Chapter 5 Biopotential Electrodes

- Biopotential electrodes
  - Interface between the body and the electronic measuring circuit
  - Transducer: ionic current in the body ⇔ electronic current in the circuit

5.1 The Electrode-Electrolyte Interface

- Net current crossing the electrode-electrolyte interface (Fig. 5.1)
  - Electrons moving in an opposite direction of the current
  - Cations (C^+) moving in the same direction as the current
  - Anions (A^-) moving in an opposite direction of the current
- Chemical reactions at the interface ("→": oxidation and "←": reduction)
  - $C \leftrightarrow C^{n+} + ne^-$
  - $A^{m-} \leftrightarrow A + me^-$
- States of the interface
  - "→" = "←" ⇒ dynamic equilibrium ⇒ zero net current
  - "→" > "←" ⇒ oxidation dominates ⇒ nonzero net current from electrode to electrolyte
  - "→" < "←" ⇒ reduction dominates ⇒ nonzero net current from electrolyte to electrode
- Equilibrium standard half-cell potential (at zero net current and at standard condition)
  - At the initial moment of contact, chemical reaction occurs ⇒ changes in local distribution and concentration of C^+ and A^- at the interface ⇒ charge neutrality is not maintained at the interface ⇒ potential difference between the interface and the rest of the electrolyte
  - Charge redistribution (separation of charge) ⇒ electric double layer
  - Measurement w.r.t. the hydrogen electrode ($\mathrm{H}_2 \leftrightarrow 2\mathrm{H} \leftrightarrow 2\mathrm{H}^+ + 2e^-$), Table 5.1

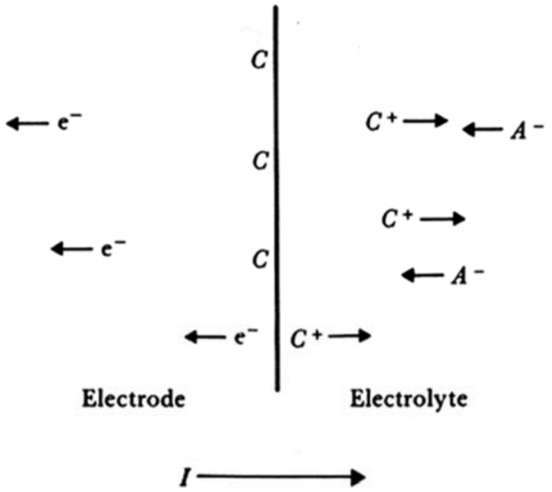


Figure 5.1 Electrode-electrolyte interface The current crosses it from left to right. The electrode consists of metallic atoms C. The electrolyte is an aqueous solution containing cations of the electrode metal C^+ and anions A^-.

5.2 Polarization

- Nonzero net current ⇒ polarization of the electrode ⇒ overpotential
- Overpotential = HCP (at nonzero net current) – equilibrium HCP
  - Ohmic overpotential, V_r
  - Concentration overpotential, V_c
  - Activation overpotential, V_a
  - Total overpotential or polarization potential, $V_p = V_r + V_c + V_a$
- HCP at non-standard condition
  - Nernst equation. $E = E^0 + \frac{RT}{nF}\ln\left(a_{C^{n+}}\right)$ where E is HCP, E^0 is the standard HCP, and $a_{C^{n+}}$ is the activity of C^{n+}.
  - In general, for $\alpha A + \beta B \leftrightarrow \gamma C + \delta D + ne^-$, $E = E^0 + \frac{RT}{nF}\ln\left(\frac{a_C^\gamma a_D^\delta}{a_A^\alpha a_B^\beta}\right)$.
- Liquid-junction potential ~ tens of mV
  - Junction of two electrolyte solutions with different concentrations

- $E_j = \frac{\mu_+ - \mu_-}{\mu_+ + \mu_-}\frac{RT}{nF}\ln\left(\frac{a'}{a''}\right)$ where μ_+ and μ_- are mobilities of the positive and negative ions, respectively, and a' and a'' are the activities of the two solutions.

5.3 Polarizable and Nonpolarizable Electrodes

❍ Two types of electrode

- Perfectly polarizable electrode
    - Behaves like a capacitor
    - Only displacement current
    - Electrode made of noble metals such as platinum
    - Concentration overpotential dominates
- Perfectly nonpolarizable electrode
    - No overpotential
    - Current passes freely
    - Ag/AgCl electrode and calomel electrode

The Silver-Silver Chloride Electrode

- Nonpolarizable electrode
- Electrode: Ag with AgCl coating
- Electrolyte: saturated with AgCl
- Chemical reactions: $\mathrm{Ag} \leftrightarrow \mathrm{Ag}^+ + e^-$
  $\mathrm{Ag}^+ + \mathrm{Cl}^- \leftrightarrow \mathrm{AgCl}\downarrow$ (deposit on the electrode)
- Solubility product is constant and is the rate of precipitation and of returning to solution of AgCl. At equilibrium condition, $K_s = a_{\mathrm{Ag}^+} \times a_{\mathrm{Cl}^-} \approx 10^{-10}$. Since $a_{\mathrm{Cl}^-} \approx 1$ in biological solution, $a_{\mathrm{Ag}^+} \approx 10^{-10}$.
- HCP is $E = E^0_{\mathrm{Ag}} + \frac{RT}{nF}\ln\left(a_{\mathrm{Ag}^+}\right) = E^0_{\mathrm{Ag}} + \frac{RT}{nF}\ln\left(K_s\right) - \frac{RT}{nF}\ln\left(a_{\mathrm{Cl}^-}\right)$. Since, in biological solution, $a_{\mathrm{Cl}^-} \approx 1$, HCP of Ag/AgCl electrode is very stable.
- Fabrication

  - Electrolytic process (anode: Ag electrode, cathode: large Ag plate, solution: KCL or NaCl, source: 1.5 V battery)
  - Sintering process: Ag wire and powder of Ag and AgCl in a cylinder ⇒ baking at 400 °C for several hours ⇒ pellet electrode
- Used for most biopotential recordings, low noise, stable, small motion artifact

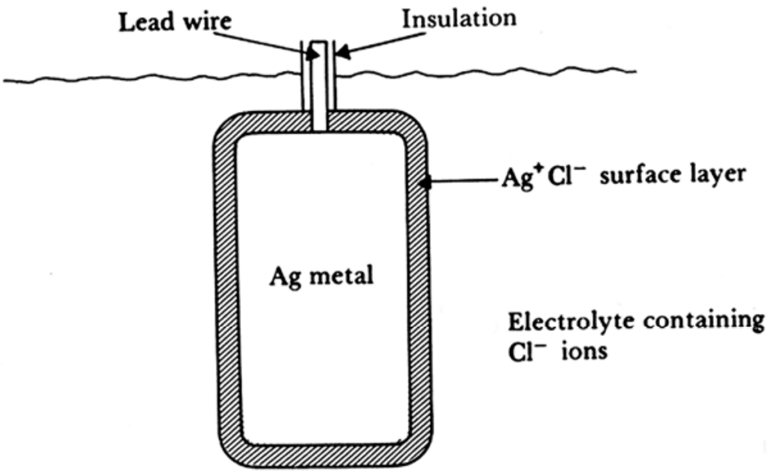


Figure 5.2 A silver/silver chloride electrode, shown in cross section.

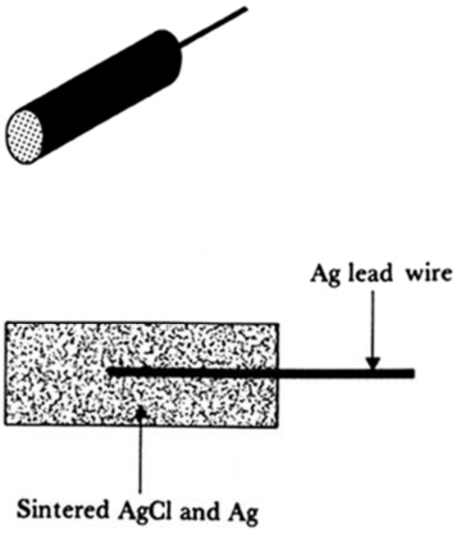


Figure 5.3 Sintered Ag/AgCl electrode.

Calomel Electrode

- Nonpolarizable electrode

- Hg_2Cl_2 in KCl solution
- Used as the reference electrode for pH measurement

5.4 Electrode Behavior and Circuit Models

❍ Equivalent circuit (Fig. 5.4)

  - Dc voltage source: HCP
  - C_d : capacitance across the charge double layer, change with frequency, current density, electrode material, and electrolyte concentration
  - R_d : leakage resistance across the charge double layer, change with frequency, current density, electrode material, and electrolyte concentration
  - R_s : resistance of electrolyte, change with electrolyte concentration

❍ Electrode impedance

  - Frequency dependent (Fig. 5.6)
  - For Ag/AgCl, amount of AgCl also affects the impedance (Fig. 5.5)

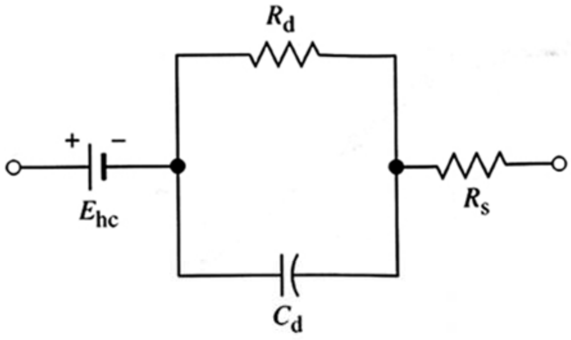


Figure 5.4 Equivalent circuit for a biopotential electrode in contact with an electrolyte E_{hc} is the half-cell potential, R_d and C_d make up the impedance associated with the electrode-electrolyte interface and polarization effects, and R_s is the series resistance associated with interface effects and due to resistance in the electrolyte.

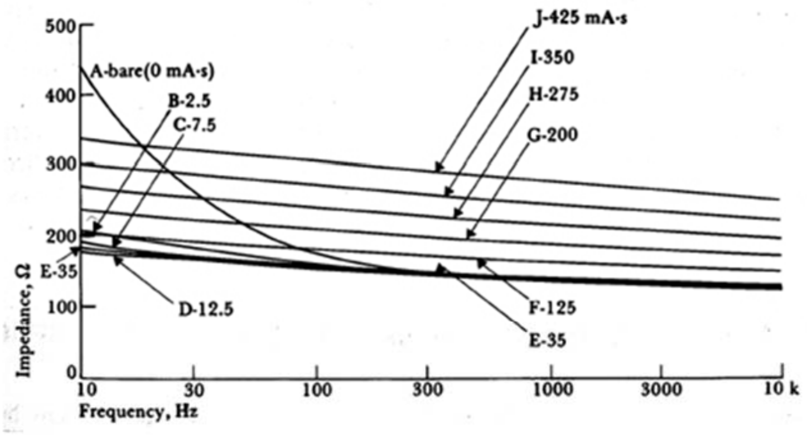


Figure 5.5 Impedance as a function of frequency for Ag electrodes coated with an electrolytically deposited AgCl layer. The electrode area is 0.25 cm^2. Numbers attached to curves indicate the number of mA·s for each deposit. (From L. A. Gedders, L. E. Baker, and A. G. Moore, "Optimum Electrolytic Chloriding of Silver Electrodes," *Medical and Biological Engineering*, 1969, 7, pp.49-56.)

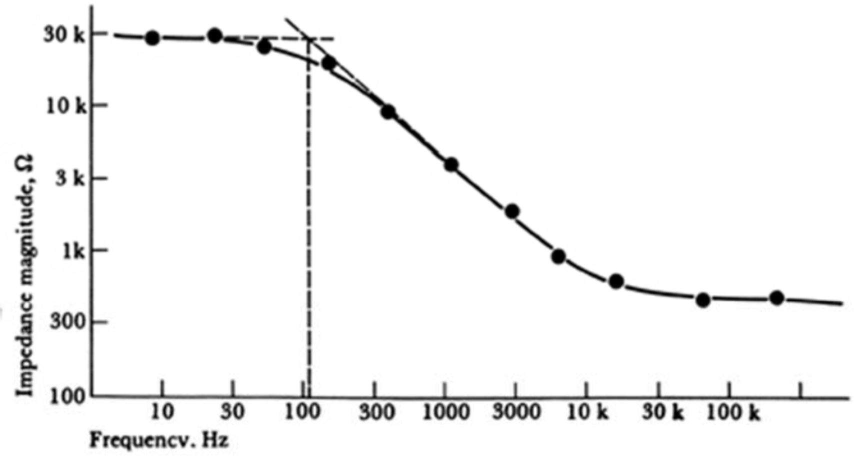


Figure 5.6 Experimentally determined magnitude of impedance as a function of frequency for electrodes.

5.5 The Electrode-Skin Interface and Motion Artifact

- Skin (Fig. 5.7)
  - Epidermis
    - Stratum corneum: outermost layer of dead cells, constantly removed
    - Stratum granulosum: cells begin to die and loose nuclear material
    - Stratum germinativum: cells divide and grow and displaced outward
  - Dermis

  - Subcutaneous layer
  - Vascular and nervous components, sweat glands, sweat ducts, hair follicles
- Electrode-electrolyte gel (Cl^-)-skin (Fig. 5.8)
  - Stratum corneum is the barrier
  - Rubbing or abrading the stratum corneum ⇒ improve the stability of biopotential

- Effect of sweat (Na^+, K^+, Cl^- ions)

- Motion artifact:
  - One electrode moved ⇒ change in charge distribution ⇒ change in HCP ⇒ change in the measured biopotential
  - Low frequency ⇒ frequency components overlap with ECG, EEG, EOG, etc
  - Need better electrolyte gel
  - Skin abrasion or puncture minimize motion artifacts (skin irritation is possible)

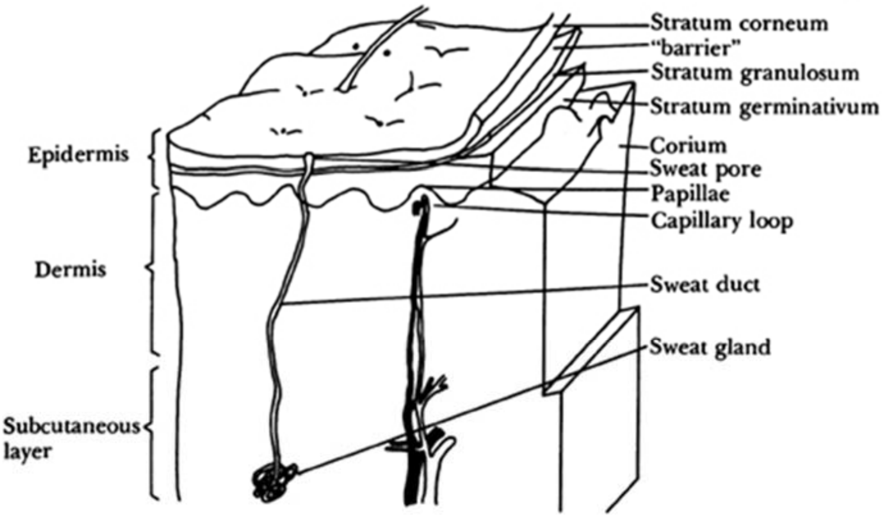


Figure 5.7 Magnified section of skin, showing the various layers (Copyright © 1977 by The Institute of Electrical and Electronics Engineers. Reprinted with permission, from *IEEE Trans. Biomed. Eng.*, March 1977, vol. BME-24, no. 2, pp. 134-139.)

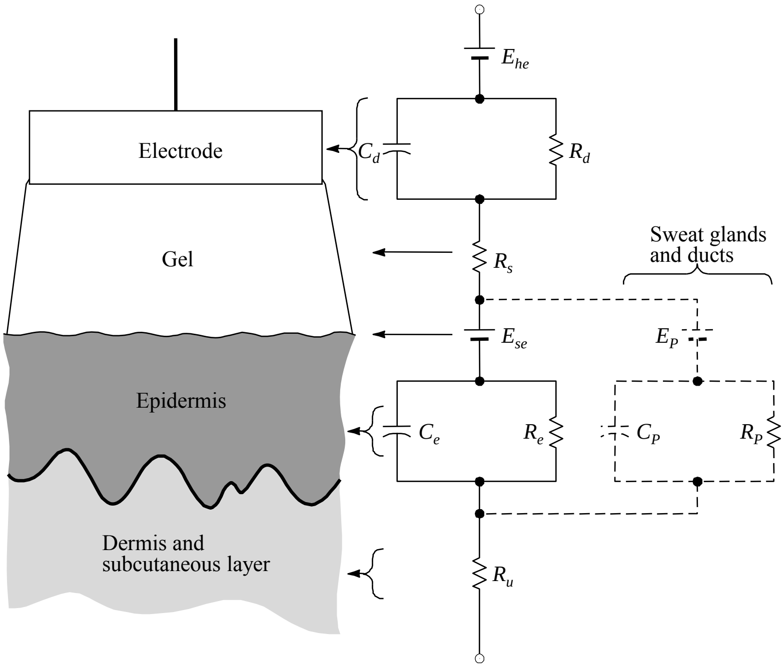


Figure 5.8 A body-surface electrode is placed against skin, showing the total electrical equivalent circuit obtained in this situation. Each circuit element on the right is at approximately the same level at which the physical process that it represents would be in the left-hand diagram.

5.6 Body-Surface Recording Electrodes

Metal-Plate Electrodes

- Material: German silver (a nickel-silver alloy) or Ag/AgCl
- Usage: ECG, EEG, EMG

Suction Electrodes

- Usage: precordial electrode for ECG

Floating Electrodes

- Recessed electrode
- Material: sintered Ag/AgCl pellet
- Usage: disposable electrode for ECG, stable against motion artifact

Flexible Electrodes

- Flexibility
- X-ray transparent

Electrode Standards

- Face-to-face bench testing
    - Offset voltage < 100 mV
    - Noise < 150 μV
    - Impedance < 2 kΩ at 10 Hz
    - Defibrillator overload recovery for 4 2-mC charges < 100 mV
    - Bias current tolerance to 100 nA for 8 h < 100 mV offset

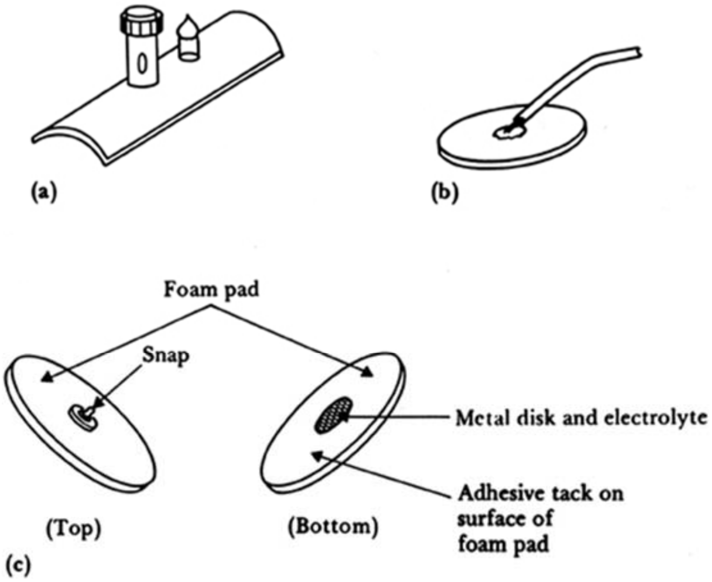


Figure 5.9 Body-surface biopotential electrodes (a) Metal-plate electrode used for application to limbs. (b) Metal-disk electrode applied with surgical tape. (c) Disposable foam-pad electrodes, often used with electrocardiograph monitoring apparatus.

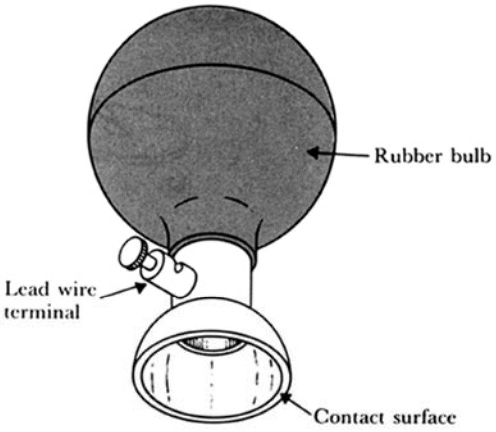


Figure 5.10 A metallic suction electrode is often used as a precordial electrode on clinical electrocardiographs.

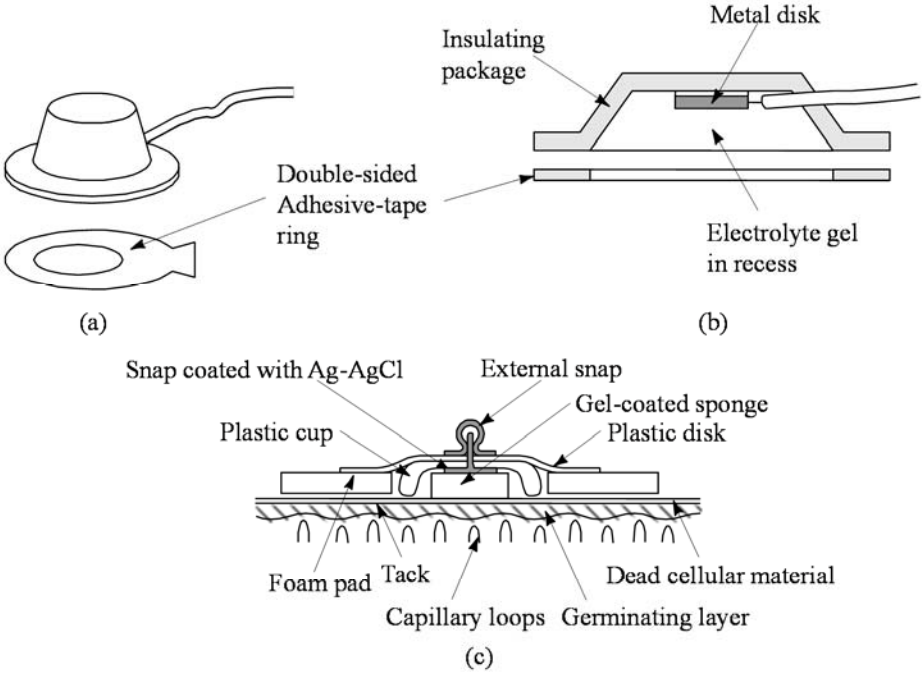


Figure 5.11 Examples of floating metal body-surface electrodes (a) Recessed electrode with top-hat structure. (b) Cross-sectional view of the electrode in (a). (c) Cross-sectional view of a disposable recessed electrode of the same general structure shown in Figure 5.9(c). The recess in this electrode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

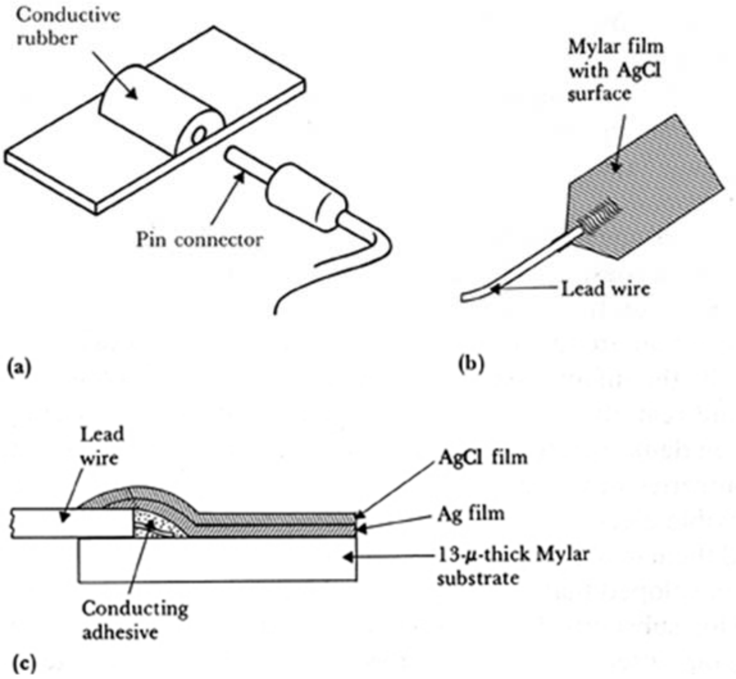


Figure 5.12 Flexible body-surface electrodes (a) Carbon-filled silicone rubber electrode. (b) Flexible thin-film neonatal electrode (after Neuman, 1973). (c) Cross-sectional view of the thin-film electrode in (b). [Parts (b) and (c) are from International Federation for Medical and Biological Engineering. *Digest of the 10th ICMBE*, 1973.]

5.7 Internal Electrodes

- No electrode gel is used and the interface is the electrode-electrolyte interface
- Percutaneous electrode
  - Electrode or lead wire crosses the skin
  - Needle electrode: insulated needle electrode, coaxial needle electrode, bipolar coaxial electrode
  - Wire electrode: fine-wire electrode, coiled fine-wire electrode
  - EMG, ECG during surgery, fetal ECG (suction electrode, helical electrode)
- Internal electrode
  - Implanted with radiotelemetry connection
  - Wire-loop electrode
  - Silver-sphere cortical surface electrode
  - Multielement depth electrode

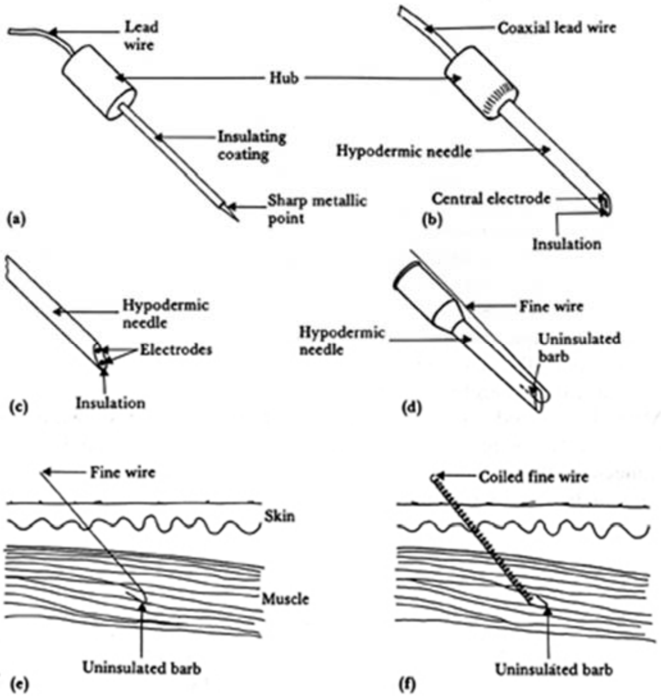


Figure 5.13 Needle and wire electrodes for percutaneous measurement of biopotentials (a) Insulated needle electrode. (b) Coaxial needle electrode. (c) Bipolar coaxial electrode. (d) Fine-wire electrode connected to hypodermic needle, before being inserted. (e) Cross-sectional view of skin and muscle,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

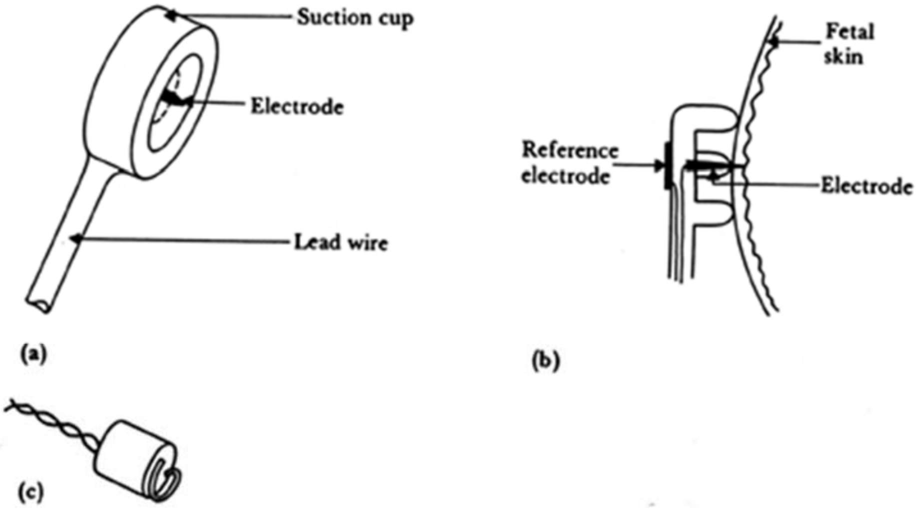


Figure 5.14 Electrodes for detecting fetal electrocardiogram during labor, by means of intracutaneous needles (a) Suction electrode. (b) Cross-sectional view of suction electrode in place, showing penetration of probe through epidermis. (c) Helical electrode, which is attached to fetal skin by corkscrew type action.

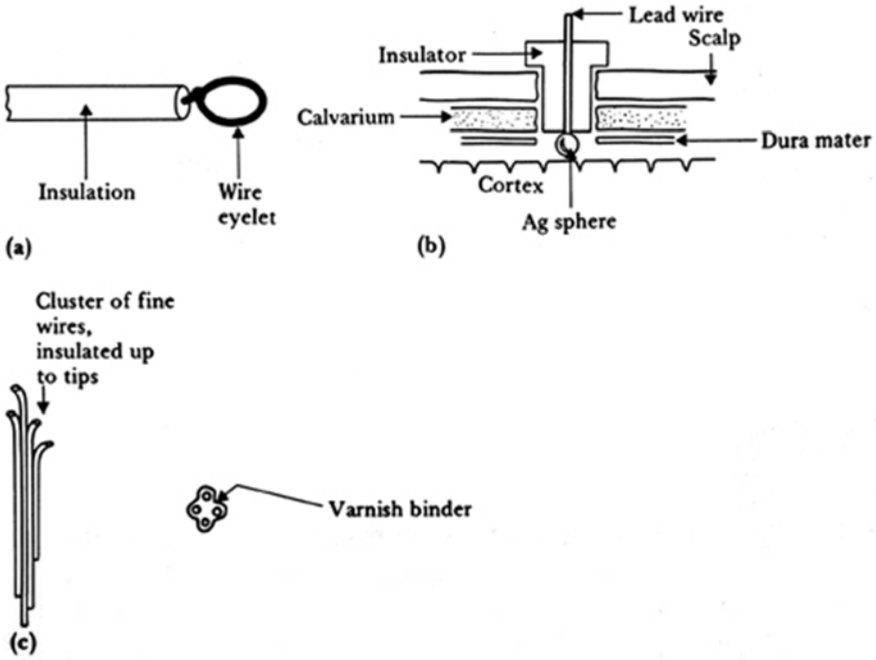


Figure 5.15 Implantable electrodes for detecting biopotentials (a) Wire-loop electrode. (b) Silver-sphere cortical-surface potential electrode. (c) Multielement depth electrode.

5.8 Electrode Arrays

- One-dimensional linear array of six pairs of electrodes
  - Microfabrication technology
  - Ag/AgCl electrode, square shape, 40 × 40 μm
  - Thin film gold conductor
  - Flexible polyimide substrate or robust molybdenum substrate
  - Substrate is coated with an anodically grown oxide layer for insulation
  - Probe dimension: 10 mm (L) × 0.5 mm (W) × 125 μm (D)
  - Usage: measurement of transmural potential distribution in the beating myocardium
- Two-dimensional electrode array
  - Microfabrication technology
  - Two-dimensional extension of one-dimensional array
  - Usage: mapping of electrical potentials on the surface of the heart
- Sock electrodes
  - Individual electrode is a silver sphere with about 1 mm diameter

  - Silver spheres are incorporated into a fabric sock that fits snugly over the heart
  - Usage: epicardial potential mapping
- Multilayer ceramic integrated circuit package
  - Thin-film microfabrication technology
  - 144 Ag/AgCl electrodes on polyimide substrate
  - Usage: epicardial potential mapping
- Three-dimensional electrode array
  - Silicon microfabrication technology
  - Two-dimensional comb with about 1.5 mm long tines
  - Usage: two-dimensional potential mapping

5.9 Microelectrodes

- Electrophysiology of excitable cell ⇒ measurements of cell membrane potential
  - Small tip diameter: 0.05 – 10 μm
  - Strong material: solid-metal needle, glass needle with metal inside or surface, glass micropipet with a lumen filled with an electrolyte solution

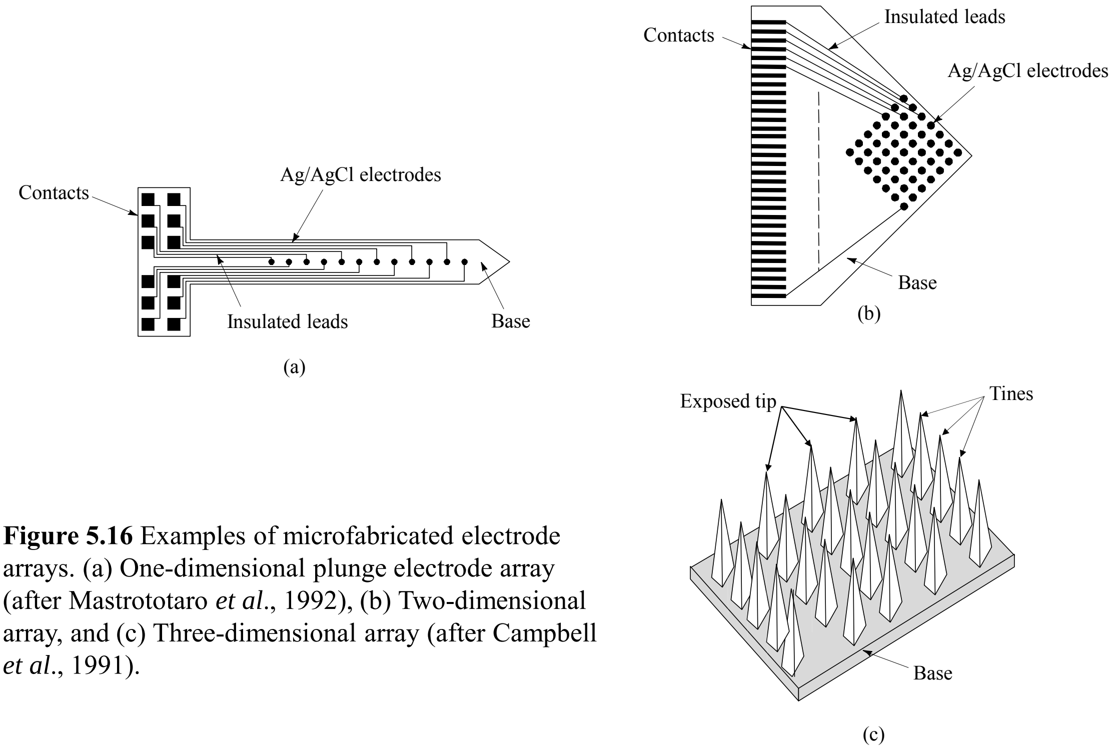


Figure 5.16 Examples of microfabricated electrode arrays. (a) One-dimensional plunge electrode array (after Mastrototaro *et al.*, 1992), (b) Two-dimensional array, and (c) Three-dimensional array (after Campbell *et al.*, 1991).

Metal Microelectrodes

- Fine needle of a strong metal with proper insulation
  - Sharp tip by electrolytic etching with the metal as anode
  - Material: stainless steel, platinum-iridium alloy, tungsten, compound tungsten carbide
  - Supporting shaft: larger metal with surface insulation
  - Insulation: a film of some polymeric material, varnish
  - Only the extreme tip remains uninsulated

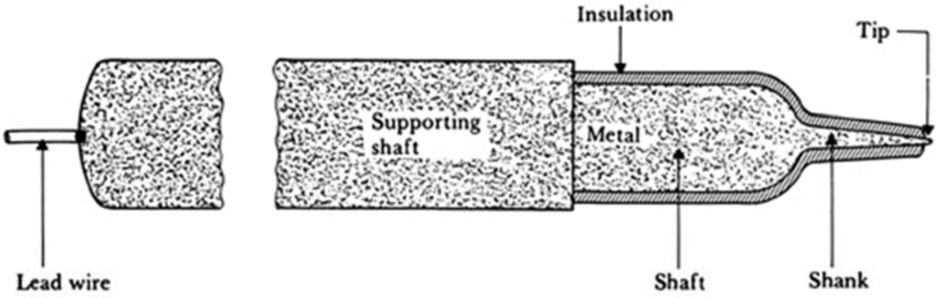


Figure 5.17 The structure of a metal microelectrode for intracellular recordings.

Supported-Metal Microelectrodes

- Glass tube with its lumen filled with a metal
  - Choose a metal with a melting point near the softening point of the glass (silver-solder alloy, platinum and silver alloy, indium, Wood's metal)
  - Fill a glass tube with melted metal ⇒ heat the tube up to the softening point ⇒ pull and cut ⇒ two micropipets filled with metal
  - Glass: support and insulation
- Deposited-metal-film microelectrode
  - Choose a solid glass rod or tube ⇒ deposit metal film (tenths of μm) ⇒ polymeric insulation coating except the tip

Micropipet Electrodes

- Glass capillary ⇒ heat up to the softening point ⇒ pull (microelectrode puller) and cut ⇒ two micropipets with tip diameter of 1 μm
- Filling solution: 3M KCl
- Metal wire electrode: Ag/AgCl, platinum, stainless steel

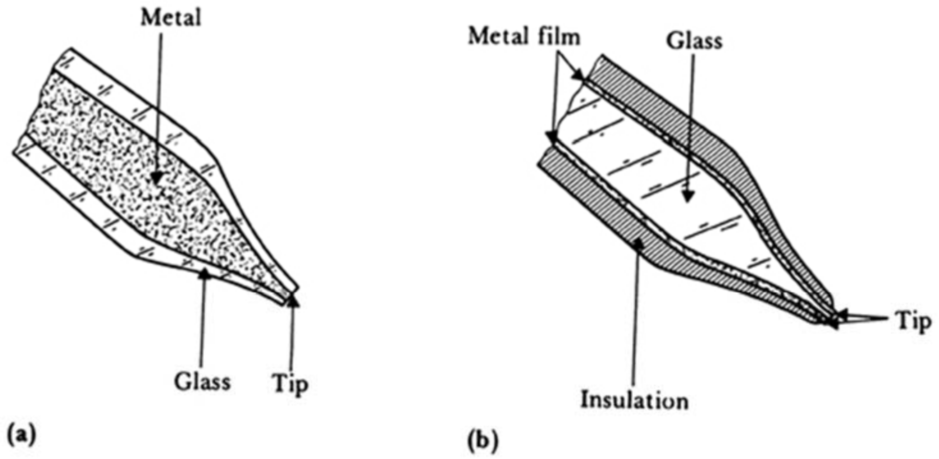


Figure 5.18 Structures of two supported metal microelectrodes (a) Metal-filled glass micropipet. (b) Glass micropipet or probe, coated with metal film.

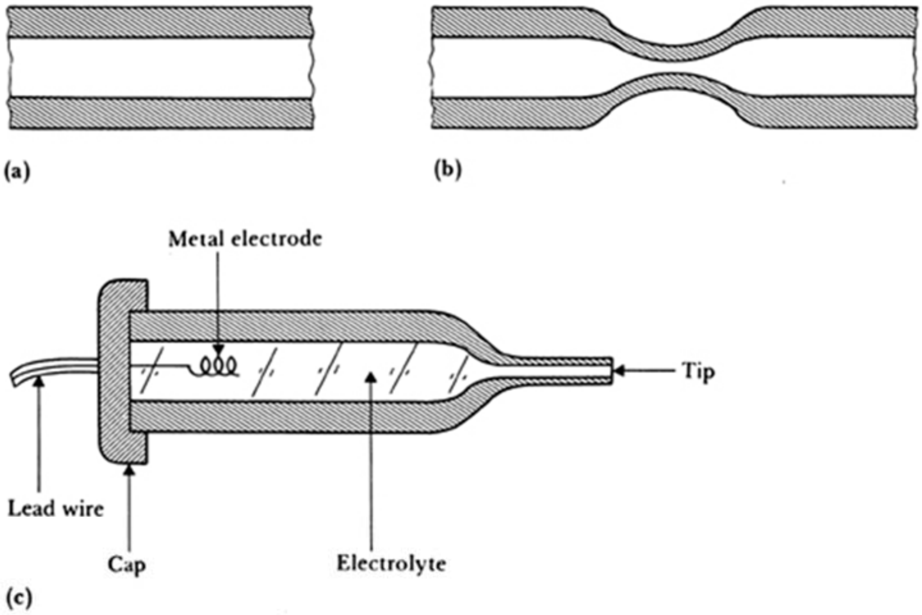


Figure 5.19 A glass micropipet electrode filled with an electrolytic solution (a) Section of fine-bore glass capillary. (b) Capillary narrowed through heating and stretching. (c) Final structure of glass-pipet microelectrode.

Microelectrodes Based on Microelectronic Technology

- Beam-lead multiple electrode
- Multielectrode silicon probe

- Multiple chamber electrode
- Peripheral-nerve electrode

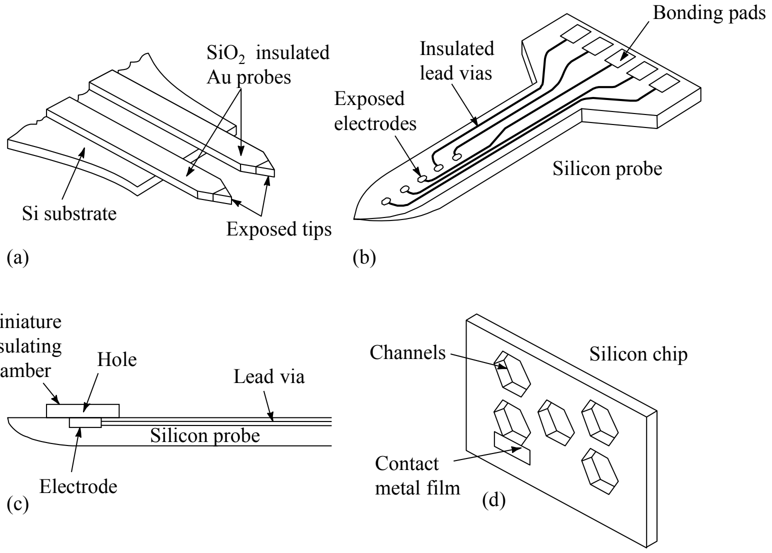


Figure 5.20 Different types of microelectrodes fabricated using microelectronic technology (a) Beam-lead multiple electrode. (Based on Figure 7 in K. D. Wise, J.B. Angell, and A. Starr, "An Integrated Circuit Approach to Extracellular Microelectrodes." Reprinted with permission from *IEEE Trans. Biomed. Eng.*, 1970, BME-17, pp. 238-246. Copyright (C) 1970 by the institute of Electrical and Electronics Engineers.) (b) Multielectrode silicon probe after Drake *et al.* (c) Multiple-chamber electrode after Prohaska *et al.* (d) Peripheral-nerve electrode based on the design of Edell.

Electrical Properties of Microelectrodes

- Metal microelectrode
  - Frequency dependent impedance: 10 – 100 MΩ
  - High-pass filtering effect
  - Good for measuring action potentials
- Glass micropipet microelectrode
  - Frequency dependent impedance: 1 – 100 MΩ
  - Low-pass filtering effect
  - Good for measuring resting membrane potential

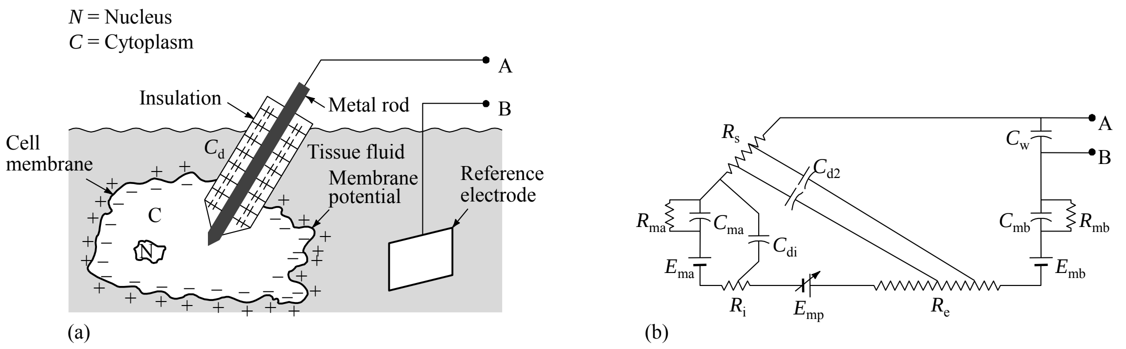
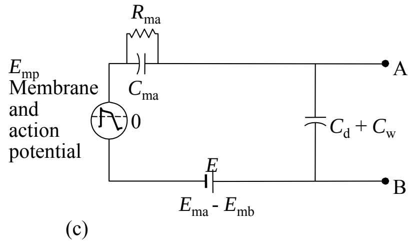


Figure 5.21 Equivalent circuit of metal microelectrode (a) Electrode with tip placed within a cell, showing origin of distributed capacitance. (b) Equivalent circuit for the situation in (a). (c) Simplified equivalent circuit. (From L. A. Geddes, *Electrodes and the Measurement of Bioelectric Events*, Wiley-Interscience, 1972. Used with permission of John Wiley and Sons, New York.)



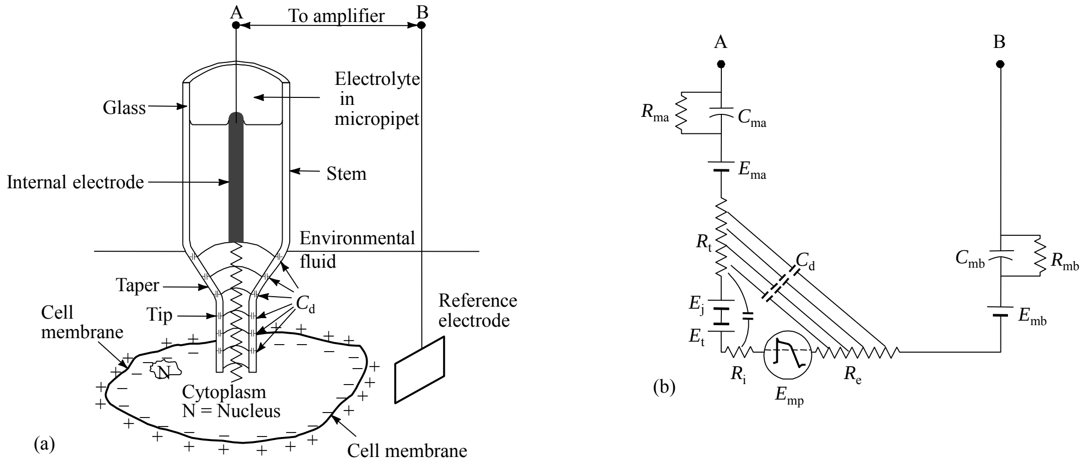
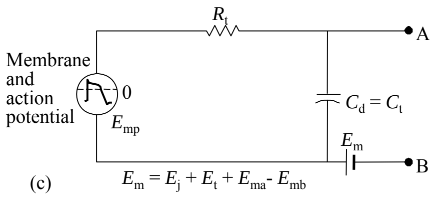


Figure 5.22 Equivalent circuit of glass micropipet microelectrode (a) Electrode with its tip placed within a cell, showing the origin of distributed capacitance. (b) Equivalent circuit for the situation in (a). (c) Simplified equivalent circuit. (From L. A. Geddes, Electrodes and the Measurement of Bioelectric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



5.10 Electrodes for Electric Stimulation of Tissue

- Larger amount of currents (~ mA or ~ A) cross the electrode-electrolyte interface
  - Cardiac pacemaker, FES, cardiac defibrillator
  - Net current may not be zero
  - Equivalent circuit depends on stimulus parameters (waveform, current, duration, frequency, etc)
- Waveshapes
  - Rectangular biphasic
  - Rectangular monophasic with dc adjustment
  - Decaying exponentials in trapezoids
  - Sinusoidal
- Two types of stimulation
  - Constant-current stimulus ⇒ voltage response is not constant
  - Constant-voltage stimulus ⇒ current response is not constant
- Material
  - Chemical reaction is not desirable since electrode is consumed, could be toxic, electrode property changes
  - Noble metal or stainless steel
  - Carbon-filled silicon rubber
  - Iridium/iridium oxide system
- Geometry
  - Edge effect

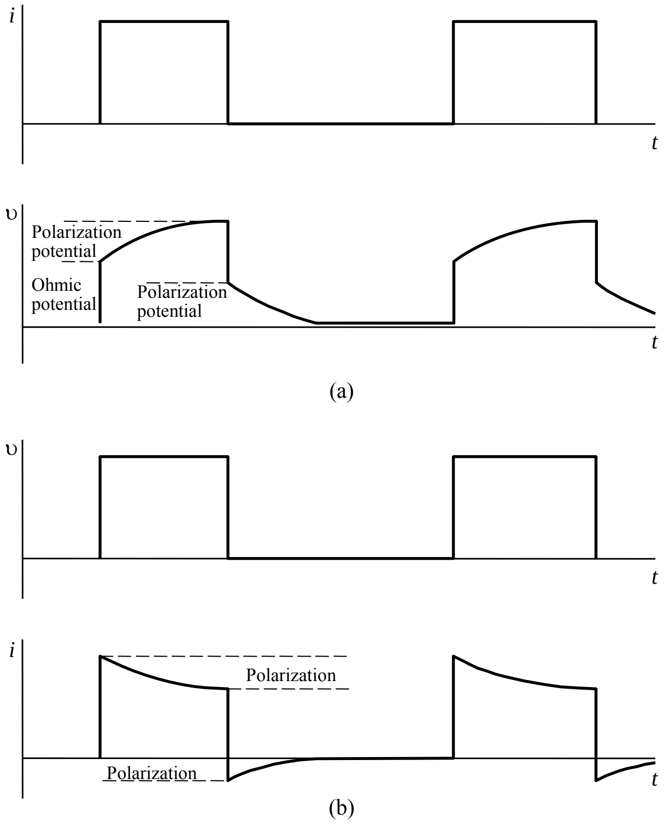


Figure 5.23 Current and voltage waveforms seen with electrodes used for electric stimulation (a) Constant-current stimulation. (b) Constant-voltage stimulation.

5.11 Practical Hints in Using Electrodes

- Any parts exposed to the electrolyte must be of the same material
  - Lead wire connection could be done by welding or mechanical bonding (crimping or peening)
- Use the same type of electrodes when pairs are used
- Use strain relief for lead wires
- Check the connection of lead wire
- Check the insulation of electrode and lead wire
- Check the input impedance of biopotential amplifier