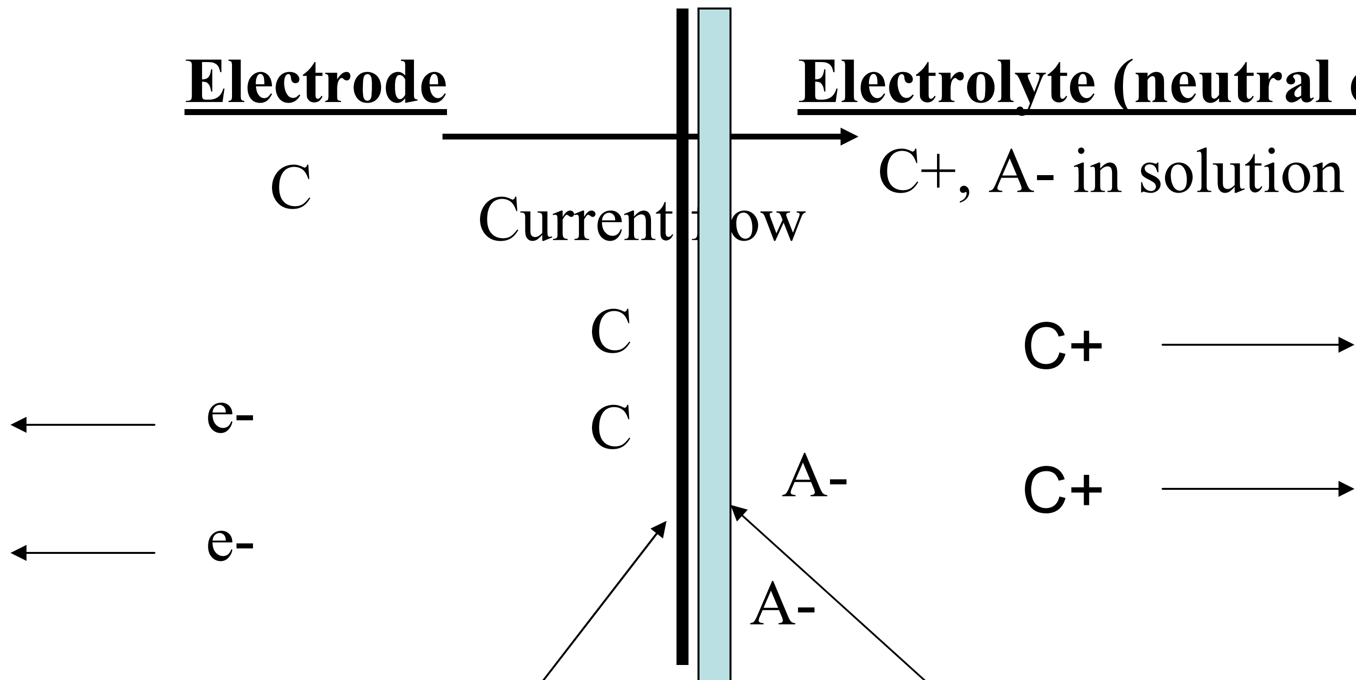
Lecture 7

Biopotential Electrodes (Ch. 5)

Electrode – Electrolyte Interface



C+ : Cation A- : Anion e- : electron

Fairly common electrode materials: Pt, Carbon, …, Au, Ag,…
Electrode metal is use in conjunction with salt, e.g. Ag-AgCl, Pt-Pt black, or polymer coats (e.g. Nafion, to improve selectivity)

Electrode – Electrolyte Interface

General Ionic Equations

a) $C \leftrightarrow C^{n+} + ne^{-}$

b) $A^{m-} \leftrightarrow A + me^{-}$

a) 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.

b) 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 of e^-)

Current flow from electrolyte to electrode : Reduction (Gain of e^-)

Half Cell Potential

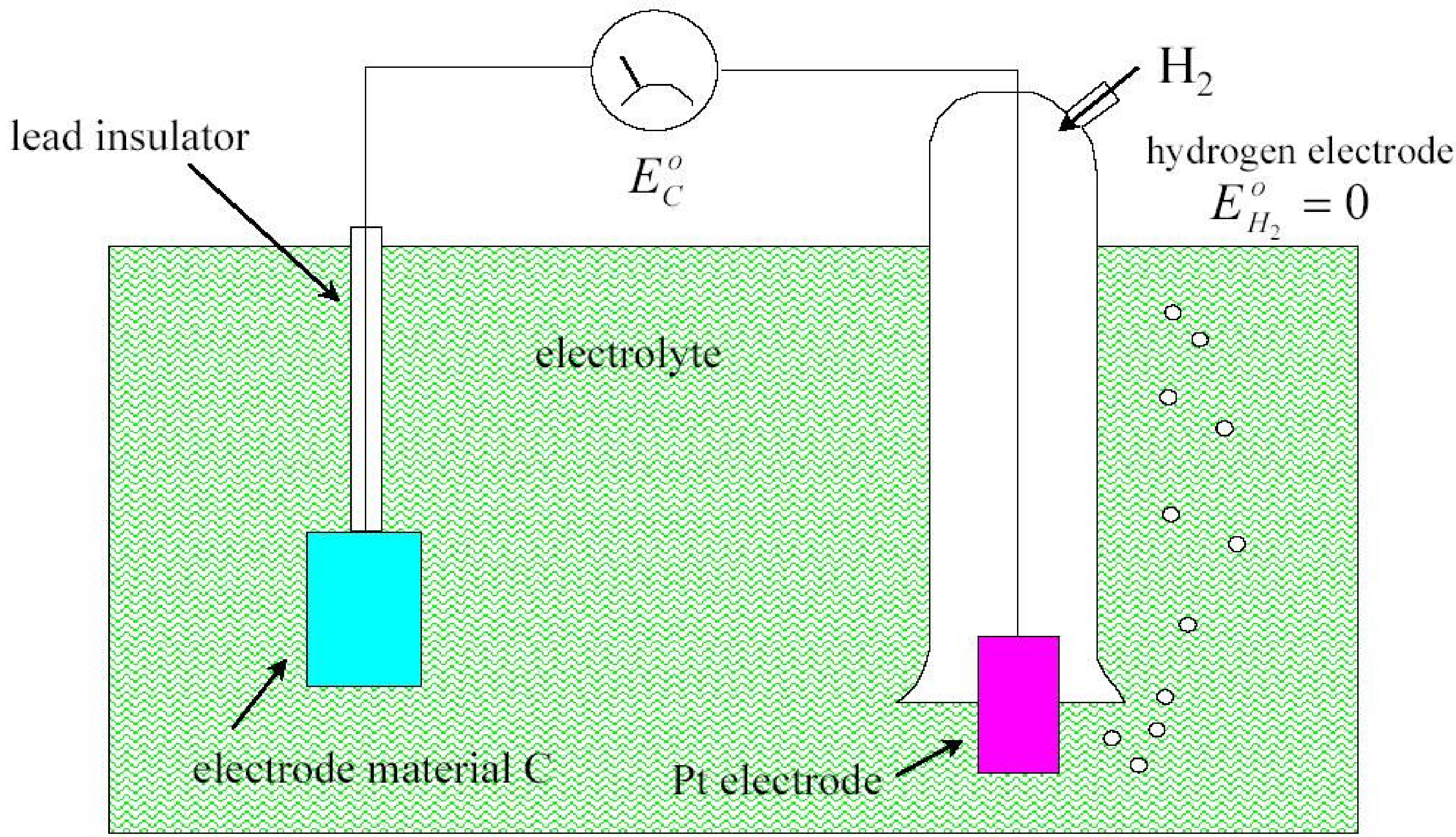
A characteristic potential difference established by the electrode and its surrounding electrolyte which depends on the metal, concentration of ions in solution and temperature (and some second order factors) .

Half cell potential cannot be measured without a second electrode.

The half cell potential of the standard hydrogen electrode has been arbitrarily set to zero. Other half cell potentials are expressed as a potential difference with this electrode.

Reason for Half Cell Potential : Charge Separation at Interface
Oxidation or reduction reactions at the electrode-electrolyte interface lead to a double-charge layer, similar to that which exists along electrically active biological cell membranes.

Measuring Half Cell Potential



Note: Electrode material is metal + salt or polymer selective membrane

Some half cell potentials

reduction reaction	$E^o \ (V)$
$Al^{3+} + 3e^- \rightarrow Al$	-1.662
$Zn^{2+} + 2e^- \rightarrow Zn$	-0.762
$Cr^{3+} + 3e^- \rightarrow Cr$	-0.744
$Fe^{2+} + 2e^- \rightarrow Fe$	-0.447
$Cd^{2+} + 2e^- \rightarrow Cd$	-0.403
$Ni^{2+} + 2e^- \rightarrow Ni$	-0.257
$Pb^{2+} + 2e^- \rightarrow Pb$	-0.126
$2H^+ + 2e^- \rightarrow H_2$	0.000 ← Standard Hydrogen electrode
$AgCl + e^- \rightarrow Ag + Cl^-$	$+0.222$
$Hg_2Cl_2 + 2e^- \rightarrow 2Hg + 2Cl^-$	$+0.268$
$Cu^{2+} + 2e^- \rightarrow Cu$	$+0.342$
$Cu^+ + e^- \rightarrow Cu$	$+0.521$
$Ag^+ + e^- \rightarrow Ag$	$+0.780$
$Au^{3+} + 3e^- \rightarrow Au$	$+1.498$
$Au^+ + e^- \rightarrow Au$	$+1.692$

Note: Ag-AgCl has low junction potential & it is also very stable -> hence used in ECG electrodes!

Polarization

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

Overpotential
Difference between observed and zero-current half cell potentials

Resistance
Current changes resistance of electrolyte and thus, a voltage drop results.

Concentration
Changes in distribution of ions at the electrode-electrolyte interface

Activation
The activation energy barrier depends on the direction of current and determines kinetics

$$V_p = V_R + V_C + V_A$$

Note: Polarization and impedance of the electrode are two of the most important electrode properties to consider.

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

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

The Nernst equation for half cell potential is

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

Note: interested in ionic activity at the electrode (but note temp dependence

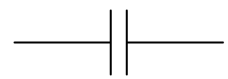
where E^0 : Standard Half Cell Potential   E : Half Cell Potential

a : Ionic Activity (generally same as concentration)

n : Number of valence electrons involved

Polarizable and Non-Polarizable Electrodes

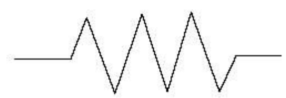
Perfectly Polarizable Electrodes



Use for recording

These are electrodes in which no actual charge crosses the electrode-electrolyte interface when a current is applied. The current across the interface is a displacement current and the electrode behaves like a capacitor. Example : Ag/AgCl Electrode

Perfectly Non-Polarizable Electrode

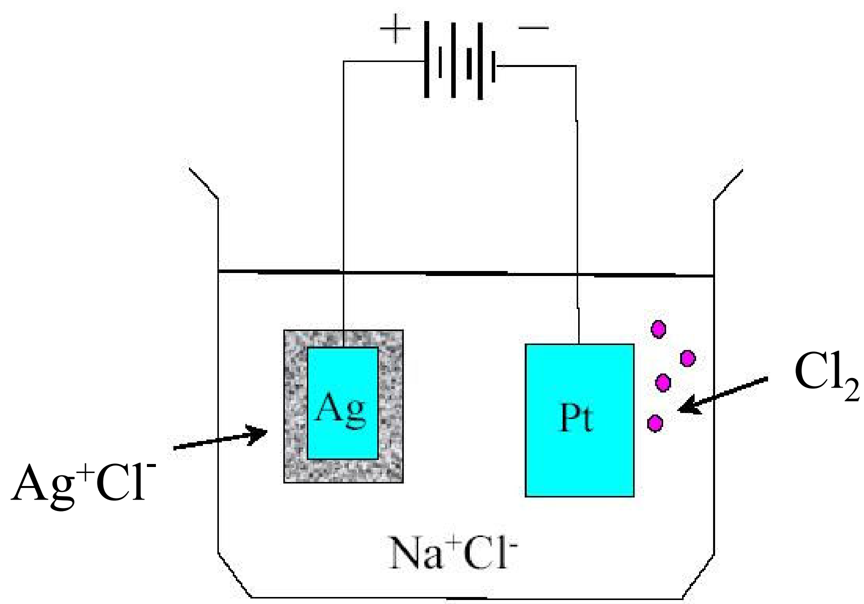


Use for stimulation

These are electrodes where current passes freely across the electrode-electrolyte interface, requiring no energy to make the transition. These electrodes see no overpotentials. Example : Platinum electrode

Example: Ag-AgCl is used in recording while Pt is use in stimulation

Ag/AgCl Electrode



Relevant ionic equations

$$Ag \leftrightarrow Ag^{+} + e^{-}$$
$$Ag^{+} + Cl^{-} \leftrightarrow AgCl \downarrow$$

Governing Nernst Equation

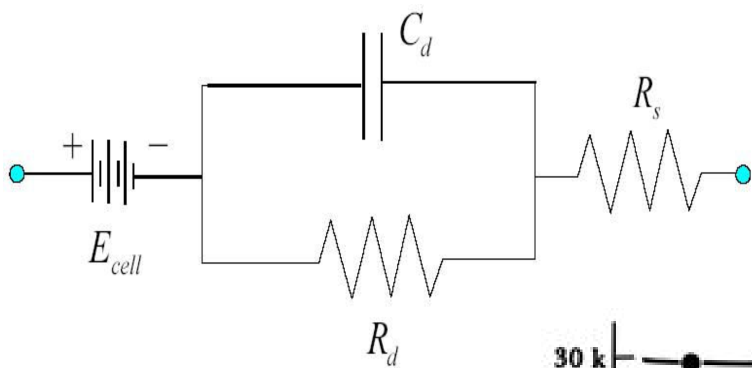
$$E = E^{0}_{Ag} + \frac{RT}{nF} \ln\left[\frac{K_s}{a_{Cl^-}}\right]$$

Solubility product of AgCl

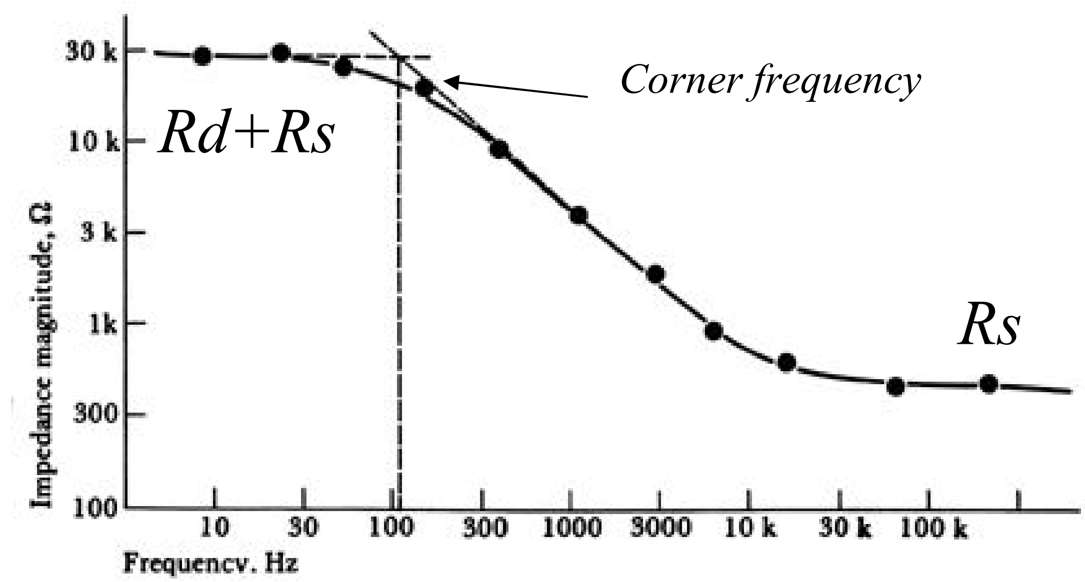
Fabrication of Ag/AgCl electrodes

1. Electrolytic deposition of AgCl
2. Sintering process forming pellet electrodes

Equivalent Circuit

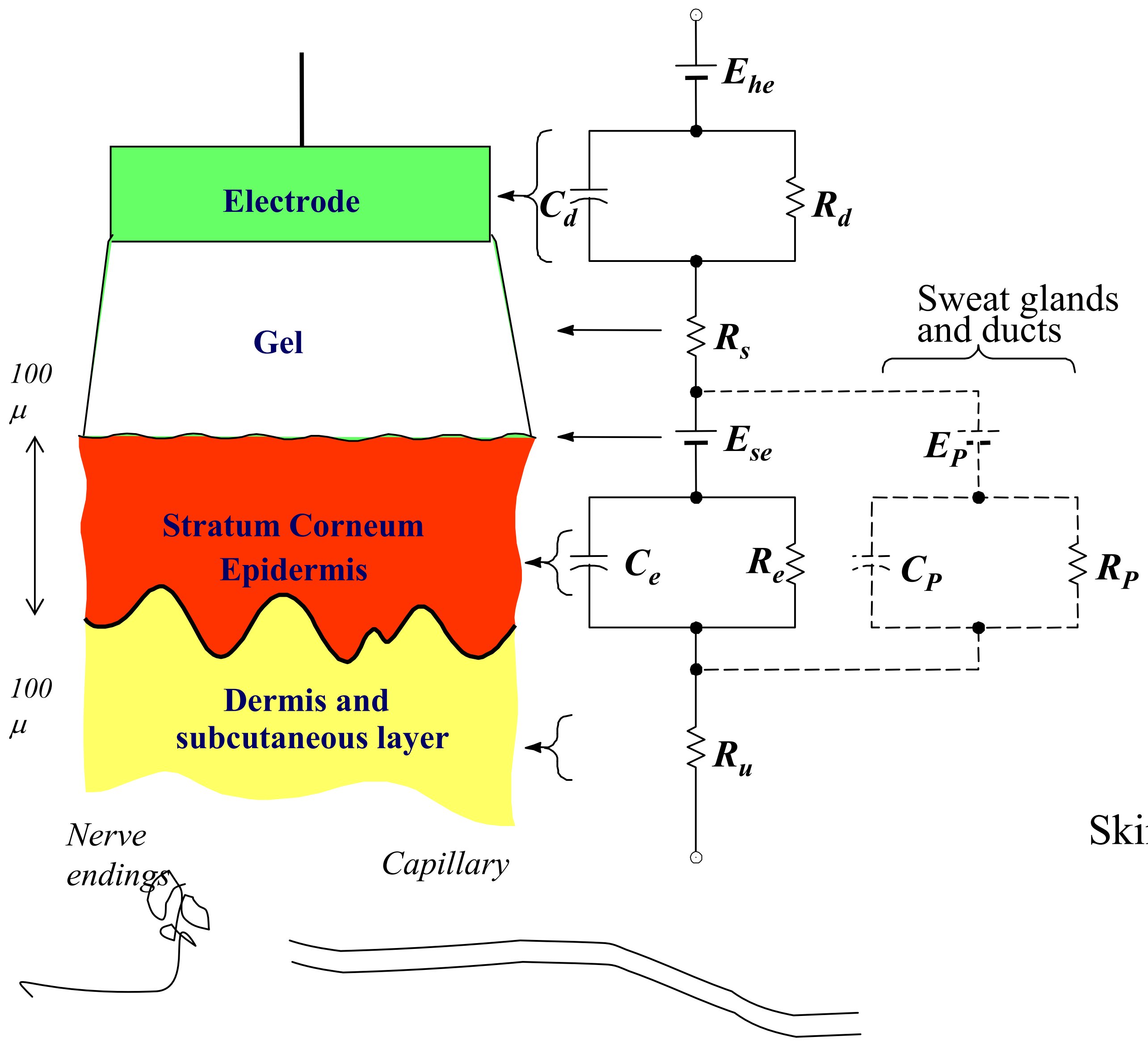


C_d : capacitance of electrode-eletrolyte interface
R_d : resistance of electrode-eletrolyte interface
R_s : resistance of electrode lead wire
E_{cell} : cell potential for electrode



Frequency Response

Electrode Skin Interface



Alter skin transport (or deliver drugs) by:

Pores produced by laser, ultrasound or by iontophoresis

Skin impedance for 1cm^2 patch:
200kΩ @1Hz
200 Ω @ 1MHz

Motion Artifact

Why

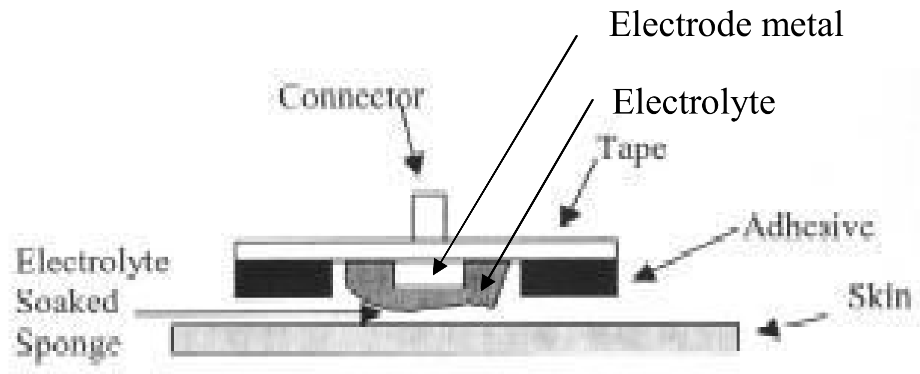
When the electrode moves with respect to the electrolyte, the distribution of the double layer of charge on polarizable electrode interface changes. This changes the half cell potential temporarily.

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

Motion artifact is minimal for non-polarizable electrodes

Body Surface Recording Electrodes



1. Metal Plate Electrodes (historic)
2. Suction Electrodes

   (historic interest)
3. Floating Electrodes
4. Flexible Electrodes

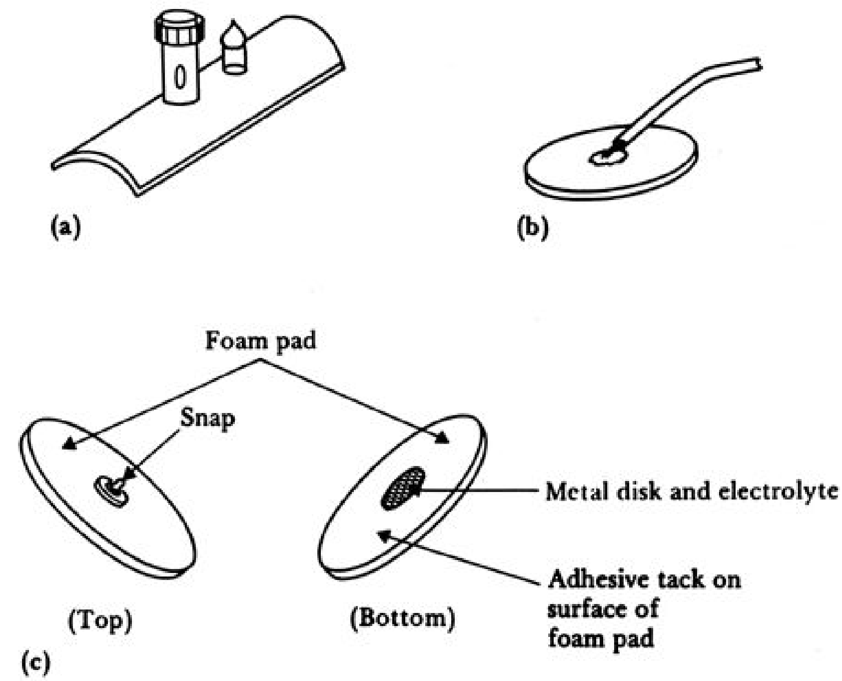
Think of the construction of electrosurgical electrode

And, how does electro-surgery work?

Commonly Used Biopotential Electrodes

Metal plate electrodes

- Large surface: Ancient, therefore still used, ECG
- Metal disk with stainless steel; platinum or gold coated
- EMG, EEG
- smaller diameters
- motion artifacts
- Disposable foam-pad: Cheap!



(a) Metal-plate electrode used for application to limbs.
(b) Metal-disk electrode applied with surgical tape.
(c)Disposable foam-pad electrodes, often used with ECG

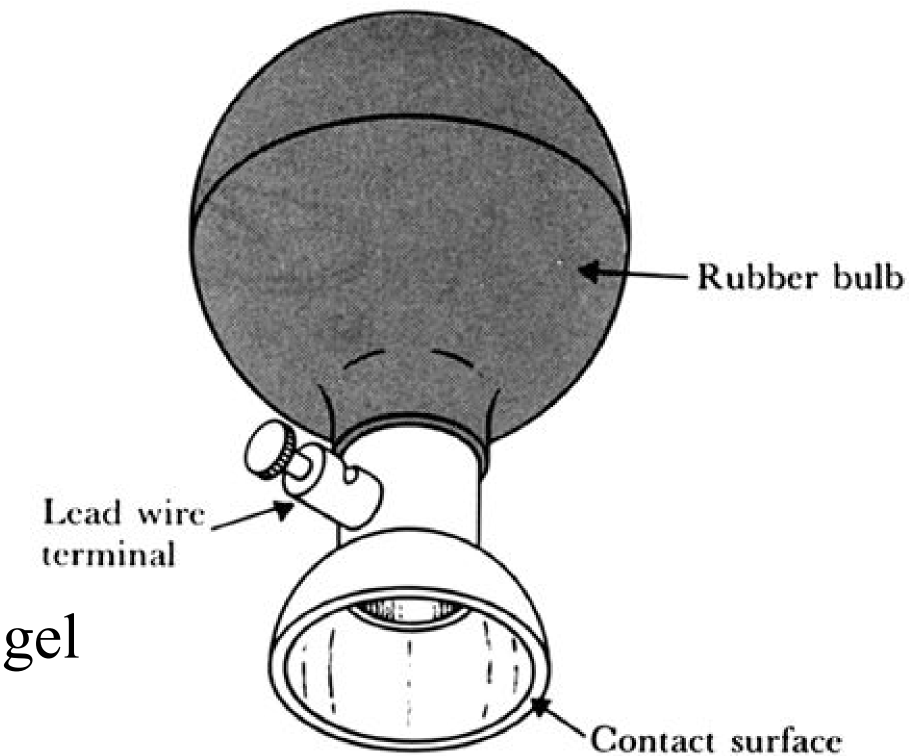
Commonly Used Biopotential Electrodes

Suction electrodes

- No straps or adhesives required
- precordial (chest) ECG
- can only be used for short periods

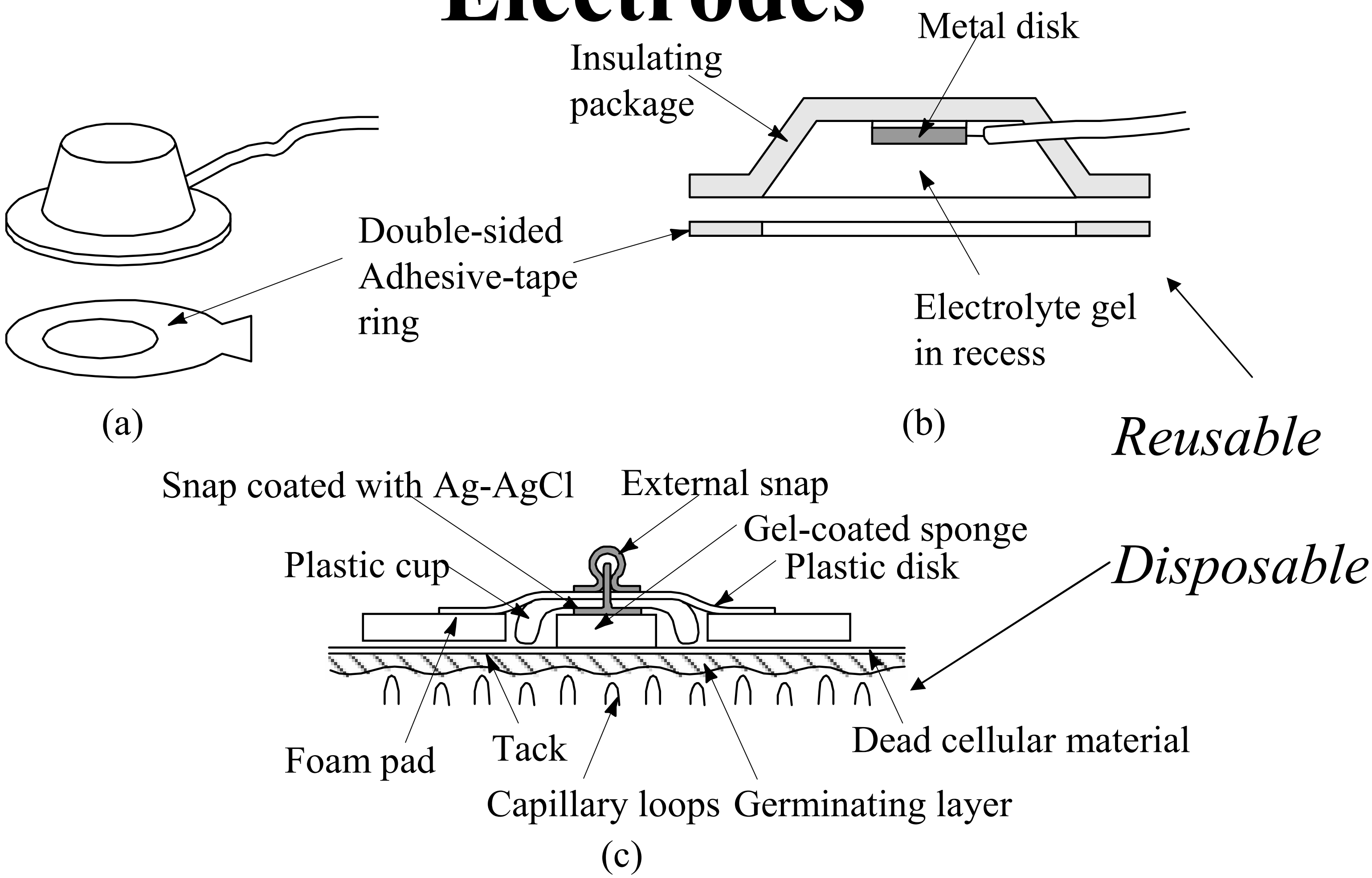
Floating electrodes

- metal disk is recessed
- swimming in the electrolyte gel
- not in contact with the skin
- reduces motion artifact



Suction Electrode

Commonly Used Biopotential Electrodes

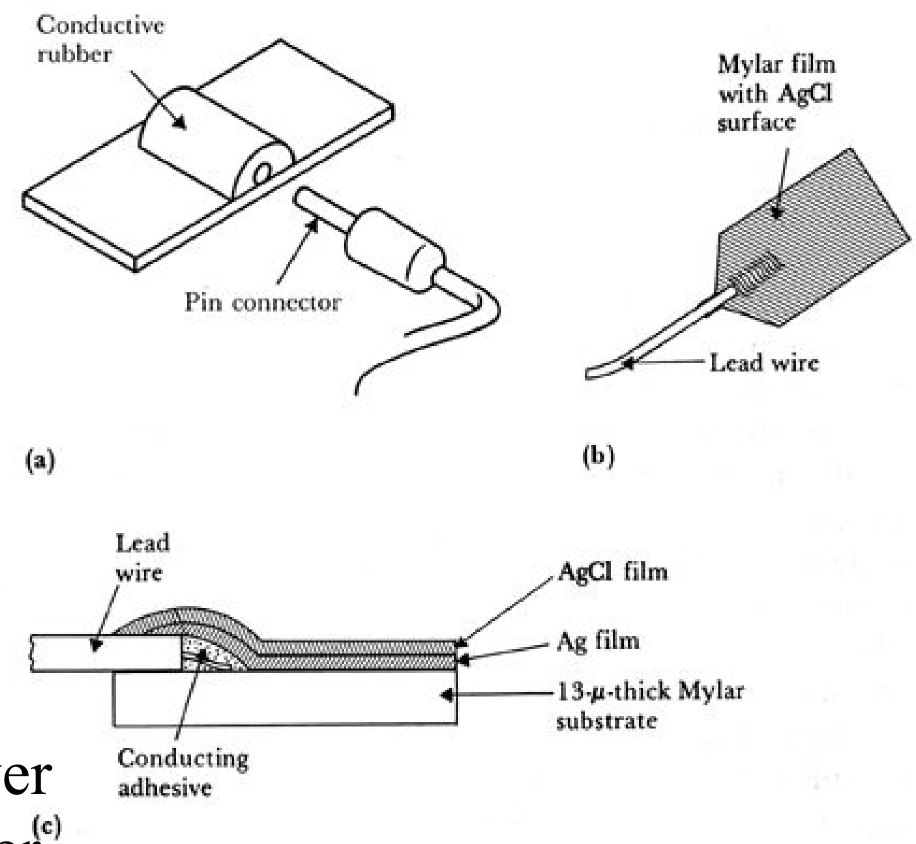


Floating Electrodes

Commonly Used Biopotential Electrodes

Flexible electrodes

- Body contours are often irregular
- Regularly shaped rigid electrodes may not always work.
- Special case : infants
- Material :
  - Polymer or nylon with silver
  - Carbon filled silicon rubber (Mylar film)

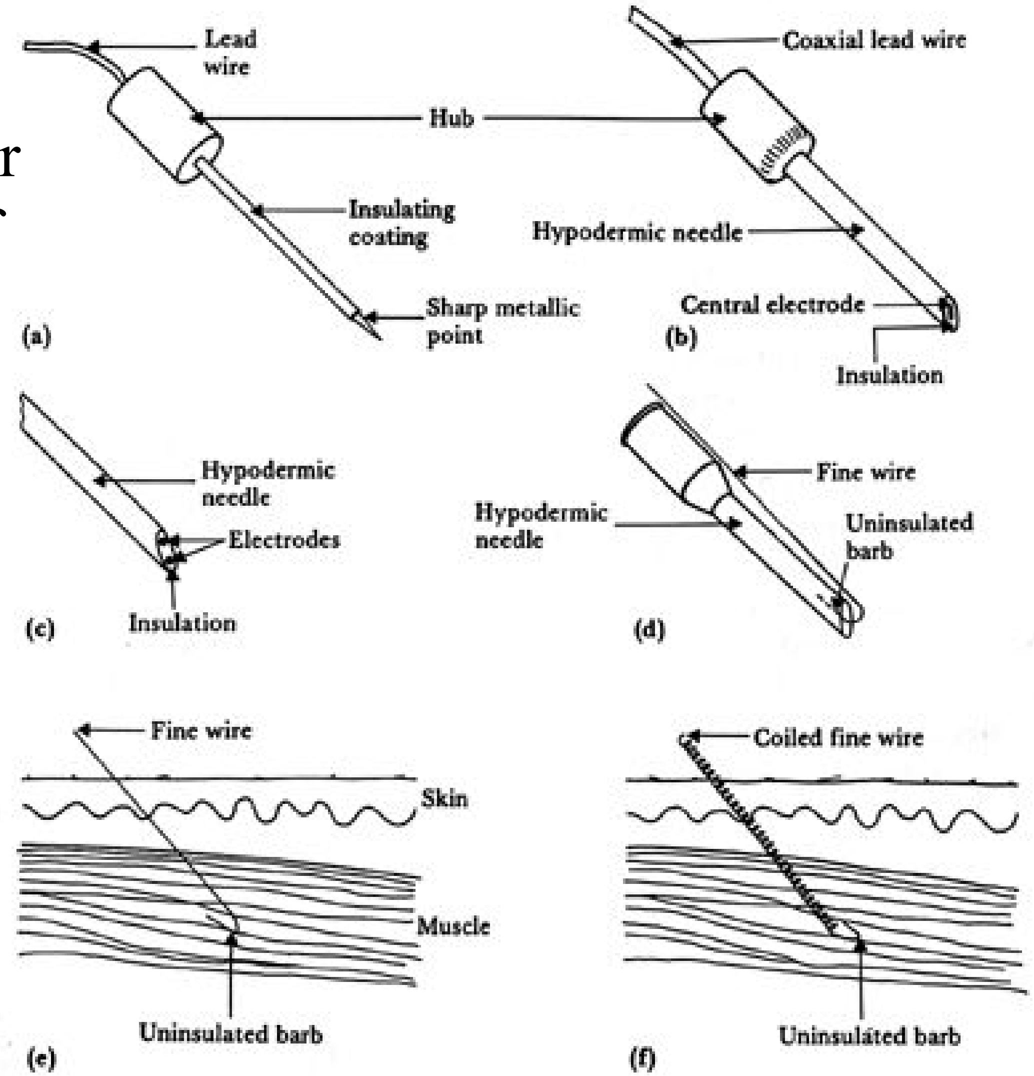


(a) Carbon-filled silicone rubber electrode.
(b) Flexible thin-film neonatal electrode.
(c) Cross-sectional view of the thin-film electrode in (b).

Internal Electrodes

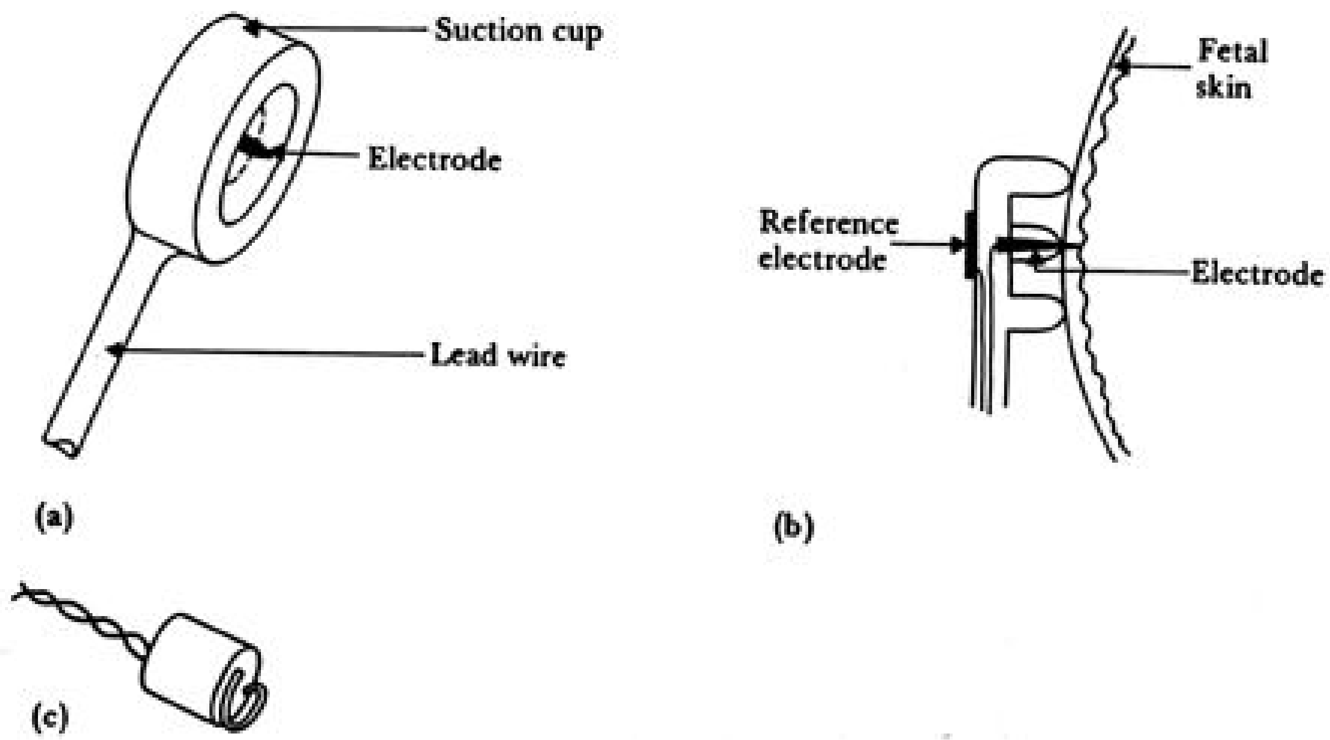
Needle and wire electrodes for percutaneous measurement of biopotentials

(a) Insulated needle electrode.
(b) Coaxial needle electrode.
(c) Bipolar coaxial electrode.
(d) Fine-wire electrode connected to hypodermic needle, before being inserted.
(e) Cross-sectional view of skin and muscle, showing coiled fine-wire electrode in place.



The latest: BION – implanted electrode for muscle recording/stimulation
Alfred E. Mann Foundation

Fetal ECG Electrodes



Electrodes for detecting fetal electrocardiogram during labor, by means of intracutaneous needles (a) Suction electrode. (b) Cross-sectional view of suction electrode in place, showing penetration of probe through epidermis. (c) Helical electrode, which is attached to fetal skin by corkscrew type action.

Problems

1. Describe one “innovative” scheme for recording breathing or respiration. The applications might be respirometry/spirometry, athletes knowing what their heart rate is, paralyzed individuals who have difficulty breathing needing a respiratory sensor to stimulate and control phrenic nerve. You may select one of these or other applications, and then identify a suitable sensor. Then design (develop suitable circuit) for interfacing to the sensor to get respiratory signal.

2. We would like to have a quadriplegic automatic control over the lighting in the room. Design a basic circuit to detect room light level and turn on a lamp when the light level falls below a set limit. You may consider a suitable sensor for light and you should consider a design that compares the sensor output to some predetermined threshold and produces a high voltage or delivers power to the lamp.

Electrodes in Biopotential Measurements

3. Describe the construction of commercial ECG electrode (not the cheap polymer electrode used in the lab). What is the common electrode metal, and why is it preferred?

So, you are an inventor who has a better idea. Describe an improvement

- to make the electrode cheaper
- more suitable for lower noise measurement for EEG
- circumvent patents that are based on plastic/foam electrode body
- attractive to consumers for use with their ECG machines at home
- reduce artifact (minimize the motion of skin/electrode) in ambulatory recording

4. In a research laboratory, scientists want to record from single cells in a culture dish. They want to record action potentials from single, isolated heart cells. What kind of electrode would they need to use (describe material and design)? Give a simplified schematic (circuit model of the electrode) described in the notes given to you.

What is the challenge involved in designing an amplifier for use with a microelectrode for single cell recording? I.e. what are the critical amplifier design characteristics and specifications (hint: this is not the usual differential/instrumentation amplifier) ?

Electrodes and Microelectrodes (miscellaneous)

- How would you detect bacteria or other microorganisms in water supply? Make sure that your method distinguishes inert particulate matter from living cellular matter.

- Draw the equivalent circuit model of the skin and an ECG electrode. Identify the key sources of electrical interference and otherwise the elements that would likely contribute to the poor quality of recordings.

- Design an amplifier interface for the following two applications: Patch clamp ion channel current amplifier: Your goal is to amplify pA level current to produce 1 Volt output.

- Strain gauge sensor amplifier: Your goal is to convert 10 ohm change in resistance of a strain gauge to produce 1 volt output.

- You are asked to design a laboratory set up for a Professor who is interested in making very low level ion channel current measurements from single cardiac cells using the patch clamping technique. What are the likely sources of interference? What would you do to ensure that there is minimal noise in the laboratory set up?

- Draw the equivalent circuit of a patch clamp glass pipette. This electrode differs slightly from the conventional microelectrode that penetrates the cell and obtains intracellular potentials, in that it seals to the cell membrane and generally measures the whole cell current. Show all the equivalent circuit elements of the electrode and the cell.

- Design a very simple, small circuit to measure/transduce the whole cell current from the patch clamp electrode and convert into the amplified voltage signal.

- For far too long the microelectrodes that have been used in the laboratory fall into two categories: glass or metal microelectrodes. These record from a single cell at a time. What is the current technology for recording from sites in the tissue from multiple cells at once (extracellularly OR intracellularly). Draw a schematic of such an electrode array.

- List some other types of electrodes or microelectrodes that have been developed for laboratory and research use.

5. Electrodes and Microelectrodes

Contrast the glass microelectrode that penetrates the cell versus patch clamp electrode. Which measures what (current/voltage) and of what magnitude? Which one is bigger/smaller? What is the impedance of microelectrode vs. patch electrode? Which one could be used to record from a single sub-micron sized ion channel?

For a research application, a scientist comes up with the idea of optically measuring potential on cell membrane. His basic idea is to use a dye that binds to cell surface. When the dye is excited by a bright light (superluminscent LED), it gives out fluorescence proportional to cell membrane voltage. The optical signal is picked up by a photo detector. Draw the circuit to pass a very large (about 100 mA) pulse of current through the LED to intensely illuminate the cell for very brief duration and then detect nA ampere level photo current produced by the fluorescence signal

You are asked to measure the impedance of the skin. In fact, lie detectors use changes in skin impedance (as a measure of autonomic reflex) to indicate whether a person is lying. Draw the equivalent circuit model of human skin and electrode. Based on reasonable estimates of the skin properties, sketch a rough frequency response of the skin (from dc to 100 kHz)

Now design a circuit to measure the impedance, taking care not to violate any safety consideration.

6. Neural electrodes/microelectrodes

You want to record from neurons in the brain. However, you want to record from dozens of neurons all at once from several closely spaced microelectrodes. What material and process would you use to make the microelectrode array?

•What metal would you prefer to use to make electrode arrays of about 10 micron square size to make electrical contacts with dozens of neurons?

•What metal would you prefer to use to stimulate dozens of neurons in a deep brain microelectrode based stimulator?

•(which metal provides good recording vs stimulating properties – and at the same time not be toxic to brain tissue)?

• You are asked to develop an experimental set up to record from rat brain cells using microelectrodes. What precautions would you take to minimize the electrical interference in your recording set up?

Question/ideas!

- Make a better electrode
- Research different electrode technologies
  - Ion selective, immunosensors, ISFET, electrochemical
  - MEMS microelectrode technologies