

## CHAPTER 10 THE BIOELECTRIC CELL

### A. The Nature of Bioelectricity

**B**ioelectricity is fundamental to all of life's processes. Indeed, placing electrodes on the human body, or on any living thing, and connecting them to a sensitive voltmeter will show an assortment of both steady and time-varying electric potentials depending on where the electrodes are placed. These biopotentials result from complex biochemical processes, and their study is known as *electrophysiology*. We can derive much information about the function, health, and well-being of living things by the study of these potentials. To do this effectively, we need to understand how bioelectricity is generated, propagated, and optimally measured. Bioelectricity is a cellular phenomenon. Every living cell has a membrane potential (of about  $-70\text{mV}$ ), with the inside of the cell being negative relative to its external surface. The cell membrane potential is strongly linked to the cell membrane transport mechanisms in that much of the material that passes across the membrane is ionic (charged particles), thus if the movement of charged particles changes, then it will influence the membrane potential. Conversely, if the membrane potential changes, it will influence the movement of ions.

Although the fluid inside and outside cells is essentially neutral, there is a difference in ion concentration that produces electric potential at cell boundaries. The cells which generate an electric potential create a thin layer of negative charge on the surface of the boundary and a thin layer of positive charge on the outer surface of the membrane is the boundary. (see Figure 10.1).

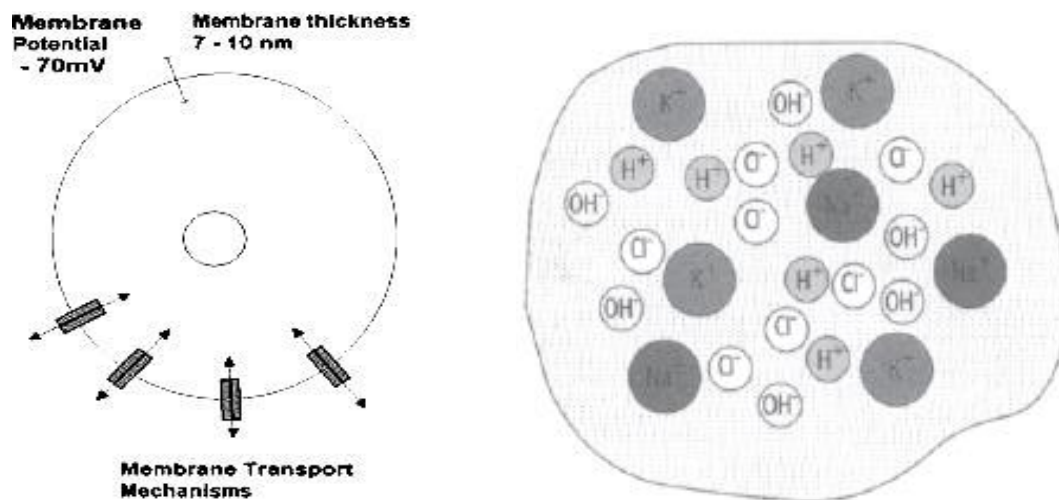


Figure 10.1. All living things have a net electroneutrality, meaning that they contain equal numbers of positive and negatively charged ions within their biological fluids and structure.

The most fundamental bioelectric processes of life occur at the level of membranes. In living things, there are many processes that create segregation of charge and so produce electric fields within cells and tissues. Bioelectric events start when cells expend metabolic energy to actively transport sodium outside the cell and potassium inside the cell. The movement of sodium, potassium, chloride, and, to a lesser extent, calcium and

magnesium ions occurs through the functionality of molecular pumps and selective channels within the cell membrane.

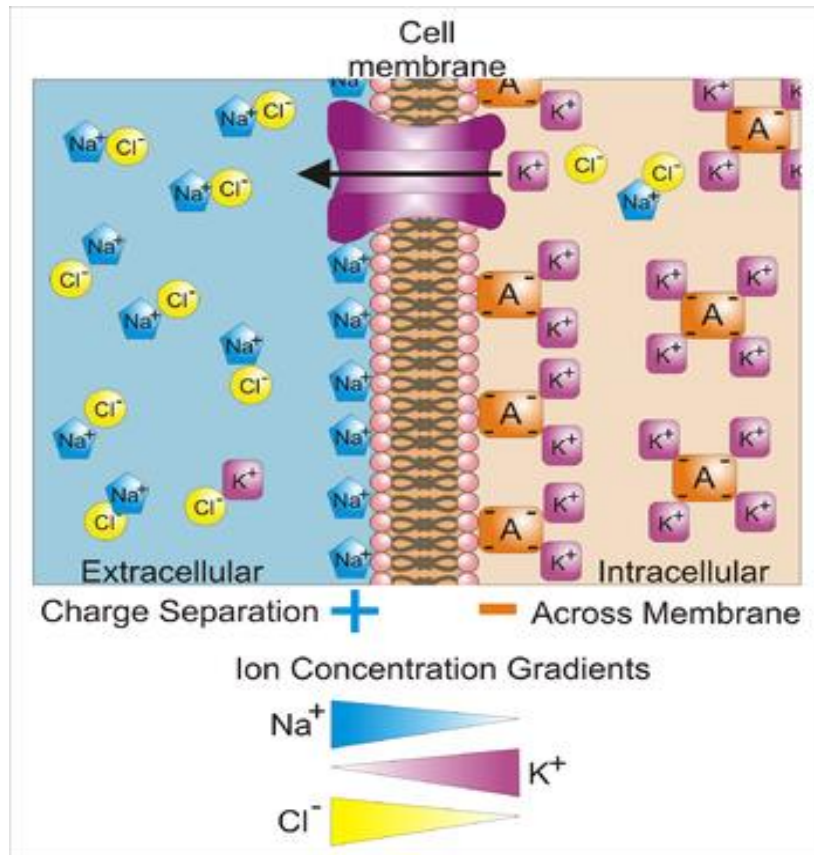


Figure 10.2. The concentrations of ions outside and inside the cell. Positive ion concentrations digrafikkan above the line and negative ion concentrations digrafikkan below the line to help describe that fluids are electrically neutral. The membrane is permeable to ions  $\text{K}^+$  and  $\text{Cl}^-$  ions, which diffuses in the opposite direction as shown. Short arrows indicate that the Coulomb force continuously inhibit the diffusion of  $\text{K}^+$  ions and  $\text{Cl}^-$  ions. If the membrane becomes permeable to  $\text{Na}^+$  ions, the diffusion gradient and Coulomb forces work to drive  $\text{Na}^+$  into the cell.

There are many ions in the cells inside and outside fluid. Ions are important in creating the cell potentials are ions  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Cl}^-$ . There is a big difference in the concentration of these ions inside and outside the cells, as shown in Figure 10.2 (a). Negative ions other than  $\text{Cl}^-$  indicated by  $\text{A}^-$ . Note that the total charge inside and outside is zero, thereby, the fluids that are electrically neutral.

To see how the cell potential is formed, consider what happens in the example of the cell membrane initially neutral and have different concentrations as shown in Figure 10.2 The cell membrane is normally impermeable to  $\text{K}^+$  and  $\text{Cl}^-$  ions; membrane was approximately 100 times less permeable to  $\text{Na}^+$  and highly impermeable to other ions. Only  $\text{K}^+$  and  $\text{Cl}^-$  which diffuses through the cell membrane in goodly numbers. Net diffusion direction is from the area of high concentration to areas of low concentration.

Therefore, the ions  $K^+$  and  $Cl^-$  ions diffuse in the opposite direction, as shown in Figure 10.2 (b). Ions  $K^+$  and  $Cl^-$  ions have opposite charge, then there is a very strong Coulomb attractive force between the ions that cause the ions to form two thin layers of charge right at the side of the cell membrane, as shown in Figure 10.2.

Diffusion of  $K^+$  and  $Cl^-$  continues until the attractive force and repulsive Coulomb stop. During the charge layers are formed on the cell membrane, increasing the Coulomb forces. Tensile similar charges not work to attract ions of  $K^+$  and  $Cl^-$  back into its regions with high concentration. Furthermore, the repulsive force similar charges work to maintain the ions in order not to leave the area with a high concentration. An equilibrium is quickly reached between the diffusion of high concentration to low concentration and Coulomb forces opposite. As soon as this equilibrium is reached, the cells are in a resting state (resting state). If more of the ions  $K^+$  and  $Cl^-$  diffuse through the cell membrane, increasing Coulomb forces and some ions move back. Net displacement is zero so that the equilibrium is stable. Coulomb force is very strong, and only about 1 out of 100,000 ions  $K^+$  and  $Cl^-$  move through the membrane. This is such a small part that does not change the overall concentration of ions. After all the fluid inside and outside the cell remains essentially neutral although some have a separate charge. However, the small charge separation is very important, because it is a source separation Bioelectricity . Potential in the cells of 70-90 mV lower than the potential outside the cell, approximately 90 mV in the nerve cells and muscle. Potential outside the cell is usually taken 0 V, resulting in the nerve cells and muscle has a resting potential of approximately -90 mV.

Equilibrium between the concentration gradient and the Coulomb force is also an energy equilibrium. Proper equilibrium electric potential energy with the potential energy due to the concentration difference is, the ability to conduct business concentration gradient by moving ions against electric potential. Energy balance equation that describes this is the Nernst equation. Nernst equation gives the voltage that will be created by the difference in concentration, but this equation only for a membrane that is permeable to a single type of ion perfect and perfect is not permeable to all other ions. In this environment the Nernst equation is

$$V = V_{in} - V_{out} = -2,30 \frac{kT}{Ze} (\log C_{in} - \log C_{out}) \quad \dots (10.1)$$

where  $V$  is the potential difference (inside minus outside),  $C_{in}$  and  $C_{out}$  are the concentrations of ions to which the membrane is permeable,  $k$  is Boltzmann's constant,  $T$  is the absolute temperature, and  $Ze$  is the charge on the ion multiplied by the electron charge ( $Z$  is valence ions). The minus sign indicates that the excess positive ions can diffuse in the fluid inside the cell produces a negative voltage in the cell. The most important aspect is that the Nernst equation potential difference is proportional to the concentration difference.

Using concentrations are given in Figure 10.2 (a), we can calculate how much potential that will be created by each type of membrane permeable to ions if the ion itself. For  $Na^+$  the result is a potential in the +109 mV. Since the actual potential in the nerve approximately -90 mV, indicating that the membrane is not very permeable to  $Na^+$ . For  $K^+$  and  $Cl^-$  respectively the result is -88 mV and -70 mV. These results approach the actual

values in many types, but it need not imply that the membrane is permeable to  $K^+$  and  $Cl^-$ . This only implies that if the membrane is permeable to  $K^+$  and  $Cl^-$ , there is a slight movement under resting conditions.

The structure and characteristics of the membrane are topics of research interest. Many things are not yet understood, but it can be stated that the resting potential is definitely a big influence membrane structure and characteristics. Although only 90 mV resting potential, it is at ptensial membranes which have an average thickness of 8 nm. So the voltage per meter is very large, on the order of 11 MV per meter. Voltage per meter is so big it can straighten molecules and have an influence on the pore and membrane permeability. For example, if the potential at the membrane, the membrane permeability change drastically, suddenly becomes about 1000 times more permeable to  $Na^+$  than the existing ones. No one knows exactly why the permeability change, but one reason is the potential effect on the membrane structure. Nature has to find a way to use such permeability changes to continue Bioelectricity signals.

### Example 10.1:

Calculate the potential of the membrane to  $K^+$  ions at a temperature of 310 K, if the concentration of  $K^+$  ions inside the cell is 140 mol/m<sup>3</sup> and outside the cell is 10 mol/m<sup>3</sup>. Boltzmaan constant  $k = 1.38 \times 10^{-23} \text{ J / K}$ .  $K^+$  ion charge is  $e = 1.60 \times 10^{-19} \text{ C}$ .

### Completion:

We use equation (10.1) with  $z = 1$ , in order to obtain

$$V = V_{in} - V_{out} = -2,30 \frac{kT}{Ze} (\log C_{in} - \log C_{out})$$

$$V = -2,30 \frac{(1,38 \times 10^{-23} \text{ J/K})(310 \text{ K})}{(1)(1,60 \times 10^{-19} \text{ C})} (\log 140 \text{ mol/m}^3 - \log 5 \text{ mol/m}^3)$$

$$V = (-614,9625 \times 10^{-4})(1,447158032) \text{ volt}$$

$$V = -88,9947921 \times 10^{-3} \text{ volt}$$

$$V = -89 \text{ mV.}$$

## B. Neural System

The use of electrical phenomenon in most living organisms found in animal nervous system. Nerve cells are also called neurons form a complex network in the body that receive, process and forward information from one part of the body to other body parts. Center is located in the brain tissue, which has the ability to store and analyze information. Based on this information the nervous system controls various body parts. The nervous

system is very complex. For example, the human nervous system consists of about 1010 neurons that are connected. Therefore, it is not surprising that the overall function is still little understood, although the nervous system has been studied for hundreds of years. It is not known how the information is stored and processed by the nervous system; are also unknown how neurons grow into certain patterns to the function. However, some aspects of the nervous system is now well recognized. In particular, over 40 years ago, methods of propagation of nerve through the nervous system have been established firmly. The messages are electrical impulses transmitted by neurons. When a neuron receives an appropriate stimulus neurons that generate electrical pulses that propagated along the cable-like structure. Pulses was large and its duration is constant, not depending on the intensity of stimulation. The strength of the stimulus is carried by a number of pulses generated. When the pulses reach the end of the " wiring, " pulses that activate neurons or other muscle cells.

## 1. Neurons

Neurons, which is the basic unit of the nervous system, can be divided into three groups: sensory neurons (sensory), motor neurons, and interneurons (neurons connecting). Sensory neurons receive sensory stimuli from the external environment and internal monitoring body. Depending on the particular function, sensory neurons carry messages about such factors of heat, light, pressure, muscle tension, and smell to the centers of higher nervous system for processing. Motor neurons carry messages that control muscle cells. These messages are based on information provided by the sensory neurons and central nervous system located in the brain. Connecting neuron passing information between neurons.

When neurons rise, neurons that transmit signals consisting of electric Bio temporary reversal of the membrane potential of neurons. Reversal potential originated from a localized area of the neuron and propagate along the membrane to the other locations. Reversal potential is called depolarization. Potential cells immediately return to a state of normal or negative polarity at the break with a positive and beyond. Back to the resting state is called repolarization.

Each neuron consists of a cell body which is where the nerve endings input (called dendrites) attached and a long tail (called axons) that propagate signals from the neuron cell body. Dendrites carry signals from the sensor into the body 's cells. Consider Figure 10.3. Axons or nerve fibers carry signals or Bioelectricity impulses from the nerve cell body to the muscles, glands, or other neurons. Several types of stimuli can trigger neurons continue to rise and nerve impulses to some other place. The types of stimuli that include changes in pressure, temperature changes, electrical signals from other neurons, the electrical currents from the outside, and chemical substances transmitted through the connection between the neurons (called synapses)

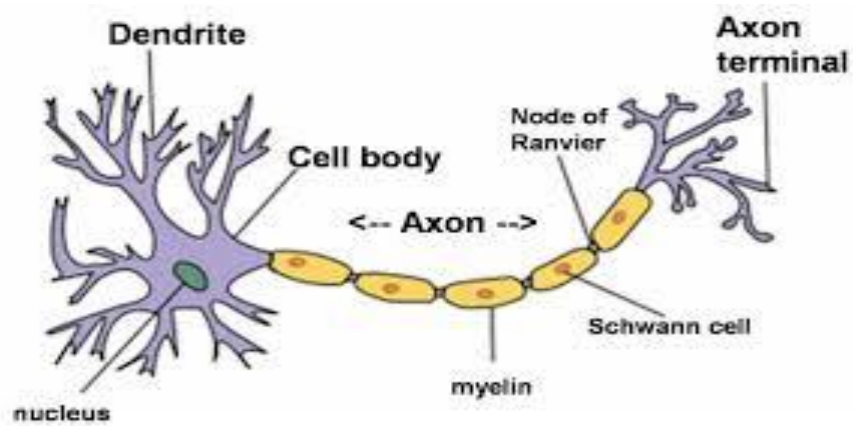


Figure 10.3. Neurons (user.tamuk.edu).

A sensory-motor neuron circuit shown in Figure 10.4 is simple. A stimulation of the muscle generates nerve impulses spread to the spine. Here the signal is transmitted to the motor neurons, which in turn send impulses to the muscle control. Most of the nerve relationship is much more complicated.

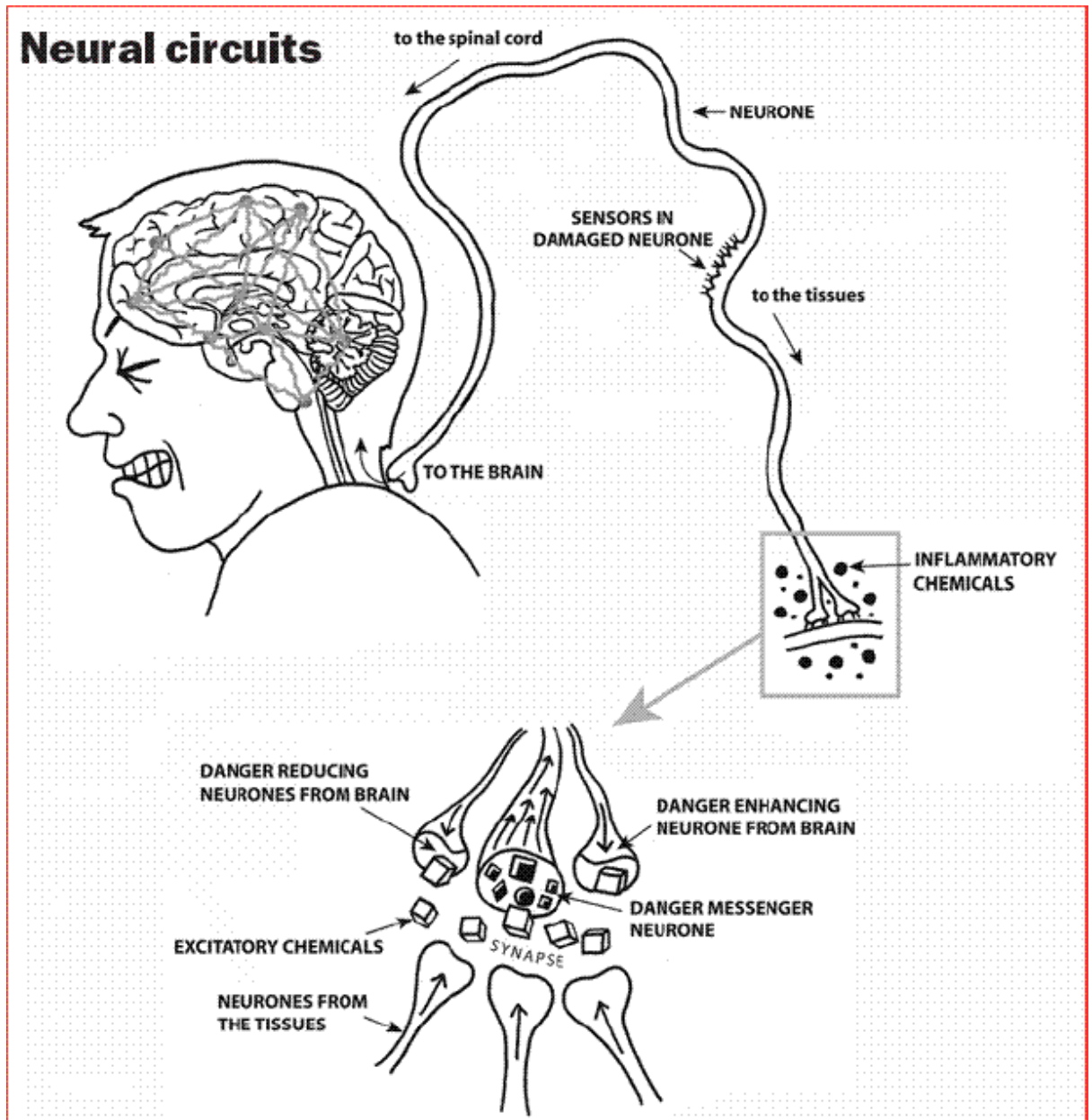


Figure 10.4. Simple neural circuit

Axon, which is an extension of neuronal cells, delivering electrical impulses from the cell body. Some really long axons. For example, in people, axons that connect the spine and the fingers and toes of more than one meter panjangnya. Some axons are wrapped with jointed sheath of a fatty substance called myelin. The sections approximately 2 mm in length, separated by gaps called nodes of Ranvier. The myelin sheath increases the rate of pulse propagation along the axon. Although each axon propagate their signals itself independently, often many axons that share common trajectory in the body. These axons are usually grouped into a nerve bundle.

The ability of neurons to forward messages caused by the electrical characteristics of the particular axon. Most of the data on the electrical properties and

chemical axon obtained by inserting a needle-like instrument investigation into the axon. By means of such an inquiry it is possible to measure the currents flowing in the axons and to take samples of their chemical composition. Such experiments are usually difficult because most of the axon diameter is very small. Even the largest axons in the human nervous system has a diameter of only about 20  $\mu\text{m}$ . However, the squid has a very large axons with a diameter of approximately 1000  $\mu\text{m}$  (= 0.10 mm) is large enough to include such an investigation tool.

## 2. Electric Potential in The Axon and The Action Potential

In the aqueous environment of the body, salt and various molecules dissociate into ions of positive and negative. As a result, the body fluid is a good conductor of electricity. Neural processing of nerve signals propagate up and can be understood by taking into account two factors, namely diffusion through a semipermeable membrane and the Coulomb force, as our earlier discussion. Furthermore, active transport processes must be included to maintain the cell potential in a long period of time.

When a nerve stimulation causes the rise, stimuli that increase cell membrane permeability to  $\text{Na}^+$ . Cell membrane to approximately 1000 times more permeable to  $\text{Na}^+$  than the normal state, making it approximately 10 times more permeable to  $\text{Na}^+$  than  $\text{K}^+$ . Because of differences in the concentration of  $\text{Na}^+$  is large, rapid diffusion of  $\text{Na}^+$  ions into the cell occurs. The influx of  $\text{Na}^+$  makes the cell interior positive rather than negative. Potential inside the cell resting potential increased from -90 mV to about +40 mV. This is the depolarization which is the first stage in the overall process. This is shown in Figure 10.5 (a). Dipole layer on the membrane essentially been reversed, but only a small fraction of the ions need to move to a potential reverse.

The reversal potential on the cell membrane (depolarization) apparently alters the structure such that the two membrane permeability changes occur. First, the permeability to  $\text{Na}^+$  returned to normal (very small), and second, the  $\text{K}^+$  permeability increases by a factor of 30 while. The first change is to desist from further entry of  $\text{Na}^+$ , and the second change allows the diffusion of  $\text{K}^+$  out quickly. So the membrane potential back to its normal resting value; thus, the membrane was repolarisasi. Dipole layer has been set back only by a small net loss in the concentration gradient that drives the system. Finally, the  $\text{K}^+$  permeability returned to normal, which is the end of the process. These events are depicted in Figure 10.5 (a), and the graph membrane permeability to  $\text{Na}^+$  and  $\text{K}^+$  as a function of time is shown in Figure 10.5 (b).

Cell potential changes from negative to positive and back again during depolarization- repolarization equal to a voltage pulse. This is a voltage pulse and the nerve impulse called an action potential. In Figure 10.5 (a) a nerve action potential digambarkan. Action potentials can occur in most animal cells, but it has some of the action potential of the most important influences in the nerve cells and muscle. Neurons can forward to another action potential, creating a variety of responses. In muscle cells causes contraction of muscle action potentials. As in neurons, the action potential in muscle cells may originate within the cell itself or diimbaskan by outside sources.



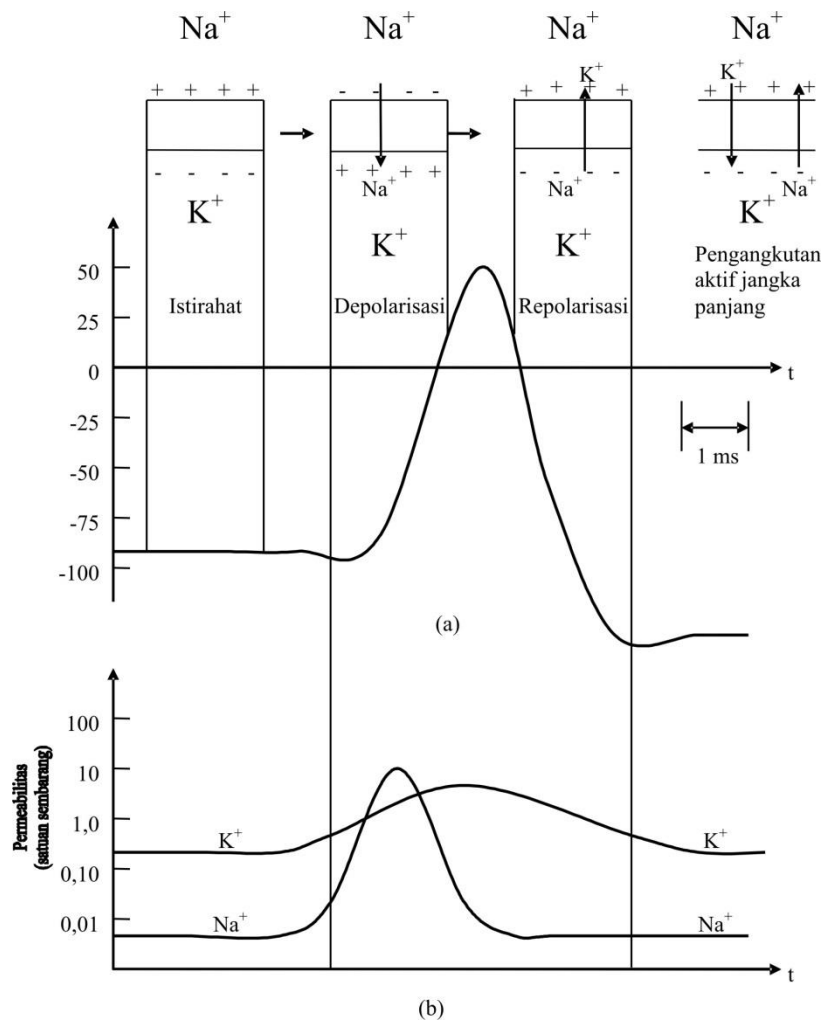


Figure 10.5. (a) The action potential in a particular place on a nerve. The voltage in the neurons was described as a function of time. Rapid movement of ions occurs only during depolarization- repolarization. Active transport is used for the long term to maintain the concentration gradient. (b) Changes in membrane permeability associated during the action potential. Note the logarithmic scale for permeability.

Every time there is a cell rise in net loss of ions  $Na^+$  and  $K^+$  from each of the high concentration region. It should be noted that the amount of ions through the cell membrane for the generation of a very small part of the existing ions. Remember that only one out of 100,000 ions  $Na^+$  and  $K^+$  are necessary to create resting potential, and similar small part of the existing ions move through the cell membrane during generation. So the nerves rise rapidly and repeated hundreds of times before the concentration of  $Na^+$  and  $K^+$  quite emptied.

During the long period of time these cells have to get a way to move out of the interior  $Na^+$  and  $K^+$  back into the interior to maintain the concentration difference creates a potential resting potential and encourage action. To do this it must utilize active transport for the active transport of  $Na^+$  and was moving against the concentration gradient of  $K^+$  and  $Na^+$  against the Coulomb force. Trace studies have shown that the cells move out of the  $Na^+$  ions for every  $K^+$  ion-driven entry.

Therefore, active transport is done is called the sodium- potassium pump. Active transport requires energy and a part that can be measured from a cell metabolism is provided to maintain the resting potential and push the action potential. Active transport is not necessary to maintain the concentration gradient of  $\text{Cl}^-$  in neurons. Neuron membrane is highly permeable to  $\text{Cl}^-$  and Coulomb forces move back and forth through the membrane during depolarization- repolarization. Hence the influx of  $\text{Cl}^-$  is smaller when the interior becomes positive during depolarization and outflow of  $\text{Cl}^-$  similar when the interior back to negative.

Description of the action potential and the graph in Figure 10.10 tells what happened at a particular place on a cell membrane. How can this potential be forwarded to another place? The answer is that the pressure changes during depolarization of an area sufficient to alter the permeability and therefore mendepolarisasikan adjacent areas of the cell membrane. So depolarization-repolarization process in Figure 10.5 is stimulated in the adjacent cell membrane shortly after starting at a point. Adjacent regions is further stimulate additional cell membranes further, and action potential propagated along the cell membrane as shown in Figure 10.6. Of course, the propagation of the action potential is not restricted to cells where the action potential begins. Neurons can forward action potentials to other neurons, glands, and muscles. The brain is an extreme example of the relationship between the neurons are complicated.

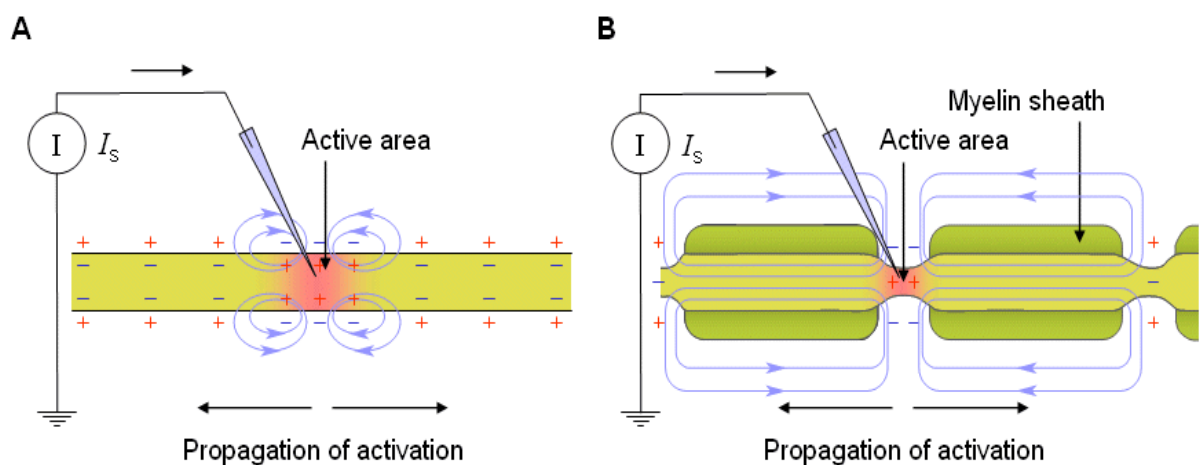


Figure 10.6. The propagation of an action potential across the membrane. A rangsangan alter membrane permeability to  $\text{Na}^+$  ions, triggering an action potential. Furthermore, the action potential change in membrane permeability adjacent and action potential propagates out from the starting point as shown.

Figure 10.6B shows the axon of a nerve cell with sections wrapped in myelin sheaths and small crevices between the myelin sheath- sheath called nodes of Ranvier. Axons are wrapped in myelin has certain advantages than axons are not encased in myelin. Electrically isolating myelin sheath of axons of generation by another axon

carries nerve bundle that allows signals without "cross talk" between axons of different nerves. The rate of propagation of axons wrapped in myelin is much larger than the axons are not encased in myelin, which is 130 m/s in axons with myelin than 0.10 m/s in axons without myelin. Furthermore, the energy needed to transmit a signal to axons wrapped in myelin is much smaller than the axons are not encased in myelin. Both types of axons were present throughout the body, and has been thought that the development of the myelin sheath is an important evolutionary step.

The reason that the axons are wrapped in myelin sheaths deliver signals with greater speed and using less energy must use properties insulating myelin. Consider Figure 10.6B, which shows the propagation of nerve impulses along the axon wrapped in myelin. When a nerve impulse or action potential reaches the myelin sheath, nerve impulses or action potentials did not cause much of ions to pass through the axons as the myelin sheath of axons of fluid separates the outside. Action potential propagates along the myelin sheath similar to a voltage pulse that will propagate through the ordinary resistor, the voltage goes missing during the action potential (recall that  $V = IR$  is the voltage drop across a resistor) but it moves very fast.

Voltage pulses will eventually become too small to stimulate something on the tip of the axon, the voltage pulse was regenerated periodically in the nodes of Ranvier. When the voltage pulse reaches the nodes of Ranvier, the voltage pulse was still large enough to stimulate the depolarization- repolarization cycle, generate an action potential is sent to the full voltage will axons regenerated on each successive gap. Ranvier nodes working as a small-amplifier amplifier along the axon. Energy consumption by the sodium- potassium pump does not have to work hard to maintain the concentration gradient, because such a small amount of cargo passing through the axon membrane in air- myelin area. The rate of propagation is larger than the axons are not encased in a myelin because most axons wrapped in myelin. Indeed, the rate of the myelin sheath is so great compared with the gaps so that the action potential seems almost jump from one gap to the next gap. Such propagation is called propagation of jumps (saltatory).

Bioelectricity generation and propagation is a complex process involving some physical events that occur simultaneously, such as diffusion, Coulomb force, and active transport. Nevertheless, many basic properties of Bioelectricity at the cellular level that can be understood by the principles of physics. Of course a detailed understanding requires a lot of knowledge about the chemistry and biology as well as physics go, but some issues are still a mystery.

### 3. Axon as Electrical Wiring

In the analysis of the electrical properties of the axon we will use some of the techniques of electrical engineering. It is necessary to understand the nervous system.

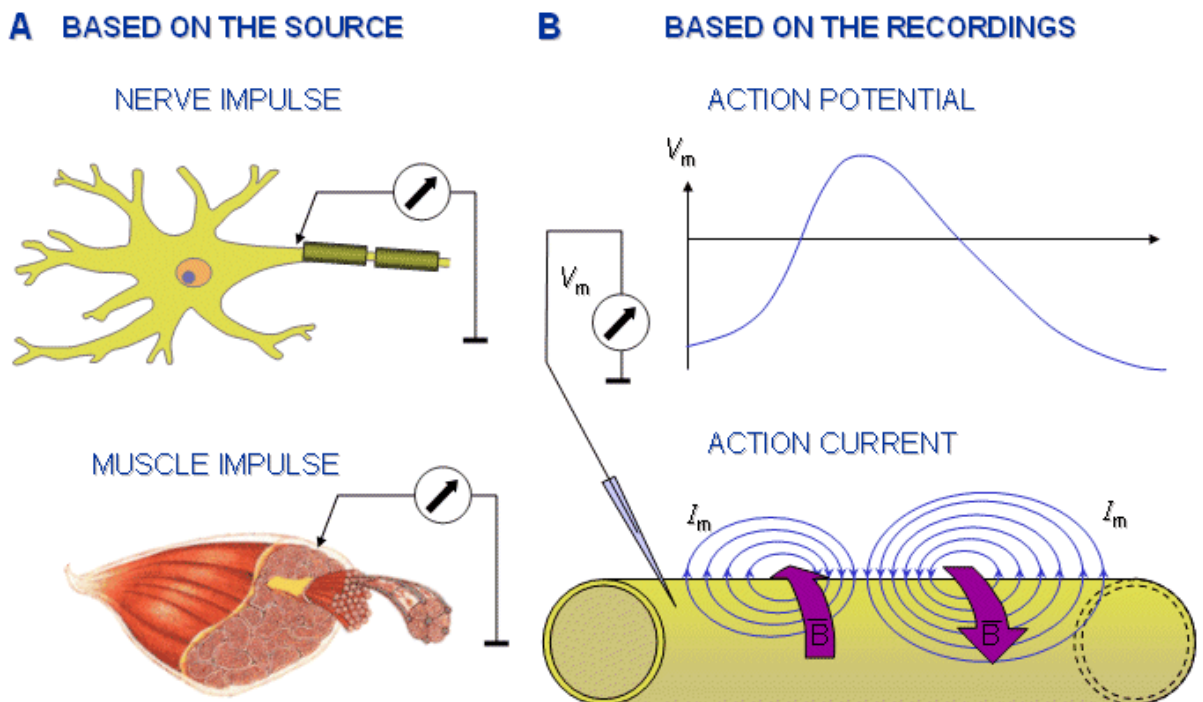


Figure 10.8. Clarification of the terminology used in connection with the action impulse: A) The source of the action impulse may be nerve or muscle cell. Correspondingly it is called a nerve impulse or a muscle impulse. B) The electric quantity measured from the action impulse may be potential or current. Correspondingly the recording is called an action potential or an action current. (<http://www.bem.fi/book/02/02.htm>).

Although axons are often compared to electrical cables, there is a big difference between the two. Nevertheless, it is possible to gain insight into the function of axons by analyzing it as a power cable that is immersed in a conductive fluid. In such an analysis, we must take into account the fluid resistance inside and outside the axon and the axon membrane electrical properties. Because the membrane is a leaky insulator, membranes have the capacity and resistance characteristics. Therefore we need four parameters to determine the nature of the axon cable.

Capacitance and resistance axons continuously distributed throughout the length of the cable. Therefore, something that is impossible to describe the whole axon (or some other cable) with only four components of the circuit. We must pay attention to the axon as a series of parts of the electrical circuit is very small- docked together. When a potential difference is applied between the inner and outer sides of the axon, the four currents can be recognized: the axon- side flow, stream- side outside the axon, the current through the resistive component of the membrane, and the membrane capacitive current through the component. Consider Figure 10.8. Electrical circuit that describes a small portion of axons with  $\Delta x$  is shown in the picture. In this small section- side fluid resistance and fluid outer- outer sides respectively are  $R_o$  and  $R_i$ .

Membrane capacitance and resistance are shown as  $C_m$  and  $R_m$ . The entire axon is a long series of these subunits are docked together. This is shown in Figure 10.9. The values of the circuit parameters for example wrapped in myelin and axons are not encased in myelin with radius  $10.0 \times 10^{-6}$  m in the list in Table 10.1.

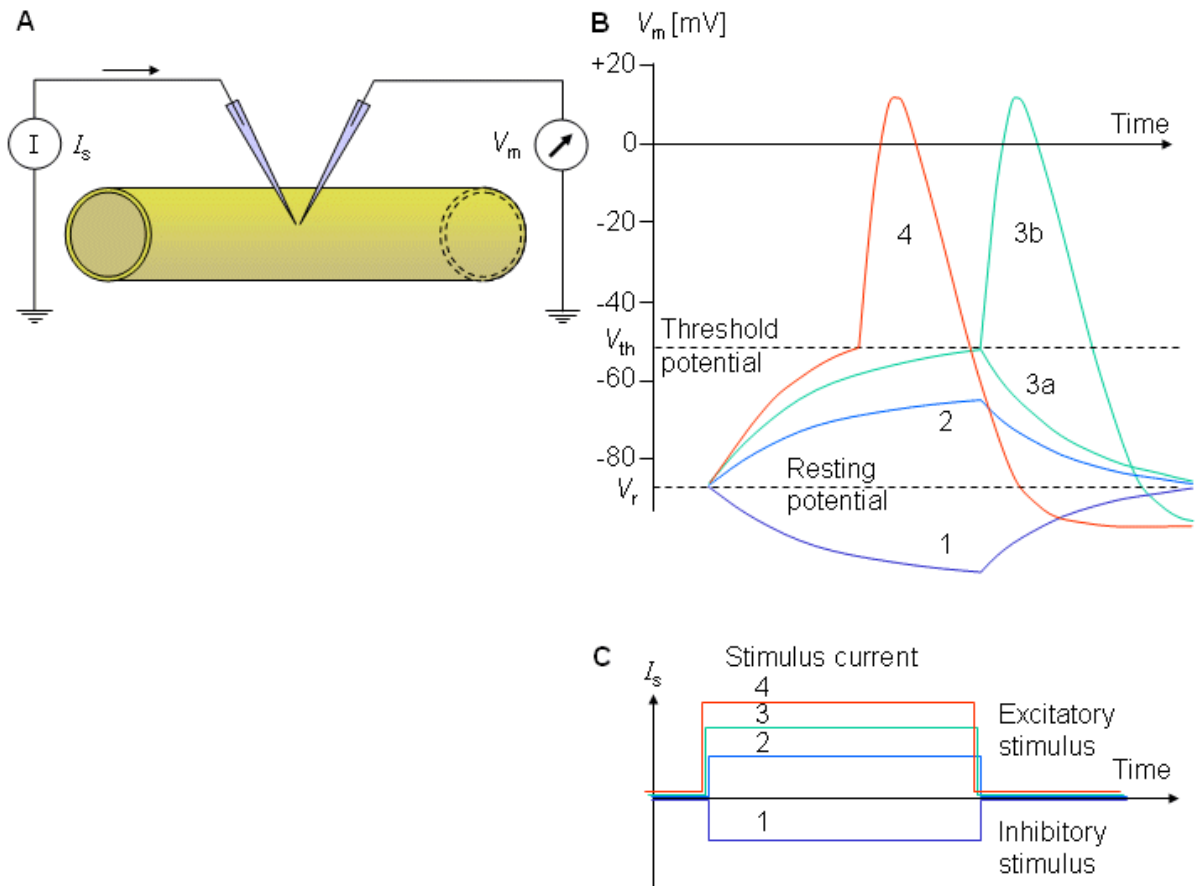


Figure 10.9. Axon is described as an electrical cord.  
 (<http://www.bem.fi/book/02/02.htm>).

Performance testing promptly axons showed that the circuit in Figure 10.9 does not explain the most striking characteristic of the axon. Electrical signals propagate along such series at a rate approaching the speed of light ( $3.0 \times 10^8$  m / s), while the pulse propagates along the axon at a rate of about 100 mostly m / s. Furthermore, the circuit in Figure 10.9 melesapkan (eliminate) the electrical signals very quickly, and yet we know that the action potential propagating along the axon without attenuation (weakening). Therefore we must conclude that the electrical signals propagate along the axon is not a simple passive process.

Table 10.1.

The properties of axons example

Properties	Akson are not wrapped myelin	Akson wrapped <i>myelin</i>
The radius of axons	$5,00 \times 10^{-6}$ m	$5,00 \times 10^{-6}$ m

Resistance per unit length of the fluid on the inside and the outside of the axon (R)	$6,37 \times 10^9$ ohm/m	$6,37 \times 10^9$ ohm/m
Conductivity per unit length of the axon membrane ( $g_m$ )	$1,25 \times 10^{-4}$ mho/m	$3,00 \times 10^{-7}$ mho/m
Capacitance per unit length of the axon	$3,00 \times 10^{-7}$ F/m	$8,00 \times 10^{-10}$ F/m

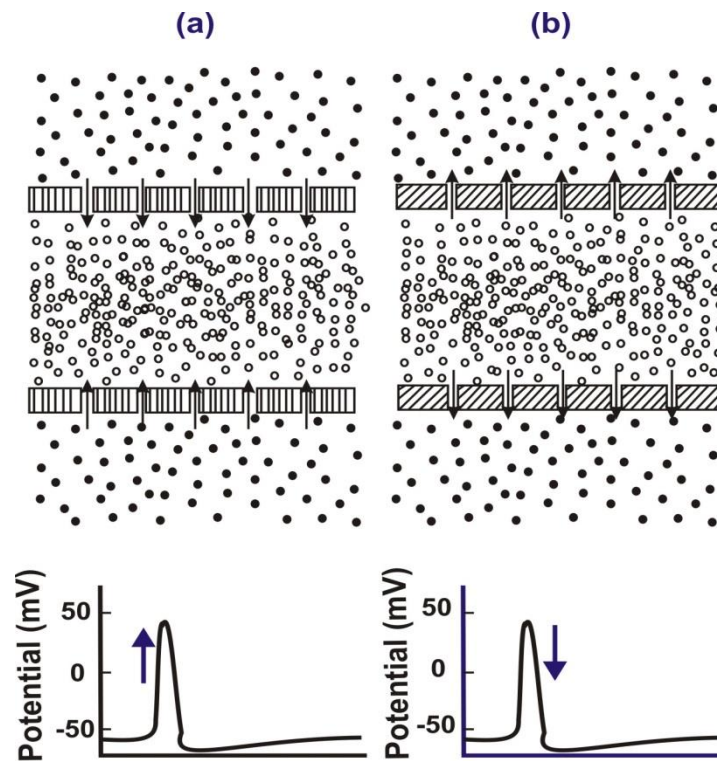


Figure 10.10. Action potential. (a) The action potential began with the axon membrane becomes very permeable to sodium ions (circles filled black) that enters the axon and make it positive. (b) The gates closed sodium and potassium ions (circles not filled black) and make a left axon interior negative again (Davidovits, 2001: 177).

After years of research an impulse propagation along the axon is now known to be rather good. Consider Figure 10.10. As a part of the voltage at the membrane is lowered below a threshold value, the axon membrane permeability to sodium ions increases rapidly. As a result, sodium ions stormed into the axon, eliminate the negative charges and in fact encourage the local potential in the axon becomes positive side. This process resulted in a sharp rise in the beginning of the action potential pulse. Sharp positive spike on the part of the axon increase permeability to sodium immediately in front of it which in turn resulted in a surge in that area. In this way successive interference propagated to the axon, similar to the flames spread to the fuse.

Axon, unlike fuses, renew yourself. At the peak of the action potential axon membrane closes its gates for sodium ions and open the gates for potassium ions. Potassium ions are now storming out, and consequently the potential down the axon to the negative value slightly below the resting potential. After a few milliseconds of potential axon back to the resting state and parts of the axon was ready to accept another pulse.

The number of ions flowing in and out of axons during the pulse was so small that the ion density in the axon has not changed much. The cumulative effect of many pulses offset by metabolic pumps that keep the concentration at the appropriate levels. We can estimate the amount of sodium ions into the axon during the rise phase of the action potential. Inrush of sodium ions alter the amount of electric charge inside the axon. We can express the change in the charge  $\Delta Q$  capacitor voltage change  $\Delta V$  in the membrane C, namely:

$$\Delta Q = C\Delta V \quad \dots (10.2)$$

In the resting state, the axon voltage was -70 mV. During the pulse, the voltage changes around +30 mV, resulting in a net change in membrane pressure of 100 mV. We can also estimate the minimum energy required to propagate impulses along the axon. During the propagation of the pulse, the entire axon capacitance emptied in a row and then have to be recharged again. The energy required to recharge the meter axons without myelin is

$$E = \frac{1}{2} C(\Delta V)^2 \quad \dots (10.3)$$

where C is the capacitance per meter axons.

#### 4. Axon circuit analysis

The circuit in Figure 10.9 does not contain the delivery mechanisms of axon pulse. It is possible to incorporate this mechanism into the circuit by connecting a small signal generator along the circuit. But such a circuit is quite complicated. Even the circuit in Figure 10.9 can not be analyzed without calculus. We will simplify the problem by ignoring the axon membrane capacity. The circuit as shown in Figure 10.11 (a). This description applies only when fully charged capacitors so that the capacitive current is zero. With this model we will be able to calculate the voltage attenuation along the cable when given a steady voltage at one end. But this simplified model can not make predictions about the behavior of the time-dependent axon.

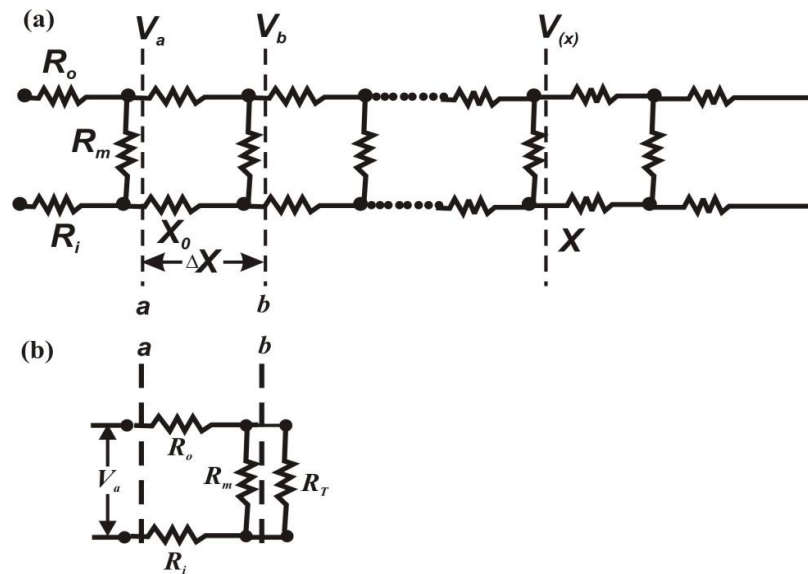


Figure 10.11. (a) Estimates of the circuit in Figure 10.8 with negligible capacitance. (b) Barriers to the right of the line b is replaced with an equivalent barrier \$R\_T\$ (Davidovits, 2001: 179).

The problem is to calculate the voltage \$V(x)\$ at point \$x\$ when the voltage \$V\_a\$ is given at the point \$x\_0\$. Consider Figure 10.11 (a). The approach was to first calculate the voltage drop across a cable section of length \$\Delta x\$ is cut by the line \$a\$ and line \$b\$. We assume that the total cable resistance to the right of the line \$b\$ is \$R\_T\$. Therefore, the entire cable on the right line \$b\$ is replaced with \$R\_T\$ as shown in Figure 10.11 (b). Because of the infinite cable, any obstacle to the right of the vertical cutting line \$b\$ is equivalent to \$R\_T\$ as well. In particular, barriers to the right of a line is \$R\_T\$. Therefore, we can calculate the \$R\_T\$ by equating the barriers on the right line \$a\$ in Figure 10.11 (b) with \$R\_T\$, which is

$$R_T = R_o + R_i + \frac{R_T R_m}{R_T + R_m} \quad \dots (10.4)$$

Measurements showed that the barriers on the inside and the outside of the axon is approximately equal. Therefore, \$R\_o = R\_i = R\$ and equation (10.4) becomes simpler as

$$R_T = 2R + \frac{R_T R_m}{R_T + R_m} \quad \dots (10.10)$$

Solutions of equation (10.10) yields

$$R_T = R + \left[ R^2 + 2R R_m \right]^{1/2} \quad \dots (10.6)$$

Simple circuit analysis shows that



$$V_b = \frac{V_a}{1 + \left[ \frac{(2R)(R_T + R_m)}{R_T R_m} \right]} = \frac{V_a}{1 + \beta} \quad \dots (10.7)$$

with  $\beta$  is the amount in brackets.

We can calculate from the measured parameters in Table 10.1. Resistance  $R$  and  $R_m$  are the values for a small section of length  $\Delta x$  axons. Therefore,

$$R = r\Delta x \quad \text{and} \quad \frac{1}{R_m} = g_m \Delta x \quad \text{or} \quad R_m = \frac{1}{g_m \Delta x}$$

From equation (10.6) it can be shown that if  $x$  is very small, then

$$R_T = \left( \frac{2r}{g_m} \right)^{1/2} \quad \dots (10.8)$$

$$\text{and} \quad \beta = (2rg_m)^{1/2} \Delta x = \frac{\Delta x}{\lambda} \quad \dots (10.9)$$

$$\text{with.} \quad \lambda = \left( \frac{1}{2rg_m} \right)^{1/2} \quad \dots (10.10)$$

Now back to the equation (10.8), since  $\Delta x$  is small and can be omitted,  $\beta$  is very small as well. Therefore the rate  $1 / (1 + \beta)$  is approximately equal to  $(1 - \beta)$ . As a result, the voltage  $V_b$  at  $b$ , within  $\Delta x$  of  $a$ , is

$$V_b = V_a \left[ 1 - \frac{\Delta x}{\lambda} \right] \quad \dots (10.11)$$

To obtain the voltage at a distance  $x$  from the line, we divide this distance becomes so  $n\Delta x$  increment  $\Delta x = x$ . Then we can apply respectively to the table and obtain the voltage at  $x$  as

$$V_b = V_a \left[ 1 - \frac{\Delta x}{\lambda} \right]^n \quad \dots (10.12)$$

Can be shown that, for small  $\Delta x$  and large  $n$ , equation (10.12) can be written as

$$V_b = V_a e^{-x/\lambda} \quad \dots (10.13)$$

### Example 10.2:

Based on Table 10.1 calculate  $\lambda$  axons are not encased in myelin.

**Completion:**

By using equation (10.10) is obtained

$$\lambda = \left( \frac{1}{2rg_m} \right)^{1/2}$$

$$\lambda = \left( \frac{1}{2(6,37 \times 10^9 \text{ ohm/m})(1,25 \times 10^{-4} \text{ ohm/m})} \right)^{1/2}$$

$$\lambda = 8,0 \times 10^{-4} \text{ m} = 0,8 \text{ mm}$$

**5. Synaptic Transmission**

So far we have noticed propagation of an electrical impulse to the axon. Now we will describe briefly how the pulse was transmitted from the axon to other neuron or muscle cells.

At the far end of the axon branches into nerve endings that stretched into the cells to be activated. Through these nerve endings of axons transmit signals, usually to the number of cells. In some cases the action potential transmitted from the nerve endings to the cells with electrical conduction. Nerve endings are actually not in contact with the cells. There is a gap, the width of approximately 1 nm, between the nerve endings and cell bodies. The area of interaction between the nerve endings and target cells called synapses. Consider Figure 10.12. When the impulse reaches the synapse, a chemical is released at the nerve endings that rapidly diffuses through the gap and stimulate adjacent cells. Chemicals that are released in files with discrete sizes.

Synaptic neurons normally come into contact with many sources. Often the number of synapses must be activated simultaneously to initiate action potentials in the target cell. Action potentials generated by a neuron is always the same size. Neurons work in a variety of: Neurons generate action potentials with a standard size or did not rise at all. In some instances chemicals that are released at synapses stimulated cells but not preclude response to impulses coming along different channels.

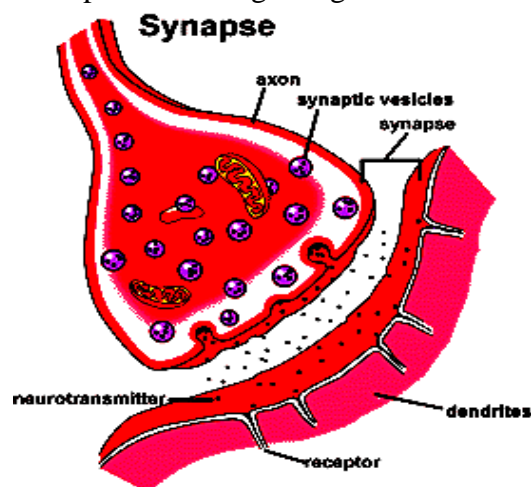


Figure 10.12. Synapses (www.getting-in.com).

## 6. The muscle action potential

Action potential, the brief (about one-thousandth of a second) reversal of electric polarization of the membrane of a nerve cell (neuron) or muscle cell. In the neuron an action potential produces the nerve impulse, and in the muscle cell it produces the contraction required for all movement. Sometimes called a propagated potential because a wave of excitation is actively transmitted along the nerve or muscle fibre, an action potential is conducted at speeds that range from 1 to 100 metres (3 to 300 feet) per second, depending on the properties of the fibre and its environment.

Muscle fibers generate and propagate impulses in the same way as neurons. Action potential in the muscle fiber initiated by impulses coming from the motor neurons. Before stimulation, a neuron or muscle cell has a slightly negative electric polarization; that is, its interior has a negative charge compared with the extracellular fluid. This polarized state is created by a high concentration of positively charged sodium ions outside the cell and a high concentration of negatively charged chloride ions (as well as a lower concentration of positively charged potassium) inside. The resulting resting potential usually measures about  $-75$  millivolts (mV; 0.0075 volt), the minus sign indicating a negative charge inside. This stimulation causes the potential drop across the membrane fibers that initiate processes involved in the propagation of an ionic pulse. Action potential shape was the same as in neurons except that the duration of time is usually longer. In skeletal muscle, the action potential last approximately 20 ms, whereas in cardiac muscle action potential that could end a quarter of a second.

After the action potential passes through the muscle fibers, the muscle to contract. Details of this process are not yet fully known. In the skeletal muscle fibers, mechanoreceptor organs, called the muscle spindle, forwarding information on the state of muscle contraction. This information is transmitted through neurons for processing and further work. In this way the motion of the muscle is under the control continuously.

In the generation of the action potential, stimulation of the cell by neurotransmitters or by sensory receptor cells partially opens channel-shaped protein molecules in the membrane. Sodium diffuses into the cell, shifting that part of the membrane toward a less-negative polarization. If this local potential reaches a critical state called the threshold potential (measuring about  $-60$  mV), then sodium channels open completely. Sodium floods that part of the cell, which instantly depolarizes to an action potential of about  $+55$  mV. Depolarization activates sodium channels in adjacent parts of the membrane, so that the impulse moves along the fibre (<http://www.britannica.com/EBchecked/topic/4491/action-potential>).

If the entry of sodium into the fibre were not balanced by the exit of another ion of positive charge, an action potential could not decline from its peak value and return to the resting potential. The declining phase of the action potential is caused by the closing of sodium channels and the opening of potassium channels, which allows a charge approximately equal to that brought into the cell to leave in the form of potassium ions. Subsequently, protein transport molecules pump sodium ions out of the cell and potassium ions in. This restores the original ion concentrations and readies

the cell for a new action potential. The Nobel Prize for Physiology or Medicine was awarded in 1963 to Sir A.L. Hodgkin, Sir A.F. Huxley, and Sir John Eccles for formulating these ionic mechanisms involved in nerve cell activity.

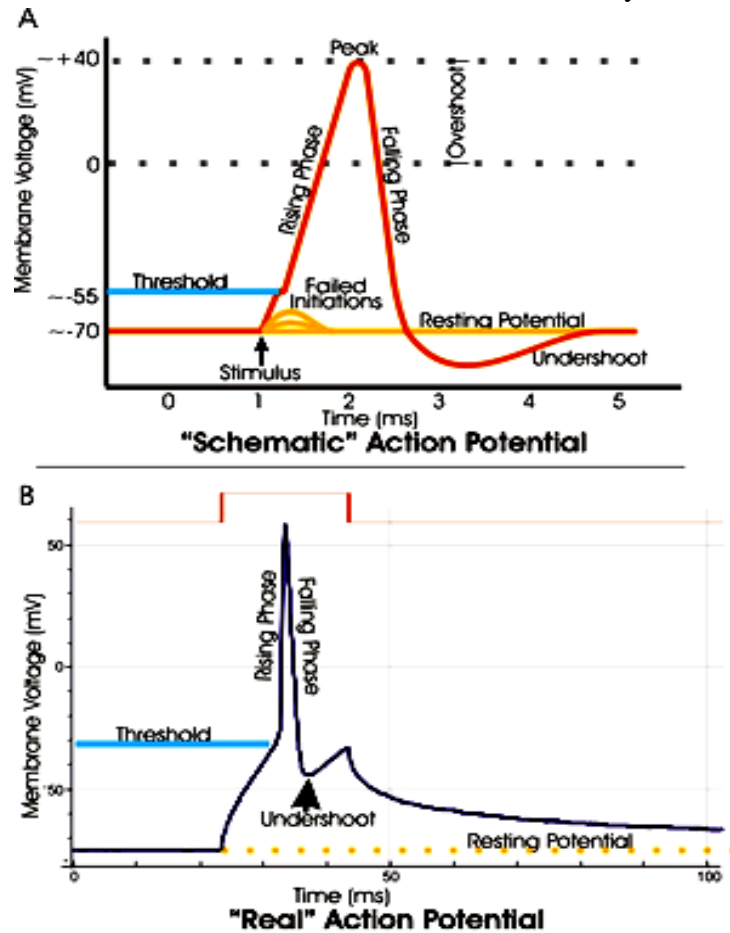


Figure 10.13. **A.** view of an idealized action potential shows its various phases as the action potential passes a point on a cell membrane. **B.** Recordings of action potentials are often distorted compared to the schematic view because of variations in electrophysiological techniques used to make the recording ([http://en.wikipedia.org/wiki/Action\\_potential](http://en.wikipedia.org/wiki/Action_potential)) cc.

### EXERCISE

To improve your understanding of the material above, do the exercises below!

- 1) Calculate the potential of the membrane to  $\text{Na}^+$  ions at a temperature of 310K, when the concentration of  $\text{Na}^+$  ions in the cell is 110 mol/m<sup>3</sup> and outside the cell is 140 mol/m<sup>3</sup>. Boltzmann's constant  $k = 1.38 \times 10^{-23} \text{ J / K}$ .  $\text{K}^+$  ion charge is  $e = 1.60 \times 10^{-19} \text{ C}$ !
- 2) Give a brief description of the action potential formation in the cell membrane?

- 3) Provide an explanation of the difference between the function of synapses, axons, and dendrites in a neuron?
- 4) Provide a description of the sodium- potassium pump!
- 5) Explain the advantages nerve segments were wrapped in myelin related to the nature of the insulating myelin!

### Instructions to Answer Exercise

If you have difficulty in completing these exercises, consult the instructions for the completion of each of the following questions.

- 1) Consider the example about 10.1.
- 2) Re-read the subject of Bioelectricity generation.
- 3) Read more about the transmission of signals from the neuron cell body to the outside, and a signal from the outside into the cell body of neurons.
- 4) Read carefully about the sodium- potassium pump.
- 5) Read the back of myelin and its function.

### RESUME

Bioelectricity is a cellular phenomenon. Electrical potential across the cell membrane occurs due to differences in the concentration of ions inside the cell and outside the cell. The creation of the cell electric potential is related to the diffusion of ions through a semipermeable membrane and Coulomb forces between the ions. Ions are important in creating the cell potentials are ions Na<sup>+</sup>, K<sup>+</sup>, and Cl<sup>-</sup>.

The equation that describes the energy balance between ion concentration gradient and the Coulomb force is shown by the Nernst equation; potential difference inside and outside the cell is expressed as

$$V = V_{\text{in}} - V_{\text{out}} = -2,30 \frac{kT}{Ze} (\log C_{\text{in}} - \log C_{\text{out}})$$

where  $V$  is the potential difference (inside minus outside),  $C_{\text{in}}$  and  $C_{\text{out}}$  are respectively the ion concentrations inside and outside the cell membrane,  $k$  is Boltzmann's constant,  $T$  is the absolute temperature, and  $Ze$  is the charge on the ion multiplied electron charge ( $Z$  is the valence of ion).

Electrical phenomenon that is found in living organisms are highly complex nervous system. Nerve cells are also called neurons form a complex network in the body that receive, process and forward information from one part of the body to other body parts. Center is located in the brain tissue, which has the ability to store and analyze information.

In the axons of neurons there is a potential site of action at the time of cell activity. The process of formation of the action potential can be explained by the

sodium- potassium pump. Axons can also be analyzed as an electrical cord that propagate action potentials.

Changes in electric charge  $\Delta Q$  in axons because the flow of ions in and out axons to changes in membrane voltage on the capacitor  $\Delta V$  C, expressed as

$$\Delta Q = C\Delta V$$

E is the energy required to recharge the meter axon is

$$E = \frac{1}{2}C(\Delta V)^2$$

where C is the capacitance per meter axons.

Based on sequence analysis of the axon, the voltage in the axon decreases exponentially. If the steady-state voltage  $V_a$  is given at one point on the axon membrane, the voltage  $V_b$  at another point within x of that point can be expressed as

$$V_b = V_a e^{-x/\lambda}$$

with

$$\lambda = \left( \frac{1}{2rg_m} \right)^{1/2}$$

r is the resistance per unit length of the fluid inside and outside the axon, gm is the conductivity per unit length of the axon membrane