Thus, a loud sound produces a graded potential of greater magnitude than a softer sound. Because graded potentials weaken quickly, they function primarily to convey in coming information over distances, usually along the dendrite towards the neuron's cell body.

Though the nervous system expends a great deal of energy to maintain this state of readiness yet leaks a little under the minimum strength of

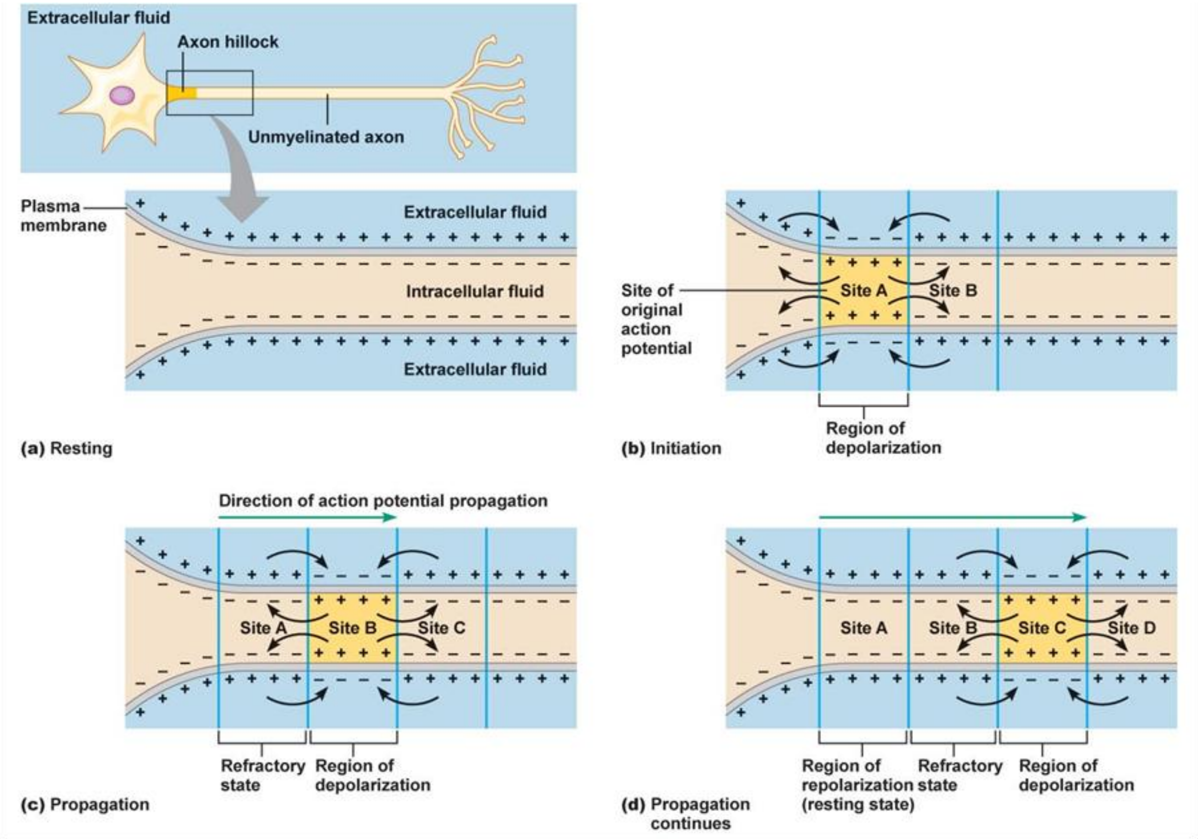


Figure 4. Formation of spikes and their propagation through neurons.

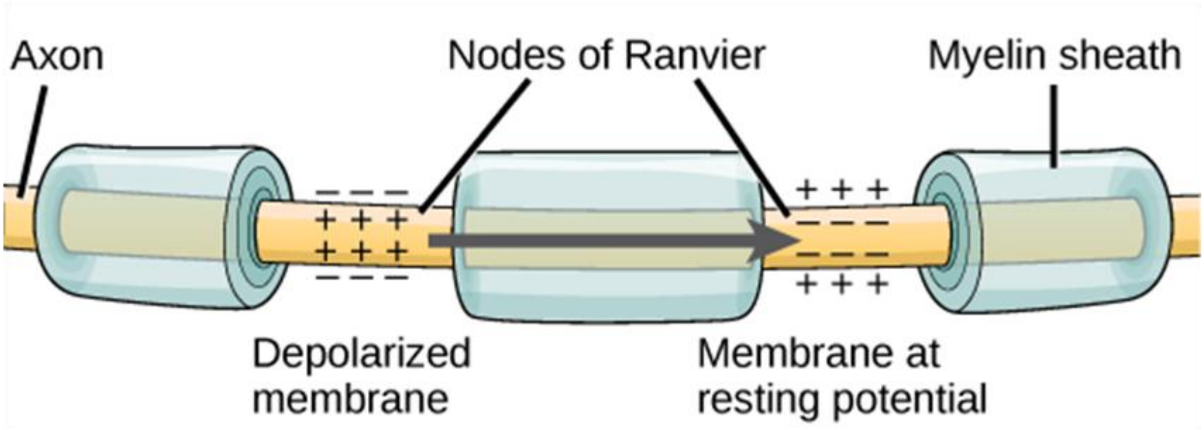


Figure 5. Transmission of action potential from one node of ranvier to other.

stimulus known as the threshold stimulus allowing some charged particles to slip in and other to slip out as these cell membranes are not a perfect barriers.[5] When an effective external stimulus or another neuron stimulates a neuron, positively charged particles enter the membrane through specialized ions channels, thereby shortly eliminating the negative charge just inside the neurons membrane that results the fluctuation in the electrical charges from negative to positive called depolarized state (Fig. 4b) and back again along the cell membrane through repolarization (Fig. 4d). The nerve fiber does not respond at all to the stimulus less than the threshold stimulus and responds a maximum action potential irrespective of the strength of stimulus greater than the threshold stimulus. This is all-or-nothing principle of the action potential.

After a short period of about 1-2 ms, positively charged particles actively pumped back out side of the neuron's membrane via the ions channels. Because of this active process, the inner membrane of a neuron regains its negative charge to maintain potential of -70 mV relative to the outside and thus the cell is again ready to fire once more. Actually, the membrane potential first rises sharply from about -55 mV to 50 mv under effective stimulus and almost immediately declines sharply to 20 mV (Fig. 2). These changes produce a spikes-like record known as the spike potential. The spike first follows a slower decline in the potential (negative after potential) and then by a potential more negative than the resting potential (positive after potential). The potential then gradually returns to the resting potential. These change in the electrical disturbance in spikes' along cell membrane, serve as the basis for the communication in nervous system, travel along the nerve fibers in the form of neural impulses. The speed of neural impulses varies from 30 to 150 ms^{-1} (in human 0.6-120 ms^{-1}) that depends not only on myelination but also on the fiber's diameter and the ions conduction. The impulses travel slower in thinner fibers than in thicker one.

Vertebrates like squids possessing unmyelinated fibers, possess very thick fibers for conducting impulses rapidly to their distant long arms. In unmyelinated fibers, these ionic change repeat over the membrane all along the length of the fibers. Therefore, the action potential propagates all along the membrane over the entire length of the fiber. However, in myelinated fiber, the action potential jumps from one free space between the consecutive myelin sheaths so called as node of Ranvier to the next due to ionic conduction of nerve impulses (Fig. 5). This is the reason, nerve impulses conduct far more rapidly in myelinated fibers than in unmyelinated ones.[6]

CAPACITANCE OF CELL MEMBRANE

The conduction of neural impulses in living cells depends mainly on the conductivity of the membrane of the axon because the neurons operate mainly on the potential difference caused by ionic concentration difference between interior and exterior sides of membrane. Let V_i and V_o are the interior and exterior potentials of membrane, then, in accordance with the Nernst equation, the ionic concentration ratio in equilibrium is

$$\frac{C_i}{C_o} = e^{-ze(V_i - V_o)/kT}$$

$$\frac{C_i}{C_o} = 13.7; \mathit{For} + \mathit{ve\ ions}$$

$$\frac{C_i}{C_o} = 0.073; \mathit{For} - \mathit{ve\ ions}$$

where z is the valence of ions, $e = 1.6\text{x}10^{-19}$ C is electronic charge, $k = 1.38\text{x}10^{-23}\,JK^{-1}$ is the Boltzmann constant, T is the absolute temperature, C_i and C_o are the interior and exterior concentrations, respectively.

The thickness of cell membrane uncovered with myelin is x ~ 5-6 nm and covered with myelin it is ~ 2 µm. The strength of electric field E in the cell membrane under potential difference $\Delta V = V_i - V_o$ along the interior of the axon due to depolarization is

$$E = -\frac{\Delta V}{\Delta x} \approx \frac{72mV}{6nm} \approx 12MVm^{-1}$$

The accumulation of electric charge over the surface S of the cell membrane is

$$Q = C_m \Delta V = \varepsilon_0 KSE$$

where $K \approx 7$ is the dielectric constant and C_m is the neural capacitance of the cell membrane. The extracellular and intercellular fluids are the two conducting fluids surrounding the insulator membrane make the axon membrane as cylindrical capacitor as shown in Figure 6.

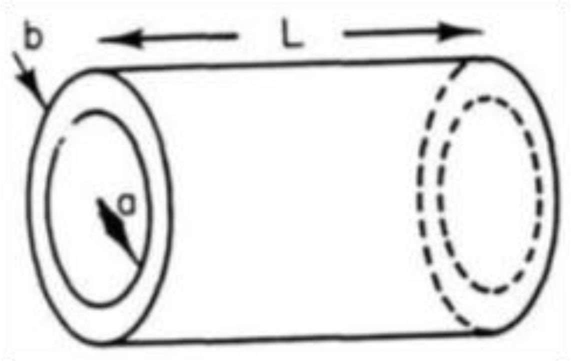


Figure 6. A cylindrical neural capacitance of thickness *b*, radius *a* and length *L*.

The neural capacitance of cell membrane of thickness *b* is

$$C_m = \frac{Q}{\Delta V} = \frac{\varepsilon_0 KSE}{\Delta V} = \frac{\varepsilon_0 KSE}{Eb} = \frac{\varepsilon_0 KS}{b}$$

Therefore, neural capacitance per unit surface area of the cell membrane is

$$\frac{C_m}{S} = \frac{\varepsilon_0 K}{b} \approx 0.01Fm^{-2}$$

The surface charge density of the cell membrane is now given as

$$\sigma_m = \frac{Q}{S} = \varepsilon_0 KE \approx 700\mu Cm^{-2}$$

For myelinated fiber, the thickness of membrane is much larger which reduces the neural capacitance per unit area by a factor of nearly 300.

LEAKAGE OF ELECTRIC CHARGE ACROSS CELL MEMBRANE

The cell membrane is not a perfect insulator and hence the electric charge will leak across the membrane as it offers a resistance equal to

$$r_m = \frac{\rho_m b}{S}$$

is the electrical resistivity of the cell membrane material.

Neural capacitance and resistance are in parallel to each other as in Figure 7.

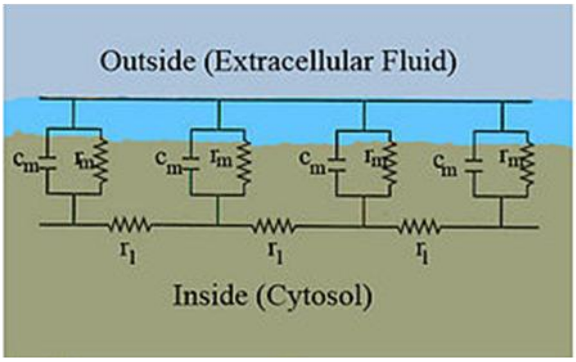


Figure 7. Each unit of parallel couple of membrane capacitance and resistance are in series with interior resistance.

Therefore, the leakage of current through the neural resistance discharges the neural capacitance. Now, we have

$$\frac{dQ}{dt} = \frac{dC_m V}{dt} = -i_m = -\frac{V}{r_m}$$

$$\therefore \frac{dV}{V} = -\frac{dt}{r_m C_m}$$

Integration operation on both sides results to

$$V = V_0 e^{-t/\tau}$$

where time constant

$$\tau = r_m C_m = \varepsilon_0 K \rho_m \approx 10^{-3} s$$

The resistance and the capacitance of the portion of axon membrane in terms of the axon radius a and length L using $S = 2\pi aL$ is

$$r_m = \frac{\rho_m b}{2\pi aL}$$

$$C_m = \frac{2\pi\varepsilon_0 KaL}{b}$$

Clearly, the resistance of the axon decreases with increases in length while its capacitance increases with increasing length.

RESISTANCE ALONG THE AXON

The interior fluid resists the current flowing through it. The resistivity ρ_i of fluid, the radius a and the length L of the axon determine the resistance as below:

$$R_i = \rho_i \frac{L}{\pi a^2}$$

The axoplasma resistivity is $\rho_i \approx 0.5\ \Omega m$. The longitudinal internal resistance per unit length is

$$r_l = \frac{R_i}{L} = \frac{\rho_i}{\pi a^2}$$

PULSE PROPAGATION THROUGH AXON MEMBRANE

When a section of membrane is excited by electrical current or external current or external stimulus, the membrane permeability changes, ion exchange takes place across the membrane causing a rapid change in potential according to Nernst equation. This changes the polarity because positively charged ions enter the interior of the axon. The time constant determines the polarization time scale. Because of the potential difference along the outer surface of the axon, electrical currents are induced in the internal conductive fluids. Therefore, the depolarization moves along the axon and application of Kirchhoff's law for current conditions in the axon describe the process of movement.

Current across the membrane

$$i_m = \frac{dQ}{dt} = C_m \frac{dV_m}{dt}$$

Current along the inside of the axon

$$i_i = \frac{\Delta V}{R_i} = \frac{dV}{r_l dx}$$

In accordance with the Kirchhoff's current law KCL, the total out going currents is equal to total incoming currents (Fig. 8) i.e.

$$i_i(x) - i_i(x + \delta x) - i_m = \Delta i_i - i_m = C_m \frac{dV}{dt}$$

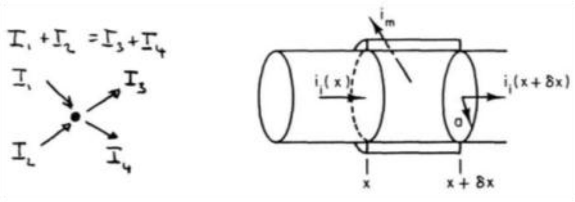


Figure 8. Kirchhoff's current law is algebraic sum of all current at a junction is zero.

Dividing both sides by elemental surface area $dS = 2\pi a dx$ results to

$$\frac{C_m}{\Delta S}\frac{dV}{dt} = -\frac{i_m}{\Delta S} + \frac{1}{2\pi a r_l}\frac{d^2V}{dx^2}$$

which describes the propagation of a pulse along a conductive material.

The change of potential with time is a function of the leakage current through the surface of the membrane and the change of voltage along the axis. The neural capacitance C_m and resistance r_m, and internal resistance r_i determine the speed of the neural impulses. As larger the capacitance, as longer the time constant it takes the cell membrane to discharge, therefore, a slower propagation speed of the neural impulses. Similarly, as larger the internal resistance, as smaller the axial current i_i is. However, the resistance is in inverse to the axon radius i.e. as larger the radius, as faster the propagation velocity of the neural impulses.

The cable equation can be reformulated as

$$\frac{dV}{dt} = -\frac{i_m}{C_m} + \frac{\Delta S}{2\pi a}\frac{1}{r_l C_m}\frac{d^2V}{dx^2}$$

with $\frac{C_m}{\Delta S} = \frac{K\varepsilon_0}{b}$, $r_l = \frac{\rho_i}{\pi a^2}$, $i_m = \frac{\Delta V}{r_m}$,

and $\Delta V = V_{peak} - V_{rest} \approx 70mV$

$$\therefore \frac{dV}{dt} = \frac{\Delta V}{\tau} + \frac{ba}{2\rho_i K\varepsilon_0}\frac{d^2V}{dx^2}$$

Multiplying with the time constant $\tau = K\varepsilon_0\rho_m$ yields to

$$\frac{dV}{dt} = \Delta V + \frac{\tau ba}{2\rho_i K\varepsilon_0}\frac{d^2V}{dx^2} = \Delta V + \frac{ba}{2}\frac{\rho_m}{\rho_i}\frac{d^2V}{dx^2}$$

Introducing the space constant

$$\lambda = \sqrt{\frac{\rho_m}{\rho_i}\frac{ba}{2}}$$

which is the node of Ranvier and using the time constant τ results to the final formulation for the motion of the signal along the axon with time as

$$\Delta V = \lambda^2\frac{d^2V}{dx^2} - \tau\frac{dV}{dt}$$

For an unmyelinated axon of $a = 2.5\ \mu m$ and $b = 6\ nm$, and a myelinated axon of $a = 2.5\ \mu m$ and $b = 2\ \mu m$, the space constants are λ_{um} = 0.49 *mm* and λ_{um} =8.9 *mm*, respectively along with time constant τ = 1 *ms*.

The speed of impulse *v* in an axon fiber can be determined as the ratio of space constant to the time constant i.e.

$$v = \frac{\lambda}{\tau} = \frac{1}{\varepsilon_0 K}\sqrt{\frac{ba}{2\rho_i\rho_m}}$$

The signal speed in unmyelinated axon fiber with b = 6 *nm* is $v = 313\sqrt{a}ms^{-1}$. Clearly, the neural impulse speed increases linearly with square root of the radius (Fig. 9). There are severe limitations as the radius of unmyelinated human fiber axons are typically smaller than $1\mu m$.

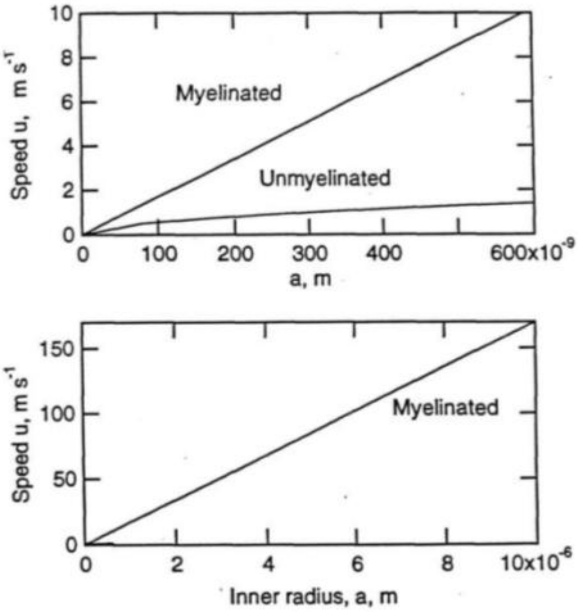


Figure 9. Speed versus radius graph for myelinated and unmyelinated neural fibers. The impulse speed increases linearly with axon radius *a*.

For a myelinated axon fiber, there is a fixed relation between the radius *a* of the axon and the thickness *b* of the myelin layer i.e. $b = \approx 0.4a$. This simplifies the expression for the space constant λ. Thus,

$$\lambda = a\sqrt{0.2\frac{\rho_m}{\rho_i}} = a\sqrt{0.2\frac{1.6\times10^7}{0.5}} \approx 2530a$$

This yields for the speed of the impulse signals in a myelinated axon as:

$$v = \frac{\lambda}{\tau} = \frac{2530a}{\varepsilon_0 K\rho_m} = 2.6\times10^6\,ams^{-1}$$

Thus, living cells communicate with finite speed to the brain via electrical systems of nerves.

CONCLUSION

Complex nets of nerves are like an electrical system in the living body through which living cells communicate the information to the brain via neural impulses. The transmission of electrical pulses into neuronal sensors and motor nerve system create electric potential difference whose measurements are the clinical tool to understand the human body functions e.g. electrocardiogram ECG for heart function, electroencephalogram EEG for brain function, electromyogram EMG for muscles activity, etc.

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