Membrane transport, Resting membrane potential

for pharmacy students

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SEMMELWEIS EGYETEM 1769

Lecture topics

Topics

- **Cell membrane** (function, structure, semipermeability)
- **Membrane transport**
  - Passive diffusion
    - uncharged particle and ion diffusion
    - permeability coefficient
  - Facilitated diffusion (channels, carriers, ionophores)
  - Active transport
- **Membrane potential**
  - Characteristics
  - Generation
    - Nerst equation
    - Donnan potential
    - Goldman-Hodgkin-Katz equation

Related practice topics

- Sensor
- ECG
- Diffusion

Textbook chapters

- III/4.1. Transport phenomena in resting cells
- III/4.2. Resting membrane potential

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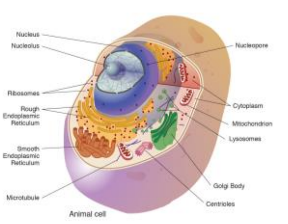
Cell membrane function



https://www.genome.gov/genetics-glossary/Cell

Cell

- The basic structural and functional unit of life.
- „cellula" (lt.) = small room
- Prokaryotic and eukaryotic cell types.
- Each cell has cytoplasm and cell membrane (plasma membrane)

Function of cell membrane: barrier that precisely controls the level of solutes inside and outside the cell.

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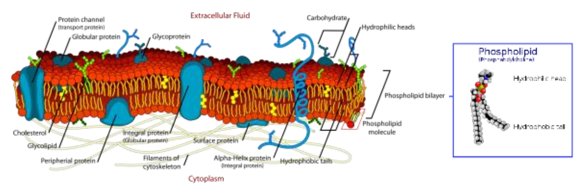
Cell membrane structure



https://commons.wikimedia.org/wiki/File:Cell_membrane_detailed_diagram_en.svg

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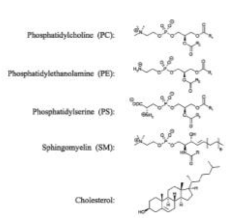
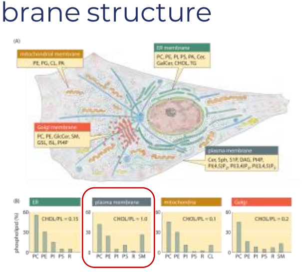
Cell membrane structure



Brandon J. Payliss, et al. Chemistry and Physics of Lipids, 193,2015,36-51.



Cell Biology by the Numbers. Figure adapted from G. van Meer et al., Nature Mol. Cell Biol., 9:112, 2008.)

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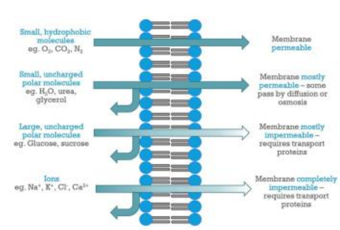
Semipermeability



https://www.wizeprep.com/online-courses/16916/chapter/3/core/3/1

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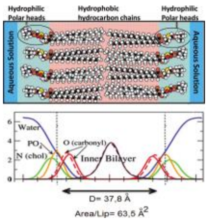
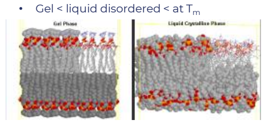
Structure and semipermeability



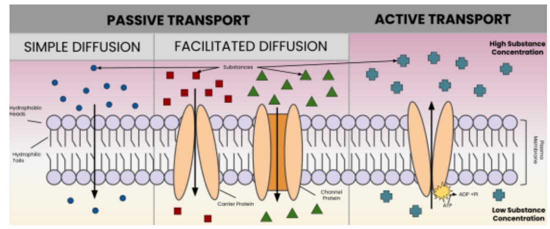
Disalvo, E; Frias, M (2019). The Role of Water in the Responsive Properties in Lipid Interphase of Biomimetic Systems.

Aspects of semipermeability

- ~40 Å thick hydrophobic membrane core
- Permeability is composition dependent
- Affected by environmental factors
- Tighter packing of fatty acid chains lead to lower permeability
- Gel < liquid disordered < at T_m

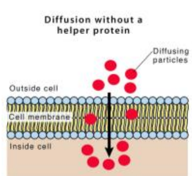


Membrane transport types



https://commons.wikimedia.org/wiki/File:Passive_vs_Active_Membrane_Transport.svg

Passive diffusion of uncharged particles



https://www.sciencefacts.net/simple-diffusion-vs-facilitated-diffusion.html

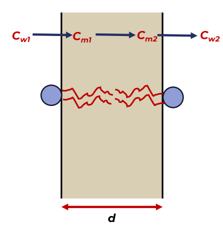
- Energy source: (electro)chemical gradient of the solute
- Passive diffusion requires no additional energy source.
- Steps:
  - solute must first lose its waters of hydration
  - diffuse across the membrane
  - and then regain its waters on the opposite side.
- The limiting step involves the energy required to lose the waters of hydration.

TABLE 19.2 Relationship Between the Waters of Hydration (Number of –OH Groups on a Homologous Series of Solutes) and the Activation Energy for Transmembrane Diffusion

Solute	Activation energy (kJ/mol)
Glycol (HO–CH$_2$–CH$_2$–OH)	60
Glycerol (HO–CH$_2$–CH(OH)–CH$_2$–OH)	77
Erythritol (HO–CH$_2$–CH(OH)–CH(OH)–CH$_2$–OH)	87

W. Stilwell: An Introduction to Biological Membranes (2016) http://dx.doi.org/10.1016/B978-0-444-63772-7.00019-1

Passive diffusion of uncharged particles



Fick's first law:

$$J_m = -D \cdot \frac{\Delta c}{\Delta x}$$

$$J_m = -D_m \cdot \frac{c_{m2} - c_{m1}}{d}$$

Adolf Fick 1829-1901

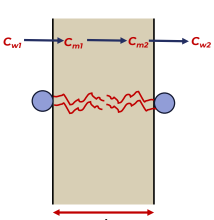
J_m: *material flux density*

D: *diffusion coefficient*

$\frac{\Delta c}{\Delta x}$: *conc. gradient*

D_m: *membrane diff. coeff.*

Permeability coefficient I.



$$J_m = -D_m \cdot \frac{c_{m2} - c_{m1}}{d}$$

$$p_m = \frac{D_m}{d}$$

membrane permeability constant $[\frac{m}{s}]$

$$J_m = -p_m \cdot (c_{m2} - c_{m1})$$

$$\frac{c_{m1}}{c_{w1}} = \frac{c_{m2}}{c_{w2}} = constant = K$$

partition coefficient

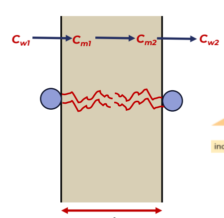
$$J_m = -p_m \cdot K(c_{w2} - c_{w1})$$

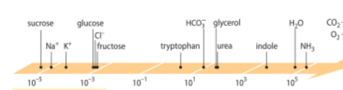
$$p = p_m \cdot K$$

permeability coefficient $[\frac{m}{s}]$

Material flux density (Fick I.): $J_m = -p(c_{w2} - c_{w1})$

Permeability coefficient II.





http://book.bionumbers.org/what-is-the-permeability-of-the-cell-membrane/

Permeability coefficient III.

leakage timescale through membrane (rapid if small molecule is uncharged e.g., glycerol)

$$\text{flux} = \frac{\text{number}}{\text{area} \times \text{sec}} \Longrightarrow \text{total amount lost} = \underbrace{p \times (c_{in} - c_{out})}_{\text{flux}} \times \underbrace{A}_{\text{total area}}$$

(p: permeability)

leakage timescale, τ

$$\tau = \frac{\text{number of molecules inside}}{\text{amount lost each second}} = \frac{V \times c_{in}}{p \times A \times (c_{in} - c_{out})} = \frac{c_{in} \times \frac{4}{3}\pi r^3}{c_{in} \times p \times 4\pi r^2} = \frac{r}{3p}$$

assume $c_{out} = 0$

for glycerol in *E. coli*

$$\tau = \frac{r}{3p} = \frac{1}{3} \times \frac{10^{-6}\,\text{m}}{4 \times 10^{-8}\,\frac{\text{m}}{\text{s}}} = 10\,\text{s}$$

(10^{-6} m: bacterial cell size; 4×10^{-8} m/s: glycerol permeability)

so if the similar glyceraldehyde used in glycolysis was not phosphorylated it would rapidly leak from cell

http://book.bionumbers.org/what-is-the-permeability-of-the-cell-membrane/

Passive diffusion of ions

Onsager equation:

$$J = L \cdot X$$
$$X = \frac{-\Delta\mu}{\Delta x}$$
$$\mu = \mu_0 + RT \cdot \ln c$$

Fick's first law

$$J = -\frac{LRT}{c} \cdot \frac{\Delta c}{\Delta x}$$

($\frac{LRT}{c}$: D)

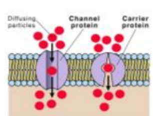
For a charged particle (k):

$$J_k = L_k \cdot X_k = -L_k \cdot \frac{-\Delta\mu_e}{\Delta x} = -D_k\left(\frac{\Delta c_k}{\Delta x} + c_k \frac{z_k F}{RT} \frac{\Delta\varphi}{\Delta x}\right)$$

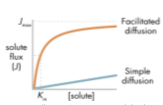
J_k: flux density of k[th] particle; $\frac{-\Delta\mu_e}{\Delta x}$: electrochemical potential gradient; $\frac{\Delta c_k}{\Delta x}$: concentration gradient; $\frac{\Delta\varphi}{\Delta x}$: electric potential gradient

J_m: material flux density
D: diffusion coefficient
$\frac{\Delta c}{\Delta x}$: conc. gradient
J: flux density
L: conductivity coeff.
X: thermodynamic force
μ: chemical potential
μ_0: molar free enthalpy
R: univ. gas constant
μ_e: electrochemical potential
F: Faraday constant
z: valency
φ: electric potential

Facilitated diffusion



https://www.sciencefacts.net/simple-diffusion-vs-facilitated-diffusion.html



https://neurotext.library.stonybrook.edu/C1/C1_7/C1_7.html

- Energy source: inherent solute **electrochemical gradient**
- Gradient determines direction (**theoretically reversible**)
- No additional energy is required to transport the solute
- Final solute distribution reaches equilibrium across the membrane.
- Orders of magnitude **faster rate** than passive diffusion
- Protein-based **mediator molecules** embedded in the membrane
- **Strongly selective** for certain particles
- Exhibits Michaelis-Menten **saturation** kinetics
- Can be selectively **inhibited**
- Mediators: carriers, gated ion-channels, ionophores

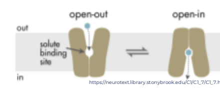
Facilitated diffusion

I. Channel proteins

- Transport mainly ions
- Supramolecular structures of several subunits → span the membrane → hydrophilic core is formed
- No conformational change during transport
- Gating: stimuli-responsive conformational change → opens or closes the channel
- Stimuli: voltage; ligand; second messenger; mechanics
- Rate cca. 10^6 s^{-1}

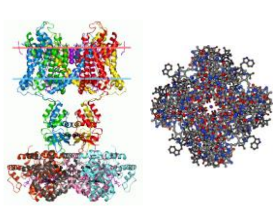
II. Carrier proteins

- Integral membrane proteins
- Bind specifically an ion or molecule
- Reversible conformational change enables the transport
- $E_{activation}$ is given by the bindig energy of substrate
- Min. 100x slower than channel proteins

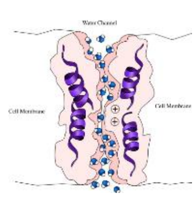


https://neurotext.library.stonybrook.edu/C1/C1_7/C1_7.html

Facilitated diffusion - examples



Potassium channels

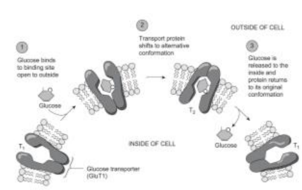


Aquaporin channels

Facilitated diffusion - examples

Glucose transporters (GLUT)

- Superfamily of carrier proteins
- Occur in nearly all cells
- Abundant in small intestines
- Integral membrane proteins
- 12 alpha helices in membrane spanning region.
- Activation energy of glucose should be > 100 kJ/mol (passive diffusion)
- BUT it is only 16 kJ/mol (with GLUT).

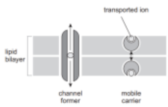


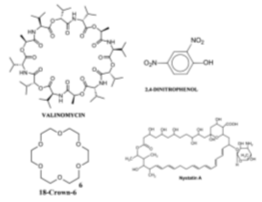
W. Stilwell: An Introduction to Biological Membranes (2016) http://dx.doi.org/10.1016/B978-0-444-63772-7.00019-1

Facilitated diffusion

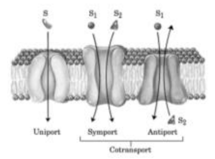
III. Ionophores („Ion bearers")

- Small, lipid soluble molecules of usually microbial origin
- **Channel formers:** long lasting, stationary structures; many ions at a time; rapid flow across a membrane.
- **Mobile carriers:** ion binding on one side of a membrane; dissolving; membrane crossing; release. They can only carry one ion at a time.





Active transport



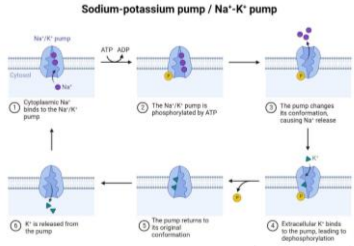
W. Stillwell: An Introduction to Biological Membranes (2016) http://dx.doi.org/10.1016/B978-0-444-63772-7.00019-1

Characteristics

- Particles are transported against gradient → nonequilibrium distribution of solutes accross the membrane
- Requires energy! Possible sources:
  - ATP hydrolysis – ATPases
  - Light – photo transporters
  - Electrochemical gradient of another substrate – coupled (secondary) active transporters
- Uniporters / co-transporters
- Symporters / antiporters

Active transport - examples

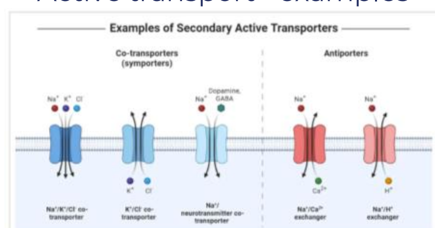
Sodium-potassium pump / Na^+-K^+ pump



https://thebiologynotes.com/active-transport/

- ATPase
- antiporter
- accounts for one-third of human energy expenditure
- 3 Na^+ out / 2 K^+ in
- electrogenic
- Blocker: ouabain, digoxin

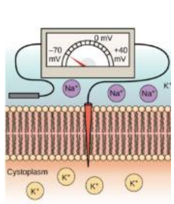
Active transport - examples



Secondary Active Transport

https://thebiologynotes.com/active-transport/

Membrane potential

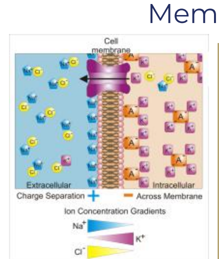


https://courses/lumenlearning.com/wm-biology2/chapter/resting-membrane-potential/

Transmembrane potential / Membrane voltage / „Resting membrane potential"

- Electric potential difference between inner and outer surface of the membrane
- Present in all living cell
- Varies among cell types (-30 mV to -90 mV)
- Negative sign: cell interior is negative compared to extracellular space
- Functions:
  - providing power to operate a variety of "molecular devices" embedded in the membrane (cell as battery)
  - in electrically excitable cells such as neurons and muscle cells, it is used for transmitting signals between different parts of a cell

Membrane potential



By Synaptidude, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=21460910

- Two sides of the membrane has different ionic composition

	Intracellular concentration [mM]			Extracellular concentration [mM]		
Cell type	Na^+	K^+	Cl^-	Na^+	K^+	Cl^-
Squid giant axon	72	345	61	455	10	540
Frog muscle	20	139	3,8	120	2,5	120
Rat muscle	12	180	3,8	150	4,5	110

- Large phosphate and protein anions inside – p ~ 0
- p is different for the different ions
- Electric and chemical potential difference occurs between the two sides.

Generation of membrane potential I.

Model 1

Presumptions:

- Closed thermodynamic system
- Membrane permable to ions
- Cytoplasm and extracellular space are in thermodynamic **equilibrium** – for **each** ion!
- No net transport of ions
- Thermodynamic force is 0
- Electrochemical potential is the same at the two sides for each type of ion:

$$\mu_{e,i}^{int} - \mu_{e,i}^{ext} = 0$$

$$\mu_0 + RTlnc_i^{ext} + zF\varphi_i^{ext} = \mu_0 + RTlnc_i^{int} + zF\varphi_i^{int}$$

$$\varphi_i^{int} - \varphi_i^{ext} = U_0 = \frac{RT}{z_i F} ln \frac{c_i^{ext}}{c_i^{int}}$$ Nerst equation

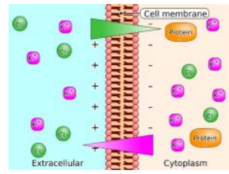
Electric potential of i^th ion in equilibrium = equilibrium potential = electromotive force of a concentration cell of the i^th ion

	Squid giant axon	Frog muscle
$U_{measured}$	-62 mV	-92 mV
U_{0Na+}	47 mV	46 mV
U_{0K+}	-91 mV	-103 mV
U_{0Cl-}	-56 mV	-88 mV

Results: model failed

- Nerst equation is inadequate to interpret resting potential
- It is not a closed system in equilibrium
- Transport of individual ions is not independent

Generation of membrane potential II.



Donnan equilibrium (Gibbs-Donnan effect)

- Closed thermodynamic system
- Presence of nonpermeable charged particles in one side of a membrane leads to noneven distribution of ions (passive process!).
- Membrane is permeable only to K^+ and Cl^-
- Electroneutrality at the two sides,
- Electrochemical potential is the same at the two sides.

Donnan potential:

- Equilibrium potential difference due to ionic concentration differences (determinded by the presence of nondiffusible anions)
- Typical value: U_{Donnan} ~ -14 mV → relatively small contribution to membrane potential.

Generation of membrane potential III.

Goldman-Hodgkin-Katz equation

- Passive ion diffusion maintains an electric potential difference
- Permeability is different for different ions
- Flux of individual ions ≠ 0
- At rest the transmembrane potential difference is constant →, total electric charge and particle flux must be 0.
- Thus, flux of ions may depend on each other

Steady state elecrodiffusion:

- Constant electrochemical potential gradient → constant flow of ions → electrically compensate each other → no net charge accumulation
- Na+/K+ pumps maintains constant ion

flux density of k^th particle:

$$J_k = -u_k kt(\frac{\Delta c_k}{\Delta x} + c_k \frac{z_k F}{RT}\frac{\Delta\varphi}{\Delta x})$$

D ; *electric potential difference* ; *electrochemical potential gradient*

$$\Sigma J_k = 0$$

$$U = \Delta\varphi = \frac{RT}{F} ln \frac{p_{K^+}[K^+]_{ext} + p_{Na^+}[Na^+]_{ext} + p_{Cl^-}[Cl^+]_{int}}{p_{K^+}[K^+]_{int} + p_{Na^+}[Na^+]_{int} + p_{Cl^-}[Cl^+]_{ext}}$$

	Squid giant axon	Frog muscle
$U_{measured}$	-62 mV	-92 mV
U_{GHK}	-61.3 mV	-89.2 mV

Pharmaceutical importance - examples

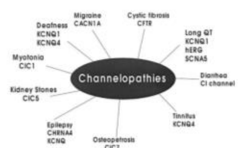


FIG. 2. Channelopathies. Examples of diseases associated with dysfunction of ion channels and the specific ion channel species involved.

TABLE 3
Ion channel modulator drugs on the market

Ion channel mechanism	Drug	Indication
Cl^- channel activators	Benzodiazepines: Nitrazepam, Lorazepam, Clonazepam, Diazepam	Anti-anxiety, Insomnia, Epilepsy, Anti-spastics
K_{ATP} channel blockers	Sulphonylureas: Tolbutamide, Glibenclamide, Glipizide	Type II diabetes
K^+ channel blocker	Amiodarone, Dofetilide, Sotalol	Cardiac arrhythmia
Ca^{2+} channel blockers	Verapamil, Nifedipine, Diltiazem, Amlodipine, Felodipine, Lacidipine	Cardiac arrhythmia, Arterial hypertension
Na^+ channel blockers	Lidocaine, Lamotrigine, Phenytoin, Carbamazepine	Local anesthesia, Epilepsy
	Chinidine, Disopyramide, Mexiletine	Cardiac arrhythmia

Willumsen, Niels & Bech, Morten & Olesen, Søren-Peter & Jensen, Bo & Korsgaard, Mads & Christophersen, Palle. (2003). High Throughput Electrophysiology: New Perspectives for Ion Channel Drug Discovery. Receptors & channels. 9. 3-12. 10.1080/10606820308259.

Thanks for your attention!

Dr. Tamás Bozó

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