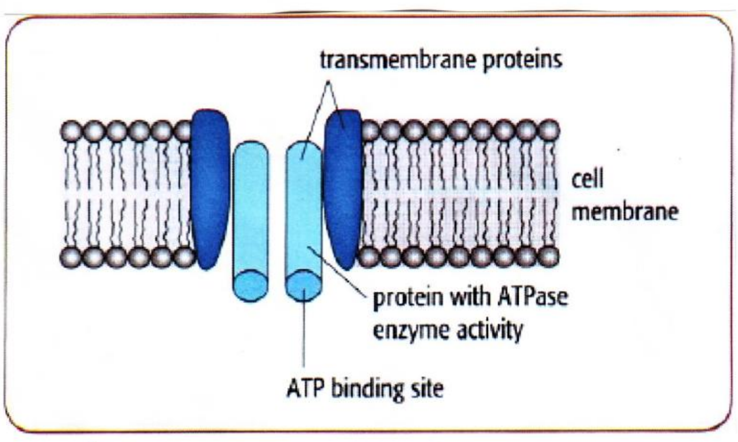
Sodium and potassium ion transfer

The role of Na^+ and K^+ in ion transfer across cell membranes

The Na^+ ion concentration within most animal cells is lower than in the tissue fluid surrounding the cells.

The K^+ ion concentration within most animal cells is higher than in the tissue fluid surrounding the cells.

These differences in concentration are maintained by a Na^+, K^+ ion pump situated in the cell membrane.



The Na^+, K^+ ion pump in the cell membrane helps maintain the concentration of these ions constant.

The movement of ions through the cell membrane can only occur in the presence of ATP.

The ion pump consists of a number of proteins, some of which can hydrolyse ATP.

The protein has ATPase activity.

The ion pump works on active transport because the ions are being moved against a concentration gradient.

Against a concentration gradient – means the ions are being pumped from a place where they are in a lower concentration to a place where they are in higher concentration.

Active transport always requires energy.

The energy is provided by $ATP \rightarrow ADP + P_i$.

The pump works in the following way:

- three Na^+ ions and ATP bind to the inner surface of the protein.
- when ATP is hydrolised to $ADP + P_i$, the protein changes shape so that Na^+ ions can move out of the cell.

- as the Na^+ ions are released two K^+ ions outside the cell attach to the protein.
- the K^+ ions move inwards and are released inside the cell when a new ATP molecule binds to the inner surface of the protein.
- the cycle then repeats itself.

When we are resting, about a third of the ATP we make in our bodies is used for pumping ions into and out of our cells.

Some plant steroids inhibit the Na^+, K^+ ion pump.

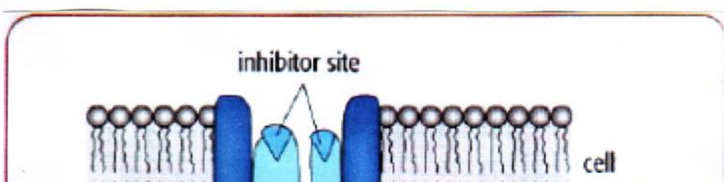
Plant steroids such as ouabain and digitoxigenin inhibit the transport of Na^+ and K^+ ions through cell membranes.

They are non-competitive inhibitors.

They act by inhibiting the reaction of the ATPase protein which hydrolyses the ATP.

The steroids bind on the outside of the inner protein subunits.

This changes the structure of these subunits so that the ATPase activity is inhibited.



Particular plant steroids inhibit the transport of Na^+ and K^+ ions across cell membranes by binding to the outside of the protein.

The protein changes shape thus inhibiting the ATPase activity on the inside of the cell.

Vanadate (V) ions, VO_4^{3-} also inhibit the action of the Na^+, K^+ ATPase, but they do this from the inner side of the membrane.

Diabetes and certain diseases of the nervous system, muscles and heart can all be related to incorrect functioning of the protein channels which pump ions and water in through the cell membranes.

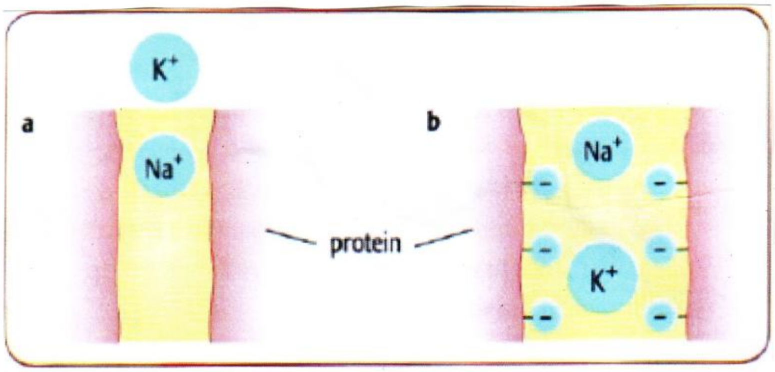
Ion transport across a membrane depends on the size and hydration of the ion

The ability of an ion to pass through the ion channels depends on the charge and size of the ion. Ions in aqueous solution are usually hydrated. Their overall size depends on their hydrated radius.

The charge and the nature of the groups on the protein walls of the ion channel may also play a part.

The protein walls of the ion channel contain some negatively charged amino acid side-chains.

The relatively narrow width of the sodium channel between the proteins in the cell membrane makes it more permeable to the smaller hydrated sodium ion than the larger hydrated potassium ion.



a. The size of the hydrated ion affects the ability of positively charged ions to move through the sodium ion channel.

b. The ease of complex formation with amino acid side-chains affects the ability of ions to move through the potassium ion channel.

The potassium ions lose their hydration layer and bind to the negatively charged amino acid side-chains.

The energy required to remove the hydration shell is compensated for by the formation of new bonds with the amino acid side-chains.

The potassium ions regain their water of hydration when they reach the other side of the membrane.

Sodium ions do not go through the potassium ion channel because they are too small to form complexes with the amino acid side-chains and be pushed through.

Exercise

Ion-specific channels are important in maintaining the correct balance of ions in cells.

The K^+ ion channels depend on the hydrated potassium ions losing their hydration shell in order for transport to take place.

The Na^+ ion channels depend on the hydrated ions keeping their hydration shells.

a. Is the loss of the hydration layer exothermic or endothermic? Explain your answer.

b. What interactions of the K^+ ions replace those with water?

c. Why are Na^+ ions not able to use the same channel as the K^+ ions?

d. i) Explain why Li^+ ions do not move through the Na^+ ion channel as rapidly as Na^+ ions.

ii) Explain why K^+ ions do not move through the Na^+ ion channel.

Workings

a. Endothermic.

Energy input is required to break the ion-dipole attraction between the ions and the water molecules.

b. The K^+ ions are attracted to the negatively charged $-COO^-$ groups of amino acid side-chains in the proteins walls of the ion channels.

c. Na^+ ions are too small to form complexes with the amino acid side-chains and therefore could not be pushed through.

d. i) A hydrated Li^+ ion is much smaller than a hydrated Na^+ ion.

So, compared with Na^+ it does not form as strong an attraction with the negatively charged amino acid side-chains in the walls of the ion channel.

ii) Hydrated K^+ ions much larger than hydrated Na^+ ions so do not easily fit into the ion channel.

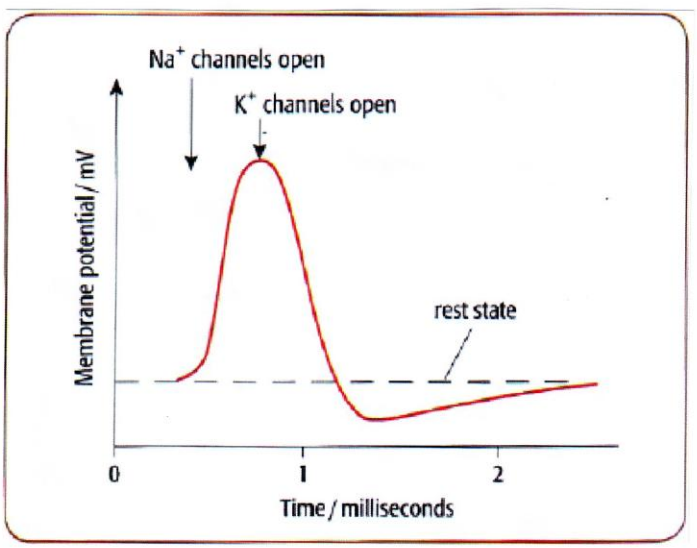
The role of Na^+ and K^+ ions in nerve impulses

A nervous impulse is an electrical signal produced by a flow of ions across the nerve cell membrane. Differences in the flow of K^+ and Na^+ ions into and out of the cell membranes give rise to an electrical potential.

The energy for the flow of ions comes from the hydrolysis of ATP by the ATPase enzyme.

- before a nerve is stimulated, the potential across its cell membrane is called the resting potential.
- the resting potential exists because the concentration of potassium ions is higher inside the nerve cell, and the concentration of sodium ions is higher outside the nerve cell.
- when the nerve is stimulated, Na^+ ions move into the cell.
- this increases the electrical potential across the membrane and more and more sodium channels are opened.

- eventually an equilibrium is reached.
- the Na^+ channels close and K^+ ion channels open.
- K^+ ions flow outwards.
- after the nerve signal has passed, the Na^+, K^+ ion pump then pumps the Na^+ ions out of the cell, and it pumps the K^+ ions back into the cell.
- these processes return the membrane potential to its original value, which is the resting potential



The change in electrical potential when a nerve is stimulated.

Exercise

a. Which ions are involved in the transmission of a nervous impulse?

b. How do the concentrations of these ions in the nerve cell change during the transmission of a nervous impulse?

c. Name the enzyme involved in the transport of these ions across the cell membrane.

d. What is the position of this enzyme in the cell?

e. Where does the energy come from to drive the transport of ions across the cell membrane?

Workings

a. Na^+ and K^+

b. When the nerve is stimulated the Na^+ concentration within the cell increases by Na^+ ions moving inwards from the outside.

When there is equilibrium between the Na^+ and K^+ ions, sodium ions stop moving inwards because the Na^+ ion channels close.

K^+ ion channels open and K^+ ions move out.

The K^+ concentration within the cell decreases.

c. ATPase

d. One the inner side of a protein, which is part of an ion channel and positioned across the cell membrane

e. the hydrolysis of ATP.