Biomedical Instrumentation

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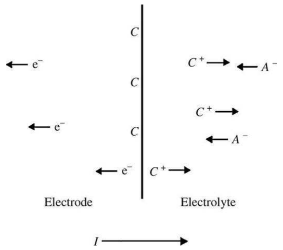
Biopotential Electrodes

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–.



$$C \rightleftarrows C^{n+} + ne^- \qquad A^{m-} \rightleftarrows A + me^-$$

where *n* is the valence of C and *m* is valence of A

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.

$$H_2 \rightleftarrows 2H \rightleftarrows 2H^+ + 2e^-$$

$$V = E^0_{Zn} - E^0_{Ag} = -0.763\ V - 0.233\ V = -0.986\ V$$

$$V_p = E^0 + V_r + V_c + V_a$$

V_p = total patential, or polarization potential, of the electrode
E^0 = half-cell potential
V_r = ohmic overpotential
V_c = concentration overpotential
V_a = activation overpotential

$$E = -\frac{RT}{nF}\ln\frac{a_1}{a_2}$$

$$E = E^0 + \frac{RT}{nF}\ln(a_{C^{n+}})$$

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

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

$$E_j = \frac{\mu_+ - \mu_-}{\mu_+ + \mu_-}\frac{RT}{nF}\ln\frac{a'}{a''}$$

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

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

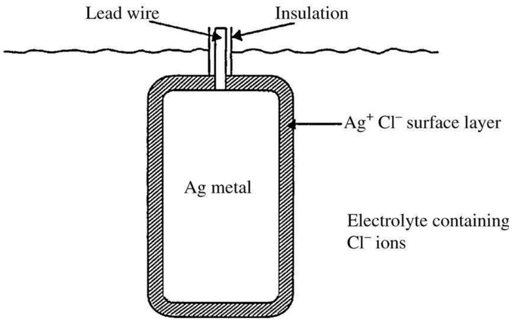
$$a_{Ag^+} \times a_{Cl^-} = K_s$$

$$E = E^0_{Ag} + \frac{RT}{nF}\ln a_{Ag^+}$$

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

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

A silver/silver chloride electrode, shown in cross section



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$$I = 100\,\mathrm{mA}\, e^{-t/10\,\mathrm{s}}$$

$$q = \int_0^\infty i\,dt = 100\,\mathrm{mA}\int_0^\infty e^{-t/10}dt = 1\,\mathrm{C}$$

$$N = \frac{1\,\mathrm{C}}{1.6\times10^{-19}\mathrm{C/atom}} = 6.25\times10^{8}\ \mathrm{atoms}$$

$$N = \frac{6.25\times10^{18}}{6.03\times10^{23}} = 1.036\times10^{-5}\ \mathrm{mol}$$

$$142.3\times1.036\times10^{-5} = 1.47\times10^{-3}\ \mathrm{g}$$

$$[\mathrm{Ag}^+][\mathrm{Cl}^-] = 1.56\times10^{-10}$$

$$[\mathrm{Ag}^+] = 1.73\times10^{-10}\ \mathrm{mol/liter}$$

$$1.73\times10^{-10}\times142.3 = 2.46\times10^{-8}\ \mathrm{g}$$

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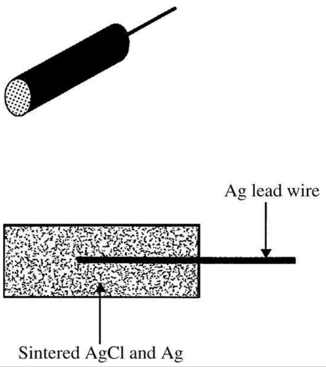
Sintered Ag/AgCI electrode



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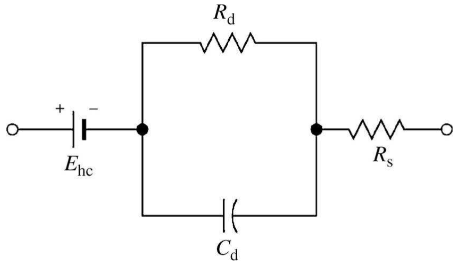
Equivalent circuit for a biopotential electrode in contact with an electrolyte



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,
Rs is the series resistance associated with interface effects and due to resistance in the electrolyte.

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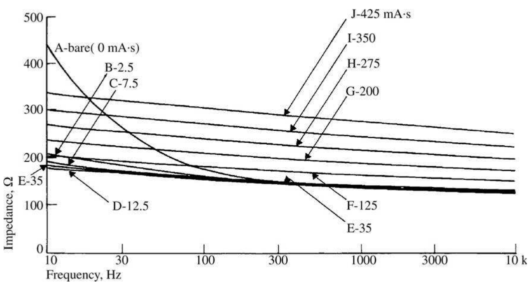
Impedance as a function of frequency for Ag electrodes coated with an electrolytically deposited AgCl layer



The electrode area is 0.25 cm2. Numbers attached to curves indicate number of mA·s for each deposit. (From L. A. Geddes, L. E. Baker, and A. G. Moore, "Optimum Electrolytic Chloriding of Silver Electrodes," *Medical and Biological Engineering,* 1969, 7, pp. 49–56.)

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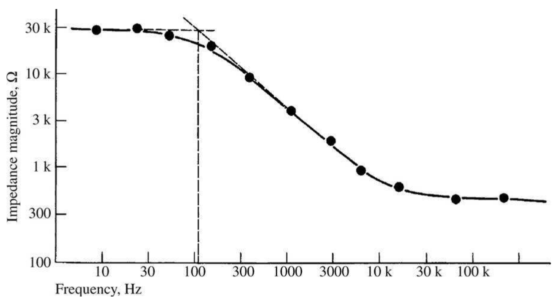
Experimentally determined magnitude of impedance as a function of frequency for electrodes



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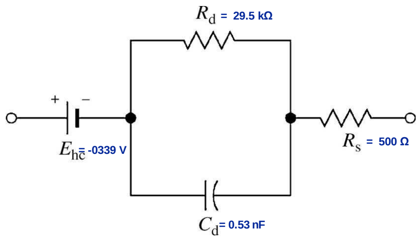
Example

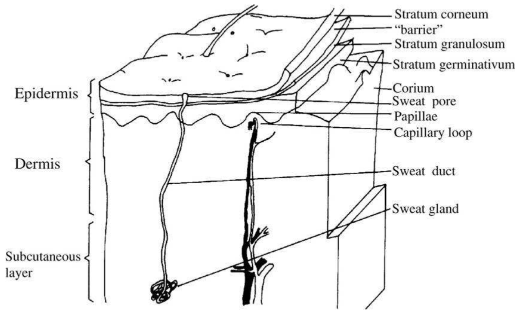
We want to develop an electrical model for a specific biopotential electrode studies in the laboratory. The electrode is characterized by placing it in a physiological saline bath in the laboratory, along with an Ag/AgCl electrode having a much greater surface area and a known half-cell potential of 0.233 V. The dc voltage between the two electrodes is measured with a very-high-impedance voltmeter and found to be 0.572 V with the test electrode negative The magnitude of the impedance between two electrodes is measured as a function of frequency at very low currents; it is found to be that given in Figure in slide 12. From these data, determine a circuit model for the electrode.

Solution

Half cell potential of the test electrode E_{hc} = 0.223 V – 0.572 = -0339 V
At frequencies greater than 20 kHz C_d is short circuit. Thus R_s = 500 Ω = 0.5 kΩ,
At frequencies less than 50 Hz C_d is open circuit. Thus $R_s + R_d$ = 30 kΩ. Thus
R_d = 30 kΩ - R_s = 29.5 kΩ
Corner frequency is 100 Hz. Thus
$C_d = 1/(2\pi f R_d) = 1/(2\pi 100\times 29500) = 5.3\times 10^{-8}$ F $= 0.53\times 10^{-9}$ F = 0.53 nF



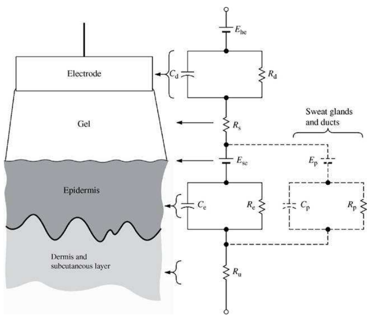
Magnified section of skin, showing the various layers



(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.)

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.

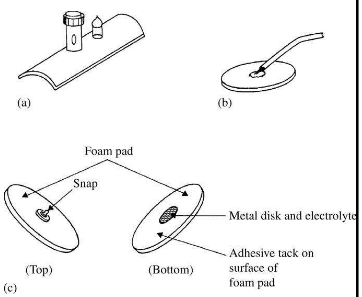


Body-surface biopotential electrodes

(a) Metal-plate electrode used for application to limbs,

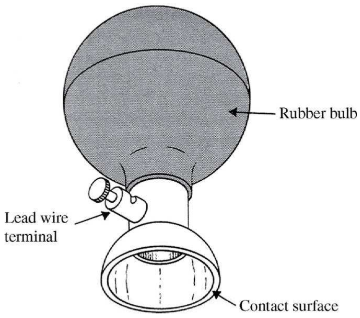
(b) Metal-disk electrode applied with surgical tape,

(c) Disposable foam-pad electrodes, often used with electrocardiographic monitoring apparatus.

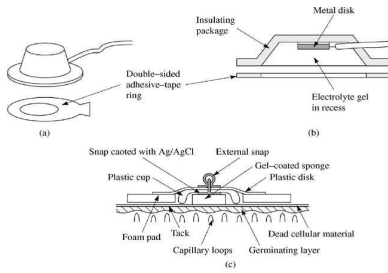


A metallic suction electrode

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



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 (c) in slide 17. The recess in this electrode is formed from an open foam disk, saturated with electrolyte gel and placed over the metal electrode.

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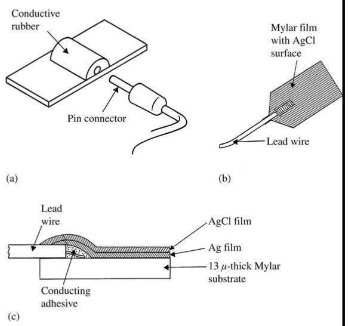
Flexible body-surface electrodes

(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.]



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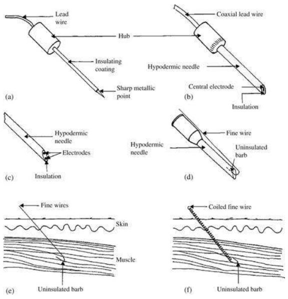
Needle and wire electrodes for percutaneous measurement of biopotentials

(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.



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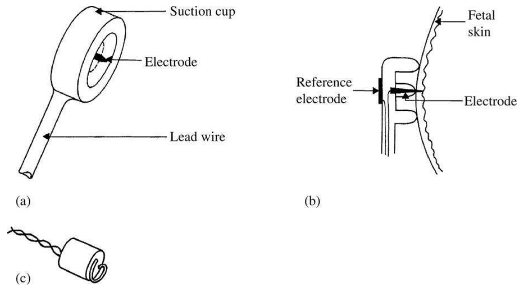
Electrodes for detecting fetal electrocardiogram during labor, by means of intracutaneous needles



(a) Suction electrode,
(b) Cross-sectional view of suction electrode in place, showing penetration of probe through epidermis,
(c) Helical electrode, that is attached to fetal skin by corkscrew-type action.

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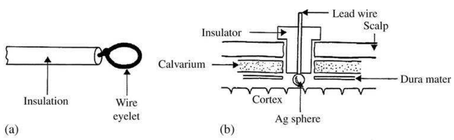
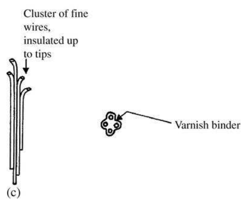
Implantable electrodes for detecting biopotentials





(a) Wire-loop electrode,
(b) platinum-sphere cortical-surface potential electrode,
(c) Multielement depth electrode.

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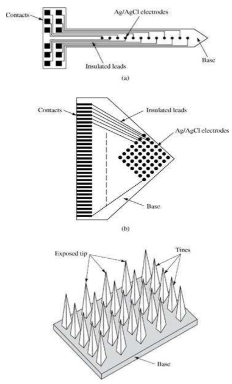
Examples of microfabricated electrode arrays



(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).

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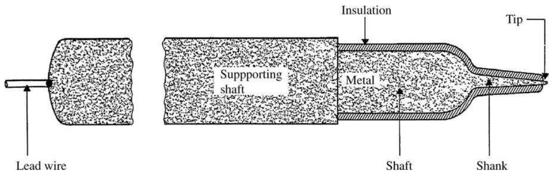
The structure of a metal microelectrode for intracellular recordings



$$\frac{C_{\mathrm{dl}}}{L} = \frac{2\pi\varepsilon_{\mathrm{r}}\varepsilon_0}{\ln D/d}$$

Capacitance per unit length

ε_0 = dielectric constant of free space
ε_r = relative dielectric constant of insulation material
D = diameter of cylinder consisting of electrode plus insulation
D = diameter of electrode
L = length of shank

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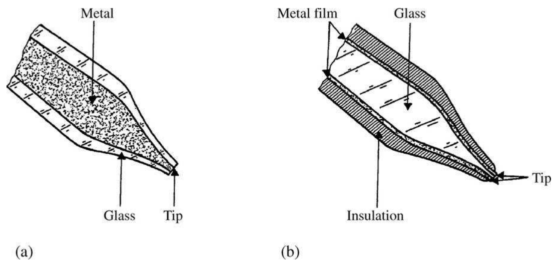
Structures of two supported metal microelectrodes



(a) Metal-filled glass micropipet.
(b) Glass micropipet or probe, coated with metal film.

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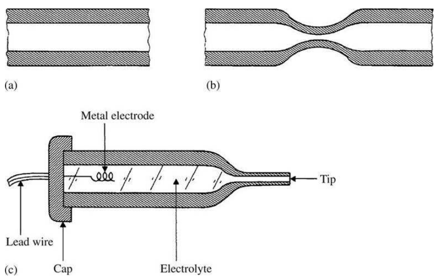
A glass micropipet electrode filled with an electrolytic solution



$$E_{\mathrm{m}} = E_{\mathrm{j}} + E_{\mathrm{t}} + E_{\mathrm{ma}} - E_{\mathrm{mb}}$$

(a) Section of fine-bore glass capillary,
(b) Capillary narrowed through heating and stretching,
(c) Final structure of glass-pipet microelectrode.

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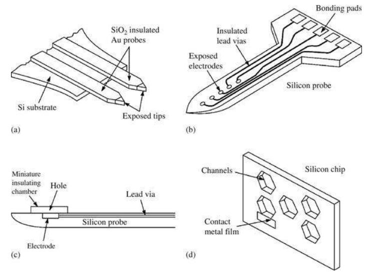
Different types of microelectrodes fabricated using microelectronic technology



(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.)**
(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.

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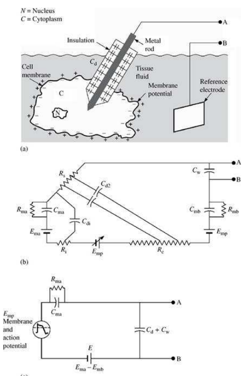
Equivalent circuit of metal microelectrode



(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.)**

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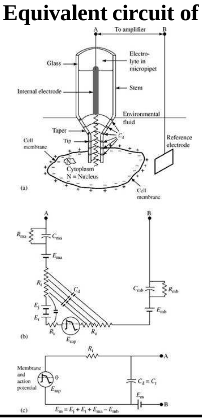
Equivalent circuit of glass micropipet microelectrode



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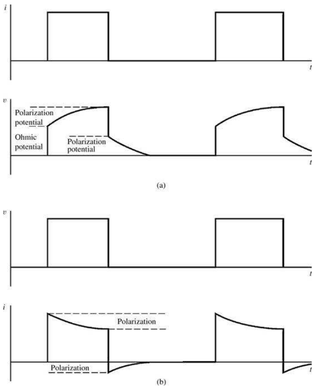
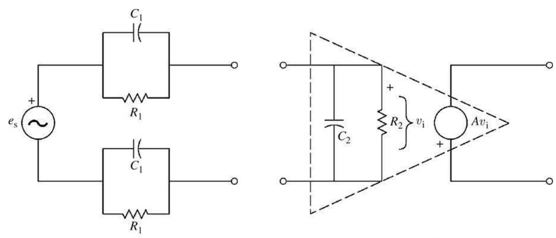
Current and voltage waveforms seen with electrodes used for electric stimulation



(a) Constant-current stimulation,

(b) Constant-voltage stimulation.

Simplified equivalent circuit of a Needle type EMG electrode pair and equivalent circuit of the input stage of an amplifier



Electrode equivalent circuit

Amplifier

Needle type EMG electrode

Example

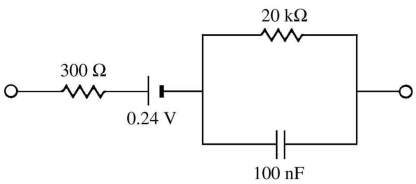
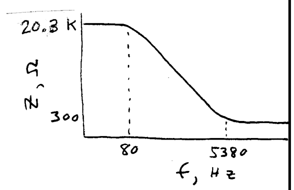


Figure shows equivalent circuit of a biopotential electrode. A pair of these electrodes are tested in a beaker of physiological saline solution. The test consists of measuring the magnitude of the impedance between the electrodes as a function of frequency via low-level sinusoidal excitation so that the impedances are not affected by the current crossing the electrode–electrolyte interface. The impedance of the saline solution is small enough to be neglected. Sketch a Bode plot (log of impedance magnitude versus log of frequency) of the impedance between the electrodes over a frequency range of 1 to 100,000 Hz.

Solution

Assume Figure in previous slide models both electrodes of the pair.
The low corner frequency is
Fc = 1/(2πRC) = 1/(2π·20 kΩ·100 nF)
= 80 Hz.
The high corner frequency is
Fc = 1/(2π RC)
= 1/(2π·20 kΩ||300 Ω·100 nF)
= 5380 Hz.
The slope between the two corner frequencies is –1 on a log-log plot.

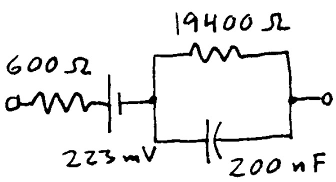


Example

A pair of biopotential electrodes are implanted in an animal to measure the electrocardiogram for a radiotelemetry system. One must know the equivalent circuit for these electrodes in order to design the optimal input circuit for the telemetry system. Measurements made on the pair of electrodes have shown that the polarization capacitance for the pair is 200 nF and that the half-cell potential for each electrode is 223 mV. The magnitude of the impedance between the two electrodes was measured via sinusoidal excitation at several different frequencies. The results of this measurement are given in the accompanying table. On the basis of all of this information, draw an equivalent circuit for the electrode pair. State what each component in your circuit represents physically, and give its value.

Frequency	Impedance (Magnitude) (Ω)
5 Hz	20,000
10 Hz	19,998
.	.
.	.
.	.
40 kHz	602
50 kHz	600
100 kHz	600

Solution



The 600 Ω is the tissue impedance plus the electrode/electrolyte high-frequency interface impedance.
The 19400 Ω is the electrode/electrolyte low-frequency interface impedance.
The 200 nF is the electrode/electrolyte interface capacitance.
The 223 mV is the electrode/electrolyte polarization voltage.