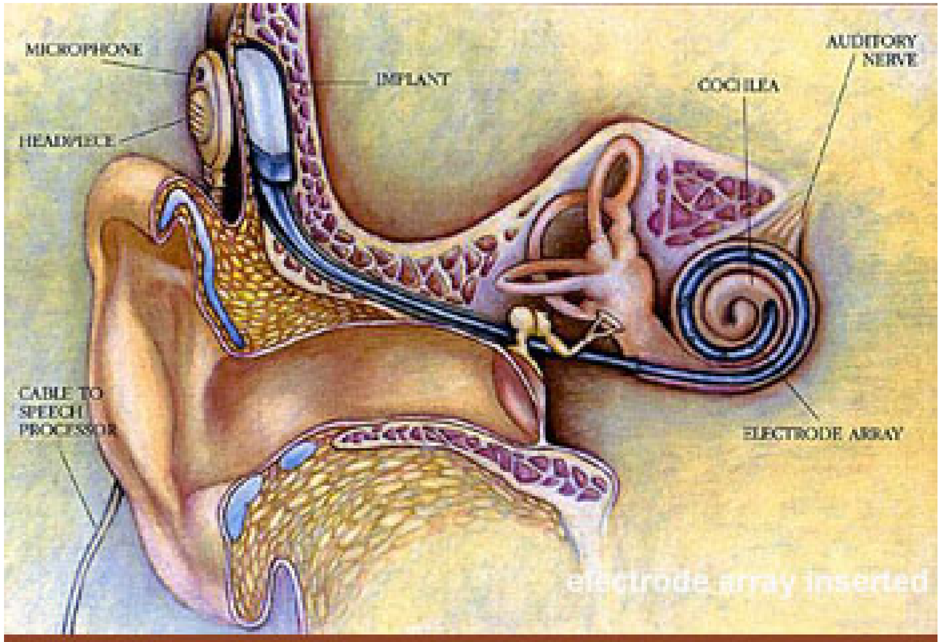
BME 701
Lecture 1

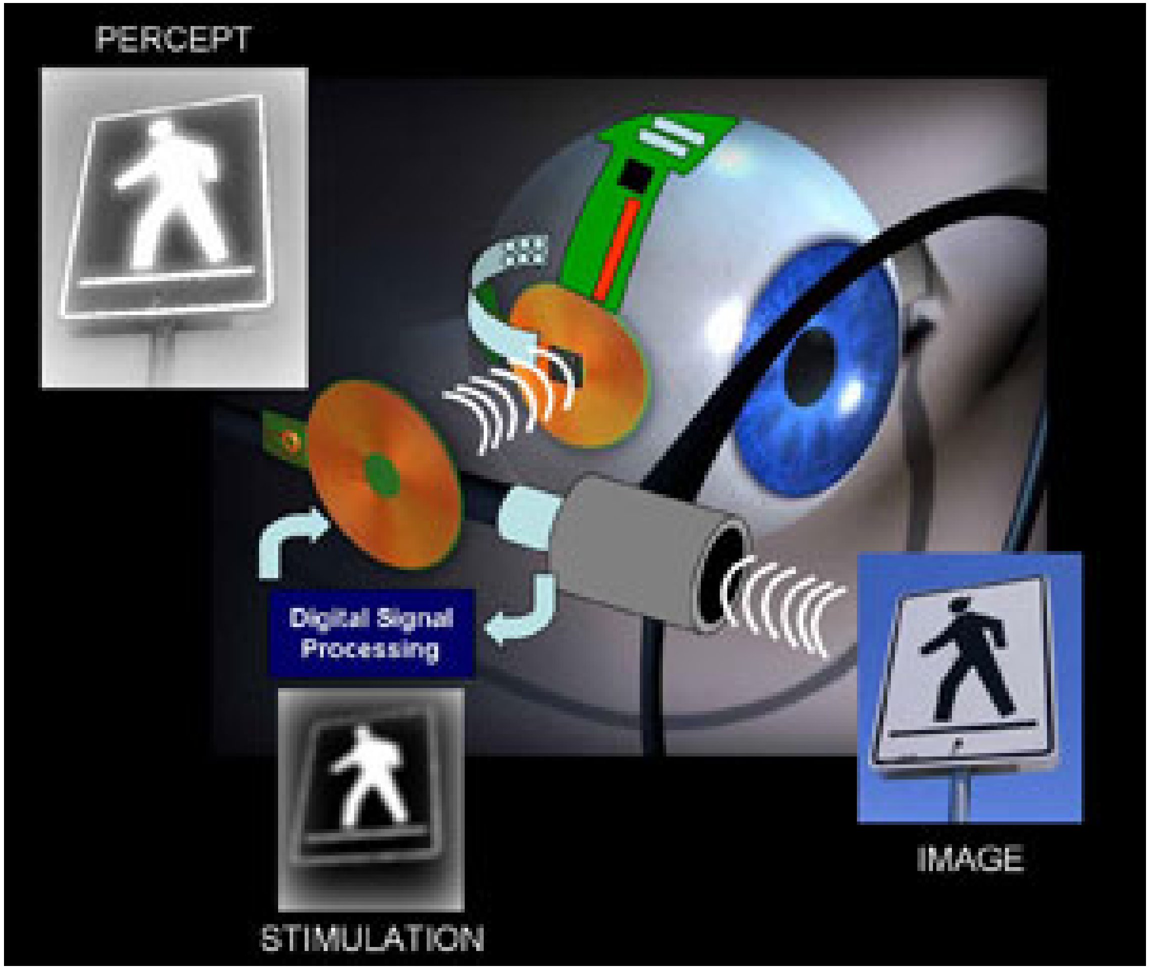
Measurement and Instrumentation

Cochlear Implant

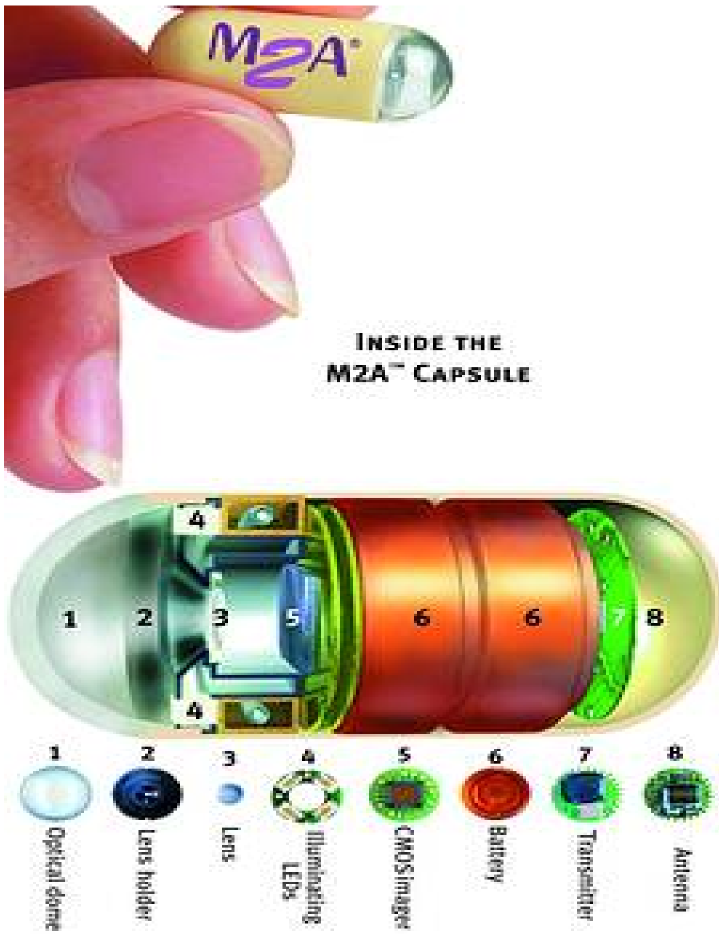


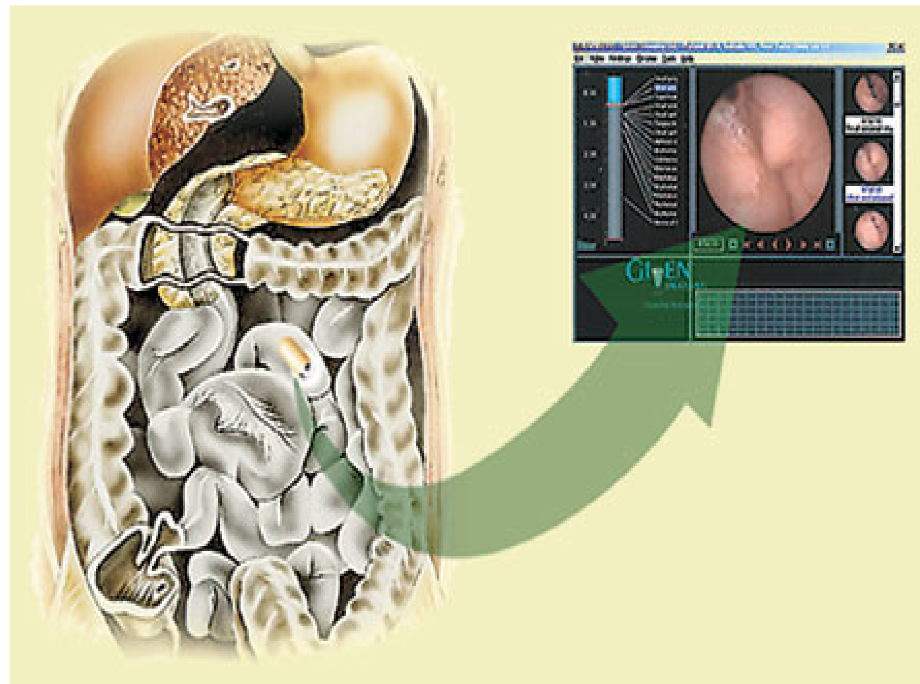
Schematic of cochlear implant; note electrode array inserted into cochlea.

Advances in Vision (Retinal Stimulation)



Mini Gastric Imaging





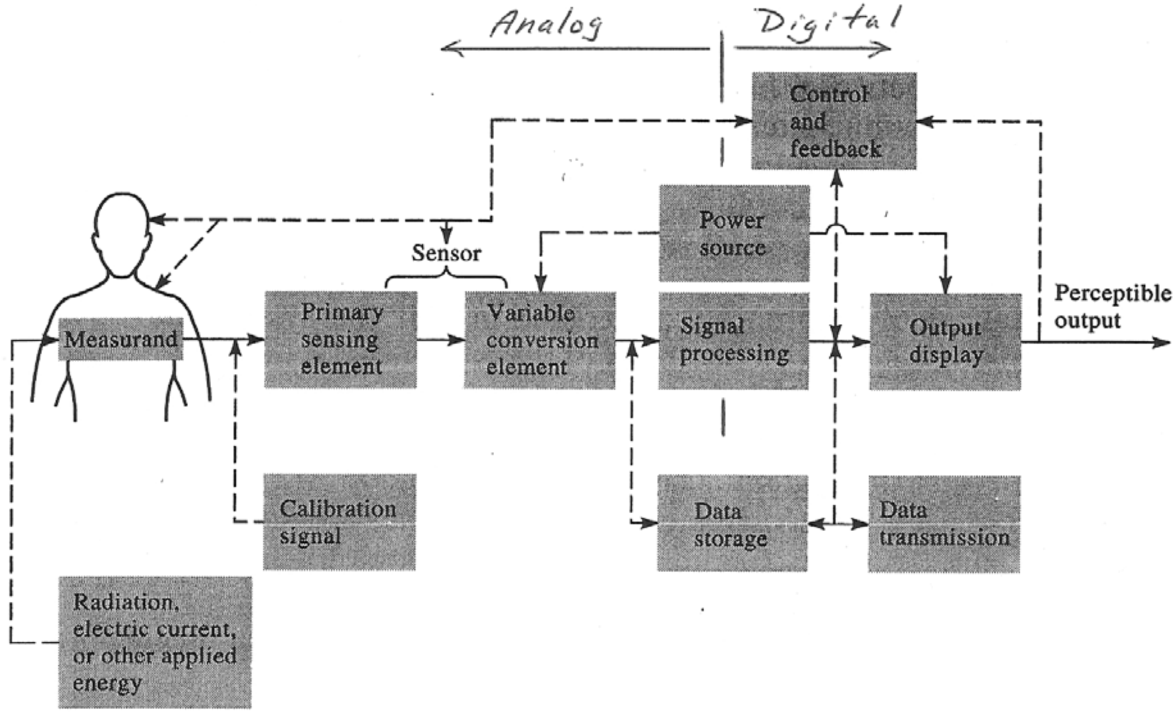


Figure 1.1 Generalized instrumentation system The sensor converts energy or information from the measurand to another form (usually electric). This signal is then processed and displayed so that humans can perceive the information. Elements and connections shown by dashed lines are optional for some applications.

Measurand: Biopotentials
Central Nervous System (Brain) EEG
Spinal and Peripheral Neurons } EMG
Muscle Fibres
others: EOG

Sensor (Transducer): Electrodes
Convert ionic flows and concentrations to electronic

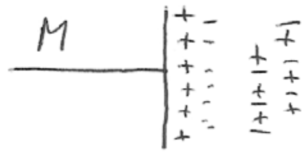
Aspects of Measurement

- General Instrumentation
- Transducers (Electrodes)
- General Recording Situation
- Sources of Noise and Solutions
- Effects of electrode size, spacing and orientation
- Digitization of Signals

Characteristics of Biopotential Signals

- Determined by size of bioelectric generator
- Determined by distance and orientation of bioelectric generator to recording electrode(s)
- Determined by size and properties of electrode(s)

Electrodes



$$M \rightleftharpoons M^{+z} + ze^-$$

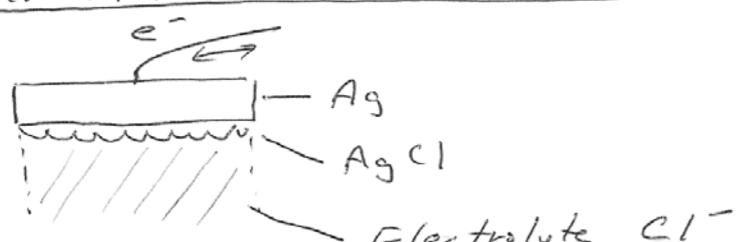
equilibrium

- thermodynamic equilibrium results in charge redistribution in vicinity of metal-solution interface
- gives rise to half-cell potential

e.g.

$$Ag \rightleftharpoons Ag^+ + e^- \qquad .7991V$$

Silver - Silver Chloride Electrode



$$AgCl \rightleftharpoons Ag^+ + Cl^- \qquad .2225V$$

$$+e^- \downarrow\uparrow -e^-$$

$$Ag$$

Half Cell Potentials for common Metals

Table 5.1 Half-cell Potentials for Common Electrode Materials at 25 °C

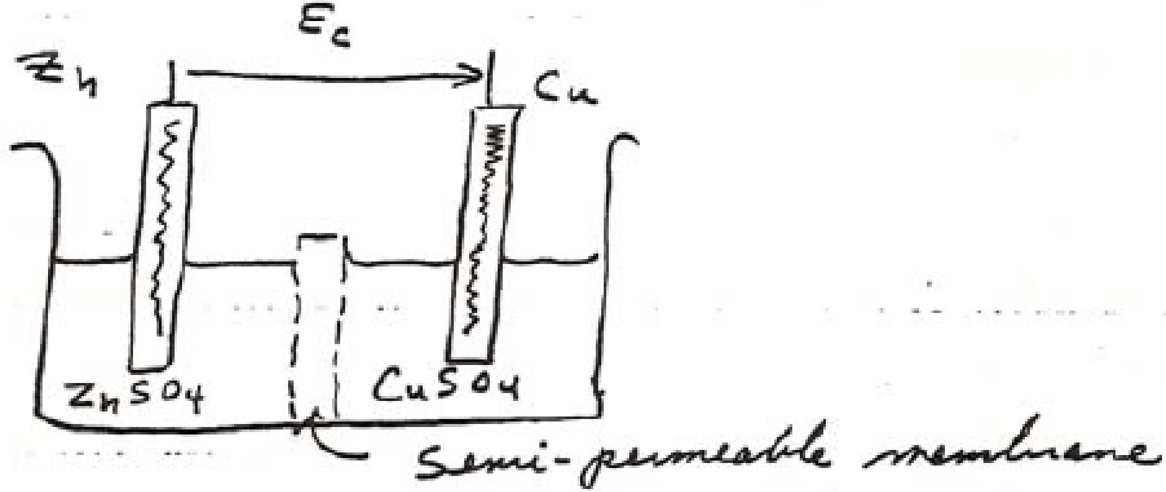
The metal undergoing the reaction shown has the sign and potential E^0 when referenced to the hydrogen electrode

Metal and Reaction	Potential E^0 (V)
$Al \rightarrow Al^{3+} + 3e^-$	−1.706
$Zn \rightarrow Zn^{2+} + 2e^-$	−0.763
$Cr \rightarrow Cr^{3+} + 3e^-$	−0.744
$Fe \rightarrow Fe^{2+} + 2e^-$	−0.409
$Cd \rightarrow Cd^{2+} + 2e^-$	−0.401
$Ni \rightarrow Ni^{2+} + 2e^-$	−0.230
$Pb \rightarrow Pb^{2+} + 2e^-$	−0.126
$H_2 \rightarrow 2H^+ + 2e^-$	0.000 by definition
$Ag + Cl^- \rightarrow AgCl + e^-$	+0.223
$2Hg + 2Cl^- \rightarrow Hg_2Cl_2 + 2e^-$	+0.268
$Cu \rightarrow Cu^{2+} + 2e^-$	+0.340
$Cu \rightarrow Cu^{+} + e^-$	+0.522
$Ag \rightarrow Ag^{+} + e^-$	+0.799
$Au \rightarrow Au^{3+} + 3e^-$	+1.420
$Au \rightarrow Au^{+} + e^-$	+1.680

SOURCE: Data from *Handbook of Chemistry and Physics*, 55th ed., Cleveland, OH: CRC Press, 1974–1975, with permission.

Electrochemical Cell

Daniel cell



In absence of any current

$$E_c = E^{\circ}_{Cu^{2+}/Cu} - E^{\circ}_{Zn^{2+}/Zn}$$

Electrochemical Cell (cont'd)

- Ignoring liquid junction potential (several mv's) E_C = 1.1 V
- Measuring an electrophysiological event requires 2 electrodes
- These form an electrochemical cell with a DC potential the difference of the two half-cell potentials
- When a small current flows equilibrium potentials changed, called polarization
- Cell potential, even for same electrodes can be as high as 600 μV.

Electrode Polarization

Half-cell potential result of equilibrium.

If current flowing in/through electrode

half cell potential changes (polarization)

$V_p = V_r + V_c + V_a$

V_p = total overvoltage

V_r = ohmic overvoltage (resistance of electrode)

V_c = concentration overvoltage
(changes in distribution of ions in electrolyte
in vicinity of electrode/electrolyte interface)

V_a = activation overvoltage
(energy required for oxidation - reduction
of metal atoms are different in general.
current flowing oxidation or reduction
predominates.

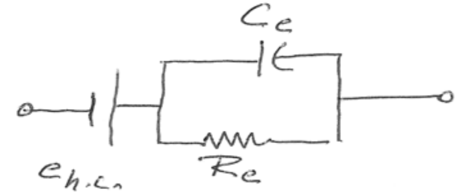
Perfectly Polarizable ⟶ Perfectly non-polarizable

Noble metals
platinum, gold,

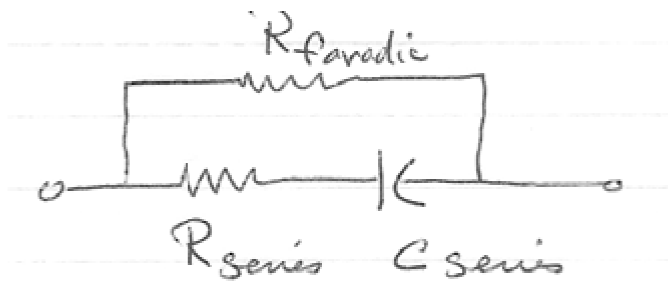
Ag - AgCl

Capacitive Electrodes

Warburg Model



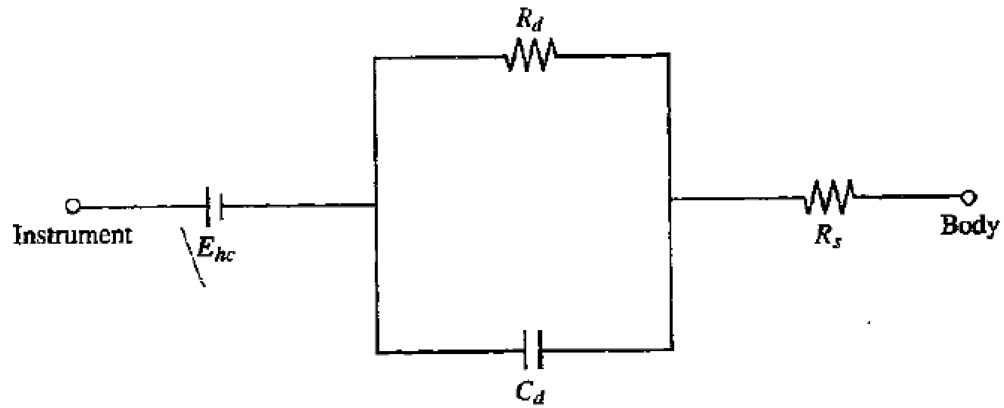
Electrode Impedance

- Can also 

guration

- R is from electrolyte resistance in vicinity of electrode surface
- C is from space charge region
- $R_{faradic}$ added to allow conduction at DC

Electrode Impedance



$$Z = R_s + \frac{\dfrac{R_d}{j2\pi f C_d}}{R_d + \dfrac{1}{j\pi f C_d}}$$

$$Z = R_s + \frac{R_d}{1 + j2\pi f C_d R_d}$$

Electrode Impedance (cont'd)

Typically values are as follows for a .25 cm^2 electrode

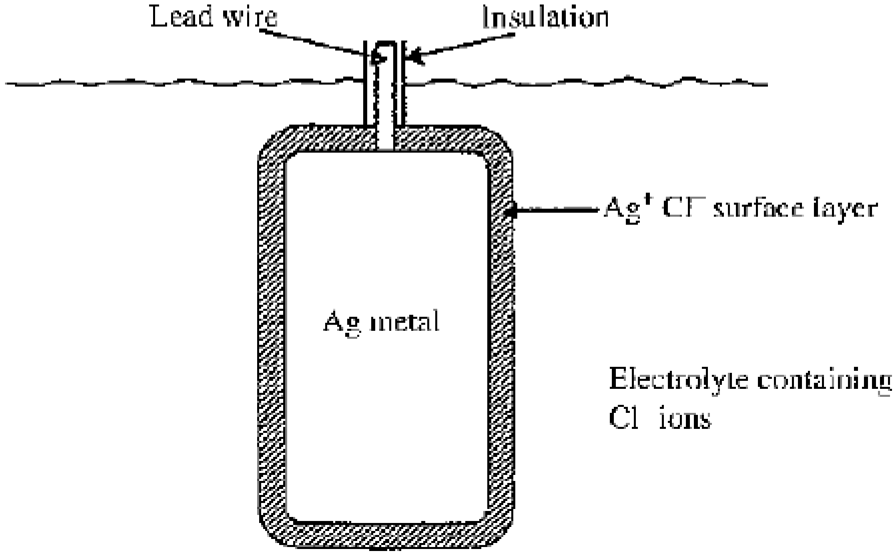
Ag 450 Ω at 10 Hz, 180 Ω at 300 Hz
Ag-AgCl 250 Ω at 10 Hz 200 Ω at 300 Hz

Reusable nickel and carbon loaded silicone rubber electrodes 1 cm^2 (used for chronic stimulation in therapy)

30K Ω at 10 Hz 700 Ω at 5 KHz.

Skin impedance is typically 200 KΩ to 1 MΩ at low frequencies per cm^2. At 1 MHz this typically drops to 250 Ω.

Ag-AgCl Electrode in Solution

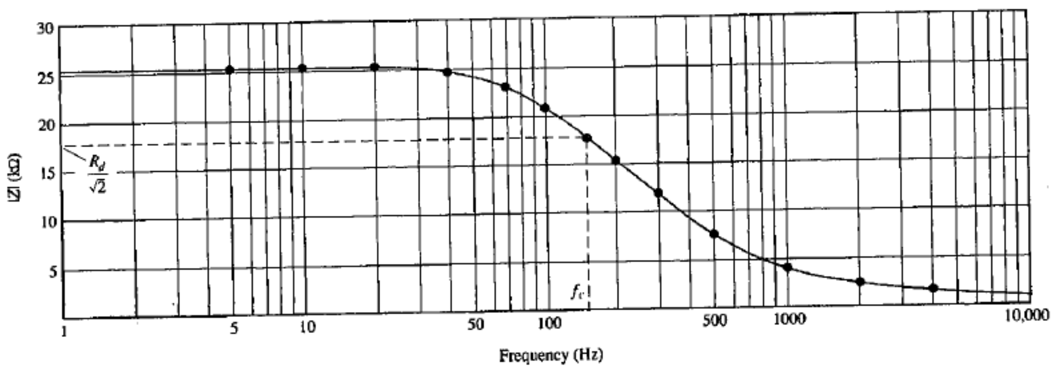


A silver/silver chloride electrode, shown in cross section.

$$Ag \rightleftarrows Ag^{+} + e^{-}$$

$$Ag^{+} + Cl^{-} \rightleftarrows AgCl \downarrow$$

Typical Impedance vs Frequency for Ag-AgCl



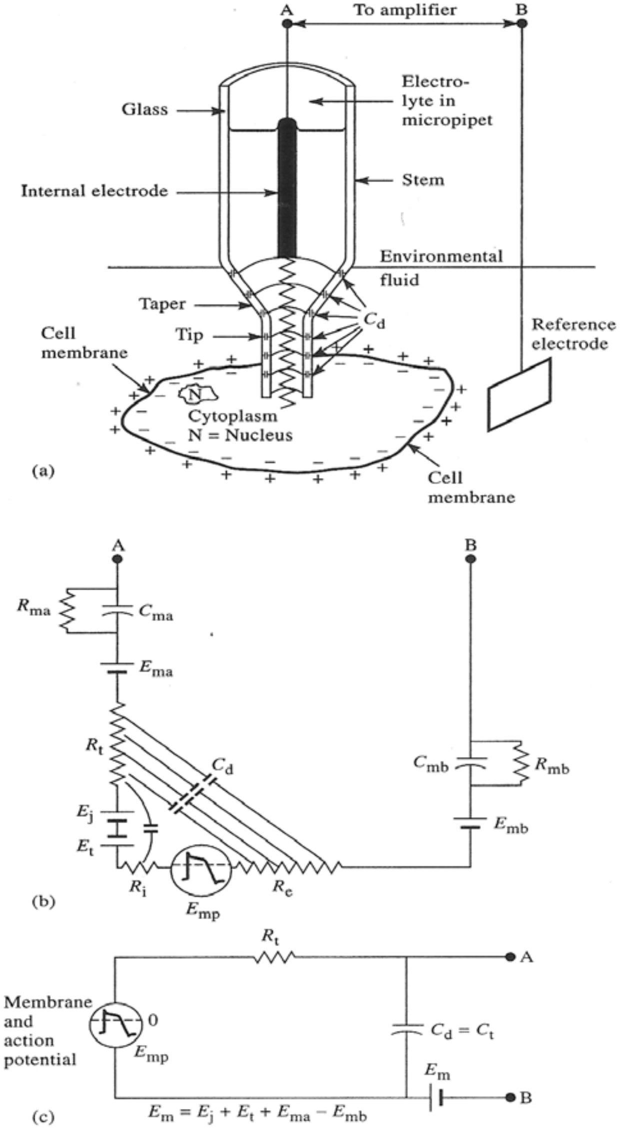


Figure 5.22 Equivalent circuit of glass micropipet microelectrode (a) Electrode with its tip placed within a cell, showing the origin of distributed capacitance. (b) Equivalent circuit for the situation in (a). (c) Simplified equivalent circuit. (From L. A. Geddes, *Electrodes and the Measurement of Bioelectric Events,* Wiley-Interscience, 1972. Used with permission of John Wiley and Sons, New York.)

Space Charge Region

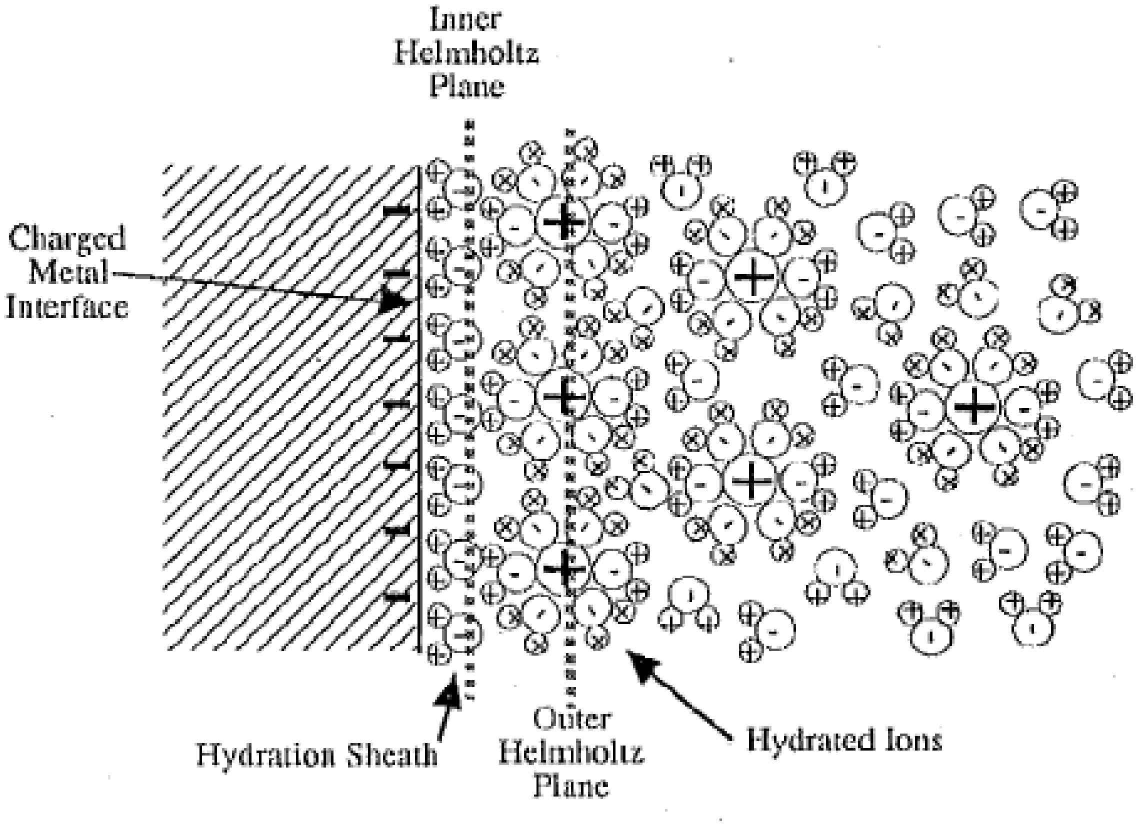


Figure 2. Space Charge Layer. Kovacs. [2]

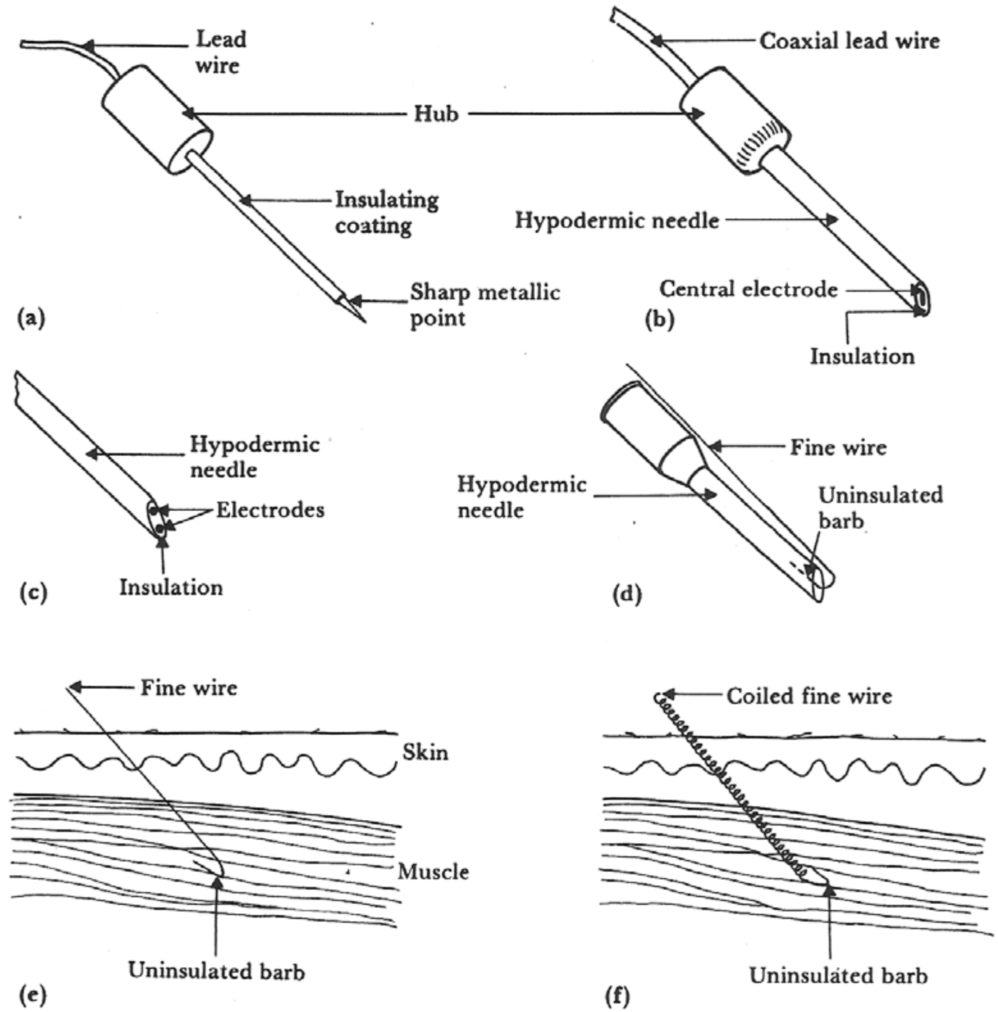


Figure 5.13 Needle and wire electrodes for percutaneous measurement of biopotentials (a) Insulated needle electrode. (b) Coaxial needle electrode. (c) Bipolar coaxial electrode. (d) Fine-wire electrode connected to hypodermic needle, before being inserted. (e) Cross-sectional view of skin and muscle, showing fine-wire electrode in place. (f) Cross-sectional view of skin and muscle, showing coiled fine-wire electrode in place.

Needle Electrode Connections

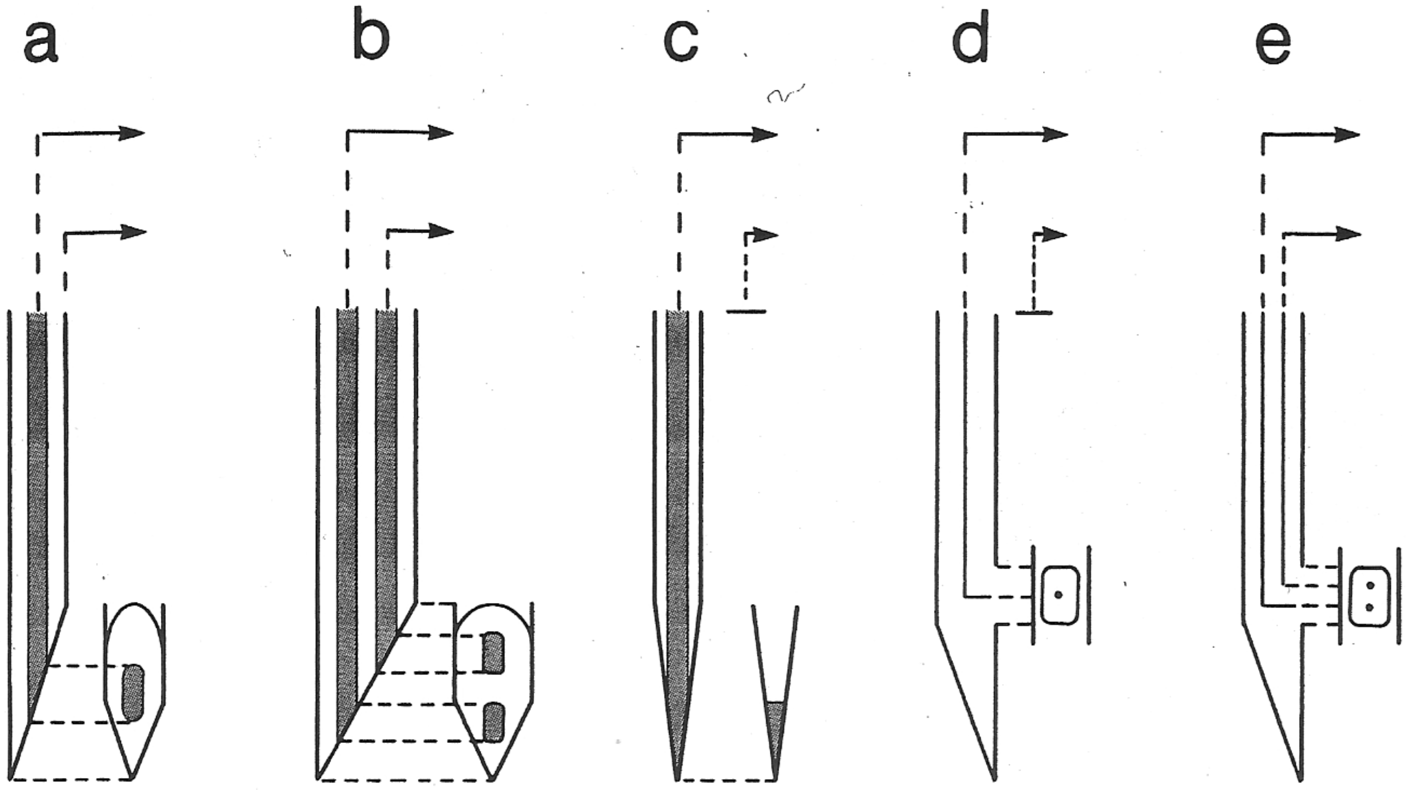


Figure 3-1

Schematic illustration of standard concentric (a), bipolar concentric (b), monopolar (c), and single fiber needles (d, e). Dimensions vary but the diameters of the outside cannulas shown are similar to 26-gauge hypodermic needles (460 μm) for (a), (d), and (e), 23-gauge needle (640 μm) for (b), and 28-gauge needle (360 μm) for (c). The exposed tip areas are about 150 μm $\times$ 600 μm for (a), 150 μm $\times$ 300 μm with spacing between wires of 200 μm center to center for (b), 0.14 mm^2 for (c), and 25 μm in diameter for (d) and (e). A separate reference electrode is necessary with monopolar needles (c) and (d) to complete the circuit. (Modified from Stålberg and Trontelj.[23])

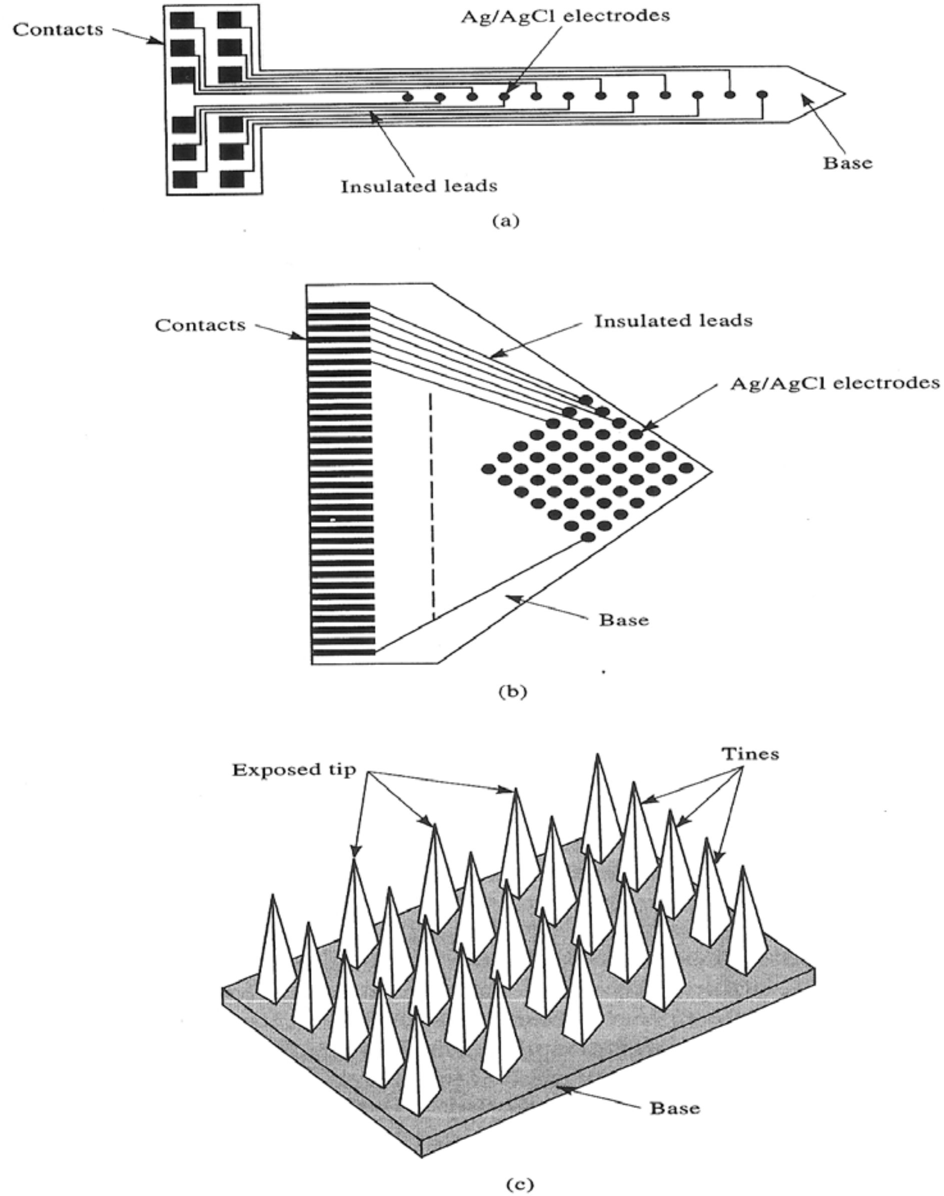


Figure 5.16 Examples of microfabricated electrode arrays. (a) One-dimensional plunge electrode array (after Mastrototaro *et al.*, 1992), (b) Two-dimensional array, and (c) Three-dimensional array (after Campbell *et al.*, 1991).

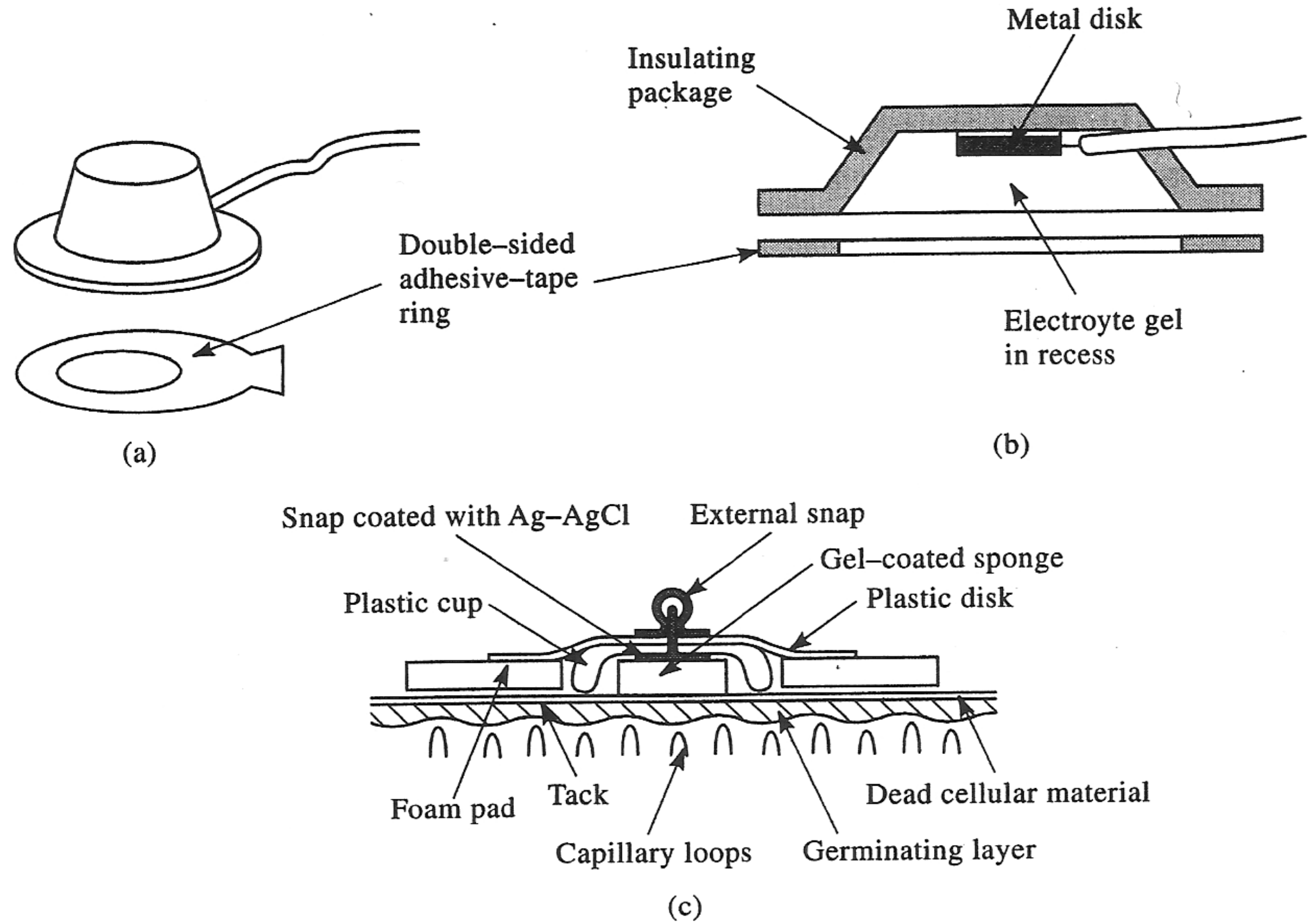


Figure 5.11 Examples of floating metal body-surface electrodes (a) Recessed electrode with top-hat structure. (b) Cross-sectional view of the electrode in (a). (c) Cross-sectional view of a disposable recessed electrode of the same general structure shown in Figure 5.9(c). The recess in this electrode is formed from an open foam disk, saturated with electrolyte gel and placed over the metal electrode.

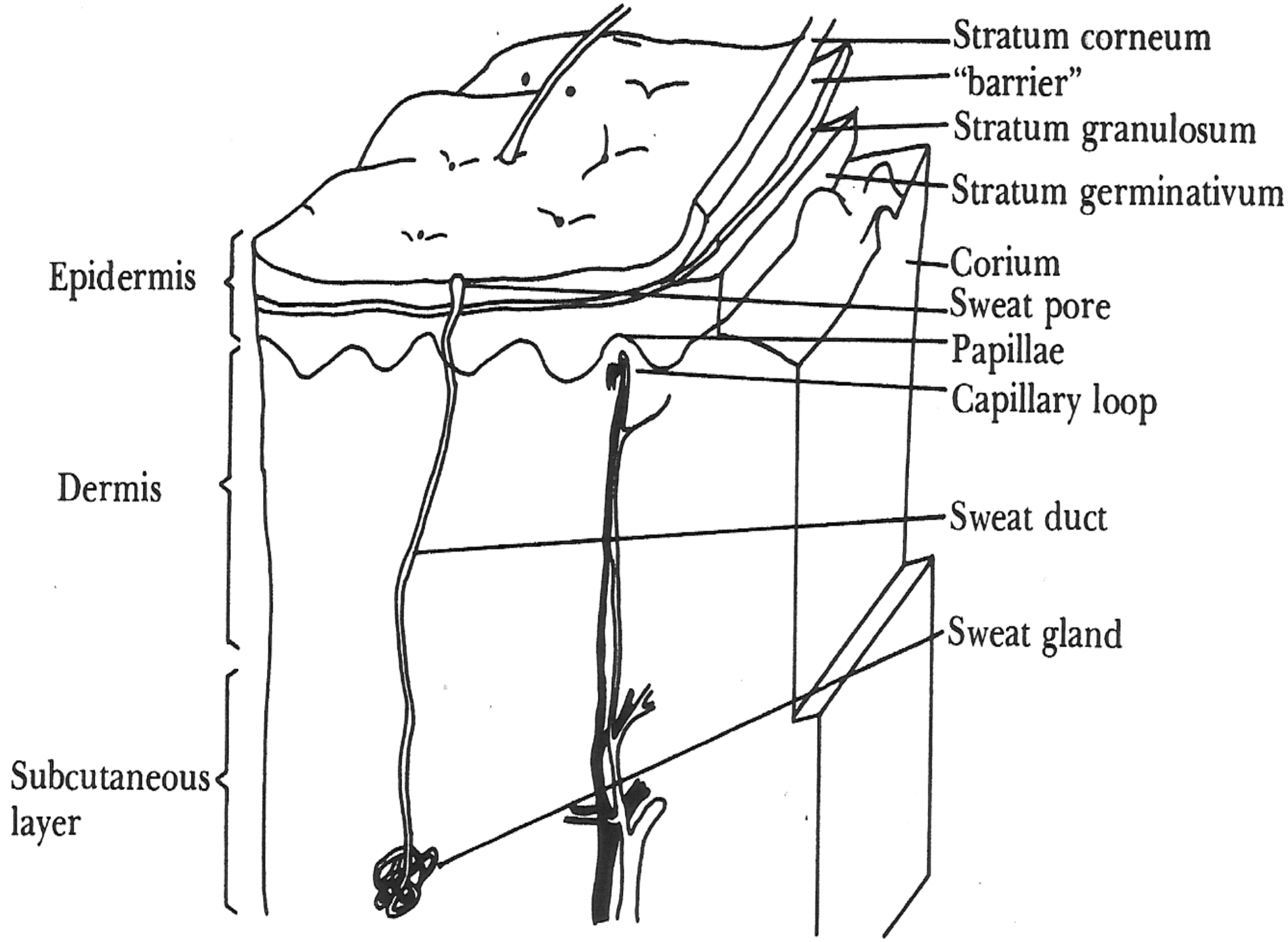


Figure 5.7 Magnified section of skin, showing the various layers (Copyright © 1977 by The Institute of Electrical and Electronics Engineers. Reprinted, with permission, from *IEEE Trans. Biomed. Eng.*, March 1977, vol. BME-24, no. 2, pp. 134–139.)

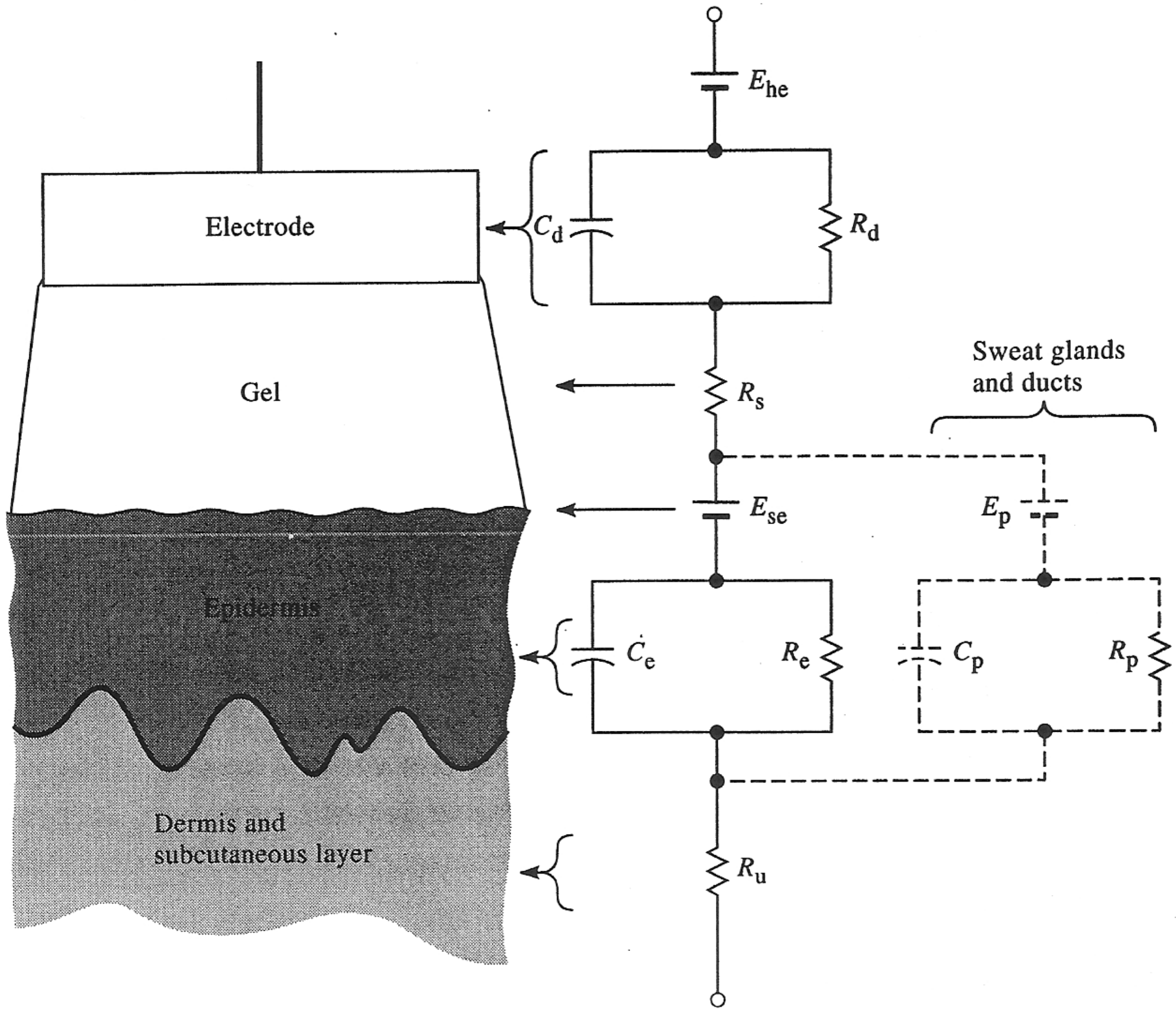


Figure 5.8 A body-surface electrode is placed against skin, showing the total electrical equivalent circuit obtained in this situation. Each circuit element on the right is at approximately the same level at which the physical process that it represents would be in the left-hand diagram.

Electrical Safety

- **Power is a constant voltage source (e.g. 110 V)**
- **Danger of electricity is determined by:**
- Current path in the body
- Frequency of current (DC and >40 kHz can't stimulate but can burn)
- Do not have to make contact for current to flow if AC
- Current determined by impedance of body (total 500 Ω), and contact/skin impedance
- Impedance of capacitor $I = C dV/dt$

Effect of Current (60 Hz)

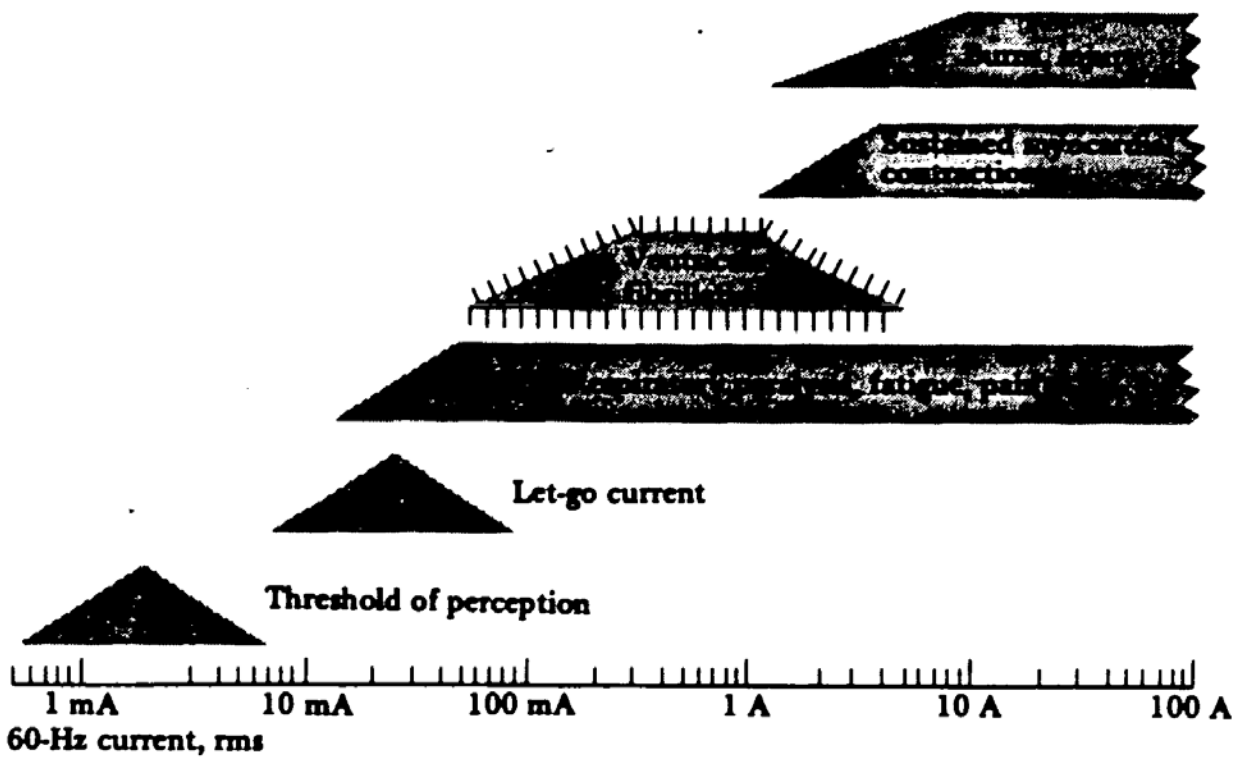
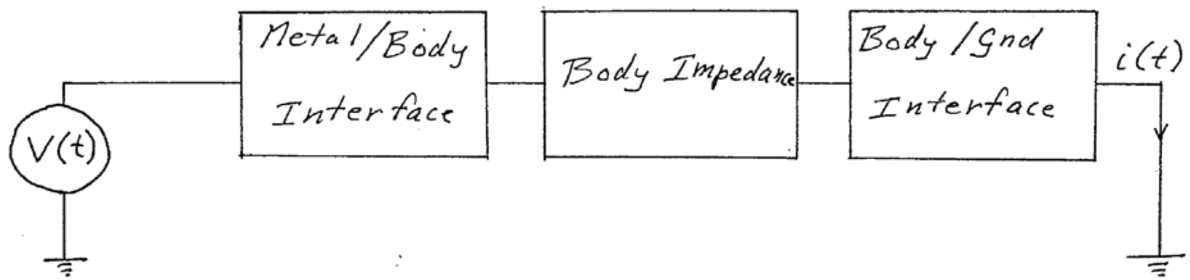
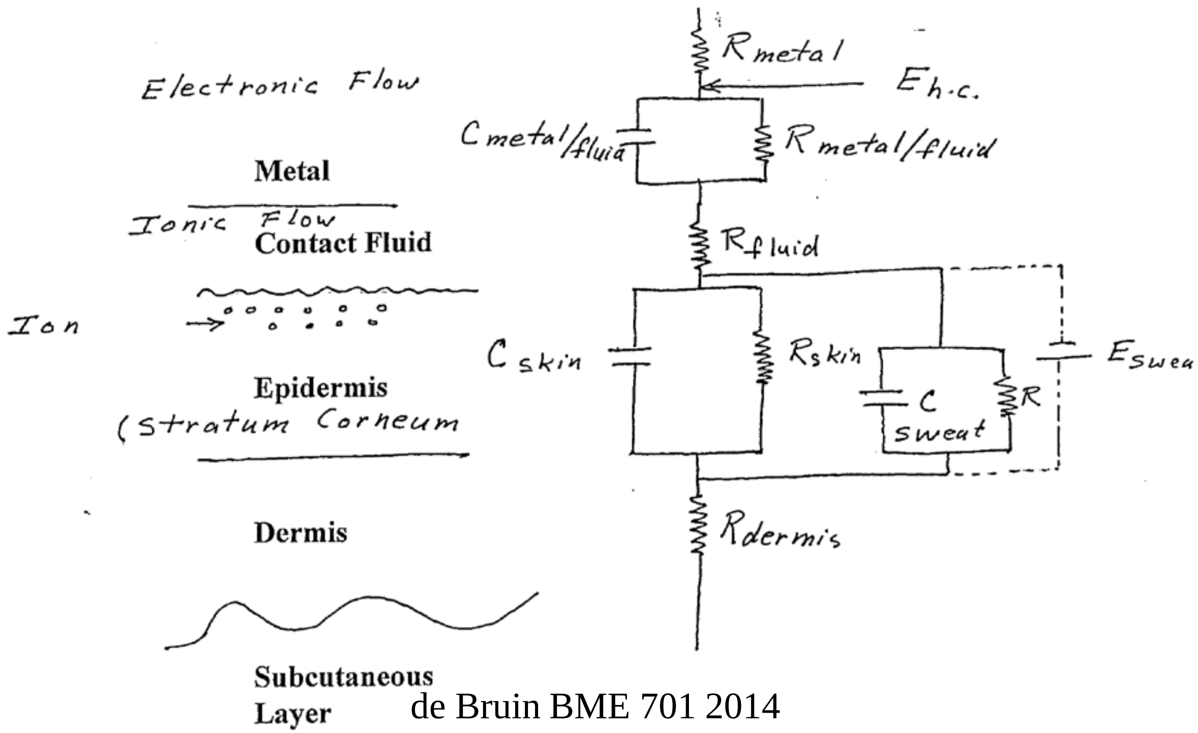


Figure 13.1 Physiological effects of electricity. Threshold or estimated mean values are given for each effect in a 70-kg male for 1- to 3-s exposure to 60-Hz current applied to copper wires grasped by the hands.

Equivalent Path



NB need complete loop for current to flow



Shock Hazards

Macroshock Hazards

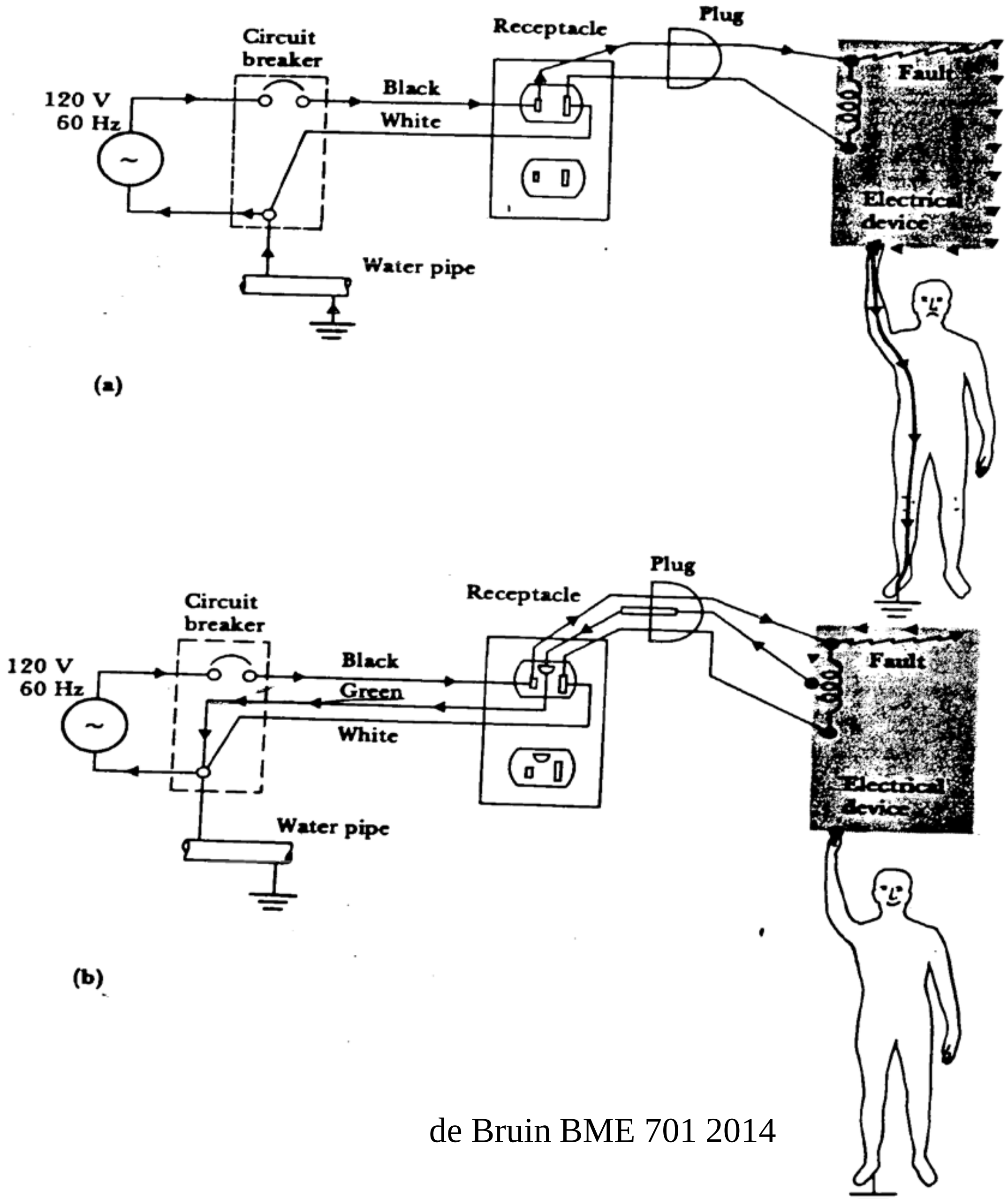
- **produced by high current levels (current density) applied to skin surface**
- **effects range from mild sensation to burns and shock (see figure)**
- **usually produced by careless handling, equipment malfunction or bad safety design**

Professional and Technical Considerations

Application of standards to equipment design, installation and operation

- **design - double insulation, grounding, enclosures, fusing, materials**
- **installation - power system, enclosures, site (see figure)**
- **operation - safe procedures, maintenance, periodic testing**

Macroshock Scenario



Microshock Hazards

Microshock Hazards (mostly Medical)

- produced by very small currents (microamps) applied to the skin or through the skin
- "leakage currents" are very small currents conducted from chassis or patient applied parts to patient or staff during normal operation of equipment
- usually a result of capacitive coupling when current flowing in equipment is a.c. (see figure)
- effects range from mild sensation to shock

Professional and Technical Considerations

- same as for macroshock
- avoid ground pathways to patient
- use of electrical isolation circuits in patient instrumentation
- use of isolated power supplies
- use of more stringent standards

Microshock Scenario

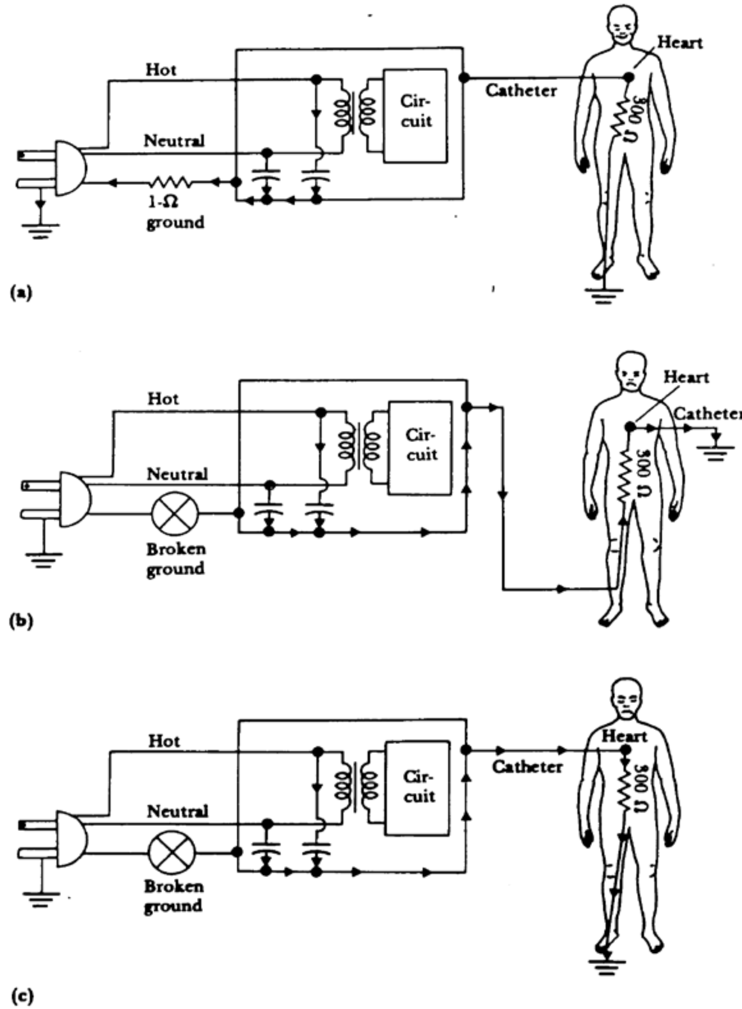


Figure 13.10 Leakage-current pathways. Assume 100 μA of leakage current from the power line to the instrument case. (a) Intact ground and 99.8 μA flows through the ground. (b) Broken ground and 100 μA flows through the heart. (c) Broken ground and 100 μA flows through the heart in the opposite direction.

Standards

- CSA/UL Standards industrial, domestic, laboratory, data processing, biomedical
- National and Provincial Codes
- Guidelines

Conditions of Measurement

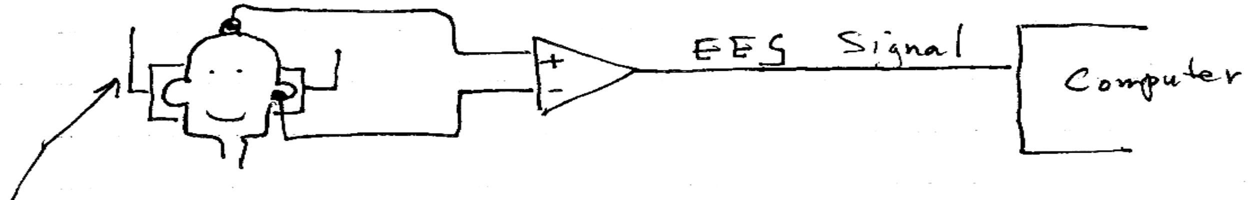
- Biopotential signals are low amplitude (<1μv – 25 mv)
- Biopotential signals are low bandwidth (d.c. – 15 kHz)
- Body is volume conductor (specificity of signal source)
- Noise is high in bandwidth of biopotential signal (60 Hz: 30 mv on skin)

Biomedical Engineering

- Understanding anatomy and physiology to select measurand
- biology/machine interface ⟶ transducer
- information to be extracted

Instrumentation Example

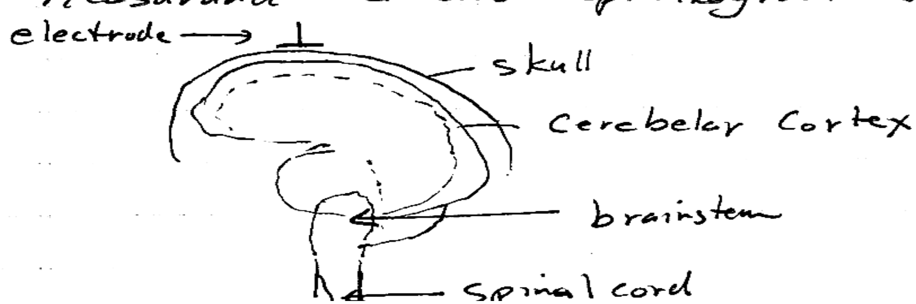
Brain Stem Auditory Evoked Potential (BSAEP)

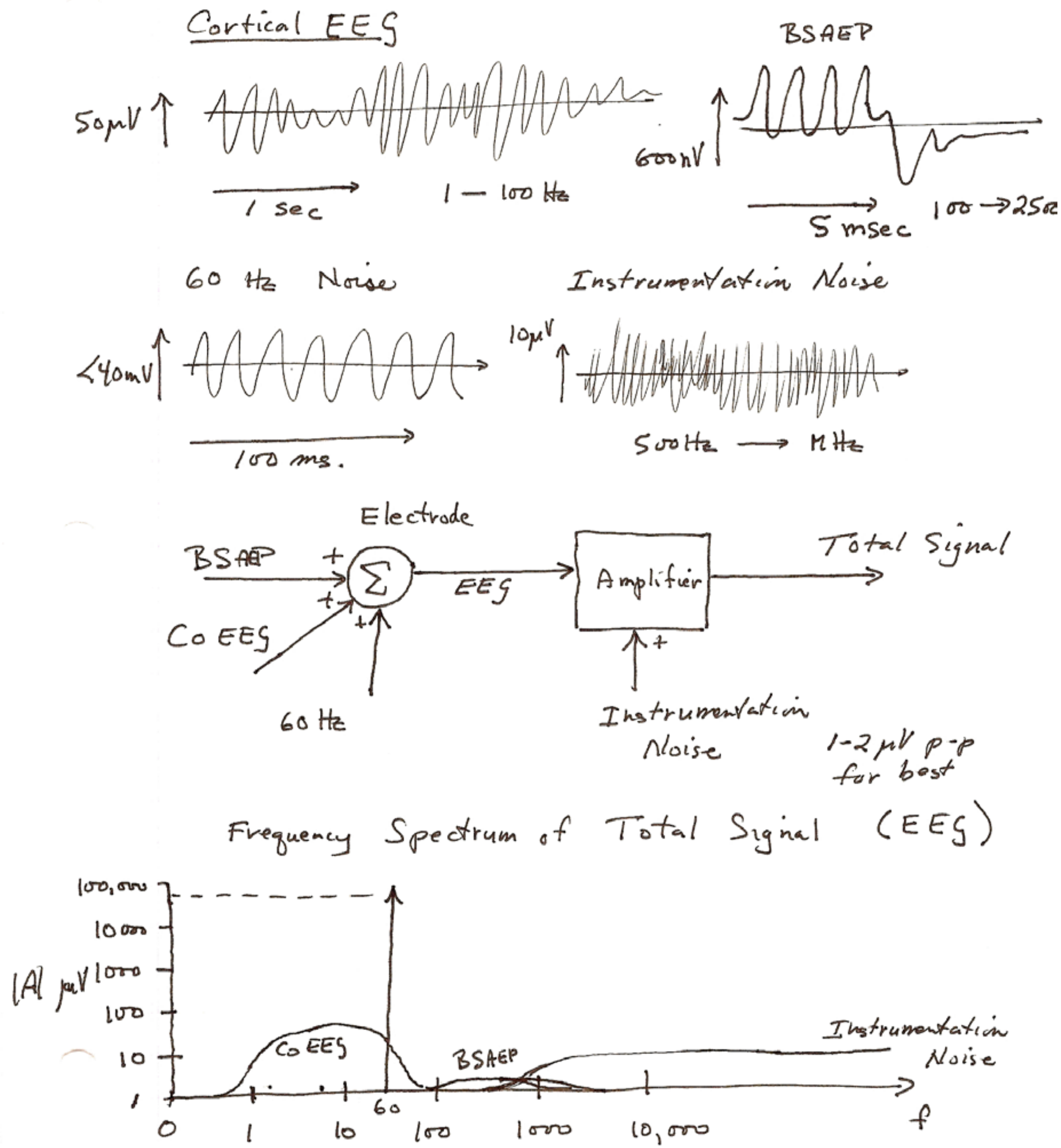


Auditory Stimulus "Click" at supra-threshold level

Purpose: to determine whether auditory pathway and associated neural structures are OK.

Measurand - Electroencephalogram (EEG)

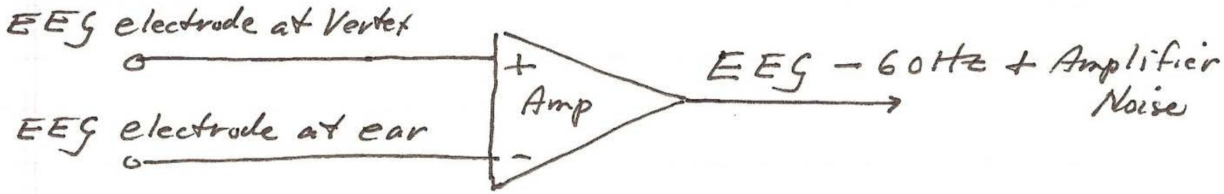



Cortical EEG
50μV
1 sec
1 — 100 Hz
BSAEP
600nV
5 msec
100 → 25Ω
60 Hz Noise
<40mV
100 ms.
Instrumentation Noise
10μV
500Hz → MHz
Electrode
BSAEP
Co EEG
60 Hz
EEG
Amplifier
Total Signal
Instrumentation Noise
1-2 μV p-p for best
Frequency Spectrum of Total Signal (EEG)
100,000
10000
1000
100
10
1
|A| μV
Co EEG
BSAEP
Instrumentation Noise
0
1
10
60
100
1000
10,000
f

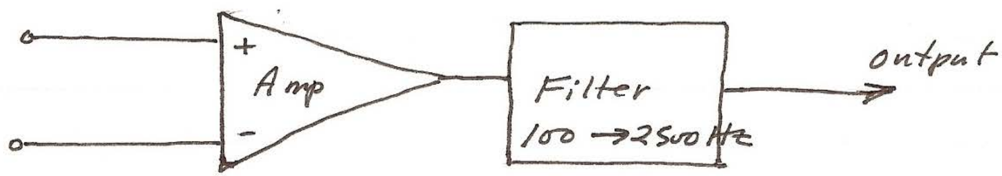
How do we Maximize SNR?

i.e. $\dfrac{\text{BSAEP Power}}{\sum \text{All other powers.}}$

60 Hz Noise Reduction



Co EEG & Instrumentation Noise Reduction



Output includes BSAEP, some Co EEG, Instr. Noise

This exhausts our possibilities in the analog domain

∴ Need to digitize and use other processing techniques

Ideal Filter Characteristics

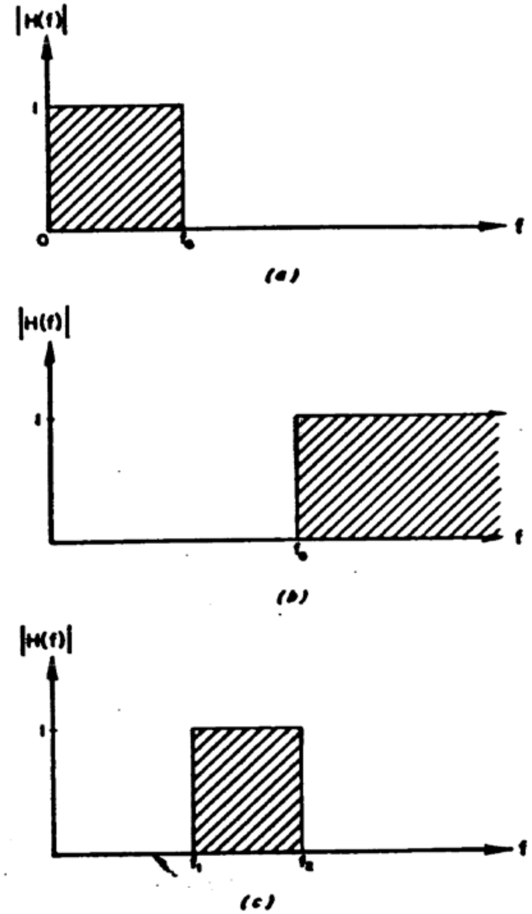


Figure 9.4 **Characteristics of ideal filters. (*a*) Lowpass. (*b*) Highpass. (*c*) Bandpass.**

Real Filter Characteristics

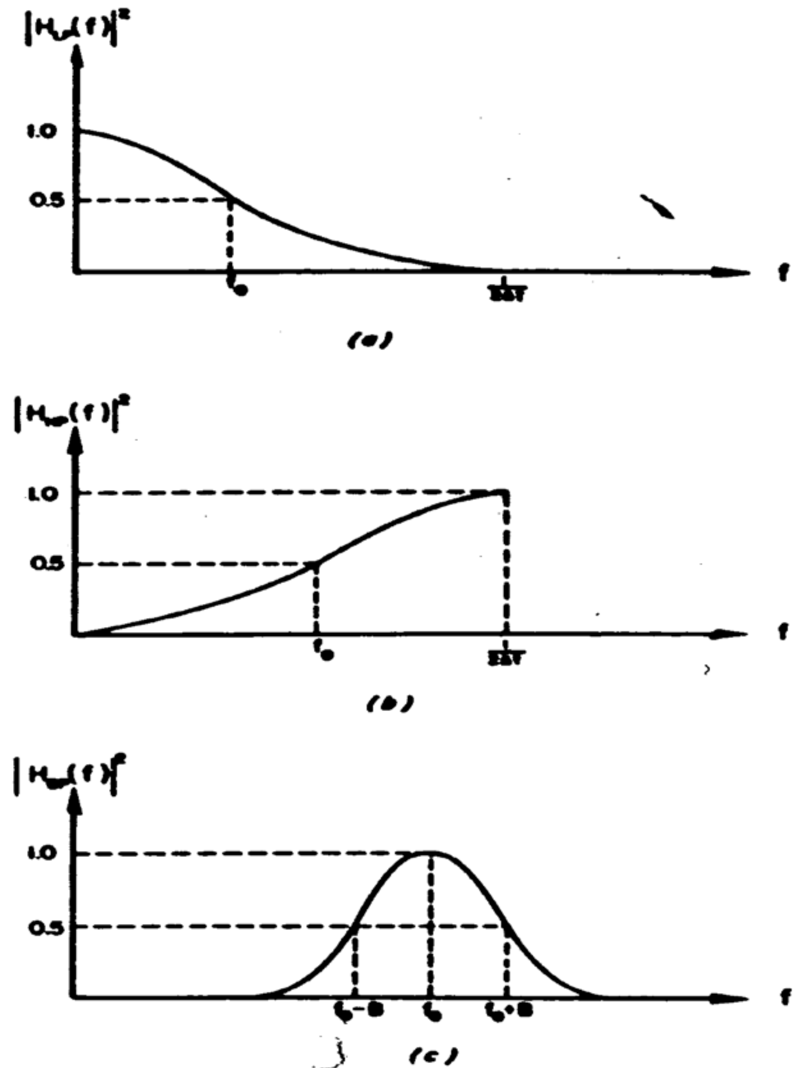
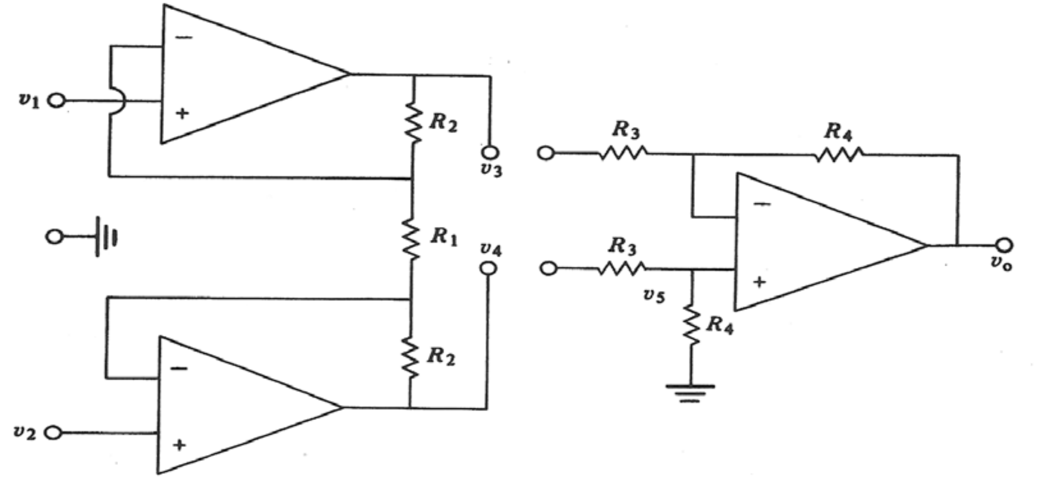
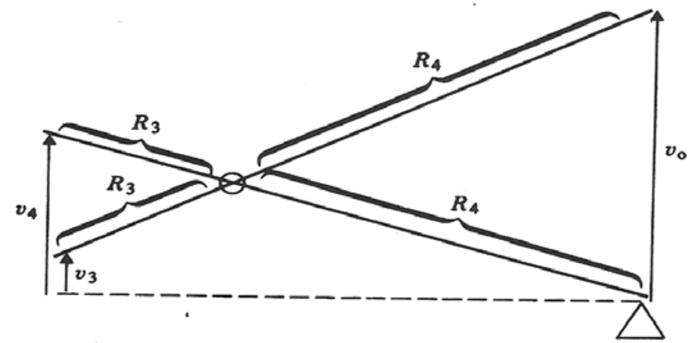


Figure 9.5 **Characteristics of digital filters. (*a*) Lowpass. (*b*) Highpass. (*c*) Bandpass.**



(a)



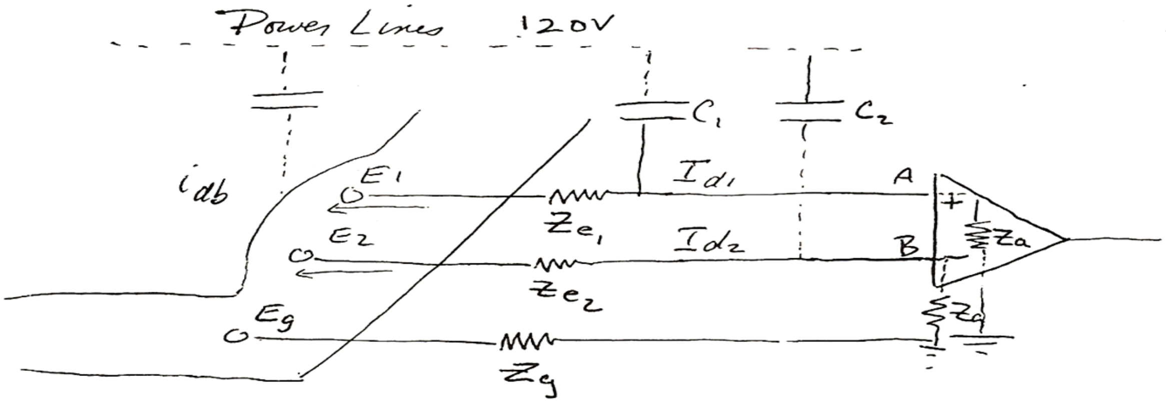
(b)

Figure 3.5 (a) The right side shows a one-op-amp differential amplifier, but it has low input impedance. The left side shows how two additional op amps can provide high input impedance and gain. (b) For the one-op-amp differential amplifier, two levers with arm lengths proportional to resistance values make possible an easy visualization of input–output characteristics.

$$V_o = \underbrace{\frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)}(v_2 - v_1)$$

$$CMRR = \frac{G_d}{G_c}$$

Sources of 60 Hz



Total body resistance = 500 Ω can usually be ignored because of the other impedances

$V_A - V_B = I_{d1} Z_{e1} - I_{d2} Z_{e2}$

If two leads are close

$I_{d1} = I_{d2}$

$\therefore V_A - V_B = I_{d1}(Z_{e1} - Z_{e2})$

For 2 meter cable $I_{d1} \simeq 2$ na

If $Z_{e1} - Z_{e2} = 20 K\Omega$

$V_A - V_B = 2 \times 10^{-9} \times 20 \times 10^3 = 40 \mu V$ of ~~ECG~~ 60Hz

This assumes that the CMRR of the amplifier is ∞.

Avoid this by shielding the cables and grounding the shield at the amplifier end.

Effects of Electrode Impedance Mismatch

For common mode signals

V_{cm} = common mode signal in the body

$= i_{db} Z_g$

$= .2 \times 10^{-6}$ amps $\times$ 50 KΩ for a typical environment

$= 10\,mV$

In this case Z_g is higher than usually found in a good recording environment.

For high electrical environments such as the OR and ICU.

$i_{db} > 1\mu A$

$V_{cm} > 50\,mV$

Considering the voltages presented at the amplifier inputs

$$V_A - V_B = \left(\frac{Z_a}{Z_a + Z_{e_1}} - \frac{Z_a}{Z_a + Z_{e_2}} \right) V_{cm}$$

$$Z_{e_1} \;\&\; Z_{e_2} << Z_a$$

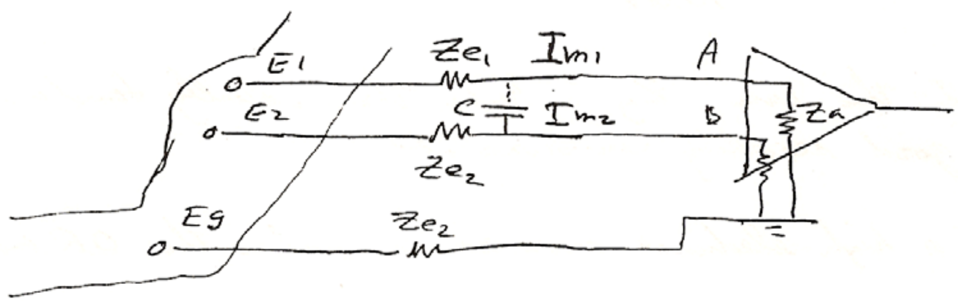
$$V_A - V_B = \frac{Z_{e_2} - Z_{e_1}}{Z_{in}} V_{cm}$$

Mismatch Cont'd and Motion Artifact

if mismatch in Ze of 20 KΩ

$$= \frac{20\,K\Omega}{5\,M\Omega} \times 50\,mV = 40\,\mu V$$

Motion Artifact



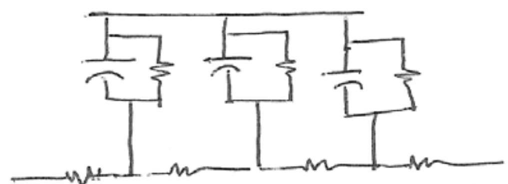
If cables connecting E_1 & E_2 to amplifier are flexed and their relative distance changed, then cross capacitance of cable changes - causing currents Im_1 & Im_2 to flow. These will flow to ground through electrodes.

$$V_A - V_B = Im_1 Ze_1 - Im_2 Ze_2$$

This results in a low frequency additive signal.

Effects of Electrode Size

Surface of electrode



skin (Electrolyte) or fluid

i.e. as electrode size increases signal from a larger volume of tissue on skin surface is averaged.

i.e. Electrode is integrator (Decreases signal bandwidth).

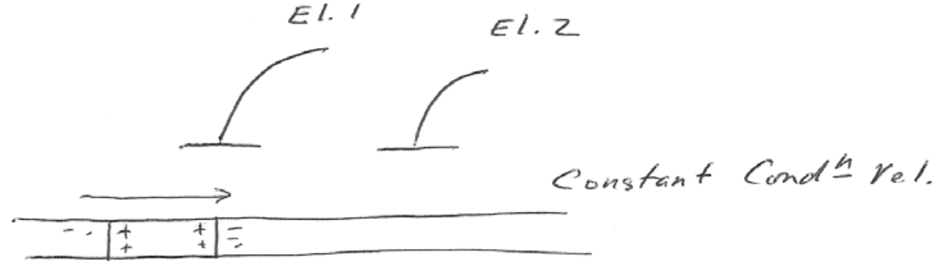
∴ Electrode Size is determined by size of bioelectric generator one is interested in.

Selectivity ⟷ single fibre?

Motor unit?

Whole muscle?

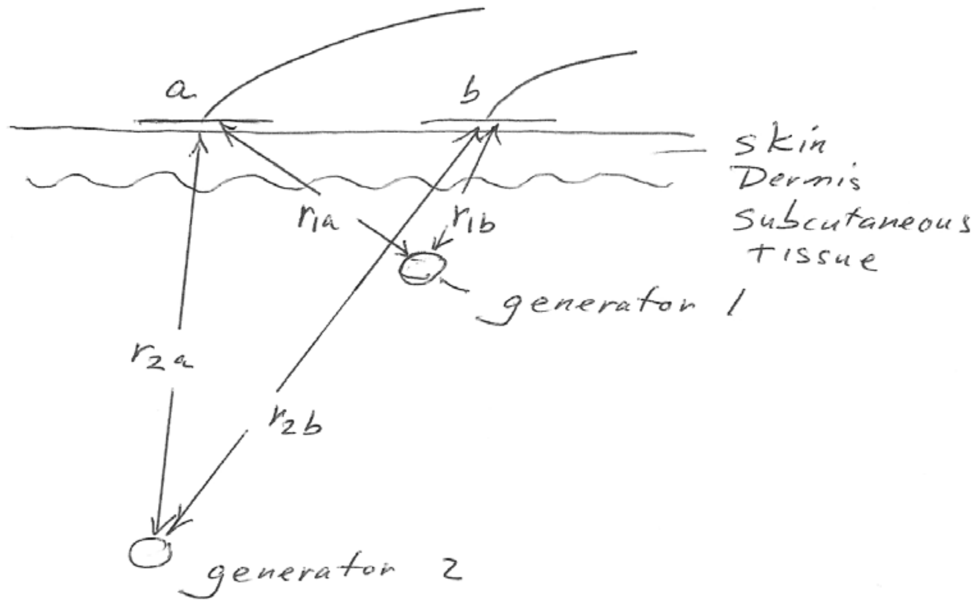
Effects of Electrode Spacing



As electrode spacing ↓ bandwidth ↑
amplitude ↓

provided both electrodes are over ~~average~~ active region.

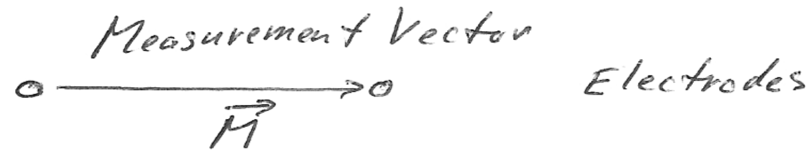
<u>Common Mode Electrophysiological Signals</u>



Common Mode Electrophysio;logical Signals (cont'd)

As $\dfrac{|r_a - r_b|}{\frac{r_a + r_b}{2}}$ decreases the generator starts to resemble a common mode source

Effect of Electrode Orientation to Generator



Measured signal $= \vec{M} \cdot \vec{D}$

$= f(D \cos\theta)$

Process of Measurement

- Understand the event (variable) you are measuring
- Is variable directly related to event?
- Is variable indirectly related to event?
- Is variable statistically related to event?
- Is event itself random?

Measurement Specifications

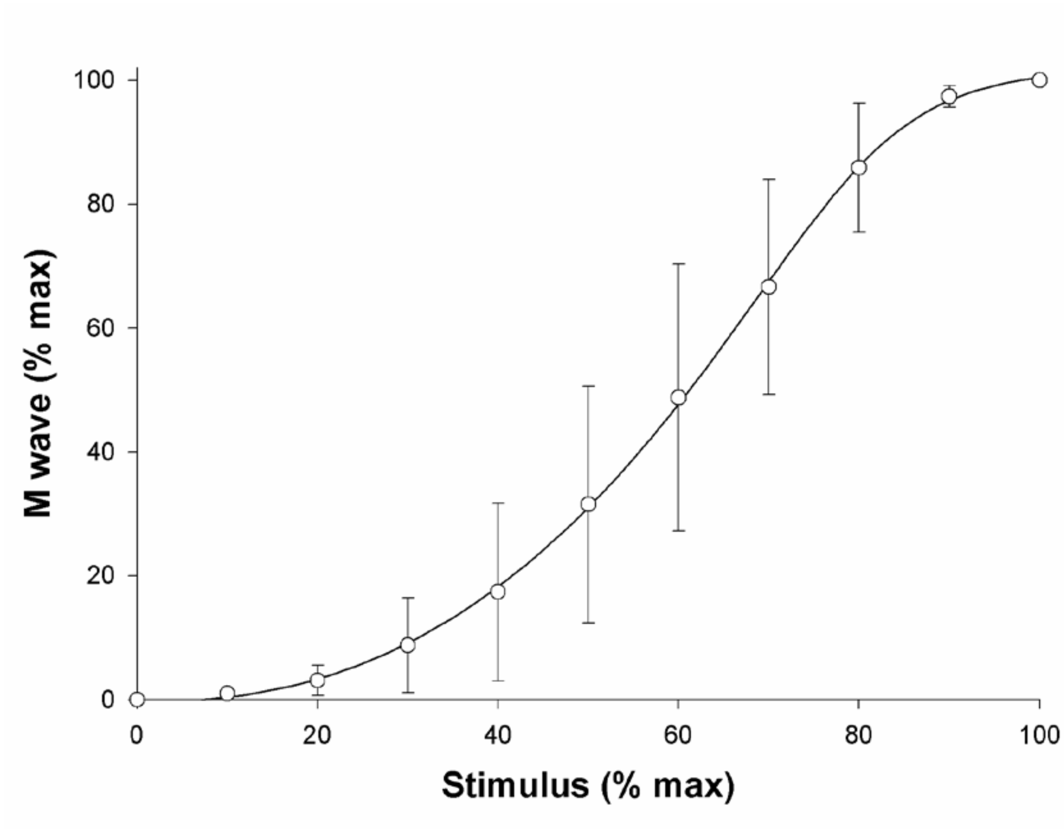
- What is amplitude range of selected variable
- What is bandwidth of variable (does variable change rapidly or slowly)?
- What is required resolution (smallest change you need to measure)?
- What is required accuracy?

Process of Measurement (cont’d)

- Is measurement biased (will final result have an offset, e.g. does it always read high)?
- What are unavoidable sources of noise?
- How much does this contaminate your measurement?
- Maximize your signal-to-noise ration SNR

Treatment of Measurements

M-waves for 8 subjects means and s.d.

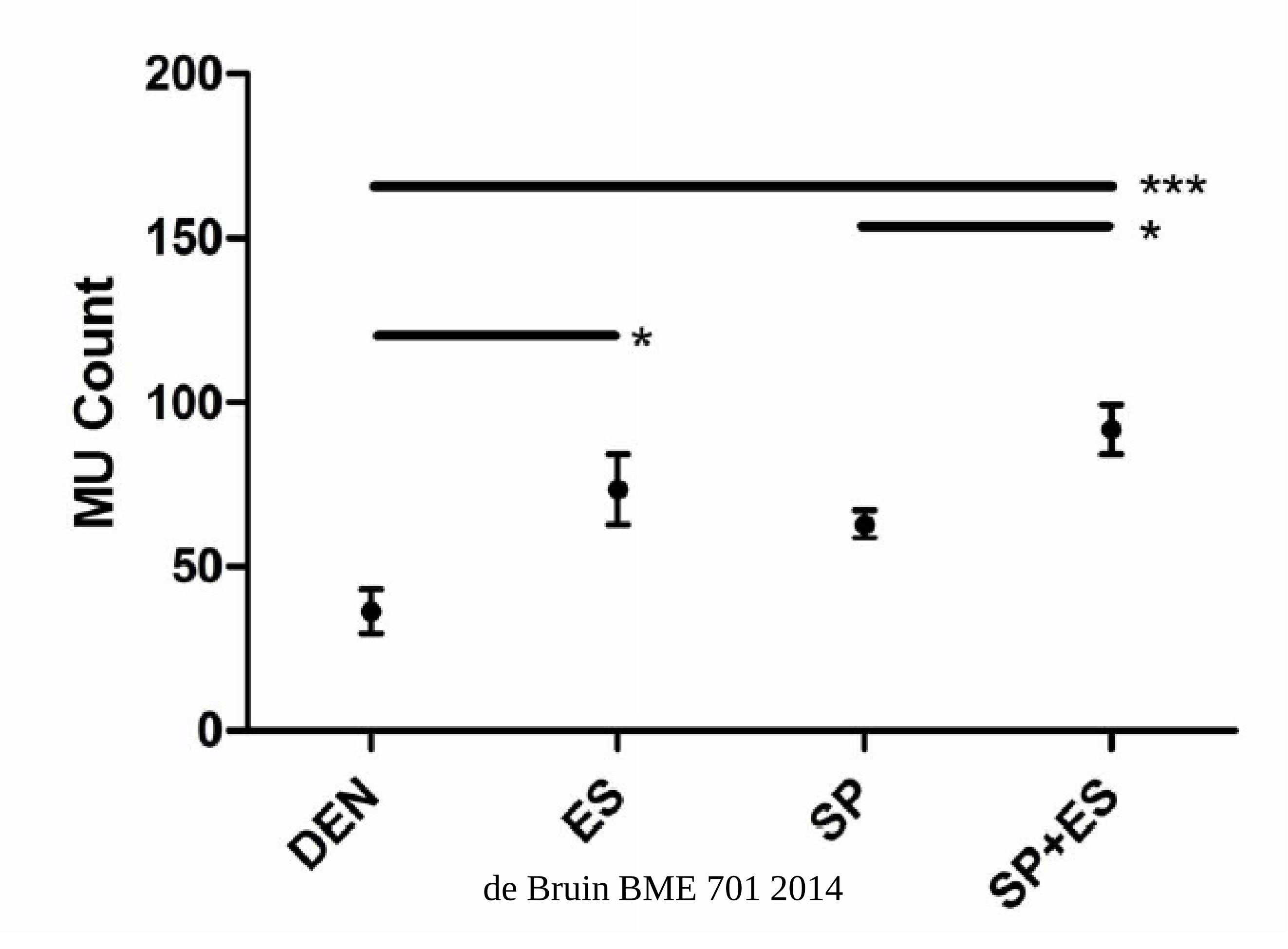


Representation of Data

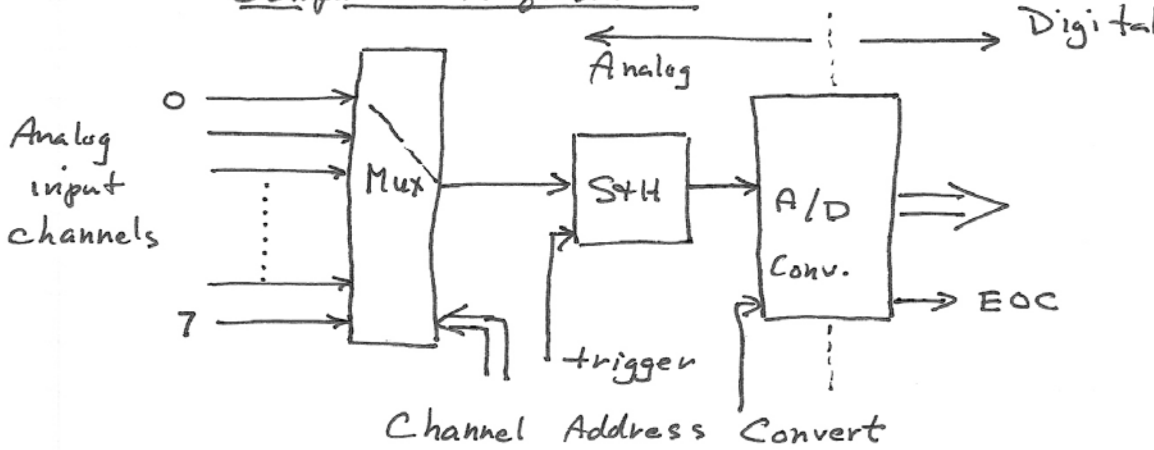
- Are variables related?
- What is your confidence interval for each measurement?
- What does significance mean (e.g. $p<.05$)
- What is significance based on?
- How can you improve your measurement?

Treatment of Results (2)

Motor Unit Counts mean plus s.e.m.



Computer Acquisition



This could be on a board in the computer, or in an external device which presents digital info to a standard computer port (eg. USB).

Multiplexor - analog switch connects output channel to one of input channels

Sample and Hold - holds input value until triggered to hold next value

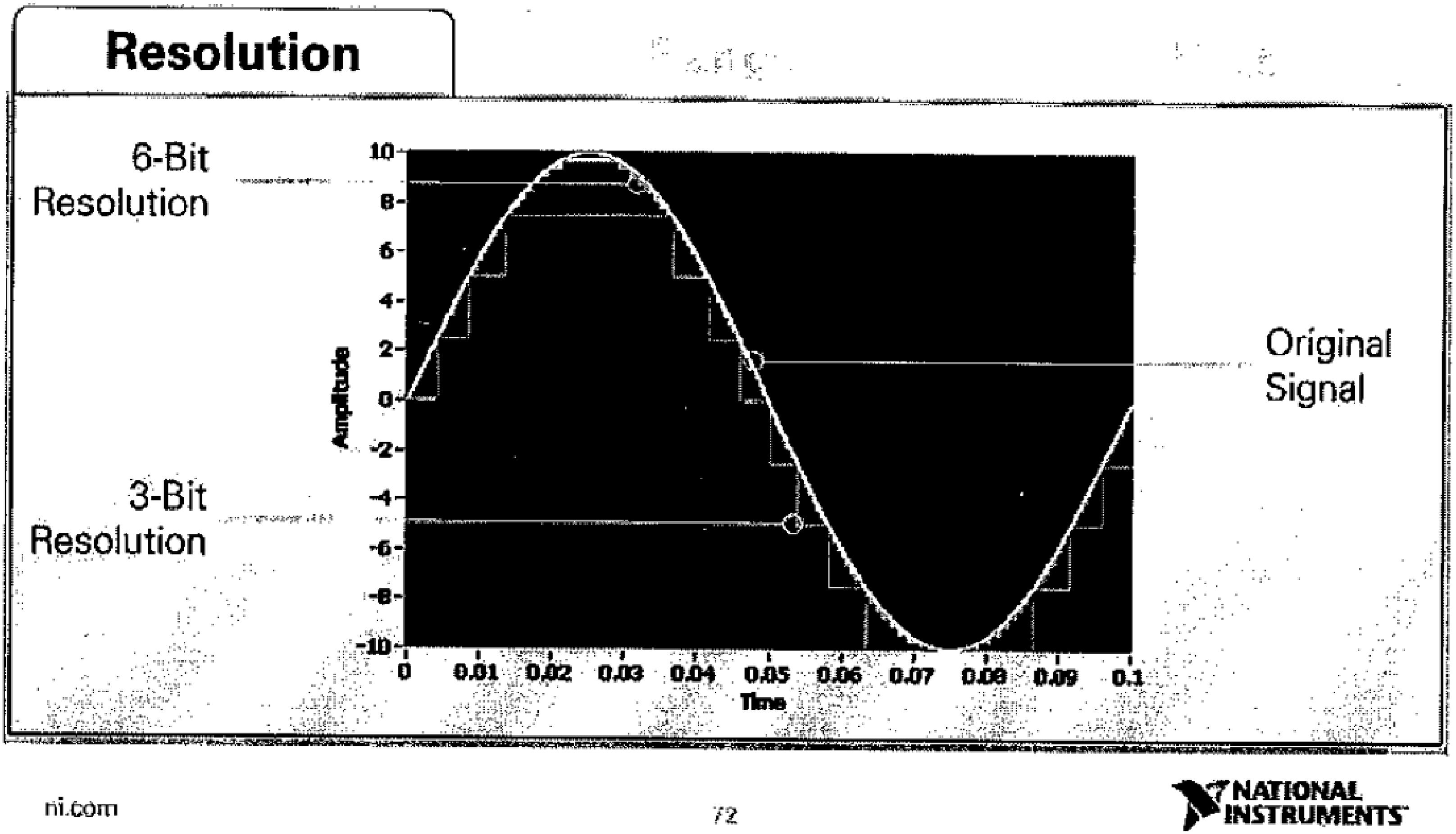
Analog-to-Digital Convertor - Output is parallel digital word containing binary equivalent of analog value. Minimum is usually 12 bits but 16-bit are very common now. Speed of conversion is important with 5 μsec typical inexpensive (i.e. 200 KHz sample rate).

Computer Data Acquisition
(Amplitude Resolution)

- Determines number of bits required
- Amplitude input range of ADC: 0→10V, 0→5V, ± 10V, ±5V or power supply of micro, etc.
- If assume ±5V with 12-bit ADC, amplitude resolution = $10/2^{12}$ = 10,000/4096 = 2.5 mV/bit ----- (1)
- Most physiological (transducer output) signals are ≤ mV
- Need to amplify and filter signals prior to data acquisition
- Can increase number of required bits of ADC
- Amplify source signal in analog stage with gain G
- Amplitude range referred to source in (1) = $(10/2^{12})/G$

Computer Data Acquisition

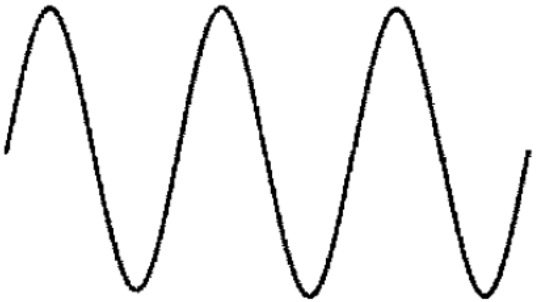
(Amplitude Resolution)



Computer Data Acquisition

Sampling Rate Considerations

- An analog input signal is continuous with respect to time.
- Sampled signal is series of discrete samples acquired at a specified sampling rate.
- The faster we sample, the more our sampled signal will look like our actual signal.
- If not sampled fast enough, a problem known as aliasing will occur.



Actual Signal

Sampled Signal

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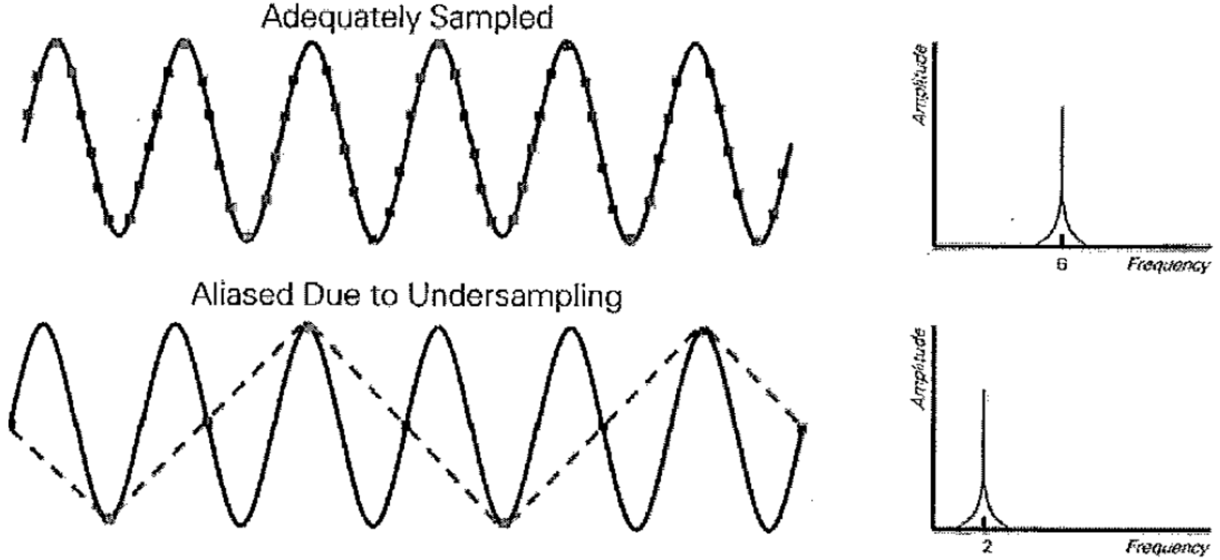
Computer Data Acquisition
(Sampling Rate)

Aliasing

- Sample rate: how often an A/D conversion takes place
- Alias: misrepresentation of a signal



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Computer Data Acquisition

Following the Nyquist Theorem Prevents Aliasing

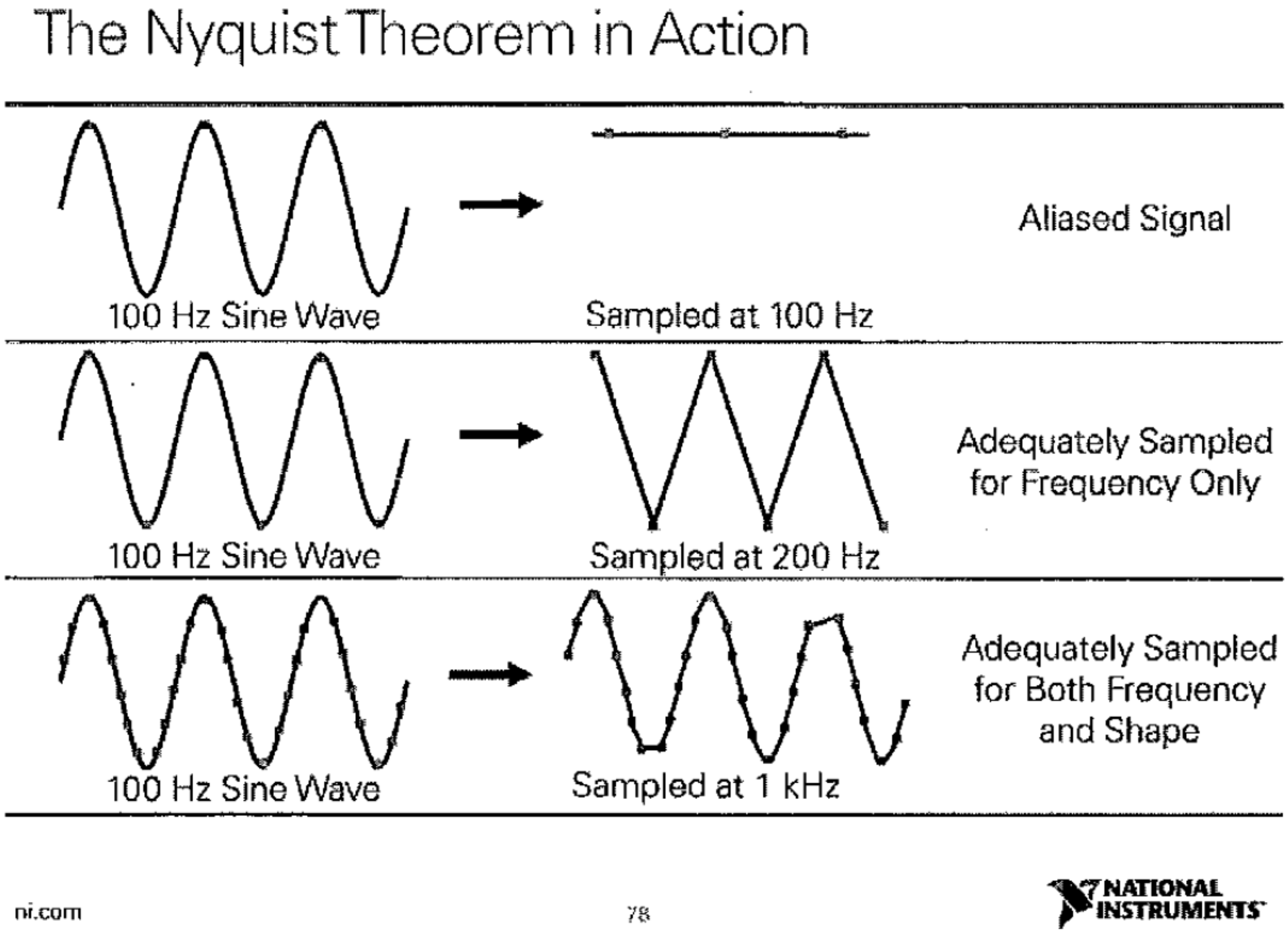
Frequency — To accurately represent the *frequency* of your original signal…

You must sample at greater than 2 times the maximum frequency component of your signal.

Shape — To accurately represent the *shape* of your original signal…

- You must sample between 5–10 times greater than the maximum frequency component of your signal.

Computer Data Acquisition
(Sampling Rate)



Computer Data Acquisition
(Sampling Rate)

- If sampling rate is f_s the $f_s/2$ is also called the folding frequency
- A frequency component ($f_s/2+\Delta f$) will be aliased into ($f_s/2-\Delta f$)
- ADC maximum sampling rates are high (>200 kHz) and memory is relatively plentiful so instrumentation signals are usually severely oversampled
- However the higher the number of samples, the longer digital signal processing takes, and the greater the number of bits required to be transmitted for each recording in wireless applications
- **There are always tradeoffs**

Noisy Signals
Improving the Signal-to-Noise Ratio (SNR)

- Select the right transducer (consider transducer noise or sensitivity to variable of interest)
- Consider connecting cables or wiring
- How soon do you amplify?
- Where do you place your filters?
- What are advantages of analog or digital filters?

Noisy Signals

Common Signal Conditioning Examples

Transducer/Signals	Signal Conditioning
Thermocouples	Amplification, Linearization, Cold-Junction Compensation
RTD (Resistance Temperature Detector)	Current Excitation, Linearization
Strain Gage	Voltage Excitation, Bridge Configuration, Linearization
Common Mode or High Voltage	Isolation Amplifier
Loads Requiring AC Switching or Large Current Flow	Electromechanical Relays or Solid-State Relays
High-Frequency Noise	Low-Pass Filters

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Other Transducers

- Position (e.g. linear or circular resistors, ultrasound echoing)
- Temperature (thermistor, thermocouple, semiconductor)
- Force/Pressure (strain gauge, piezoelectric)
- Concentrations (pH, pO_2, pCO_2, other ions)
- Light Absorption (photodiode)

Noninvasive Blood Pressure Measurement

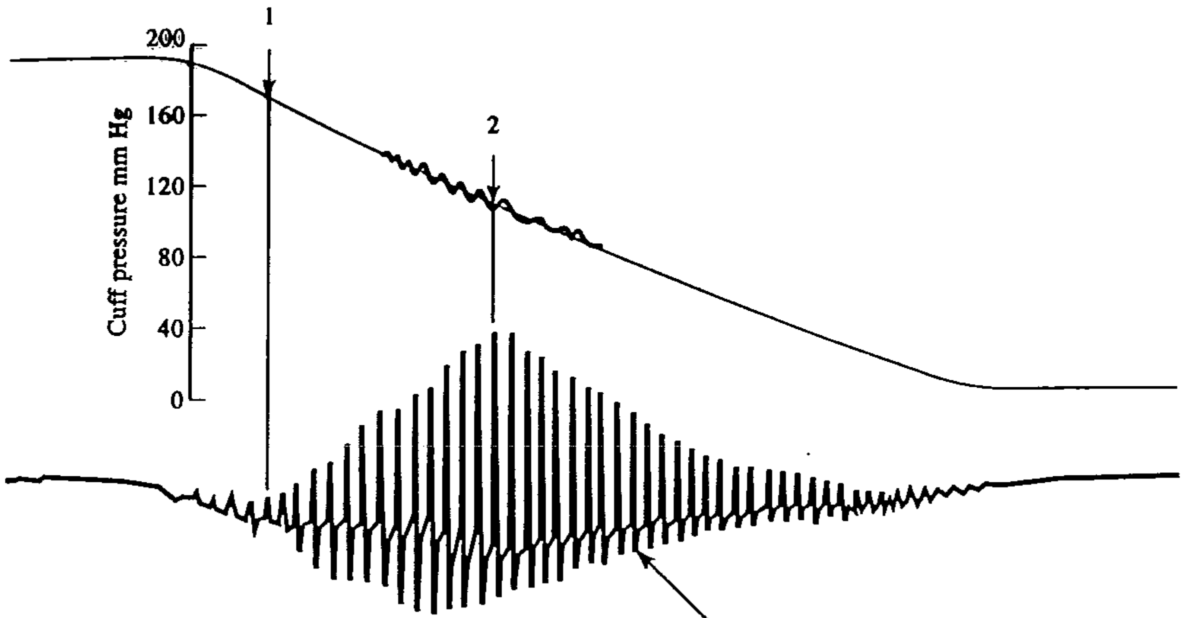

Figure 7.22 The oscillometric method A compression cuff is inflated above systolic pressure and slowly deflated. Systolic pressure is detected (Point 1) where there is a transition from small amplitude oscillations (above systolic pressure) to increasing cuff-pressure amplitude. The cuff-pressure oscillations increase to a maximum (Point 2) at the mean arterial pressure.

NIBP Monitor

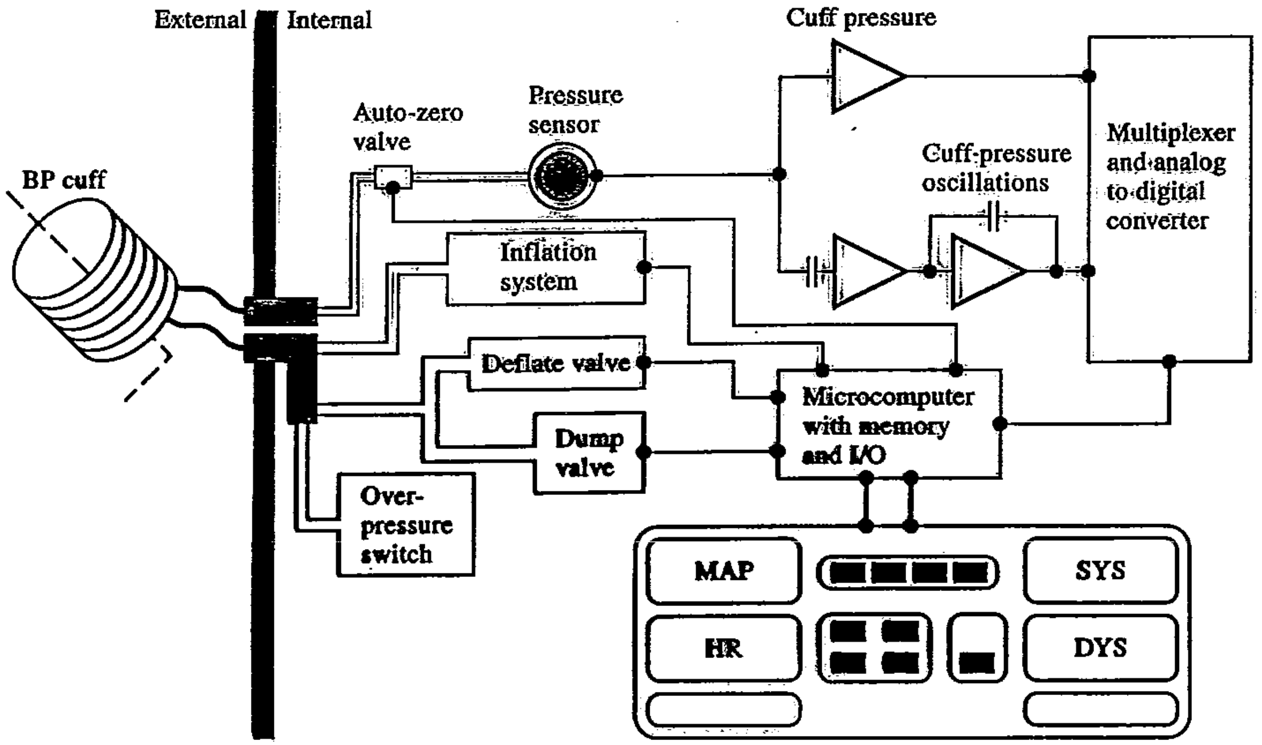

Figure 7.23 Block diagram of the major components and subsystems of an oscillometric blood-pressure monitoring device, based on the Dinamap unit, I/O = input/output; MAP = mean arterial pressure; HR = heart rate; SYS = systolic pressure; DYS = diastolic pressure. From Ramsey M III. Blood pressure monitoring: automated oscillometric devices, *J. Clin. Monit.* 1991, 7, 56–67.