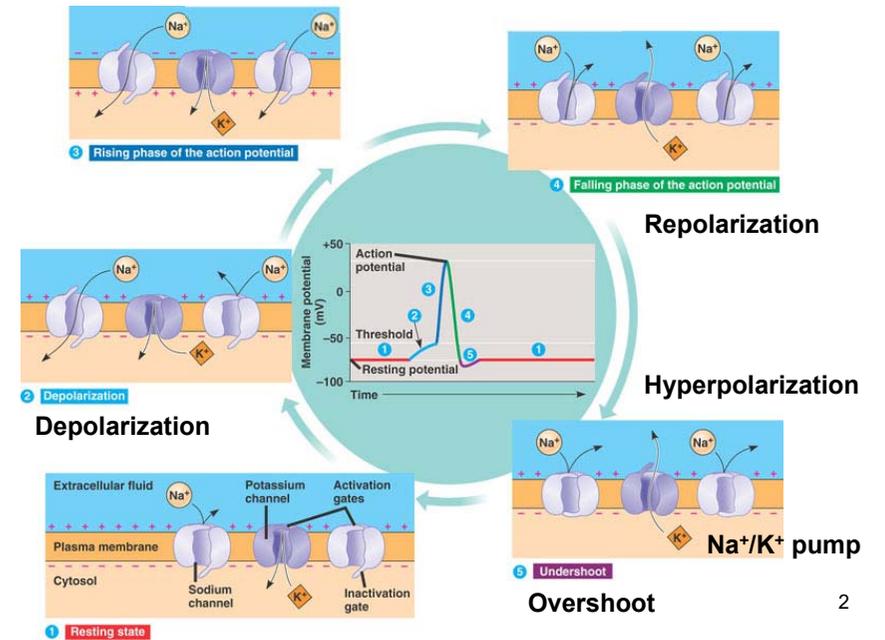


9. Bioelectricity

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

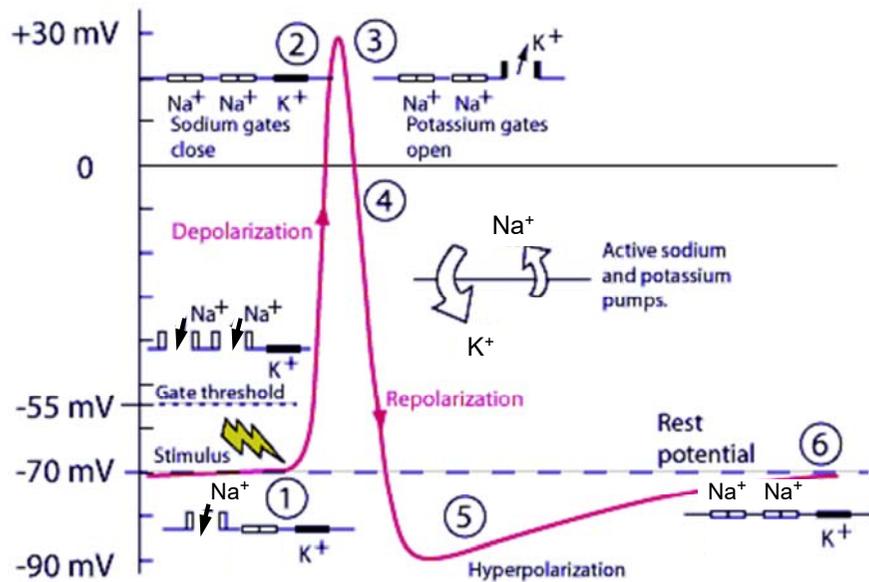
1

Ion Channels



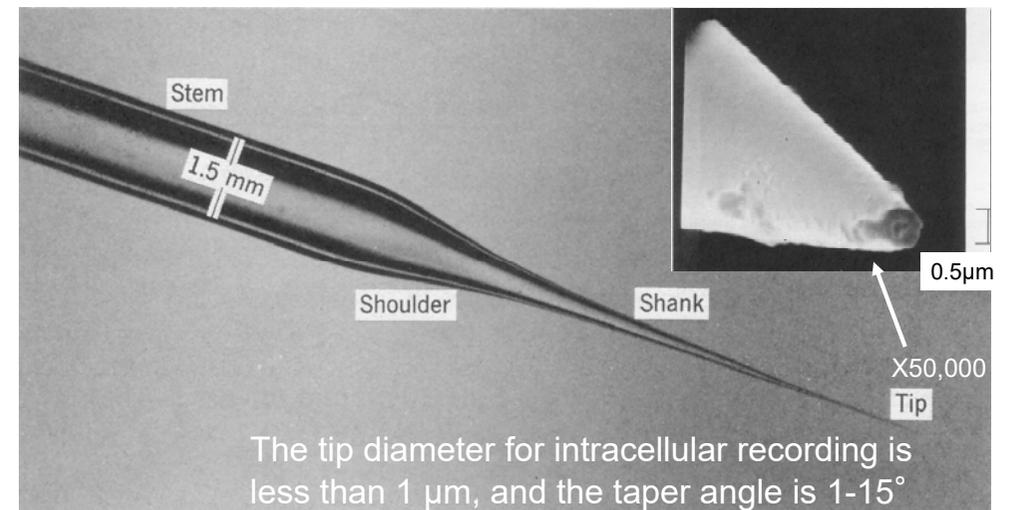
2

Action Potential (AP)



3

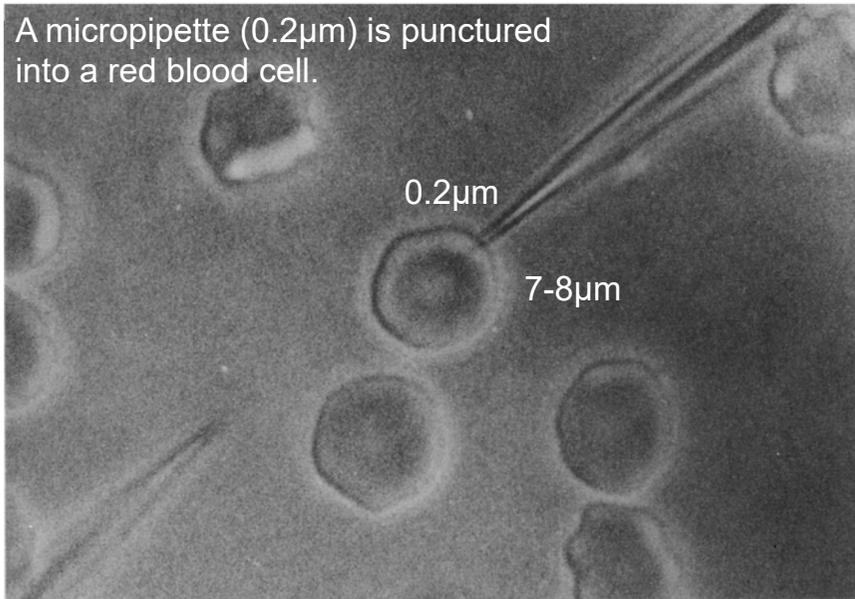
Glass Micropipette



4

Micropipette & Red Blood Cell

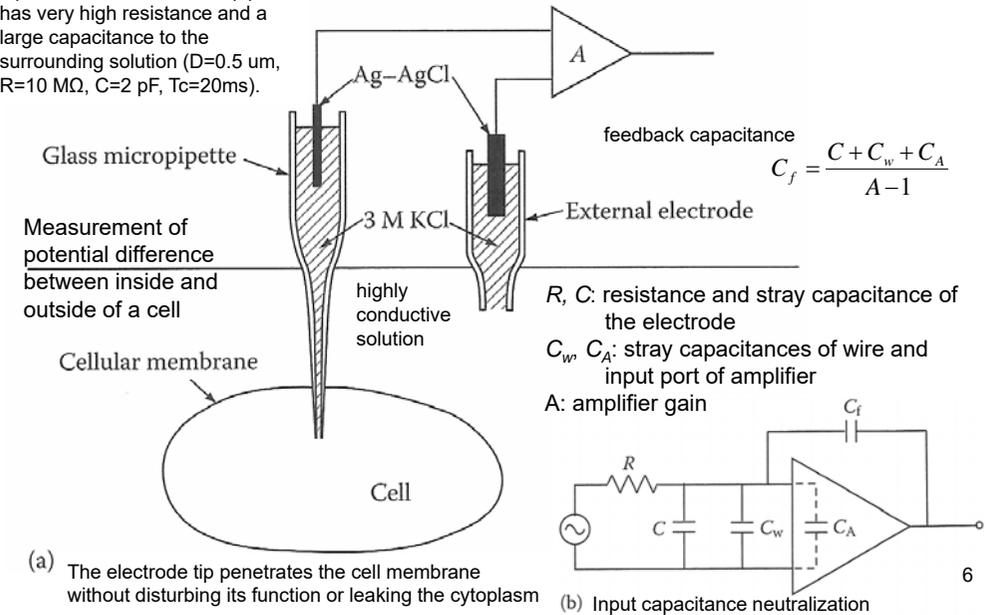
A micropipette (0.2µm) is punctured into a red blood cell.



5

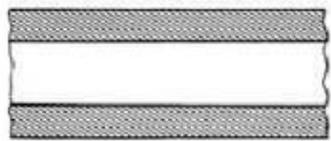
AP Measurement in a Cell

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).

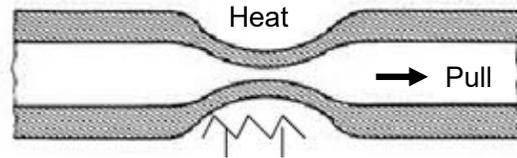


6

Micropipette Fabrication

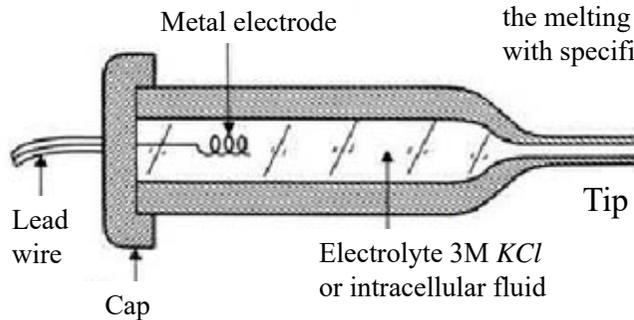


(a) Sectional view of a fine-bore glass capillary



(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

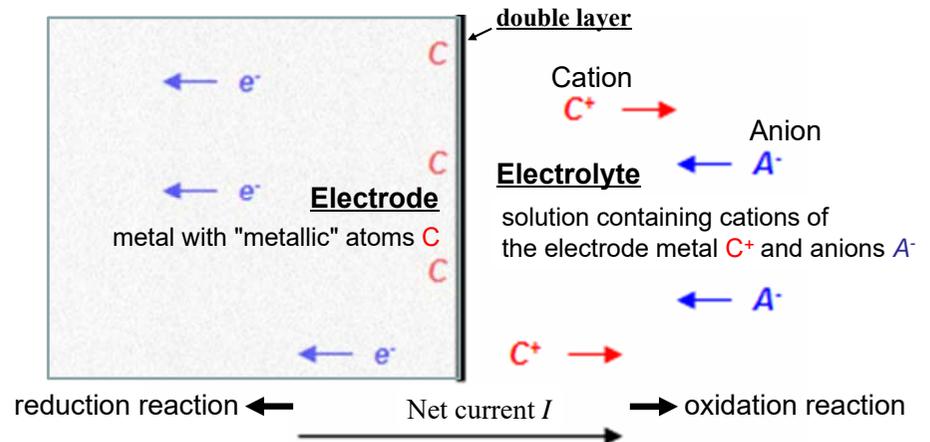


Microelectrode maker 7

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



8

Electrode-electrolyte Interface - 2

General Ionic Equations

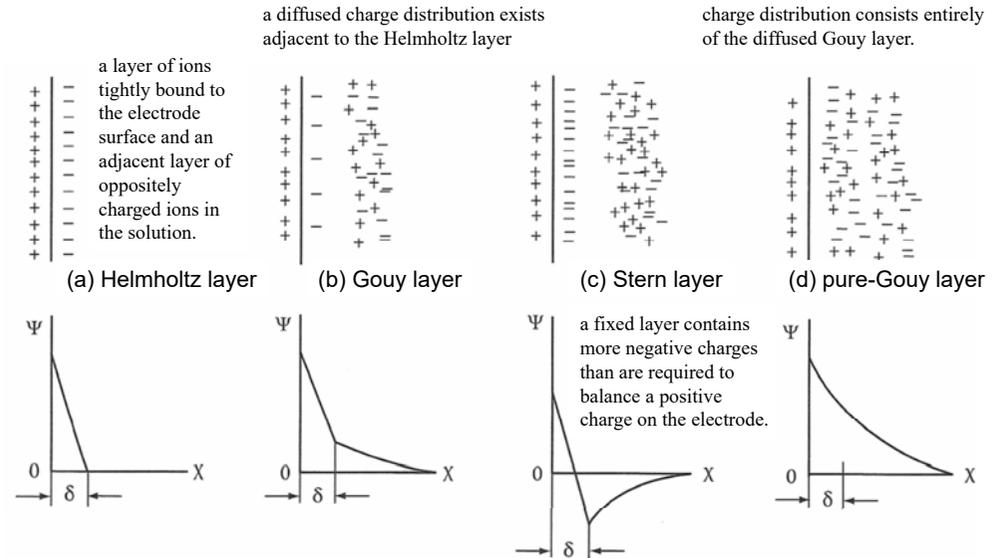


- If electrode has same material as cation, then this material gets oxidized and enters the electrolyte as a cation and electrons remain at the electrode and flow in the external circuit.
- If anion can be oxidized at the electrode to form a neutral atom, one or two electrons are given to the electrode

The dominating reaction can be inferred from the following :

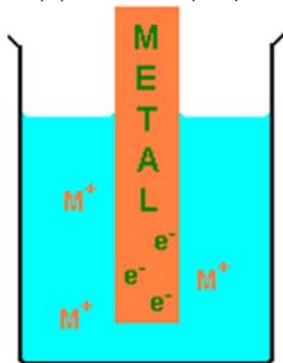
- Current flow from electrode to electrolyte : Oxidation (Loss e^{-})
- Current flow from electrolyte to electrode : Reduction (Gain e^{-})

Charge Distribution in Double Layer



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

Half-Cell Potential



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.

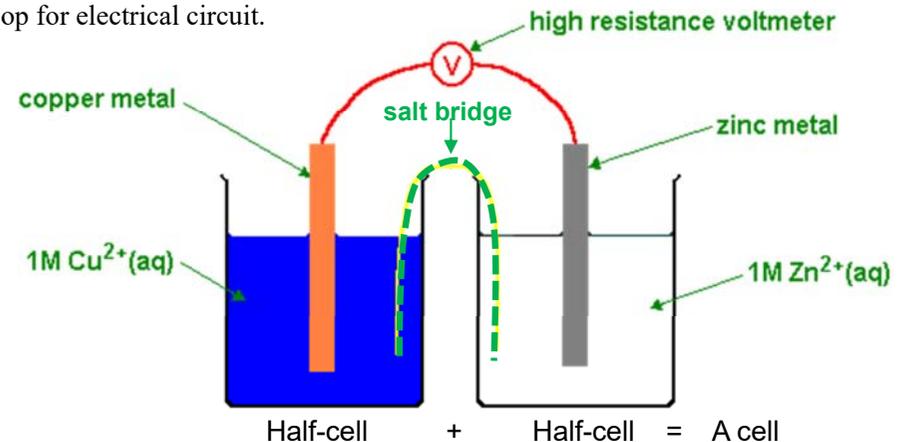
- The reaction goes either way depending on the **cation concentration in the solution**.
- When the equilibrium is set up, the region surrounding the metal is at a different potential from the rest of the solution. The potential difference (**half-cell potential**) is determined by the **metal**, the 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.

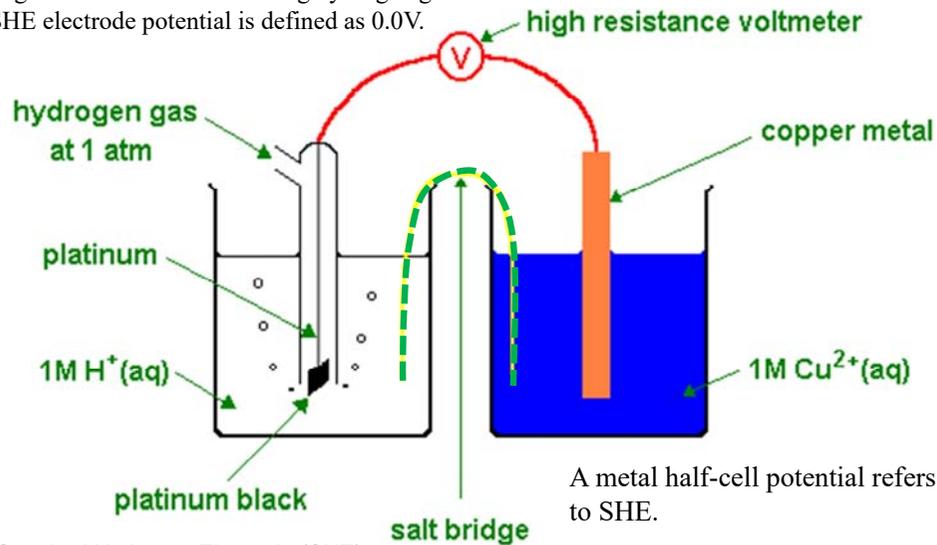
Difference in charge between a **metal** and its **solution** sets up a **half-cell potential**, or **electrode potential of the metal**.

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.



Standard Hydrogen Electrode (SHE)

Half-Cell Potentials at 25°C

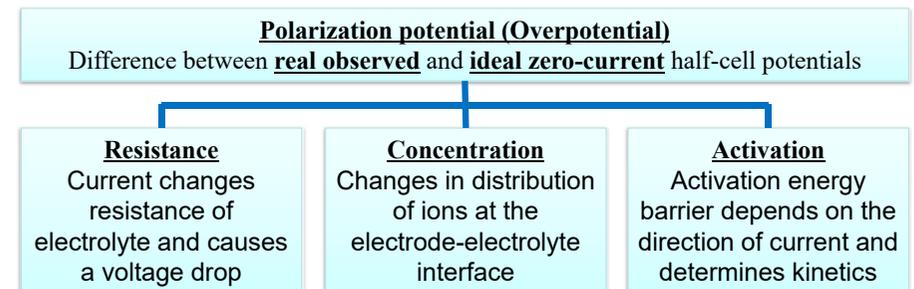
Cell	Electrode reaction → oxidation ← reduction	Potential, V
Metal-ion potentials:		
Al ³⁺ /Al	Al ⇌ Al ³⁺ + 3e ⁻	-1.66
Zn ²⁺ /Zn	Zn ⇌ Zn ²⁺ + 2e ⁻	-0.763
Fe ²⁺ /Fe	Fe ⇌ Fe ²⁺ + 2e ⁻	-0.440
Ni ²⁺ /Ni	Ni ⇌ Ni ²⁺ + 2e ⁻	-0.250
Pb ²⁺ /Pb	Pb ⇌ Pb ²⁺ + 2e ⁻	-0.126
Ag/AgCl	Ag + Cl ⁻ ⇌ AgCl + e ⁻	+0.2224
Hg/Hg ₂ Cl ₂	2Hg + 2Cl ⁻ ⇌ Hg ₂ Cl ₂ + 2e ⁻	+0.2681
Cu ²⁺ /Cu	Cu ⇌ Cu ²⁺ + 2e ⁻	+0.337
Cu ⁺ /Cu	Cu ⇌ Cu ⁺ + e ⁻	+0.521
Hg ₂ ²⁺ /Hg	2Hg ⇌ Hg ₂ ²⁺ + 2e ⁻	+0.797
Ag ⁺ /Ag	Ag ⇌ Ag ⁺ + e ⁻	+0.7991
Au ³⁺ /Au	Au ⇌ Au ³⁺ + 3e ⁻	+1.50
Au ⁺ /Au	Au ⇌ Au ⁺ + e ⁻	+1.68

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 → **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

17

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

$$V_p = V_r + V_c + V_a$$

└ activation, depends on direction of reaction
└ concentration (change in double layer)
└ ohmic (voltage drop)

18

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



Half-cell potential by **Nernst equation**

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

We are interested in ionic activity at the electrode rather than temperature dependence

- 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

19

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



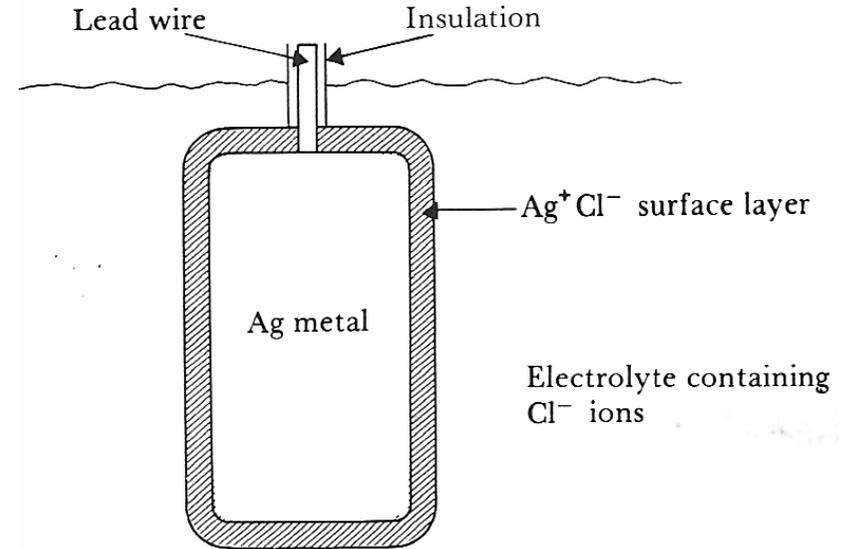
20

Polarizable and Nonpolarizable Electrodes

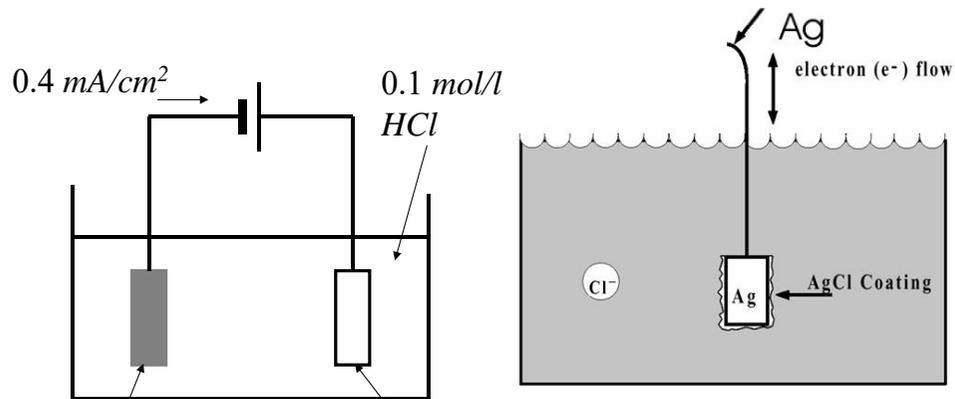
- Perfectly polarizable electrodes
 - Only **displacement current** but **no actual charge** crosses the electrode-electrolyte interface when a current is applied
 - The electrode behaves as though it was a **capacitor**
 - **Platinum** (Pt) electrode → *stimulation*
- Perfectly nonpolarizable electrodes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

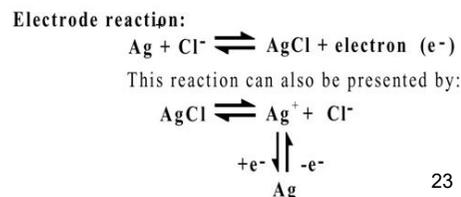
Structure of Ag/AgCl Electrode



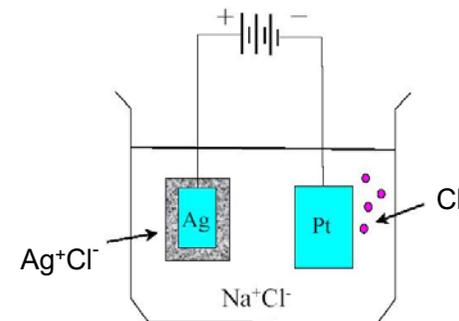
Fabrication of Ag/AgCl Electrode



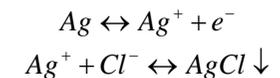
AgCl deposited on a silver plate



Potential of Ag/AgCl Electrode



Relevant ionic equations



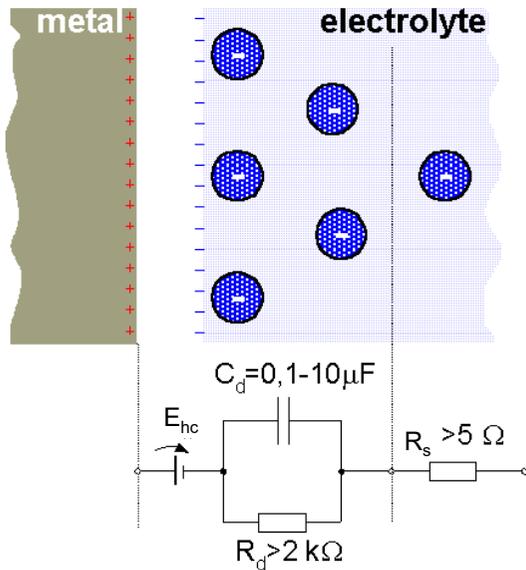
Governing Nernst Equation

$$E = E_{\text{Ag}}^0 + \frac{RT}{nF} \ln \left[\frac{K_s}{a_{\text{Cl}^-}} \right]$$

E^0 : Standard half-cell potential
 a_{Cl^-} : Chloride ion activity (proportional to ionic concentration)
 n : Number of valence electrons involved
 T : Absolute temperature
 F : Faraday constant
 R : Gas constant
 K_s : Solubility product of AgCl

A half-cell **equilibrium potential** can be calculated by the standard half-cell potential, temperature, ion activity, and reaction quotient of the underlying reactions and species used.

Equivalent Circuit of Electrode



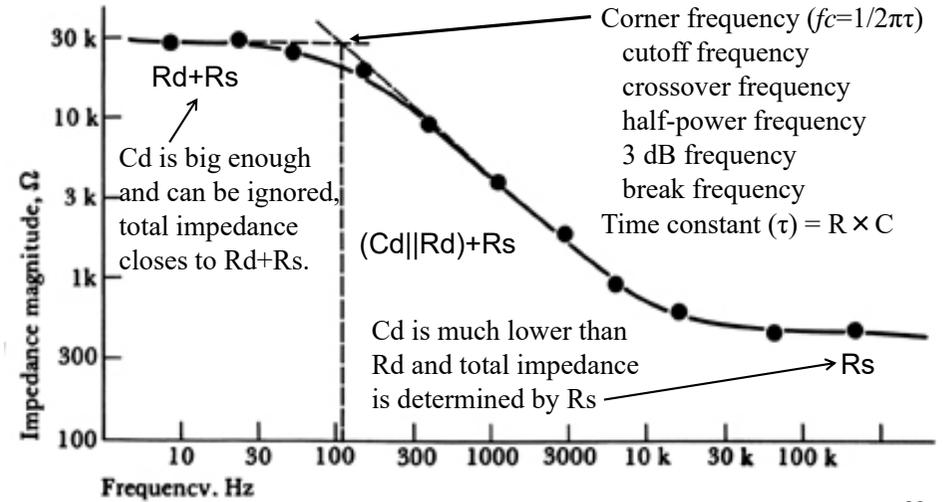
C_d :
capacitance of
electrode-electrolyte
interface

R_d :
resistance of electrode-
electrolyte interface

R_s :
series resistance in the
electrolyte and the lead
wire

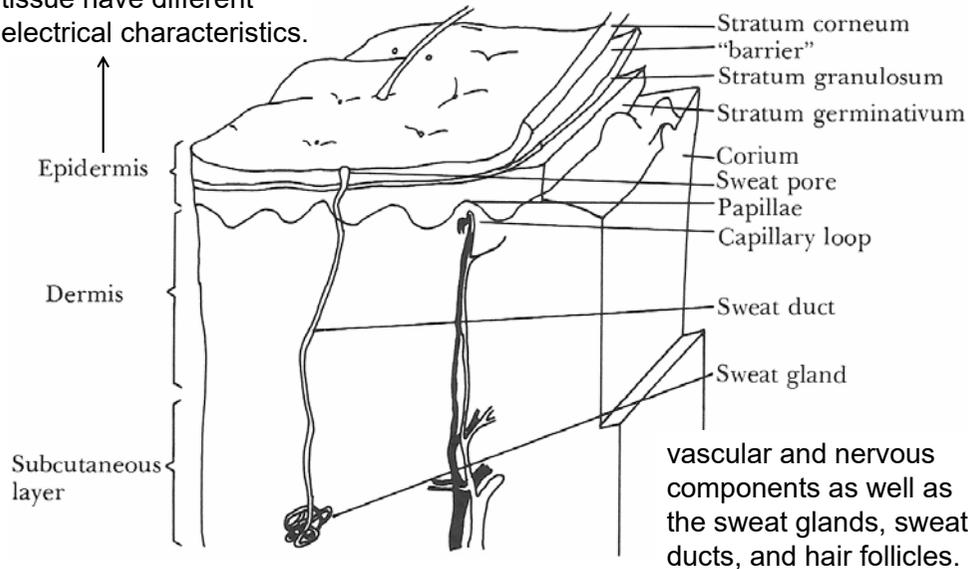
E_{hc} :
half-cell potential of the
electrode

Frequency Property of Electrode

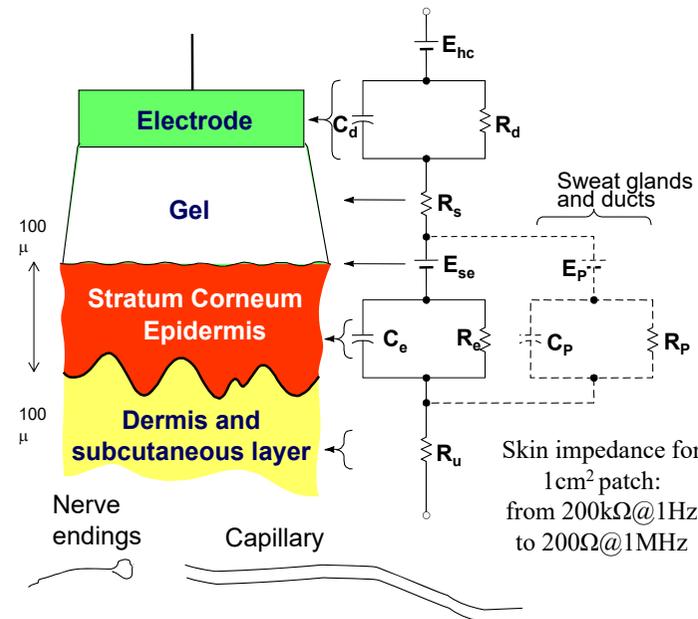


constantly renewing.
most important in
electrode-skin interface.
dead tissue and live
tissue have different
electrical characteristics.

Various Layers in Skin



Electrode-Skin Interface



R_g : resistance of
interface effects of the
gel between electrode and
skin

C_e : skin capacitance

R_e : skin resistance

E_{se} : potential at
semipermeable
epidermal layer

C_p : capacitance of
sweat gland and duct

R_p : resistance of
sweat gland and duct

E_p : potential between
sweat duct and dermis
and subcutaneous layers

R_u : pure resistance in
dermis and
subcutaneous layers

Skin impedance for
1cm² patch:
from 200kΩ@1Hz
to 200Ω@1MHz

Body-Surface Electrodes

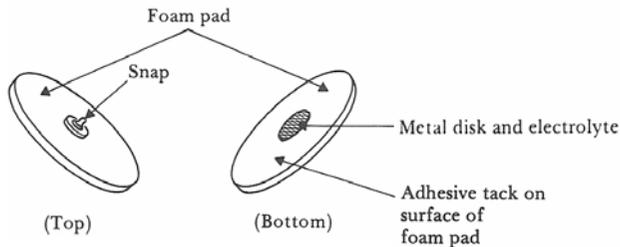
- Sense ion distribution and convert ion current to electron current
- Electrolyte solution/jelly is placed between electrode and tissue. A chemical reaction occurs at the interface between the electrolyte and the electrode.
- A conductive wire connects the electrode to the instrument.



(a) Metal-plate electrode



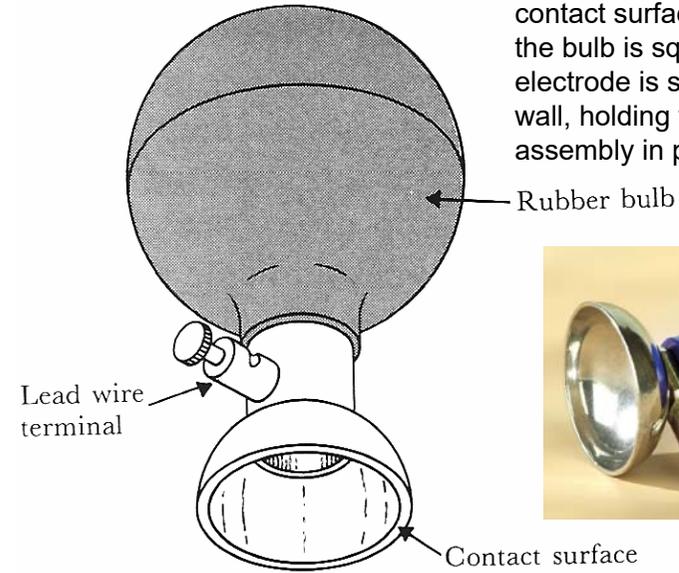
(b) Metal-disk electrode



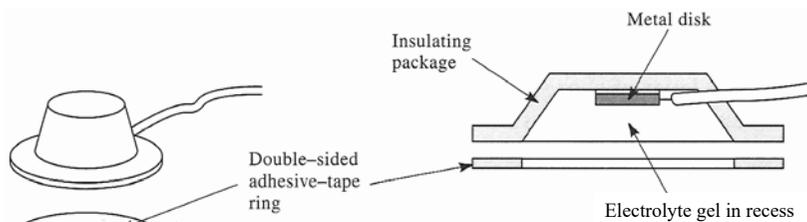
(c) Disposable foam-pad electrode

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.

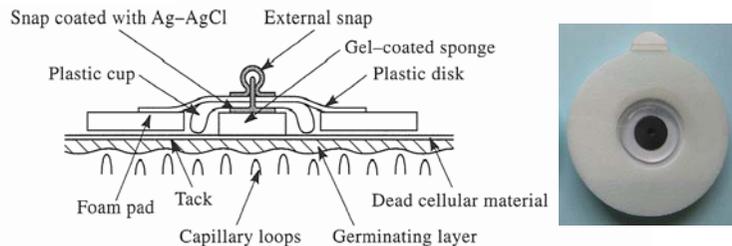


Floating Electrode



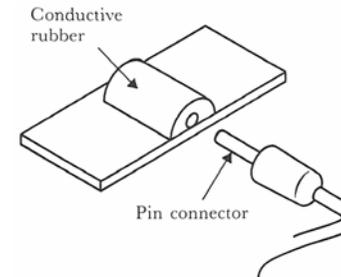
(a) top-hat recessed electrode

(b) cross-sectional view of (a)

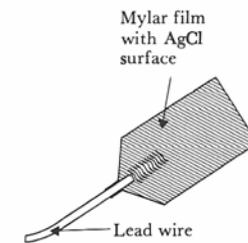


(c) cross-sectional view of a disposable recessed electrode

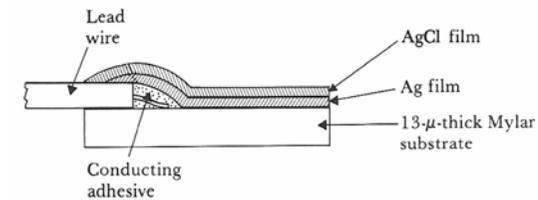
Flexible Electrode



(a) Carbon-filled silicone rubber electrode



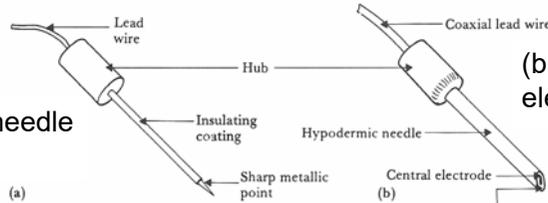
(b) Flexible thin-film neonatal electrode



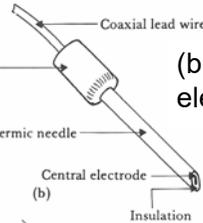
(c) cross-sectional view of (b)

Internal Electrode

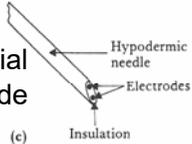
(a) Insulated needle electrode



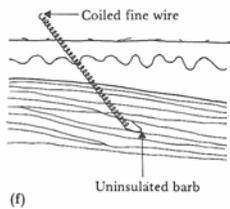
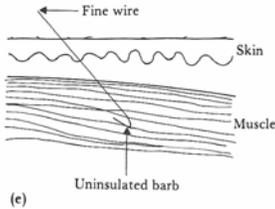
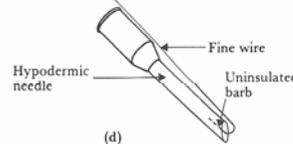
(b) Coaxial needle electrode



(c) Bipolar coaxial electrode

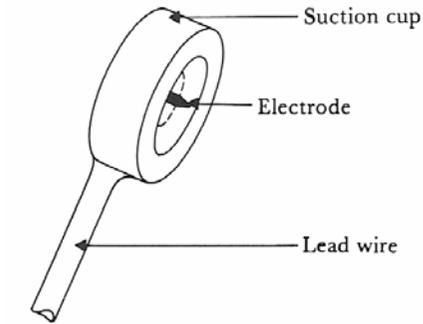


(d) Fine-wire hypodermic electrode

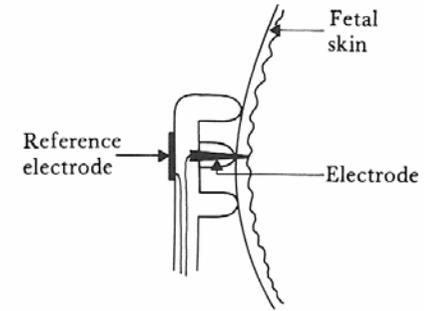


(e)(f) Fine-wire electrode within skin and muscle

Percutaneous Electrode



(a) Suction electrode



(b) Cross-sectional view of suction electrode in place

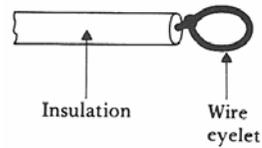


(c) Helical electrode

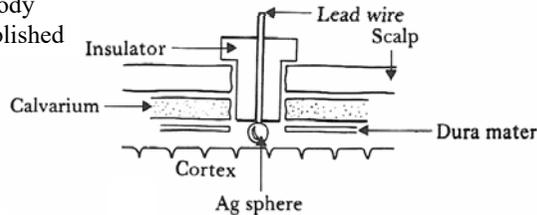
Fetal ECG monitoring by direct connection to the presenting part (usually the head) through the uterine cervix during labor.

Implantable Electrode

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



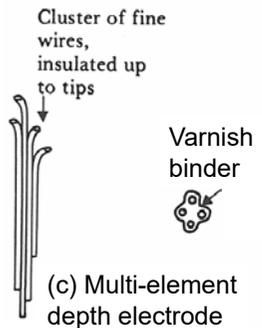
(a) Wire-loop electrode



(b) Silver-sphere cortical-surface electrode

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.

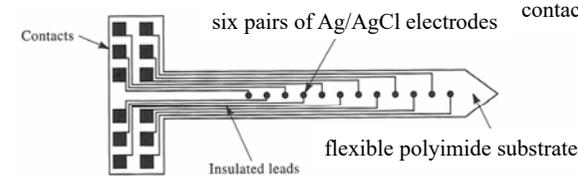


(c) Multi-element depth electrode

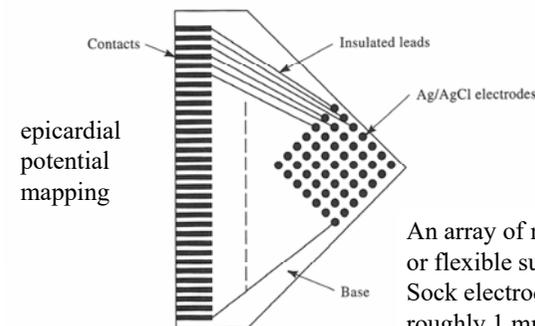
Electrode Array

transmural potential distributions in myocardium

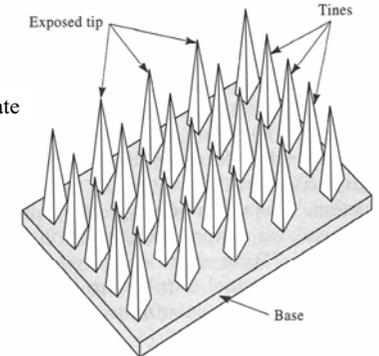
A two-dimensional comb with each tine being roughly 1.5 mm long and surrounded with insulating material up to the tip. The exposed tip serves as the electrode, and a wire connection on the base of the structure was needed to make contact with each tine electrode.



(a) One dimensional array



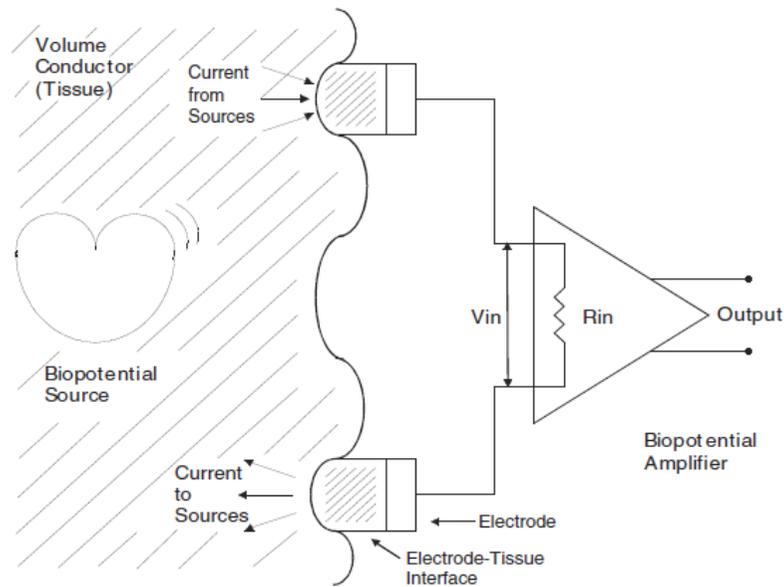
(b) Two dimensional array



(c) Three dimensional array

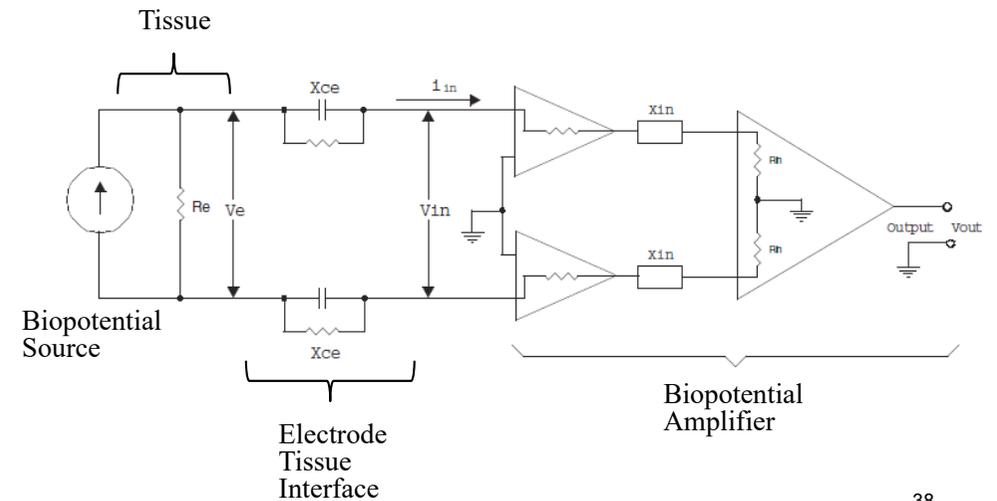
An array of miniature electrodes is formed on a rigid or flexible surface. Sock electrodes consist of individual silver spheres roughly 1 mm in diameter and are incorporated into a fabric sock that fits snugly over the heart.

Model of Biopotential Recording



37

Equivalent Circuit

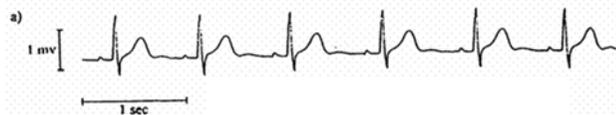


38

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)



39

Amplitudes and Spectra of Bioelectric Signals

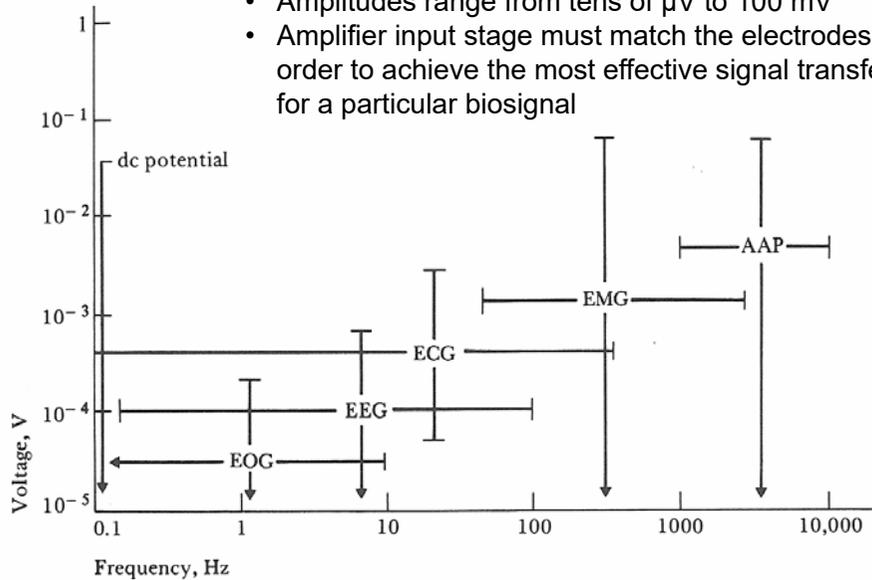
Electrophysiological Parameter	Signal Range (mV)	Signal Frequency Range (Hz)
Electrocardiography (ECG)	0.5–4	0.01–250
Electroencephalography (EEG)	0.001–0.1	d.c.–150
Electrocorticography	0.1–5.0	d.c.–150
Electrogastrography	0.1–5	d.c.–1
Electromyography (EMG)	0.01–100	d.c.–10,000
Electrooculography (EOG)	0.005–0.2	d.c.–50
Electroretinography (ERG)	0.01–0.6	d.c.–50
Nerve potentials	0.01–3	d.c.–10,000

- 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 .

40

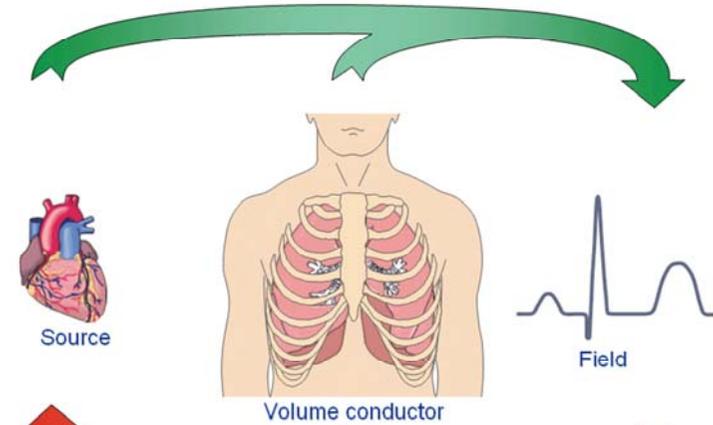
Bioelectric Signals

- 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



Two Problems

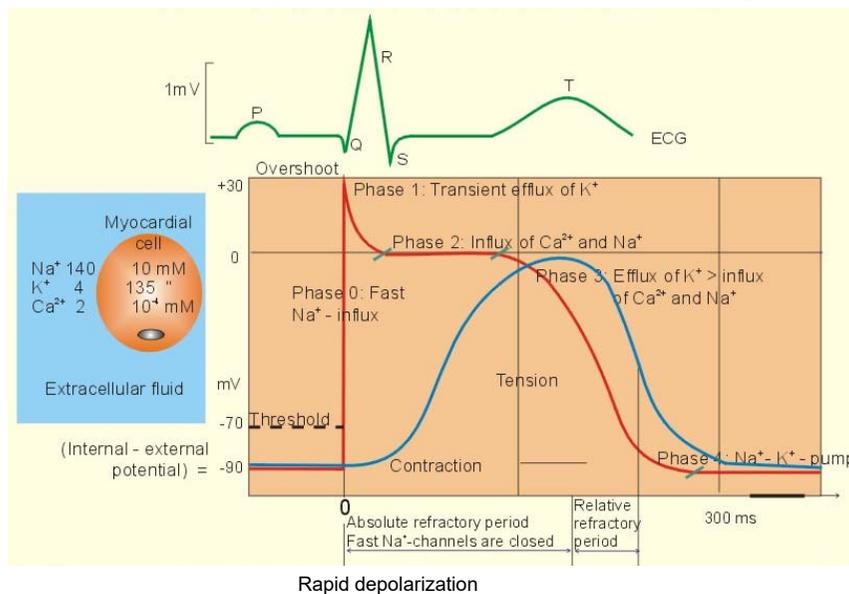
To determine the FIELD from the known source and conductor is called the **FORWARD PROBLEM**



To determine the SOURCE from the known field and conductor is called the **INVERSE PROBLEM**

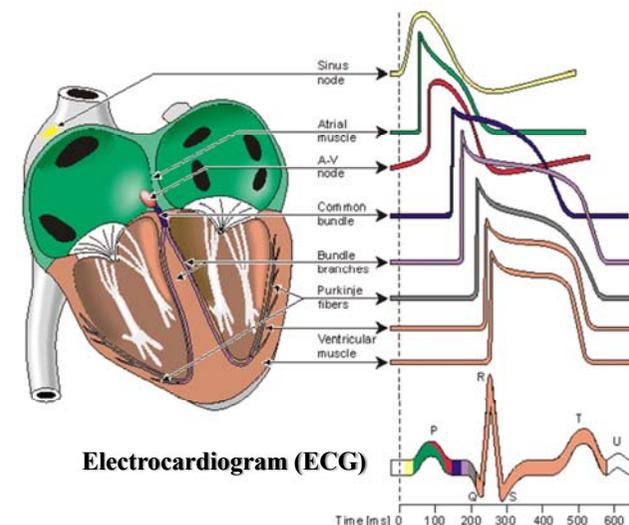
42

From Intracellular Action Potential to Body Surface Recording



Cardiac Electric Activities

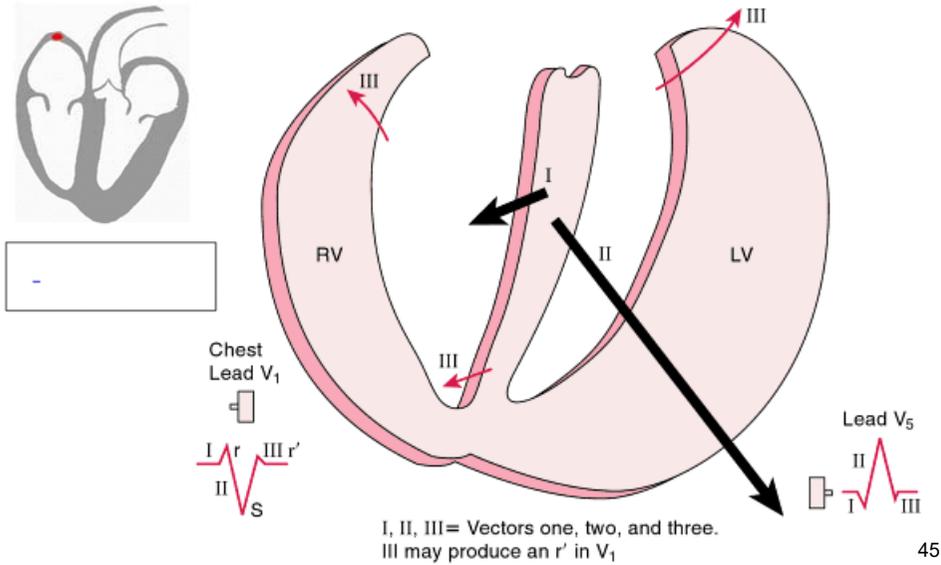
Cardiac activity is based on bioelectrical stimulation of the heart muscles. The stimulation starts from the sinus-node and reaches different parts of heart muscle through the nerve bundles, causing contraction as a time delayed spatial wave process.



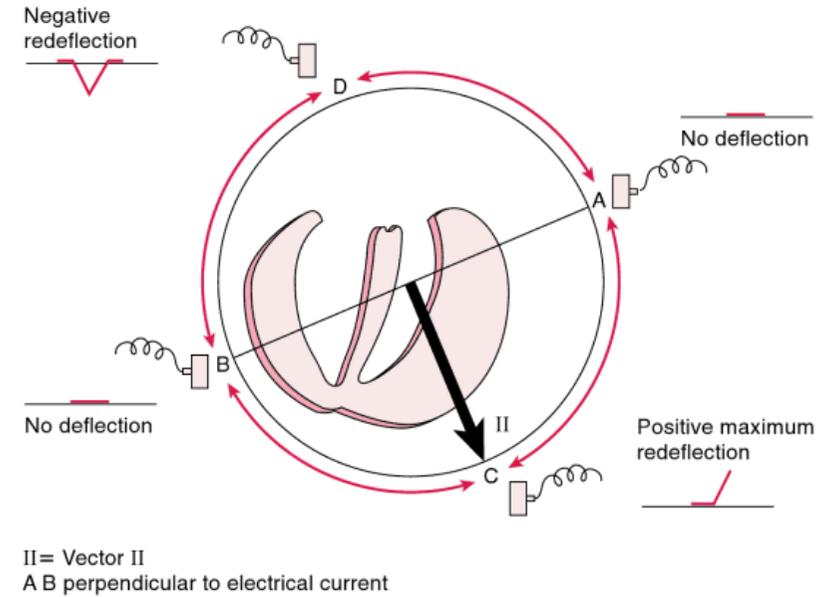
Cardiac cells in the sinus node (yellow) initiate the excitation. From there the excitation activates muscle cells in atria (green) and atria contract. The excitation progresses to the AV-node (red) and then down to Bundle Branches, from there to Purkinje fibers that activate the muscle cells in the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

44

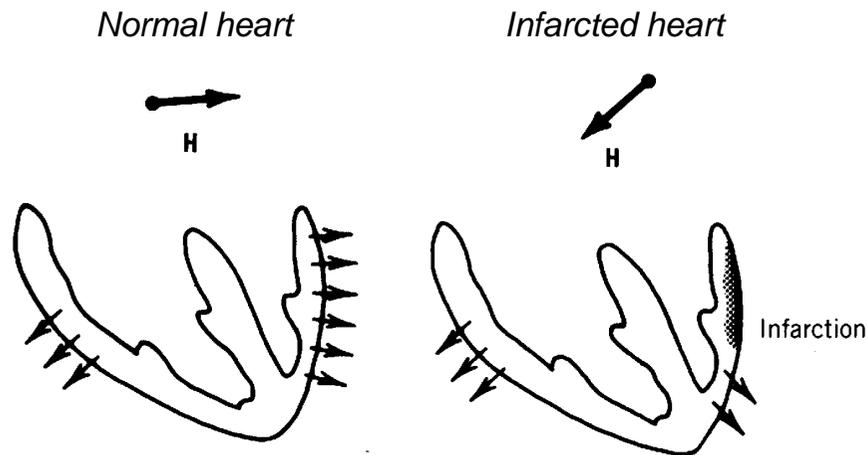
Propagation and Vector of Cardiac Electrical Activity



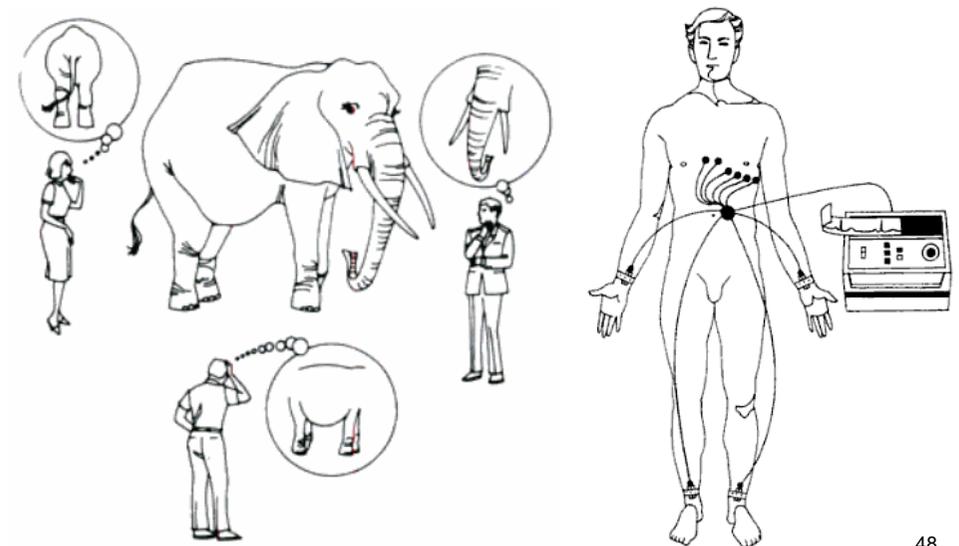
Electrode Positions and Measured Waveforms



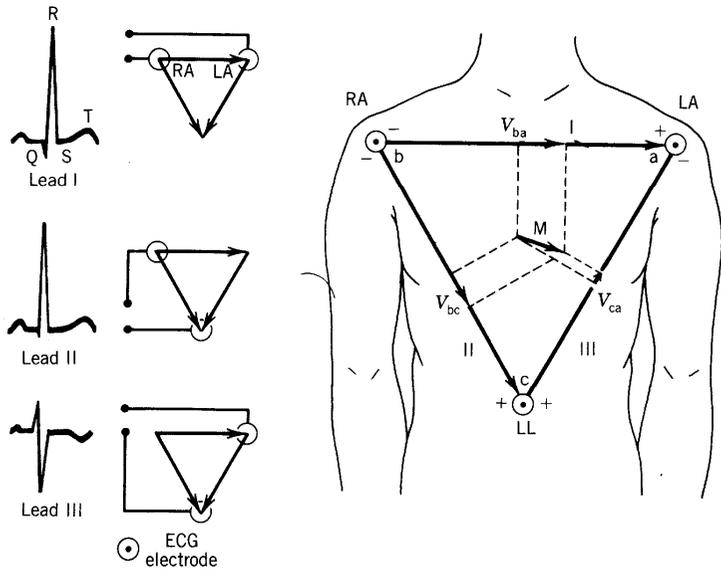
Signal Vector and Heart Disease



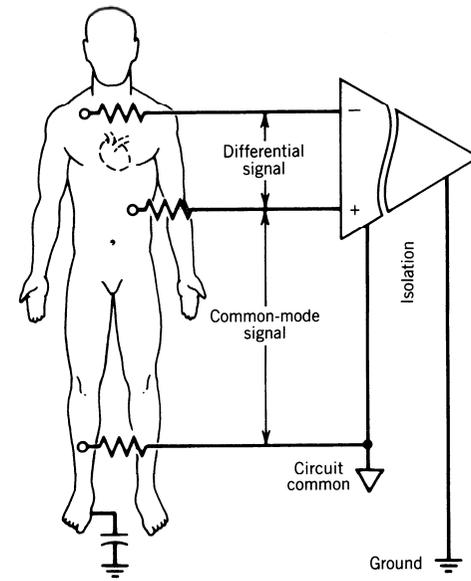
Different Viewpoints



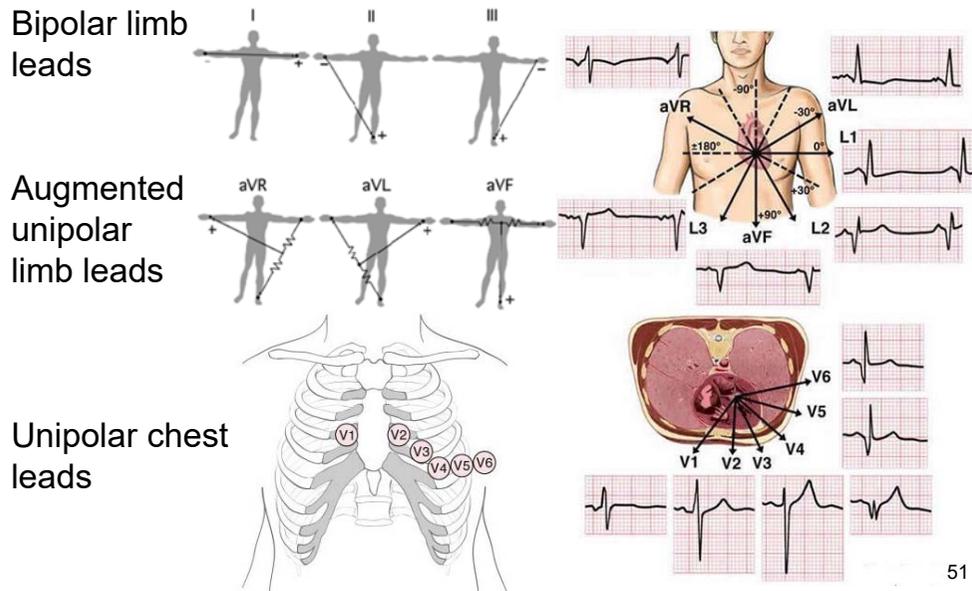
Vector and Projection



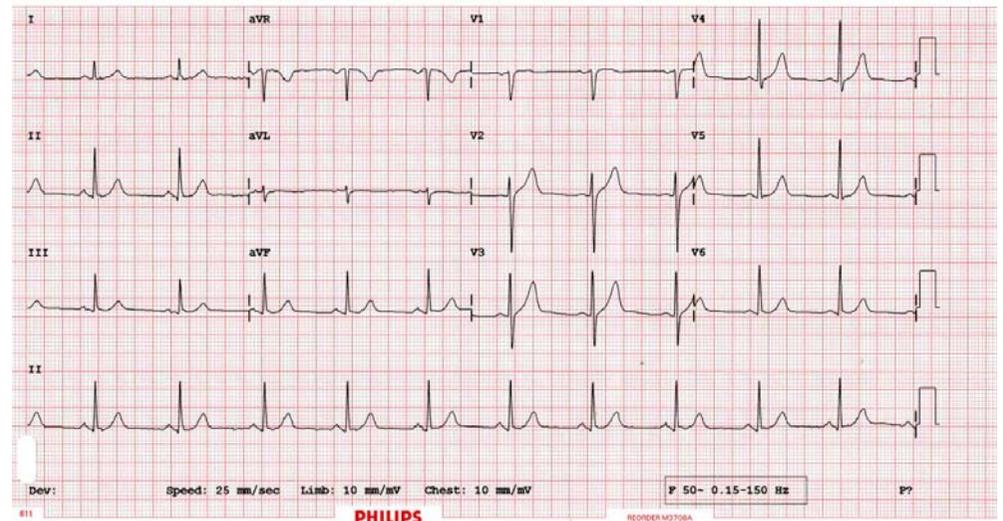
Measurement of ECG



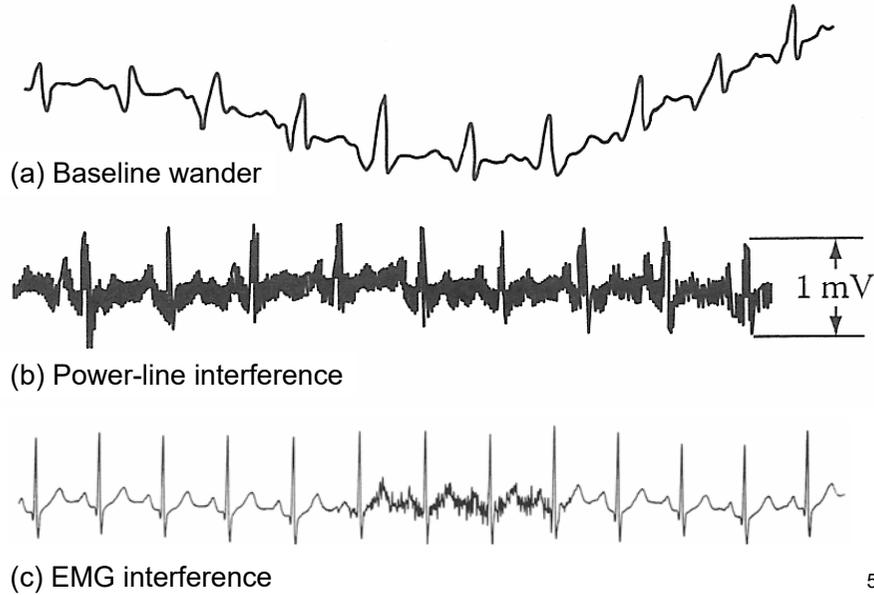
Standard 12-Lead ECG



Standard ECG Recording



Contaminated ECG



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.

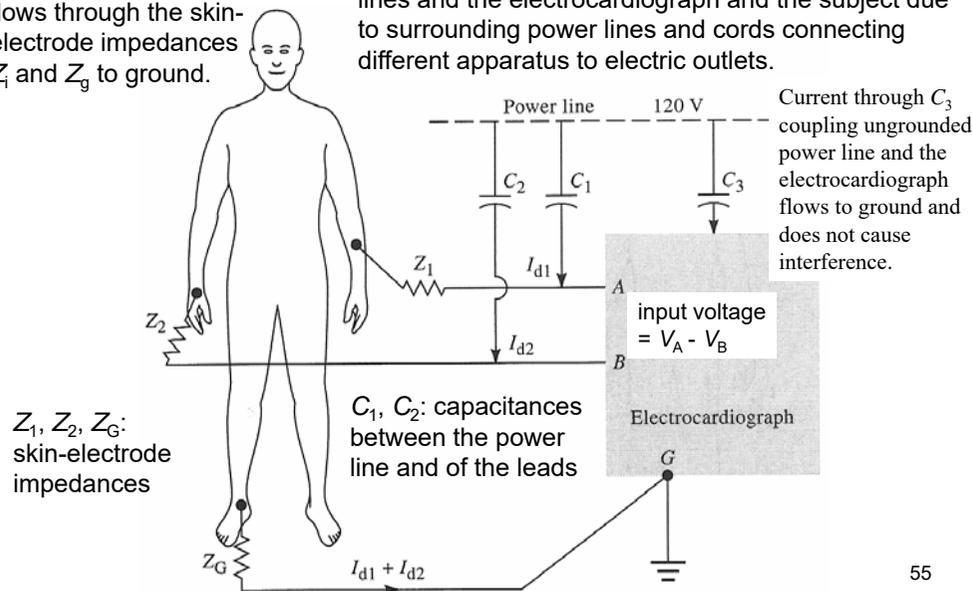
Solution

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.

i_{di} does not flow into the electrocardiograph because of its high input impedance, but flows through the skin-electrode impedances Z_1 and Z_g to ground.

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

i_d flows not to ground but to the op-amp.

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

