Using biological cells as source of electrical energy

Luigi Catacuzzeno
Dept. Chemistry, Biology and Biotechnology, University of Perugia

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Cells are the "building blocks" of life

The cell is the basic structural, functional, and biological unit of all known organisms. A cell is the smallest unit of life. A living organism is formed by about $10^{12}$ cells.

Similar cells join together to form tissues. Different tissues join together to form organs. Organs work together to form systems.
There are different types of cells in a living organism.

Red blood cells  Nerve cells  Reproductive cells

Not all cells are the same. Different cells have different functions.
Cells are delimited by a plasma membrane

The plasmamembrane delimits the cell and separates it from the extracellular ambient.

Functions of the plasmamembrane:

• exchange of water, ions, nutrients and waste substances with the extracellular space

• Reception and interpretations of signals coming from other cells

• Shape determination
The main component of the plasma membrane are phospholipids.

Phospholipids in water solution spontaneously organized to form bilayers.
Other components of the plasma-membrane are proteins and carbohydrates.

**Proteins**

**Carbohydrates**
Structure of the plasma-membrane: the fluid mosaic model (Singer and Nicholson, 1972)
Ions permeate the plasma-membrane only with the help of transmembrane proteins.
Passive and active ion transporters

**Passive transport**: ions move along their electrochemical gradient. No additional energy is required since this is a spontaneous process.

**Active transport**: ions move against their electrochemical gradient, using the energy derived by adenosine triphosphate.
Passive transport of ions is mediated by ion channels

Ion channels are integral membrane proteins forming a hydrophilic pore where ions may easily permeate.

Main properties of ion channels

1. Selectivity for one or few ions
2. Gating: The pore opens and closes depending on the conditions
Permeation through ion channels

Goldman assumption: constant electric field inside the membrane \((dU/dx = \text{constant})\).

\[ f = -D \frac{dC}{dx} - \frac{D z F}{RT} C \frac{dV}{dx} \]

Nernst-Planck equation

\[ I = P \frac{z^2 F^2}{RT} V \frac{C_{in} - C_{ex}}{1 - e^{-\frac{zFV}{RT}}} \]

Goldman-Hodgkin-Katz equation

\[ I = g (V - V_{in}) \]

Ion channels are ohmic devices

\[ V_{in} = \frac{RT}{z F} \ln \frac{C_{ex}}{C_{in}} \]

Graph showing the relationship between voltage and current.
Active transport of ions: The Na/K ATPase

ATP hydrolysis is coupled to the transport of ions

\[
\text{turnover rate} = \frac{\rho_{\text{max}}}{\left(1 + e^{\frac{25 - [Na]/i}{3}}\right)\left(1 + e^{3.5 - [K]/e}\right)}
\]
The activity of the Na/K ATPase is responsible for a permanent ionic gradient across the plasma membrane.

\[ [\text{Na}]_i = 10 \text{ mM} \]
\[ [\text{K}]_i = 135 \text{ mM} \]
\[ [\text{A}]_i = 145 \text{ mM} \]
\[ [\text{Na}]_e = 142 \text{ mM} \]
\[ [\text{K}]_e = 3 \text{ mM} \]
\[ [\text{A}]_e = 145 \text{ mM} \]

**Power absorbed by the Na/K ATPase**

Turnover rate of the Na/K ATPase: 25 - 80 ATP/s (Liang et al., 2007)

Number of Na/K ATPase in a typical cell: \(8 \times 10^4 - 3 \times 10^7\) (Liang et al., 2007)

Overall turnover: \(3 \times 10^{-6} - 4 \times 10^{-3}\) pmol ATP/s

Energy delivered by the hydrolysis of one ATP molecule: 7.3 kcal/mol

Power absorbed by Na/K ATPase in a typical cell: 0.1 pW – 100 pW
Biological cells possess an electric potential difference across the plasma-membrane

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Resting membrane potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neurons</td>
<td>-60/-75 mV</td>
</tr>
<tr>
<td>Skeletal muscle cells</td>
<td>-90 mV</td>
</tr>
<tr>
<td>Cardiac muscle cells</td>
<td>-85 mV</td>
</tr>
<tr>
<td>Epithelial cells</td>
<td>-20 mV</td>
</tr>
<tr>
<td>Glial cells</td>
<td>-80 mV</td>
</tr>
<tr>
<td>Red blood cells</td>
<td>-15 mV</td>
</tr>
</tbody>
</table>
Mechanism of generation of the electric potential difference across the plasma-membrane

1. Na/K ATPases accumulate K ions inside the cell
2. The accumulated K ions then leave the cell through K channels, creating a charge separation
Mechanism of generation of the electric potential difference across the plasma-membrane

Needed conditions:
1. It exists an ionic gradient between the inside and outside of the cell
2. The plasma-membrane is differentially permeable to the different ionic species

\[ \Delta G_{el} = \Delta G_{ch} \]

\[ zF V_m = RT \ln \frac{C_{ex}}{C_{in}} \]

\[ V_m = \frac{RT}{zF} \ln \frac{C_{ex}}{C_{in}} \quad \text{eq. di Nernst} \]

\[ I = P \frac{z^2 F^2}{RT} V \frac{C_{in} - C_{ex}}{1 - e^{-\frac{zFV}{RT}}} \]

\[ I = 0 \text{ at } V = V_m \]
The membrane potential difference across the plasma-membrane depends on the ion concentrations and membrane permeabilities

\[ I = P_i \frac{z_i^2 F^2}{RT} V \frac{C_{i,\text{in}} - C_{i,\text{ex}} e^{-\frac{z_i F V}{RT}}}{1 - e^{-\frac{z_i F V}{RT}}} + P_j \frac{z_j^2 F^2}{RT} V \frac{C_{j,\text{in}} - C_{j,\text{ex}} e^{-\frac{z_j F V}{RT}}}{1 - e^{-\frac{z_j F V}{RT}}} + \ldots \]

\[ I = 0 \quad \text{quando} \quad V = V_m \]

\[ V_m = \frac{RT}{F} \ln \left( \frac{\sum P_C C_{c,\text{ex}} + \sum P_A C_{A,\text{ex}}}{\sum P_A C_{A,\text{ex}} + \sum P_C C_{C,\text{ex}}} \right) \]

If the membrane is particularly permeable to an ion type, that ion will contribute very much to establish the resting membrane potential.
Can we extract the energy accumulated in the electric Potential difference of a cell? How much power may we extract from a typical cell?
The plasma-membrane may be assimilated to an electrical circuit, and each plasma-membrane component behaves as a particular circuit elements.

- **Specific Capacitance of a biological membrane:** 1 µF/cm²
- **Na/K ATPase:**
  - Inputs: ATP, ADP + P
  - Outputs: 2 K, 3 Na
- **Resistor connected to a battery**
- **Current Generator**
Equivalent electrical circuit for a plasma-membrane

\[
\frac{dV_m}{dt} = -\frac{I_m}{C_m}
\]

\[
I_m = I_p + \sum g (V_m - V_{inv})
\]
Model of the electric behaviour of a cell during energy harvesting

\[
\frac{dV_m}{dt} = -\frac{I_m}{C_m}
\]

\[
\frac{d[\text{ion}]}{dt} = -\frac{I_{\text{ion}}}{z F V \text{ol}}
\]

\[P = I_L V_m\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r)</td>
<td>Cell radius</td>
<td>7 µm</td>
</tr>
<tr>
<td>(C_S)</td>
<td>Specific membrane capacitance</td>
<td>0.01 pF/(\mu\text{m}^2)</td>
</tr>
<tr>
<td>(g_{KS})</td>
<td>Specific K channel conductance</td>
<td>5*10^{-4} nS/(\mu\text{m}^2)</td>
</tr>
<tr>
<td>(g_{Na})</td>
<td>Specific Na channel conductance</td>
<td>1*10^{-4} nS/(\mu\text{m}^2)</td>
</tr>
<tr>
<td>(g_{Cl})</td>
<td>Cl channel conductance</td>
<td>1*10^{-3} nS/(\mu\text{m}^2)</td>
</tr>
<tr>
<td>(R_L)</td>
<td>Load resistance</td>
<td>variable</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Maximal turnover of the Na/K ATPase</td>
<td>133 ATP/s</td>
</tr>
<tr>
<td>(D_{\text{ATPase}})</td>
<td>Density of Na/K ATPase</td>
<td>3350/(\mu\text{m}^2)</td>
</tr>
<tr>
<td>(K_O)</td>
<td>Extracellular K concentration</td>
<td>3 mM</td>
</tr>
<tr>
<td>(N_{A_0})</td>
<td>Extracellular Na concentration</td>
<td>142 mM</td>
</tr>
<tr>
<td>(C_{l_0})</td>
<td>Extracellular Cl concentration</td>
<td>145 mM</td>
</tr>
<tr>
<td>(nAA_i)</td>
<td>Intracellular impermeable anions</td>
<td>0.198 pmol</td>
</tr>
</tbody>
</table>
Estimation of the power harvested from a typical cell

\[ R_L = \infty \quad R_L = 3 \, G\Omega \]

**Efficiency**: harvested power/power absorbed by the Na/K ATPase \( 1 \, \text{pW}/(50 \, \text{pW}) = 2 \% \)
Skeletal muscle cells are very big and a much higher energy is absorbed by Na/K ATPases

Power absorbed by the Na/K ATPase

Turnover rate of the Na/K ATPase: 130 ATP/s (Plesner, 1981)
Number of Na/K ATPase in muscle cells: 3350 /µm² (Clausen, 2003)
Overall turnover: 2.27 pmol ATP/s
Energy delivered by the hydrolysis of one ATP molecule: 7.3 kcal/mol

Power absorbed by Na/K ATPase in a typical cell: 70 nW
Estimation of the power harvested from a skeletal muscle cell

\[ R_L = \infty \quad R_L = 1 \, M\Omega \]

**Efficiency**: harvested power/power absorbed by the Na/K ATPase:
5 nW/(70 nW) = 7.1%
Experimental proof of concept in Xenopus oocytes
Energy may be harvested from a single oocyte and used later for wireless communication.
Energy may be harvested repeatedly from the same cell.
Experimental proof-of-concept on myotubes

- Differentiation
- Migration and adhesion
- Fusion
- Fusion with myotubes

Myoblasts
Myocytes
Nascent myotubes
Mature myotubes
Energy may be harvested from a single myotube and stored in a capacitor.
Skeletal muscle fibers recorded from mice provide a relatively high energy
Conclusions

- Biological cells have an electrical potential difference across their plasmamembrane.
- Electrodes inserted inside cells may be used to harvest energy from the plasmamembrane potential difference.
- Single high-dimension biological cells are able to provide powers small but likely sufficient to let next generation biosensors.
- The harvested energy can be stored over time to reach values sufficiently high to operate a wireless system for a limited time.
Perspectives

Bio-cell energy harvester

Energy management module

Detector → A/D Converter → Wireless communication module

Biosensor