Membrane Potential

Electrical potentials exist across the membranes of virtually all cells of the body. Some cells, such as nerve and muscle cells, generate rapidly changing electrochemical impulses at their membranes, and these impulses are used to transmit signals along the nerve or muscle membranes.

MEMBRANE POTENTIALS

Electrical events occur in the muscle (or any living tissue) during resting condition as well as active conditions.

Electrical potential Changes during Muscular Contraction in the muscle during resting condition is called resting membrane potential.

Electrical changes that occur in active conditions, i.e. when the muscle is stimulated are together called action potential.

RESTING MEMBRANE POTENTIAL

Resting membrane potential is defined as the electrical potential difference (voltage) across the cell membrane (between inside and outside of the cell) under resting condition.

It is also called membrane potential, transmembrane potential, transmembrane potential difference or transmembrane potential gradient.

Ionic Basis of Resting Membrane Potential

Development and maintenance of resting membrane potential in a muscle fiber or a neuron are carried out by movement of ions, which produce ionic imbalance across the cell membrane. This results in the development of more positivity outside and more negativity inside the cell.

Ionic imbalance is produced by two factors:

1. Sodium-potassium pump

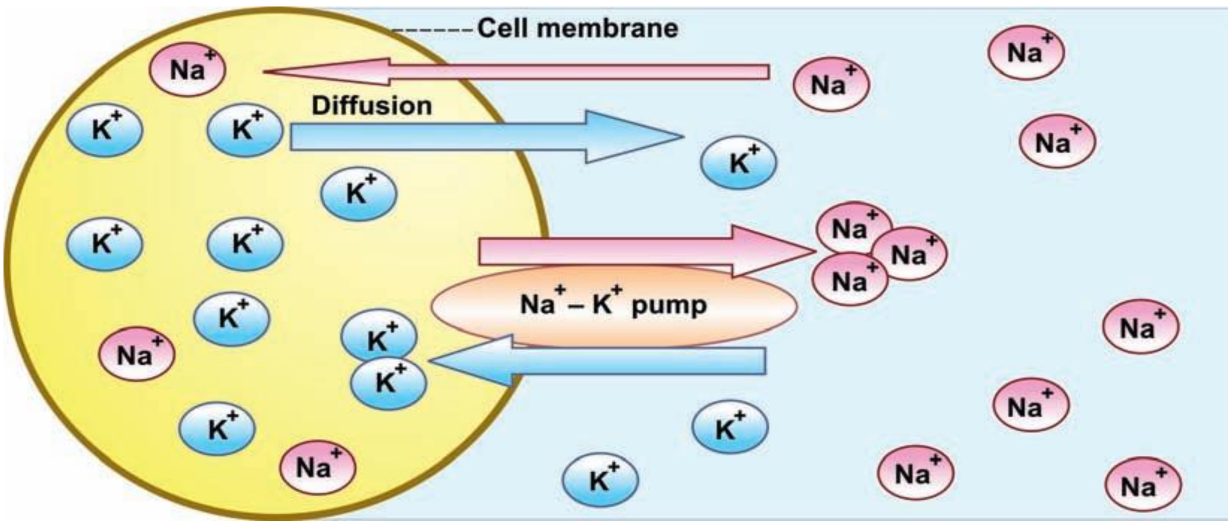
2. Selective permeability of cell membrane.

1. Sodium-potassium pump

Sodium and potassium ions are actively transported in opposite directions across the cell membrane by means of an electrogenic pump called sodium-potassium pump. It moves three sodium ions out of the cell and two potassium ions inside the cell by using energy from ATP.

Since more positive ions (cations) are pumped outside than inside, a net deficit of positive ions occurs inside the cell. It leads to negativity inside and positivity outside the cell.

2. Selective permeability of cell membrane Permeability of cell membrane depends largely on the transport channels. The transport channels are selective for the movement of some specific ions. Their permeability to these ions also varies. Most of the channels are gated channels and the specific ions can move across the membrane only when these gated channels are opened.



Two types of channels are involved:

A. Channels for major anions like proteins

B. Leak channels.

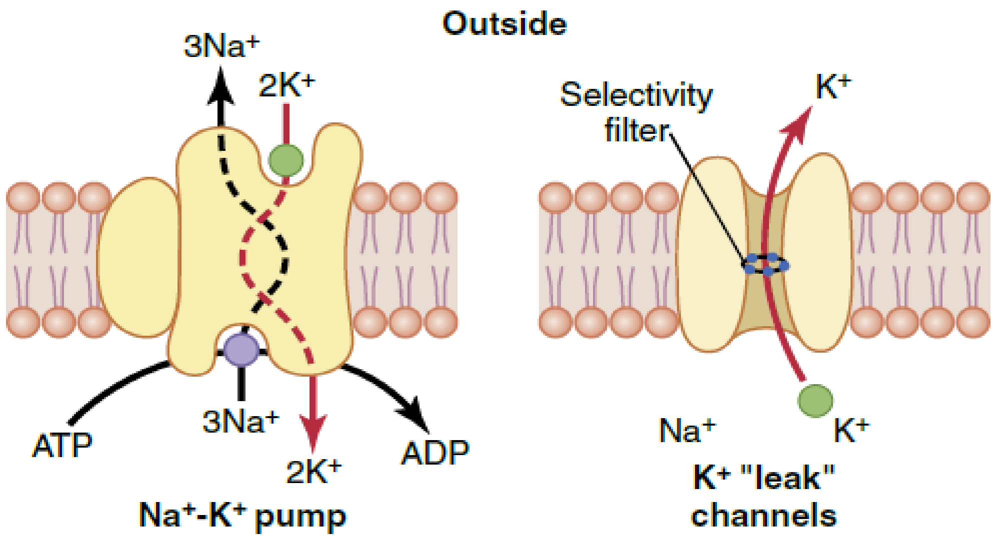
A. Channels for major anions (negatively charged substances) like proteins Channels for some of the negatively charged large substances such as proteins, organic phosphate and sulfate compounds are absent or closed. So, such substances remain inside the cell and play a major role in the development and maintenance of negativity inside the cell (resting membrane potential).

B. Leak channels are the passive channels, which maintain the resting membrane potential by allowing movement of positive ions (Na+ and K+) across the cell membrane.

Three important ions, sodium, chloride and potassium are unequally distributed across the cell membrane. Na+ and Cl– are more outside and K+ is more inside.

Since, Cl– channels are mostly closed in resting conditions Cl– are retained outside the cell. Thus, only the positive ions, Na+ and K+ can move across the cell membrane.

Na+ is actively transported (against the concentration gradient) out of cell and K+ is actively transported (against the concentration gradient) into the cell. However, because of concentration gradient, Na+ diffuses back into the cell through Na+ leak channels and K+ diffuses out of the cell through K+ leak channels.



In resting conditions, almost all the K+ leak channels are opened but most of the Na+ leak channels are closed. Because of this, K+, which are transported actively into the cell, can diffuse back out of the cell in an attempt to maintain the concentration equilibrium.

But among the Na+, which are transported actively out of the cell, only a small amount can diffuse back into the cell. That means, in resting conditions, the passive K+ efflux is much greater than the passive Na+ influx. It helps in establishing and maintaining the resting membrane potential.

After establishment of the resting membrane potential (i.e. inside negativity and outside positivity), the efflux of K+ stops in spite of concentration gradient.

It is because of two reasons:

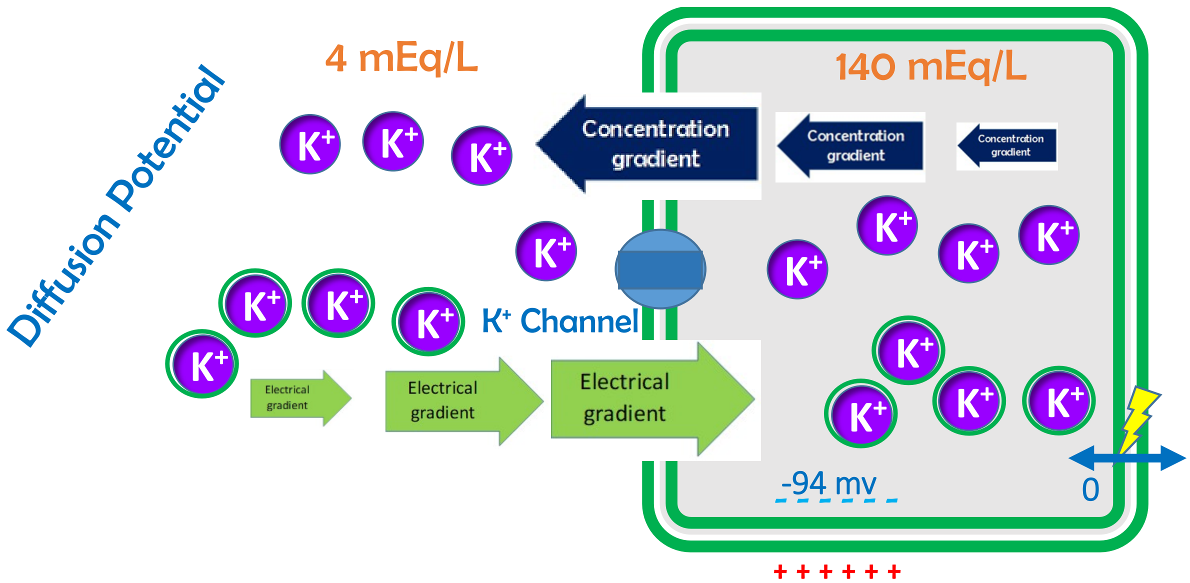
i. Positivity outside the cell repels positive K+ and prevents further efflux of these ions

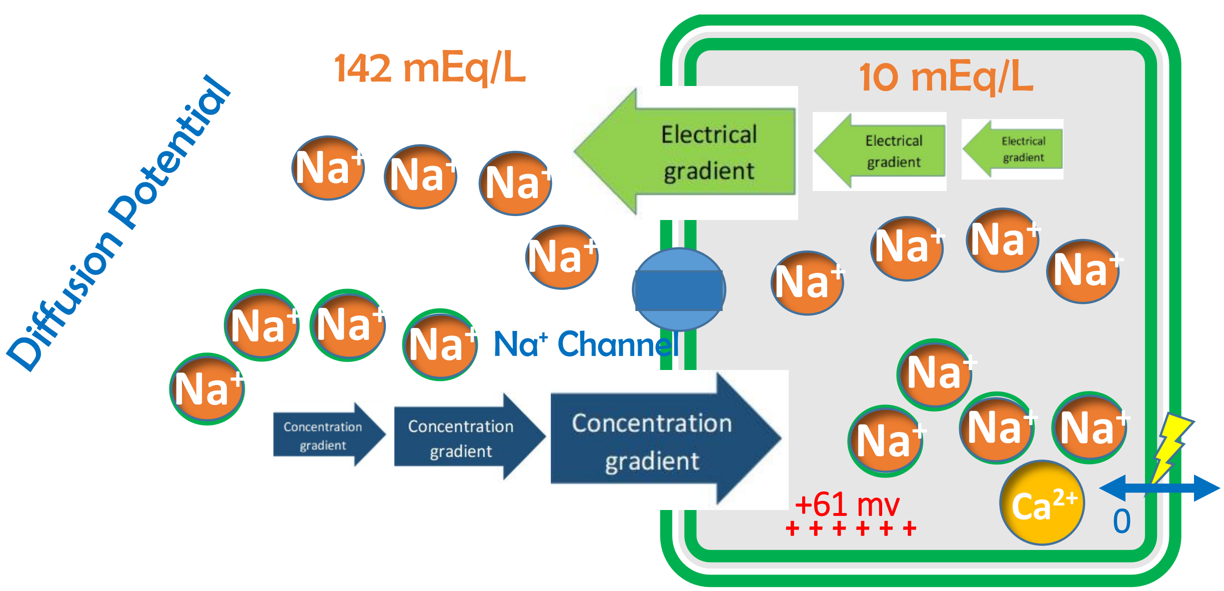
ii. Negativity inside the cell attracts positive K+ and prevents further leakage of these ions outside

Importance of intracellular potassium ions Concentration of K+ inside the cell is about 140 mEq/L. It is almost equal to that of Na+ outside. The high concentration of K+ inside the cell is essential to check the negativity. Normally, the negativity (resting membrane potential) inside the muscle fiber is –90 mV and in a nerve fiber, it is –70 mV. It is because of the presence of negatively charged proteins, organic phosphates and sulfates, which cannot move out normally. Suppose if the K+ is not present or decreased, the negativity increases beyond –120 mV, which is called hyperpolarization. At this stage, the development of action potential is either delayed or does not occur.

Physics equations for diffusion potential calculation:

Nernst Potential: The diffusion potential across a membrane that exactly opposes the net diffusion of a particular ion through the membrane for that ion.





Nernst equation:

Concentration gradient

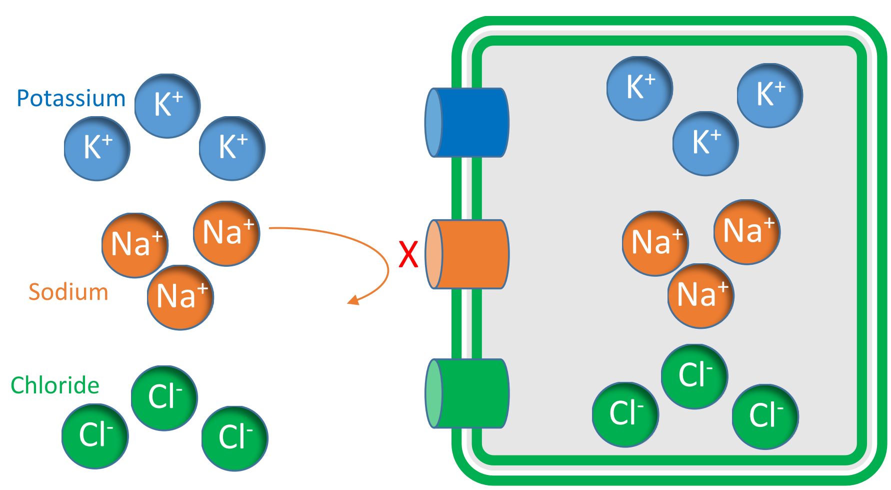
$$\text{Equilibrium potential} = -\frac{61}{\text{Electrical Charge (2)}} \times \log \frac{\text{Concentration inside}}{\text{Concentration outside}}$$

$$\text{(K) Equilibrium potential} = -\frac{61}{\text{Electrical Charge (2)}} \times \log \frac{\text{K Concentration inside}}{\text{K Concentration outside}}$$

$$= -\frac{61}{1} \times \log \frac{140}{4}$$

= - 91 mv

Goldman potential: When a membrane is permeable to several different ions gives the calculated membrane potential on the inside of the membrane when two univalent positive ions, sodium (Na+) and potassium (K+), and one univalent negative ion, chloride (Cl−).



Goldman Equation:

$$\text{Equilibrium potential} = -61 \times \log \frac{C(Na^{+}\ P\,Na^{+}) + C(K^{+}\ P\,K^{+}) + C(Cl^{-}\ PCl^{-})\ \ \textit{(Inside)}}{\underbrace{C(Na^{+}\ P\,Na^{+})}_{\text{Sodium }(+61\text{ mv})} + \underbrace{C(K^{+}\ P\,K^{+})}_{\text{Potassium }(-94\text{ mv})} + \underbrace{C(Cl^{-}\ PCl^{-})}_{\text{Chloride}}\ \ \textit{(Outside)}}$$

C = concentration, P = permeability

$$\text{At resting} = -61 \times \log \frac{\overset{\times}{C(Na^{+}\ P\,Na^{+})} + \overset{\checkmark}{C(K^{+}\ P\,K^{+})} + C(Cl^{-}\ PCl^{-})}{C(Na^{+}\ P\,Na^{+}) + C(K^{+}\ P\,K^{+}) + C(Cl^{-}\ PCl^{-})} = -70\text{ mv}$$

$$\text{When cell stimulated} = -61 \times \log \frac{\overset{\checkmark}{C(Na^{+}\ P\,Na^{+})} + \overset{\checkmark}{C(K^{+}\ P\,K^{+})} + C(Cl^{-}\ PCl^{-})}{C(Na^{+}\ P\,Na^{+}) + C(K^{+}\ P\,K^{+}) + C(Cl^{-}\ PCl^{-})}$$

Several key points become evident from the Goldman equation:

First, sodium, potassium, and chloride ions are the most important ions involved in the development of membrane potentials in nerve and muscle fibers, as well as in the neuronal cells. The concentration gradient of each of these ions across the membrane helps determine the voltage of the membrane potential.

Second, the quantitative importance of each of the ions in determining the voltage is proportional to the membrane permeability for that particular ion. If the membrane has zero permeability to sodium and chloride ions, the membrane potential becomes entirely dominated by the concentration gradient of potassium ions alone, and the resulting potential will be equal to the Nernst potential for potassium.

Third, a positive ion concentration gradient from inside the membrane to the outside causes electronegativity inside the membrane. The reason for this phenomenon is that excess positive ions diffuse to the outside when their concentration is higher inside than outside the membrane. This diffusion carries positive charges to the outside but leaves the nondiffusible negative anions on the inside, thus creating electronegativity on the inside.

The opposite effect occurs when there is a gradient for a negative ion. That is, a chloride ion gradient from the outside to the inside causes negativity inside the cell because excess negatively charged chloride ions diffuse to the inside while leaving the nondiffusible positive ions on the outside.

Fourth, as explained later, the permeability of the sodium and potassium channels undergoes rapid changes during transmission of a nerve impulse, whereas the permeability of the chloride channels does not change greatly during this process. Therefore, rapid changes in sodium and potassium permeability are primarily responsible for signal transmission in neurons.

Resting membrane potential in different cells

Cell Type	Resting Potential (mV)
Neurons	–60 to –70
Skeletal muscle	–85 to –95
Smooth muscle	–50 to –60
Cardiac muscle	–80 to –90
Hair (cochlea)	–15 to –40
Astrocyte	–80 to –90
Erythrocyte	–8 to –12
Photoreceptor	–40 (dark) to –70 (light)

RESTING MEMBRANE POTENTIAL OF NEURONS:

The resting membrane potential of large nerve fibers when they are not transmitting nerve signals is about −70 millivolts. That is, the potential inside the fiber is 70 millivolts more negative than the potential in the extracellular fluid on the outside of the fiber.

Sodium-Potassium (Na+-K+) Pump: Note that this is an electrogenic pump because three Na+ ions are pumped to the outside for each two K+ ions to the inside, leaving a net deficit of positive ions on the inside and causing a negative potential inside the cell membrane.

The Na+-K+ pump also causes large concentration gradients for sodium and potassium across the resting nerve membrane. These gradients are as follows:

Na+ (outside):142mEq/L

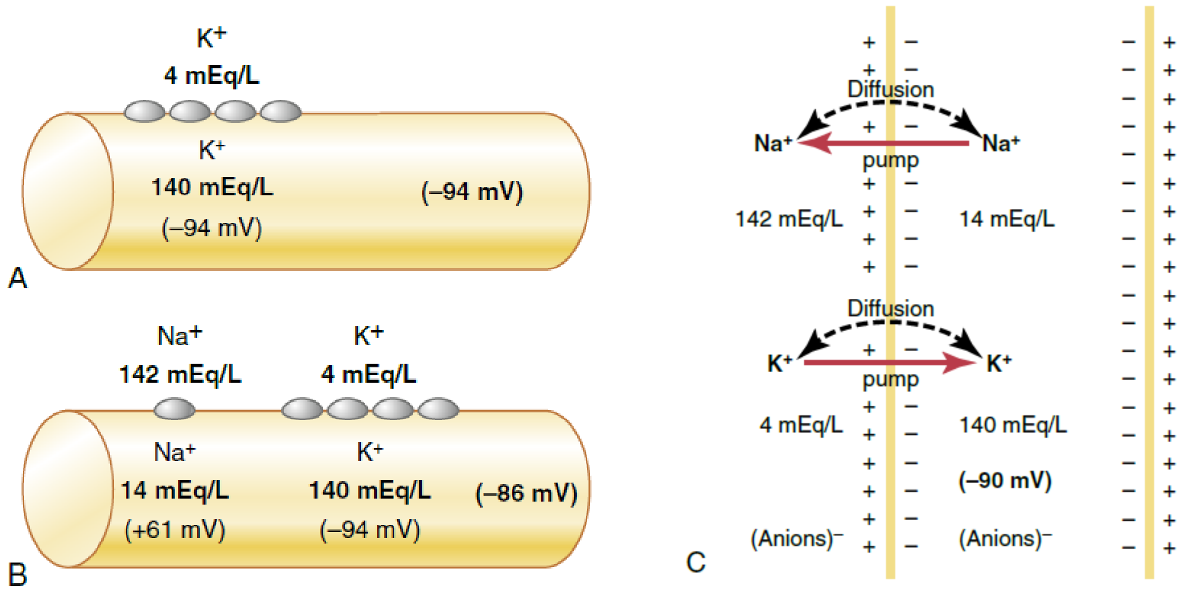
Na+ (inside):14mEq/L

K+ (outside): 4mEq/L

K+ (inside):140mEq/L

The ratios of these two respective ions from the inside to the outside are as follows:

Na^+ *inside* /Na^+ *outside*= 0.1 , K^+ inside /K^+ *outside* = 35.0



A. When the membrane potential is caused entirely by potassium diffusion alone.
B. When the membrane potential is caused by diffusion of both sodium and potassium ions.
C. When the membrane potential is caused by diffusion of both sodium and potassium ions plus pumping of both these ions by the Na+-K+ pump.

References: Guyton and Hall textbook of medical physiology. 14th edition

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