神経細胞の電気的等価回路と静止膜電位

細胞の電気的等価回路の意義

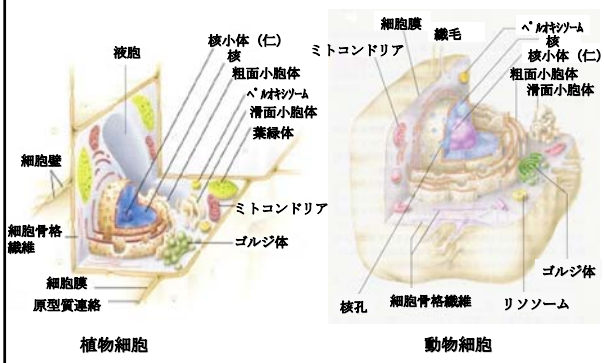
1. 細胞の膜電位の物理化学的機構の理論的解明
2. 神経細胞や筋細胞などの信号伝達及び運動特性の数理的表現
3. 人工神経や人工筋肉開発の基礎理論の確立

背　景

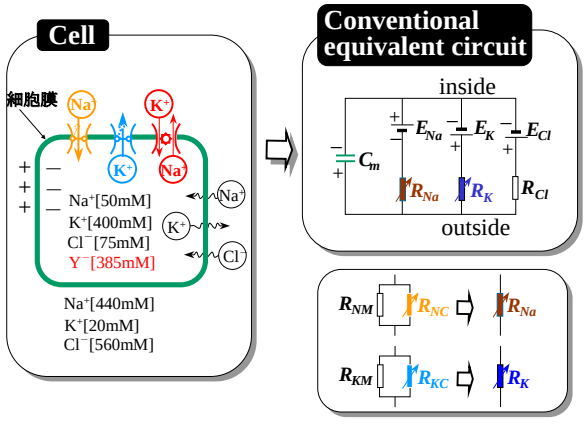
1. Hodgkin-Huxley の電気的等価回路は神経細胞の電気的特性を十分には説明できない
2. 静止膜電位の生成に関連する理論的検討が不十分である.

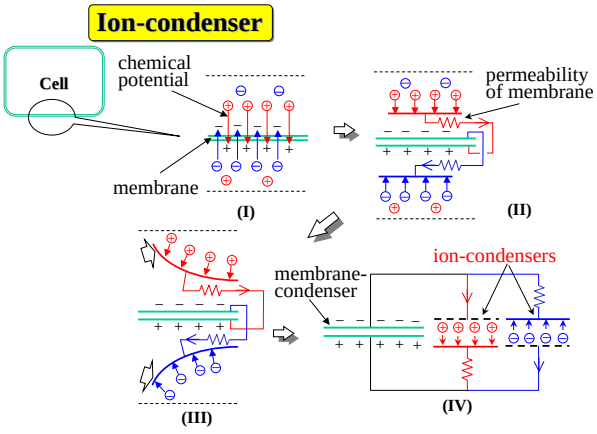
目　的

1. 細胞膜の電気的等価回路を新たに提案する
2. 膜電位の生成に関連する要因を数理的に記述する



植物細胞　　動物細胞





Normal condenser (linear condenser)

$q = C \cdot V$

q **: electrical charge**
***V*: voltage**
***C*: capacity of condenser**

Ion-condenser (nonlinear condenser)

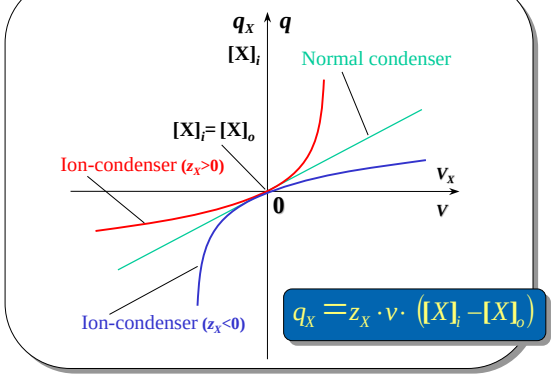
$$q_X = Z_X \cdot \nu \cdot \left([X]_i - [X]_o\right)$$

$$[X]_i = [X]_o \cdot e^{\frac{Z_X F}{RT} V_X} \quad \text{(Nernst's equation)}$$

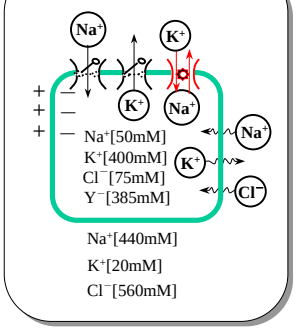
$$q_X = Z_X \cdot \nu \cdot [X]_o \cdot \left(e^{\frac{Z_X F}{RT} V_X} - 1\right)$$

q_X **: electrical charge of intracellular ion X**
V_X **: voltage of ion-condenser, i.e., chemical potential of ion X**
$[X]_i$, $[X]_o$**: concentration of extra and intracellular ion X**
z_X **: valence of X**
ν **: volume of internal flux of cell**

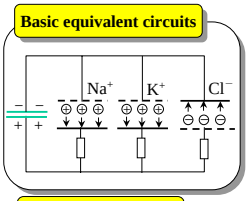
Relation of electrical charge to voltage



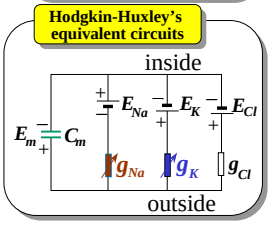
Ion transportation through the membrane of a cell



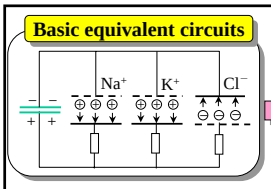
Basic equivalent circuits



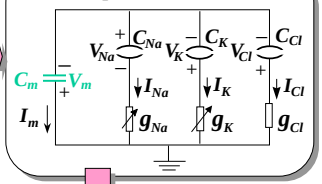
Hodgkin-Huxley's equivalent circuits



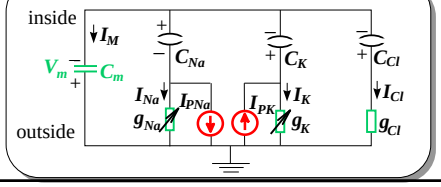
Basic equivalent circuits



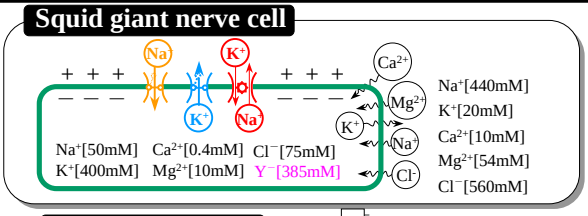
Equivalent circuit using the concept of ion-condenser



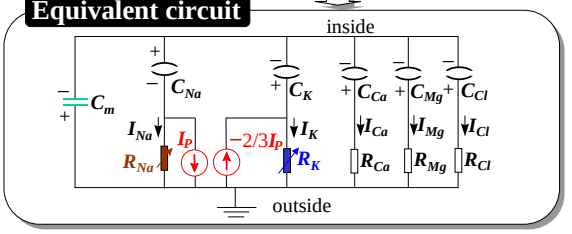
Equivalent circuit including ion-pump



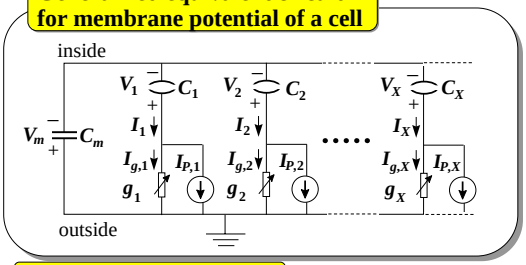
Squid giant nerve cell



Equivalent circuit



Generalized equivalent circuit for membrane potential of a cell

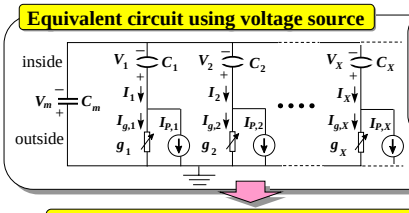


In the steady state of a cell

$$V_X = V_m - \frac{I_X}{g_X} = V_m + \frac{I_{PX}}{g_X} \qquad \sum_X q_X + \sum_Y q_Y = q_m \approx 0$$

$$q_X = z_X \nu [X]_o \left(e^{-\frac{z_X F}{RT} V_X} - 1\right) \qquad q_Y = \nu z_Y [Y]_i$$

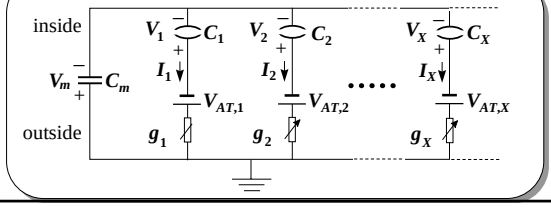
Equivalent circuit using voltage source



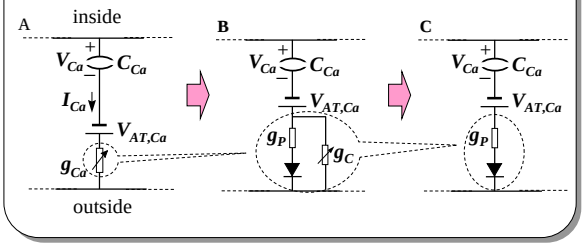
$$V_X - V_m = \frac{I_{g,X}}{g_X} = \frac{I_X - I_{P,X}}{g_X} = \frac{I_X}{g_X} - V_{AT,X}$$

$$V_{At,X} = \frac{I_{PX}}{g_X}$$

Equivalent circuit using voltage source



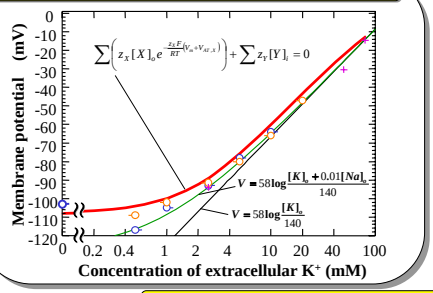
Equivalent conductance in case of Ca^{2+} that has no passive transport



g_C : equivalent conductance of Ca^{2+} channels.

g_P : equivalent conductance of Ca^{2+} pump.

Estimated results (red line) using the equation



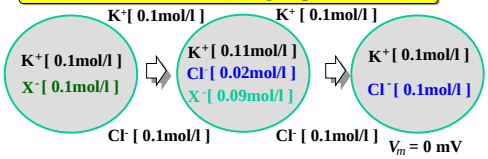
Solutions used in experiments by Hodgkin and Horowicz.

K^+	Na^+	Ca^{2+}	HPO_4^{2-}	$H_2PO_4^{2-}$	SO_4^{2-}
← (mM) →					
0 ~ 80	83 ~ 3	8	1.08	0.43	48

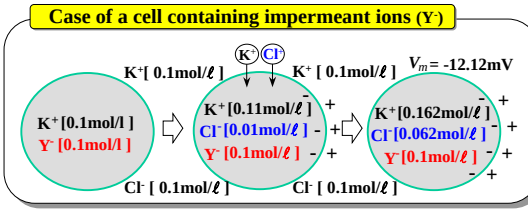
This solutions have same tonicity and ionic strength as Ringger's fluid

Flow of ions through membrane

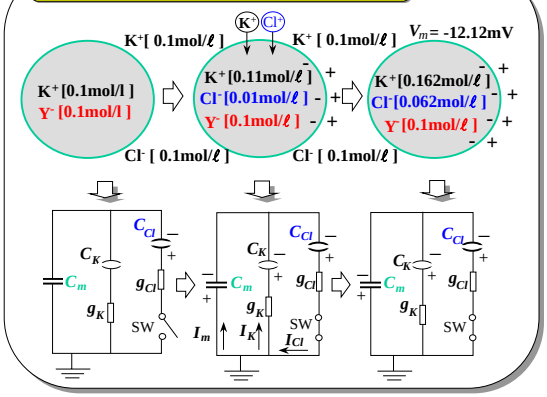
Case of a cell not containing impermeant ions



Case of a cell containing impermeant ions (Y^-)



Equivalent circuit of a cell in case of the cell containing impermeant ions (Y^-)



Generalized equation for resting membrane potential

$$\sum_X \left\{ z_X [X]_o \, e^{-\frac{z_X F}{RT}\left(V_m + \frac{I_{PX}}{g_X}\right)} \right\} + \sum_Y \left\{ z_Y [Y]_i \right\} = 0$$

$V_{At,X} = \frac{I_{PX}}{g_X}$: active transport potential of ion X

X:permeant ion;
Y: impermeant ion;
z_X:valence of X z_Y: valence of Y
I_{PX}: active transport flux of X

一定温度下での静止膜電位に影響するパラメータ

(1) 細胞外液の透過性イオンの濃度とその価数
(2) 細胞内不透過性陰イオンの濃度とその価数
(3) イオンポンプのイオン輸送能力
(4) 能動輸送されるイオンに対する膜の透過性
(5) 細胞周辺の温度