9. Bioelectricity

- Action potential
- Electrodes
- Bioelectric signals
- Body surface recordings

Ion Channels

- Repolarization
- Hyperpolarization
- Overshoot

Action Potential (AP)

Glass Micropipette

The tip diameter for intracellular recording is less than 1 μm, and the taper angle is 1-15°.
Micropipette & Red Blood Cell

A micropipette (0.2μm) is punctured into a red blood cell.

0.2μm

7-8μm

AP Measurement in a Cell

Tip is small and thin, micropipette has very high resistance and a large capacitance to the surrounding solution (D=0.5 um, R=10 MΩ, C=2 pF, Tc=20ms).

\[ C_f = \frac{C + C_w + C_A}{A-1} \]

Input capacitance neutralization

highly conductive solution

The electrode tip penetrates the cell membrane without disturbing its function or leaking the cytoplasm.

Micropipette Fabrication

(a) Sectional view of a fine-bore glass capillary

(b) Glass narrowed by heating & stretching

A part of a glass capillary is heated to the melting point and pulled by solenoid with specific tension and speed.

(c) Micropipette electrode

Electrode-electrolyte Interface - 1

If a metal is introduced in an electrolyte solution, a double layer is formed close to the metal surface and called electrode-electrolyte interface. A net current \( I \) will cross the interface from electrode to electrolyte. It consists of 3 components:

1. Electrons \( e^- \) moving in an opposite direction with the net current \( I \)
2. Anions (A\(^-\)) moving in an opposite direction with the net current \( I \)
3. Cations (C\(^+\)) moving in a same direction with the net current \( I \)

Net current \( I \)

oxidation reaction

reduction reaction

Electrode

metal with "metallic" atoms

Electrolyte

solution containing cations of the electrode metal C\(^+\) and anions A\(^-\).
Electrode-electrolyte Interface - 2

General Ionic Equations
\[ C \leftrightarrow C^{n+} + ne^- \]
\[ A^{m-} \leftrightarrow A + me^- \]

- If electrode has same material as cation, then this material gets oxidized and enters the electrolyte as a cation and electrons remain at the electrode and flow in the external circuit.
- If anion can be oxidized at the electrode to form a neutral atom, one or two electrons are given to the electrode.

The dominating reaction can be inferred from the following:
- Current flow from electrode to electrolyte: Oxidation (Loss e^-)
- Current flow from electrolyte to electrode: Reduction (Gain e^-)

Charge Distribution in Double Layer

- **Helmholtz layer**
  - A layer of ions tightly bound to the electrode surface and an adjacent layer of oppositely charged ions in the solution.
- **Gouy layer**
  - A diffused charge distribution exists adjacent to the Helmholtz layer.
- **Stern layer**
  - A fixed layer contains more negative charges than are required to balance a positive charge on the electrode.
- **Pure-Gouy layer**
  - Charge distribution consists entirely of the diffused Gouy layer.

Particular charge distribution depends on the species of electrode **metal** and the type of **electrolyte**, and determines electrode properties.

Half-Cell Potential

\[ M(s) \leftrightarrow M^+(aq) + e^- \]

- When the metal contacts with the solution containing ions of that particular metal, the reaction begins immediately. Metal atoms lose their electrons and the resulting positive ions enter the solution. Electrons left on the metal, and lead to the metal negative charged. Ions make the solution positively charged.
- If this process continues indefinitely, all the metal would dissolve. This process will stop because the increasing negative charge on the metal drags back ions from the solution to the metal, where electrons and ions make metal atoms again.
- The reaction goes either way depending on the cation concentration in the solution.
- When the equilibrium is set up, the region surrounding the metal is at a different potential from the rest of the solution. The potential difference (half-cell potential) is determined by the metal, the concentration of its ions in the solution, temperature and etc.

Cell Potential

**Salt bridge** is a filter paper soaked in potassium chloride or potassium nitrate solution, allows the ions to flow from one half-cell to another but prevents the solution flow, therefore forms a loop for electrical circuit.

Difference in charge between a metal and its solution sets up a half-cell potential, or electrode potential of the metal. Different metals have different electrode potentials. More reactive metals ionize more easily so that leave more electrons (more negative) on the metal in equilibrium.
Half-Cell Potential Measurement

Platinum black is a type of platinum with a large surface area for absorbing hydrogen gas. SHE electrode potential is defined as 0.0V.

Half-Cell Potentials at 25°C

<table>
<thead>
<tr>
<th>Cell</th>
<th>Electrode reaction</th>
<th>Potential, V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al³⁺/Al</td>
<td>Al + 3e⁻ → Al³⁺</td>
<td>−1.66</td>
</tr>
<tr>
<td>Zn²⁺/Zn</td>
<td>Zn + 2e⁻ → Zn²⁺</td>
<td>−0.763</td>
</tr>
<tr>
<td>Fe²⁺/Fe</td>
<td>Fe + 2e⁻ → Fe²⁺</td>
<td>−0.440</td>
</tr>
<tr>
<td>Ni²⁺/Ni</td>
<td>Ni + 2e⁻ → Ni²⁺</td>
<td>−0.250</td>
</tr>
<tr>
<td>Pb²⁺/Pb</td>
<td>Pb + 2e⁻ → Pb²⁺</td>
<td>−0.126</td>
</tr>
<tr>
<td>Ag/AgCl</td>
<td>Ag + Cl⁻ → AgCl + e⁻</td>
<td>+0.2224</td>
</tr>
<tr>
<td>Hg/Hg₂Cl₂</td>
<td>2Hg + 2Cl⁻ → Hg₂Cl₂ + 2e⁻</td>
<td>+0.2681</td>
</tr>
<tr>
<td>Cu²⁺/Cu</td>
<td>Cu + e⁻ → Cu²⁺</td>
<td>+0.337</td>
</tr>
<tr>
<td>Cu⁺/Cu</td>
<td>Cu + e⁻ → Cu⁺</td>
<td>+0.521</td>
</tr>
<tr>
<td>Hg²⁺/Hg</td>
<td>Hg + 2e⁻ → Hg²⁺</td>
<td>+0.797</td>
</tr>
<tr>
<td>Ag⁺/Ag</td>
<td>Ag + e⁻ → Ag⁺</td>
<td>+0.7991</td>
</tr>
<tr>
<td>Au³⁺/Au</td>
<td>Au + 3e⁻ → Au³⁺</td>
<td>+1.50</td>
</tr>
<tr>
<td>Au⁺/Au</td>
<td>Au + e⁻ → Au⁺</td>
<td>+1.68</td>
</tr>
</tbody>
</table>

Polarization - 1

- Half-cell potential of an electrode is measured under condition that **no electric current** exists between the electrode and the electrolyte
- A current can alter half-cell potential due to **polarization** of the electrode
- The **difference** between the **observed** half-cell potential and the equilibrium **zero-current** half-cell potential is called **polarization potential** (overpotential)
  - ohmic polarization potential
  - concentration polarization potential
  - activation polarization potential

Polarization - 2

If there is a current between the electrode and electrolyte, the observed half-cell potential is often altered due to polarization.

\[ V_p = V_r + V_c + V_a \]

**Polarization** and **impedance** are two of the most important properties of an electrode.
Polarization Potential - 1

- Ohmic polarization potential
  - The resistance of the electrolyte
  - A voltage drop along the path of the current in the electrolyte as a result of its resistance
  - Proportional to the current and the resistivity of the electrolyte

- Concentration polarization potential
  - The distribution of ions in the electrolyte in the vicinity of the electrode-electrolyte interface
  - Rates of oxidation and reduction at the electrode-electrolyte interface are no longer equal after a current exists between the electrode and the electrolyte → this change results in a different half-cell potential at the electrode
  - The difference between this and the equilibrium half-cell potential

Polarization Potential - 2

- Activation polarization potential
  - Metal atoms to be oxidized to metal ions that are capable of going into solution, the atoms must overcome an energy barrier → activation energy
  - Reduction reaction plates out an atom of the metal on the electrode, also involves an activation energy
  - When a current flows between the electrode and the electrolyte, either oxidation or reduction predominates, and hence the height of the activation energy depends on the direction of the current
  - This difference in energy appears as a difference in voltage between the electrode and the electrolyte

- Total polarization potential or overpotential of an electrode

\[ V_p = V_r + V_c + V_a \]

Nernst Equation

When two aqueous ionic solutions of different concentration are separated by an ion-selective semi-permeable membrane, an electric potential exists across the membrane.

For the general oxidation-reduction reaction

\[ \alpha A + \beta B \leftrightarrow \gamma C + \delta D + ne^- \]

Half-cell potential by Nernst equation

\[ E = E^0 + \frac{RT}{nF} \ln \left( \frac{a_C^{\alpha} a_D^{\beta}}{a_A^{\alpha} a_B^{\beta}} \right) \]

where, \( E^0 \): Standard half-cell potential
\( a \): Ionic activity (proportional to ionic concentration)
\( n \): Number of valence electrons involved
\( T \): Absolute temperature
\( F \): Faraday constant
\( R \): Gas constant

Electrode

- A transducer to convert ionic current (sodium, potassium, calcium, and chloride ions) in an electrolyte into electron current in a metal wire.
- The transduction can go either way, using the electrodes to measure ionic current or to generate ionic current.
- Electrodes work through redox reactions (reduction and oxidation).
- Oxidation reaction
  - happens at the anode, gains oxygen, donates electrons to the metal wire.
  - reactant loses one or more electrons, becomes more positive in charge.

\[ Ag \rightarrow Ag^+ + e^- \]

- Reduction reaction
  - happens at the cathode, loses oxygen, gets electrons from the metal wire.
  - reactant gains one or more electrons, becomes less positive in charge.

\[ Ag \leftarrow Ag^+ + e^- \]
Polarizable and Nonpolarizable Electrodes

- Perfectly polarizable electrodes
  - Only **displacement current** but **no actual charge** crosses the electrode-electrolyte interface when a current is applied
  - The electrode behaves as though it was a **capacitor**
  - Platinum (Pt) electrode → **stimulation**

- Perfectly nonpolarizable electrodes
  - **Current passes freely** across electrode-electrolyte interface, requiring no energy to make the transition.
  - **No polarization potential** (overpotential)
  - Silver/Silver Chloride (Ag/AgCl) electrode → **detection**

Real electrodes have properties that fall between these idealized limits.

Structure of Ag/AgCl Electrode

![Structure of Ag/AgCl Electrode](image)

Fabrication of Ag/AgCl Electrode

![Fabrication of Ag/AgCl Electrode](image)

Potential of Ag/AgCl Electrode

![Potential of Ag/AgCl Electrode](image)
**Equivalent Circuit of Electrode**

- **Cd**: capacitance of electrode-electrolyte interface
- **Rd**: resistance of electrode-electrolyte interface
- **Rs**: series resistance in the electrolyte and the lead wire
- **Ehc**: half-cell potential of the electrode

**Frequency Property of Electrode**

- Corner frequency ($f_c = 1/2\pi\tau$)
- Cutoff frequency
- Crossover frequency/half-power frequency
- 3 dB frequency
- Break frequency
- Time constant ($\tau = RC$)

- **Cd** is much lower than **Rd** and total impedance closes to **Rd+Rs**.

**Various Layers in Skin**

Constantly renewing, most important in electrode-skin interface. Dead tissue and live tissue have different electrical characteristics.

**Electrode-Skin Interface**

- **Rg**: resistance of interface effects of the gel between electrode and skin
- **Cg**: skin capacitance
- **Rg**: skin resistance
- **Ese**: potential at semipermeable epidermal layer
- **Cp**: capacitance of sweat gland and duct
- **Rp**: resistance of sweat gland and duct
- **Ep**: potential between sweet duct and dermis and subcutaneous layers
- **Rg**: pure resistance in dermis and subcutaneous layers

Skin impedance for 1cm² patch: from 200kΩ@1Hz to 200Ω@1MHz
Body-Surface Electrodes

- Sense ion distribution and convert ion current to electron current
- Electrolyte solution/jelly is placed between electrode and tissue. A chemical reaction occurs at the interface between the electrolyte and the electrode.
- A conductive wire connects the electrode to the instrument.

(a) Metal-plate electrode  (b) Metal-disk electrode

(c) Disposable foam-pad electrode

Suction Electrode

Electrolyte gel is placed over the contact surface of the electrode, the bulb is squeezed, and the electrode is sucked on the chest wall, holding the electrode assembly in place.

Floating Electrode

(a) Top-hat recessed electrode  (b) Cross-sectional view of (a)

(c) Cross-sectional view of a disposable recessed electrode

Flexible Electrode

(a) Carbon-filled silicone rubber electrode  (b) Flexible thin-film neonatal electrode

(c) Cross-sectional view of (b)
**Internal Electrode**

- (a) Insulated needle electrode
- (b) Coaxial needle electrode
- (c) Bipolar coaxial electrode
- (d) Fine-wire hypodermic electrode
- (e)(f) Fine-wire electrode within skin and muscle

**Percutaneous Electrode**

- (a) Suction electrode
- (b) Cross-sectional view of suction electrode in place
- (c) Helical electrode

Fetal ECG monitoring by direct connection to the presenting part (usually the head) through the uterine cervix during labor.

**Implantable Electrode**

Eyelet is sutured to a point in the body where electric contact is to be established.

- (a) Wire-loop electrode
- (b) Silver-sphere cortical-surface electrode
- (c) Multi-element depth electrode

Electrode and radio transmitter are implanted in the body.

A hole on the calvarium is drilled and a small slit is made in the exposed dura, then the silver sphere is introduced through this opening so that it rests on the surface of the cerebral cortex. The assembly is finally cemented in place onto the calvarium by means of a dental acrylic material.

A cluster of fine insulated wires held together by a varnish binder. Each wire has been cut transversely to expose an uninsulated cross section that serves as an active electrode surface. By staggering the ends of the wires into deep cortical layer, points at different depth can be measured.

**Electrode Array**

- (a) One dimensional array
- (b) Two dimensional array
- (c) Three dimensional array

A two-dimensional comb with each tine being roughly 1.5 mm long and surrounded with insulating material up to the tip. The exposed tip serves as the electrode, and a wire connection on the base of the structure was needed to make contact with each tine electrode.

An array of miniature electrodes is formed on a rigid or flexible surface. Sock electrodes consist of individual silver spheres roughly 1 mm in diameter and are incorporated into a fabric sock that fits snugly over the heart.
Bioelectric Signals

Different forms of bioelectric signals are characteristic to processes taking place in multitude of cellular sources, reach body surface through tissues and organs that form an inhomogeneous volume conductor, and can be detected from body surface.

Heart
- normal sinus rhythm electrocardiogram (ECG)

Brain
- rest & open eyes electroencephalogram (EEG)

Muscles
- flexing biceps muscles electromyogram (EMG)

Eyes
- movement of eyes electrooculogram (EOG)

Amplitudes and Spectra of Bioelectric Signals

<table>
<thead>
<tr>
<th>Electrophysiological Parameter</th>
<th>Signal Range (mV)</th>
<th>Signal Frequency Range (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrocardiography (ECG)</td>
<td>0.5–4</td>
<td>0.01–250</td>
</tr>
<tr>
<td>Electroencephalography (EEG)</td>
<td>0.001–0.1</td>
<td>d.c.–150</td>
</tr>
<tr>
<td>Electrocorticography</td>
<td>0.1–5</td>
<td>d.c.–150</td>
</tr>
<tr>
<td>Electrogastrography</td>
<td>0.1–5</td>
<td>d.c.–1</td>
</tr>
<tr>
<td>Electromyography (EMG)</td>
<td>0.01–100</td>
<td>d.c.–10,000</td>
</tr>
<tr>
<td>Electrooculography (EOG)</td>
<td>0.005–0.2</td>
<td>d.c.–50</td>
</tr>
<tr>
<td>Electroretinography (ERG)</td>
<td>0.01–0.6</td>
<td>d.c.–50</td>
</tr>
<tr>
<td>Nerve potentials</td>
<td>0.01–3</td>
<td>d.c.–10,000</td>
</tr>
</tbody>
</table>

- Original signals on body surface are in mV or μV order. Their frequency ranges from DC to very low frequencies, and spreads over kHz.
- Most electrical events in the body have amplitudes well below 1 V.
  - The resting potential of a cell may be as high as 0.05–0.1 V
  - Voltages recorded from the skull related to activity of the central nervous system may be as low as a few μV.
**Bioelectric Signals**

- Frequencies range from DC to about 10 kHz
- Amplitudes range from tens of μV to 100 mV
- Amplifier input stage must match the electrodes in order to achieve the most effective signal transfer for a particular biosignal

**From Intracellular Action Potential to Body Surface Recording**

Cardiac activity is based on bioelectrical stimulation of the heart muscles. The stimulation starts from the sinus-node and reaches different parts of heart muscle through the nerve bundles, causing contraction as a time delayed spatial wave process.

Cardiac cells in the sinus node (yellow) initiate the excitation. From there the excitation activates muscles cells in atria (green) and atria contract. The excitation progresses to the AV-node (red) and then down to Bundle Branches, from there to Purkinje fibers that activate the muscle cells in the ventricles (pink). Contraction of the ventricle follows.

**Two Problems**

To determine the FIELD from the known source and conductor is called the **FORWARD PROBLEM**

To determine the SOURCE from the known field and conductor is called the **INVERSE PROBLEM**
Propagation and Vector of Cardiac Electrical Activity

Electrode Positions and Measured Waveforms

Signal Vector and Heart Disease

Different Viewpoints
Vector and Projection

Measurement of ECG

Standard 12-Lead ECG

Bipolar limb leads

Augmented unipolar limb leads

Unipolar chest leads

Standard ECG Recording
Contaminated ECG

(a) Baseline wander

(b) Power-line interference

(c) EMG interference

Motion Artifact

What
If a pair of electrodes is in an electrolyte and one moves with respect to the other, a potential difference appears across the electrodes known as the motion artifact. This is a source of noise and interference in biopotential measurements.

Why
When the electrode moves with respect to the electrolyte, the distribution of the double layer of charge on polarizable electrode interface changes. This changes the half cell potential temporarily.

Solution
Because motion artifact results primarily from mechanical disturbances of the distribution of charge at the electrode-electrolyte interface, it is reasonable to expect that non-polarizable electrodes (Ag/AgCl) has smaller motion artifact.

Power-Line Interference

Electric field coupling happens between the power lines and the electrocardiograph and the subject due to surrounding power lines and cords connecting different apparatus to electric outlets.

Driven-Right-Leg Circuit

Common-mode voltage on the body is sensed by two averaging resistors $R_a$, inverted, amplified, and negatively fed back to the right leg.

Parallel resistances $R_l$ and $R_o$ are between the subject and ground. They can be several MΩ - large enough to limit the leakage current and secure the subject.
EEG Electrode Placements
International 10-20 System

Electroencephalogram (EEG)

Visual Evoked Potentials (VEP)

Electromyogram (EMG)