Electrodes and Tissue Resistivity

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580.435/635 Applied Bioelectrical Engineering
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What you can expect to learn today

- Resistivity (conductance) of body tissues
- How to measure resistivity
- Half cell potential and electrode impedance
- Different types of electrodes

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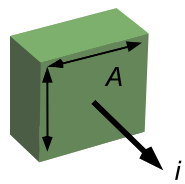
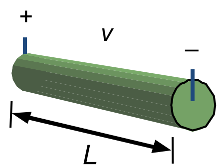
Review of Current Density and Voltage Gradient

- *Current density J* is current *i* per cross-sectional area *A* of the surface normal to the current.



$$J = \frac{i}{A}$$

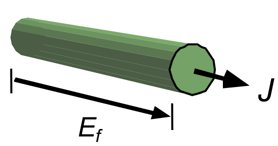
- *Voltage gradient* (or *electric field*) *E* is the change in electrical potential per unit length.



$$E = \frac{v}{L}$$

Concept of Resistivity

- The ratio between voltage gradient and current density is the *resistivity* ρ (reciprocal of *conductivity* σ). This is similar to Ohm's Law in which $R = v/i$.



$$\rho = \frac{E}{J}$$ *(units of Ω-cm)*

- For simplicity, we will assume that ρ is constant for a given tissue and independent of the level of *J*.

Resistive Properties of Biological Tissues

Mean Resistivity in Ohm-Cm

Tissue	Column 1 Kaufman and Johnston	Column 2 Burger and van Milaan	Column 3 Schwan and Kay	Column 4 Burger and van Dongen	Column 5 Rush, Abildskov, and McFee
Blood	208	160	100	160	162‡
Liver	506		840		700
Heart	216		965		ρ_h= 563* ρ_l= 252
Lung	744		1120		2100
Fat	2060		1500-5000		2500
Skeletal muscle (human or dog)	643	ρ_h= 470* ρ_l= 230	965	ρ_h= 675* ρ_l= 245	ρ_h=2300* ρ_l= 150
Skeletal muscle (rabbit)				ρ_h=1800* ρ_l= 125	
Human trunk		415			463
Dog trunk					445
Torso sheath (dog)					281†

*ρ_h and ρ_l are high and low resistivities of anisotropic tissue.
†Data from only two subjects.
‡Data taken from the literature.

from Rush S, Abildskov JA, and McFee R. Resistivity of body tissues at low frequencies. Circ Res 12:40-50, 1963.

Representative Tissue Resistivities

Specimen[a]	Resistivity (Ω-cm)	Species
Blood	150[b]	Human
Plasma	50–60	Mammal
Cerebrospinal fluid	65	Human
Bile	60	Cow, pig
Urine	30	Cow, pig
Cardiac muscle	400[c]	Dog
Skeletal muscle (T)	1600	Dog
Skeletal muscle (L)	300	Dog
Lung	1500	Mammal
Kidney	370	Mammal
Liver	820	Dog
Spleen	885	Dog
Brain (R)	580	Mammal
Fat	2500	Mammal
Skin (stratum corneum)	500 (at dc)[c]	Human
	200 (at 1 MHz)[c]	
Skin (keratin)	8×10^6 (dc)[c]	
	3000 (at 1 MHz)[c]	

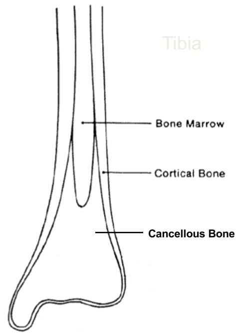
[a]R = random orientation; T = transverse current; L = longitudinal current.
[b]Values for body temperature and the low-frequency region (< 1 MHz). Magnitude depends on packed-cell volume.
[c]Yamamoto and Yamamoto (1976). Anisotropy ratio 2.0 (Van Oosterom et al., 1979).

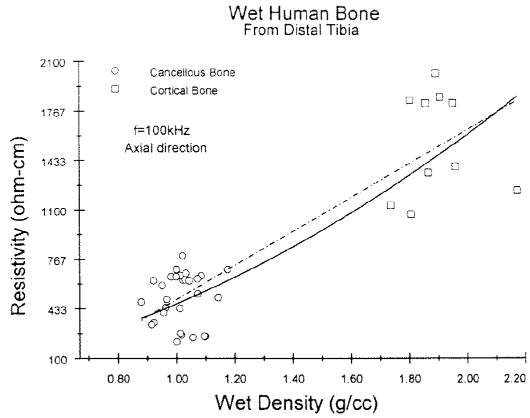
Note: values will depend on measurement conditions, such as:

frequency of waveform
temperature
orientation of tissue
species

adapted from Geddes LA and Baker LE. Principles of Applied Biomedical Instrumentation, 1969

Tissue Resistivity of Bone





Values vary with measurement conditions:
water content
conductivity of fluid
frequency of waveform
orientation
age

FIGURE 16. The resistivity as a function of wet density in the axial direction for cancellous and cortical bone combined. Both the linear and power curve regression lines are shown.

from Williams PA and Saha S. The electrical and dielectric properties of human bone tissue and their relationship with density and bone mineral content. Ann Biomed Eng 24:222-233, 1996.

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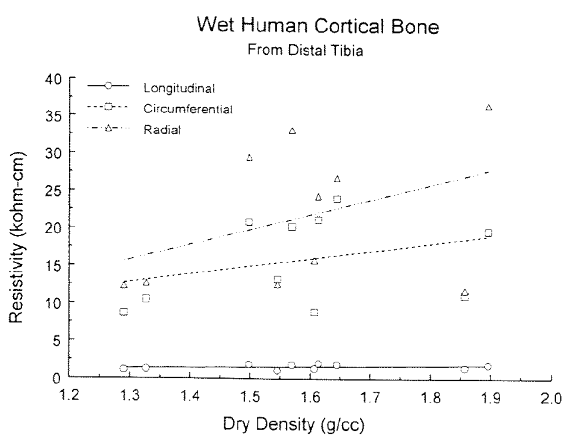
Resistivity can be a function of direction



from Williams and Saha (1996)

Resistivity is significantly higher in the circumferential and longitudinal directions compared with the radial direction.

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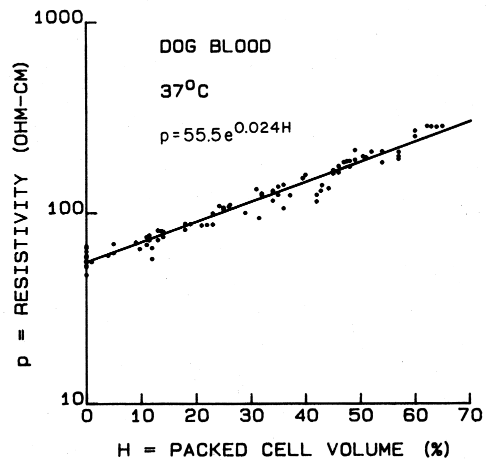
Resistive properties of biofluids are variable

- Most body fluids are not simple electrolytes, and some contain cells in suspension.
- Cells are small volume conductors surrounded by an insulating membrane.
- Hence, the resistivity of the fluid, such as blood, will depend on the concentration of cells (packed cell volume).



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Thus, measured tissue resistivity can vary a lot!

Table 3. Cardiac muscle

Substance	Resistivity (Ω-cm)	Frequency	Temp. (°C)	Electrodes	Reference	Remarks
Human	106 aver. (83–130)	200–900 Mc/s	27	2	Schwan, 1953	Autopsy material (aver. values)
	132	1 Mc/s	Near room temp.	2	Hemingway, 1932	2–3 hr after death
Dog	563	d.c. pulses 0·1 sec	Body	4	Rush, 1963	Transverse to fibers
	252	d.c. pulses 0·1 sec	Body	4	Rush, 1963	Parallel to fibers
	965 aver.	10 c/s	Body	2	Schwan, 1956–57	Anesthetized animal
	1250	10 c/s	Body	2	Schwan, 1955	Anesthetized animal
	925	100 c/s	Body	2	Schwan, 1956–57	Anesthetized animal
	1150	100 c/s	Body	2	Schwan, 1955	Anesthetized animal
	215 aver. (207–224)	1 kc/s	Body	2	Kaufman, 1943	Anesthetized animal
	875 aver. (750–1000)	1 kc/s	Body	2	Schwan, 1956	Anesthetized animal
	825 aver. (700–950)	1 kc/s	Body	2	Schwan, 1955	Anesthetized animal
	845	1 kc/s	Body	2	Schwan, 1956–57	Anesthetized animal
	600	10 kc/s	Body	2	Schwan, 1956–57	Anesthetized animal
	825 aver. (700–950)	10 kc/s	Body	2	Schwan, 1955	Anesthetized animal
	456	100 kc/s	Approx. Body	2	Kinnen, 1964	Left ventricle
	1235	Inductorium	38	2	Galeotti, 1902	Freshly extirpated
Dog–adult	1346	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
	1170 aver.	Inductorium	18	2	Galeotti, 1902	Freshly extirpated
Dog	1368	Inductorium	24	2	Galeotti, 1902	Freshly extirpated
	1380	Inductorium	12	2	Galeotti, 1902	Freshly extirpated
Dog pericardium	419 aver. (405 and 434)	1 kc/s	Body	2	Kaufman, 1943	Anesthetized animal
Rabbit	900 aver. (855–952)	1 kc/s	39	2	Crile, 1922	Author reports variability
	1252 aver.	Inductorium	18	2	Galeotti, 1902	Author reports variability
Turtle	1490, 1540	Inductorium	18	2	Galeotti, 1902	Freshly extirpated

from Geddes LA and Baker LE. The specific resistance of biological material – a compendium of data for the biomedical engineer and physiologist. Med Biol Eng 5:271-293, 1967.

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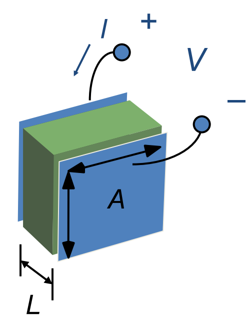
How to Measure Tissue Resistivity?

Take a Slab of Tissue

- Measure the resistance between two parallel plate electrodes placed on either side of a rectangular block of tissue with thickness L.



$$R = \frac{V}{I} = \frac{\rho L}{A} \quad \Rightarrow \quad \rho = \frac{\cancel{LI}}{\cancel{AV}} \quad \frac{AV}{LI}$$

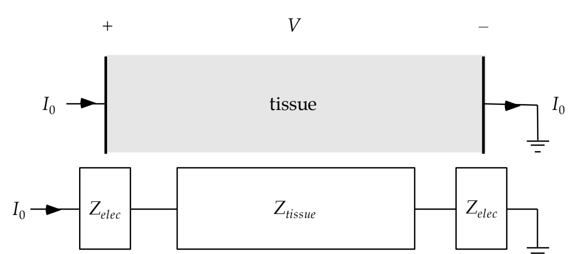
Apply I_0, measure V (or vice versa). But,

$\rho = \rho\,(f, T, H_20$, direction, species, …)

And … there are even *more* confounding factors!

Equivalent Circuit Model

Injecting current I_0 and measuring voltage V



Metal-electrode interface

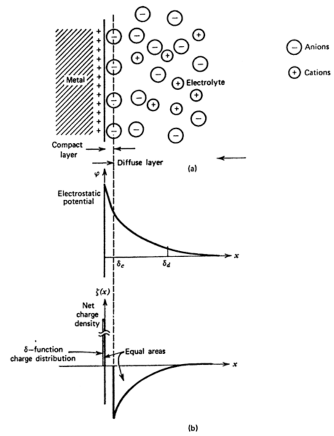


Figure 9.2. Structure of the double layer according to the model proposed by Stern (*Z. Elektrochem.*, **30**, 508 [1924]): (a) ion distribution near the interface: (b) charge density and electrostatic potential. If δ_c (~ 2Å) is the closest distance of approach of an ion to the surface, the net charge density for $0 < x < \delta_c$ will be zero. For $x > \delta_c$ the electrostatic potential decays exponentially with distance. The "characteristic" distance δ_d for a uni-univalent electrolyte $\simeq 10$ Å for a $0.1M$ concentration and is $\simeq 1000$ Å for a $10^{-5}M$ concentration.

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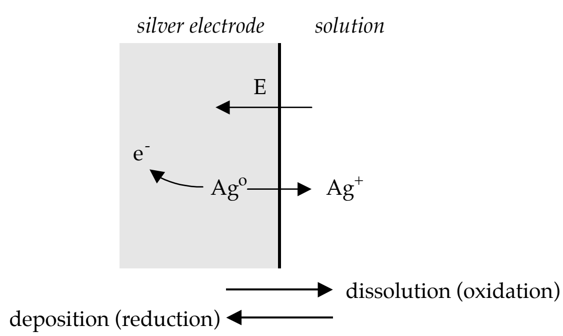
Half-cell Potential



$$\mathrm{Ag} \leftrightarrow \mathrm{Ag}^{+} + \mathrm{e}^{-}$$

$$E_{hc} = E^{0} + \frac{RT}{F} \ln a$$

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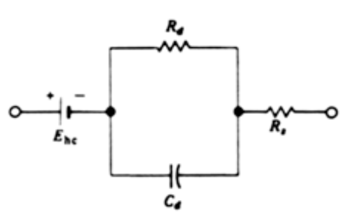
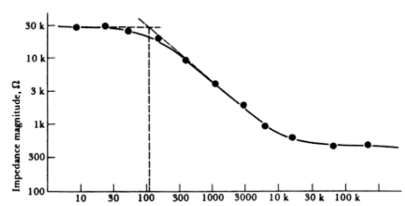
Half-cell Potentials of Common Electrode Materials

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
$Ag + Cl^- \rightarrow AgCl + e^-$	$+0.223$
$2Hg + 2Cl^- \rightarrow Hg_2Cl_2 + 2e^-$	$+0.268$
$Cu \rightarrow Cu^{2+} + 2e^-$	$+0.340$
$Cu \rightarrow Cu^+ + e^-$	$+0.522$
$Ag \rightarrow Ag^+ + e^-$	$+0.799$
$Au \rightarrow Au^{3+} + 3e^-$	$+1.420$
$Au \rightarrow Au^+ + e^-$	$+1.680$

Equivalent Circuit





gure E5.1 Experimentally determined magnitude of impedance as a function of frequency for the electrode system of Example 5.4.

Figure 5.9 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.

Other Equivalent Circuits

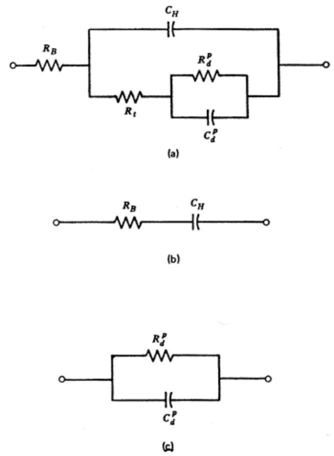


Figure 10.2. Model of Figure 10.1 including resistance polarization effects: (a) complete model; (b) high-frequency approximation; and (c) low-frequency approximation.

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Electrode Impedance Varies with Frequency

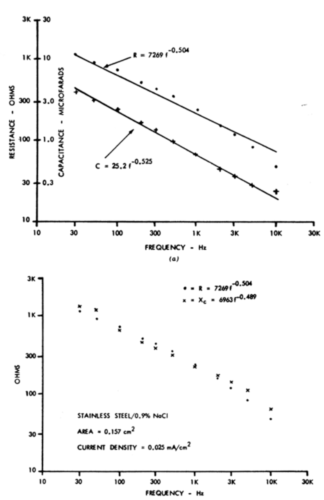

Figure 12 Stainless steel 0.9% saline electrode–electrolyte interface measured with a current density of 0.025 mA/cm^2 over a frequency range from 20 Hz to 20 kHz. (*a*) Series-equivalent resistance *R* and capacitance *C*; (*b*) series-equivalent resistance *R* and reactance $X = \frac{1}{2}\pi fC$. [From L. A. Geddes et al., *Med. Biol. Eng.* 9:511–521 (1971). By permission.]

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Electrode Impedance Varies with Current Density

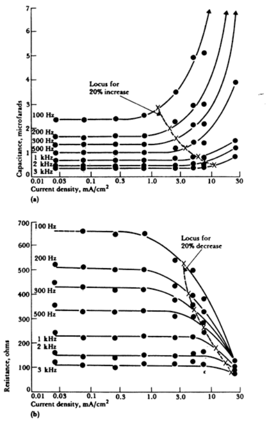
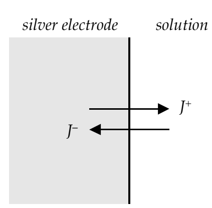


Figure 5.8 (a) Dependence of capacitance value on current density and frequency, given that the impedance of a stainless steel electrode in contact with physiological saline is represented as a series *RC* circuit. (b) Relationship among series resistance, frequency, and current density for the electrode of part (a). (From L. A. Geddes, C. P. DaCosta, and G. Wise, "The Impedance of Stainless Steel Electrodes," *Medical and Biological Engineering*, 1971, **9**, pp. 511–521.)

Polarizable vs. Non-Polarizable Electrodes

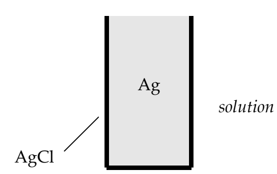
Electrode of the first kind



$$\mathrm{Ag} \leftrightarrow \mathrm{Ag}^{+} + \mathrm{e}^{-}$$

$$E_{hc} = E^{0}_{\mathrm{Ag/Ag^{+}}} + \frac{RT}{F}\ln a_{\mathrm{Ag^{+}}}$$

Electrode of the second kind



$$\mathrm{Ag} \leftrightarrow \mathrm{Ag}^{+} + \mathrm{e}^{-}$$

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

$$E_{hc} = 0.224\mathrm{V} - \frac{RT}{F}\ln a_{\mathrm{Cl^{-}}}$$

(Stable half-cell potential)

Electrodes of the Second Kind Are More Stable

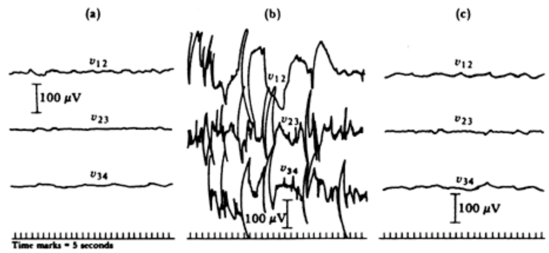


Figure 5.6 Spontaneous noise seen from pairs of electrodes immersed in a physiological saline solution (a) From spherical metallic Ag electrodes coated with AgCl film. (b) From the two electrodes when AgCl film has been removed using emery paper. (c) From the electrodes when a new AgCl layer has been deposited. (From L. A. Geddes and L. E. Baker, "Chlorided Silver Electrodes. in *Medical Research Engirieering*, 1967, 6(3), 33–34, © 1967 by Medical Research Engineering. Reprinted by permission.)

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Electrodes of the Second Kind Have Less Motion Artifact

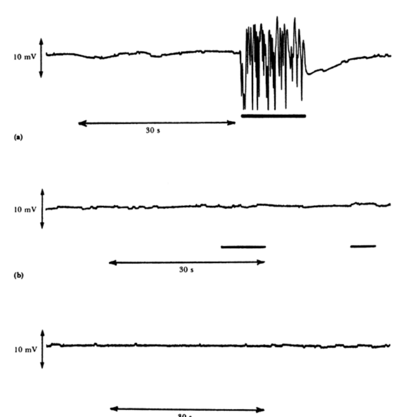

Figure 5.13 Motion artifact in Ag-AgCl electrodes (a) Metallic Ag electrodes in agitated physiological saline solution. (b) The same electrodes with an AgCl surface film in agitated physiological saline solution. (c) Output from an amplifier used for recordings when electrodes are replaced by a 1.5-kΩ resistor. Heavy lines under curves indicate periods of agitation of saline solution.

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Electrodes of the Second Kind Have Lower Impedance at Higher Frequencies

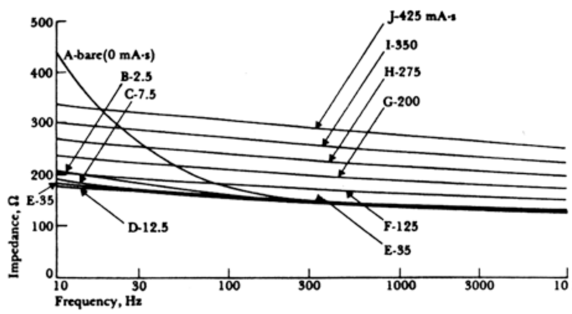


Figure 5.10 Impedance as a function of frequency for Ag electrodes coated with an electrolytically deposited AgCl layer. The electrode area is 0.25 cm^2. Numbers attached to curves indicate number of mA·s for each deposit. (From L. A. Geddes, L. E. Baker, and A. G. Moore, "Optimum Electrolytic Chloriding of Silver Electrodes," *Medical and Biological Engineering*, 1969, **7**, pp. 49–56.)

But too much AgCl coating can actually increase impedance.

Some Different Electrode Types

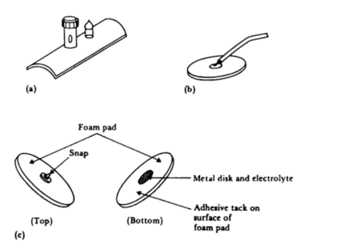


Figure 5.14 Body-surface biopotential electrodes (a) Metal-plate electrode used for application to limbs. (b) Metal-disk electrode applied with surgical tape. (c) Disposable foam-pad electrodes, often used with electrocardiographic monitoring apparatus.

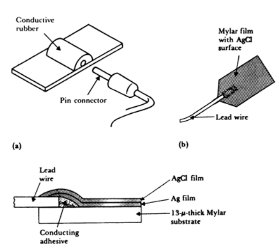
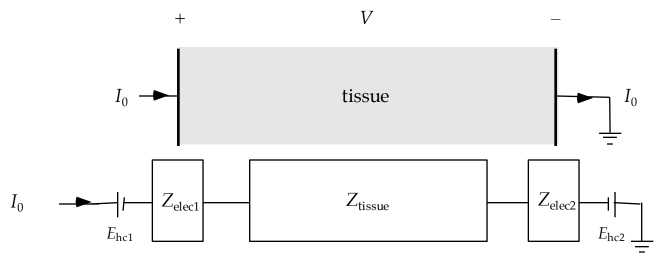


Figure 5.17 Flexible body-surface electrodes (a) Carbon-filled silicone rubber electrode. (b) Flexible thin-film neonatal electrode (after Neuman, 1973). (c) Cross-sectional view of the thin-film electrode in (b). [Parts (b) and (c) are from International Federation for Medical and Biological Engineering, *Digest of the 10th ICMBE*, 1973.]

Snap electrodes

Tab electrodes

Injecting current I_0 and measuring voltage V across the end electrodes



$Z_{tissue} = Z_{tissue}$ (f, T, H_20, direction, species, …)

$Z_{elec1} = Z_{elec1}$ (f, i, …)

$E_{hc1} = E_{hc1}$ ($[c]$)

$Z_{elec2} = Z_{elec2}$ (f, i, …)

$E_{hc2} = E_{hc2}$ ($[c]$)

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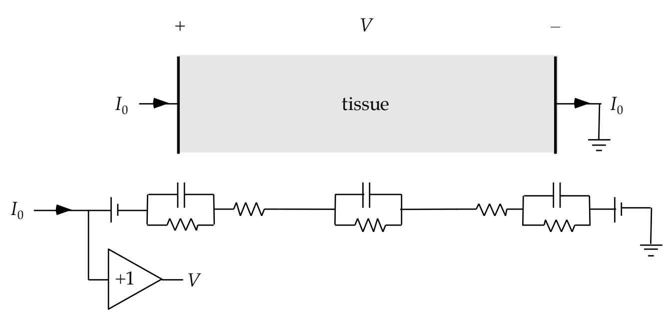
Injecting current I_0 and measuring voltage V across the end electrodes

Circuit model



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Can you devise a way to circumvent the complications of unknown electrode impedances in the measurement of tissue resistivity?

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Questions?

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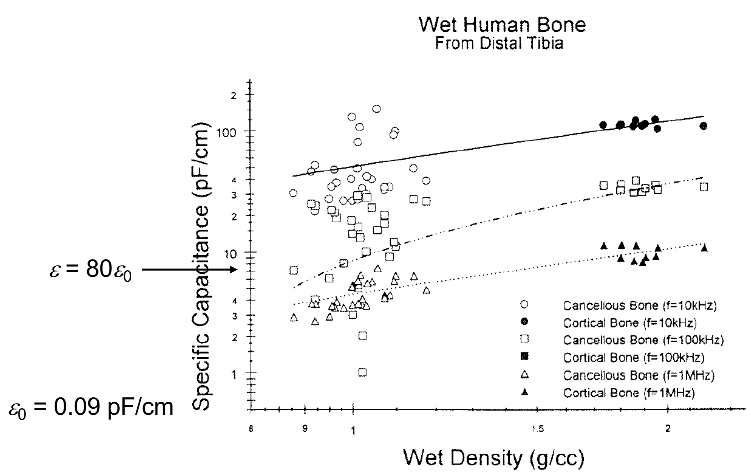
Dielectric Properties of Biological Tissues

- The permittivity ε is a measure of the polarization (internal separation of charges and formation of dipoles) that can result in a material when an electric field is applied to it. ε is defined to be the product of relative permittivity (or dielectric constant) ε_r and the permittivity of free space, ε_0 (i.e., $\varepsilon = \varepsilon_r \varepsilon_0$).

- The relative permittivity of lipid membranes is approximately 2 and that of water is approximately 80. The additional presence of organic molecules results in a relative permittivity of around 10^5- 10^7 for most tissues.

- In general, the capacitive properties of tissue become important in comparison with the resistive properties only at high frequencies.

Dielectric Properties of Bone



from Williams and Saha (1996)

Skin Adds Yet Another Layer of Complexity

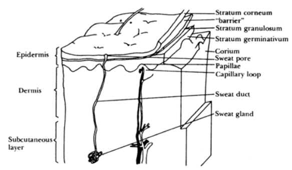


Figure 5.11 **Magnified section of skin, showing the various layers** (Copyright © 1977 by The Institute of Electrical and Electronics Engineers. Reprinted, with permission, from *IEEE Trans. Biomed. Eng.*, March 1977, vol. BME-24, no. 2, pp. 134–139.)

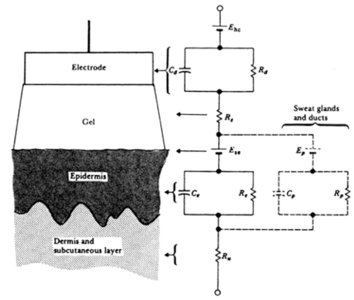


Figure 5.12 A body-surface electrode is placed against skin, showing the total electrical equivalent circuit obtained in this situation. Each circuit element on the right is at approximately the same level at which the physical process that it represents would be in the left-hand diagram.

from Williams and Saha (1996) 33