EE-511 Sensors in medical instrumentation
Section 4.2 – Biopotentials

Objectives

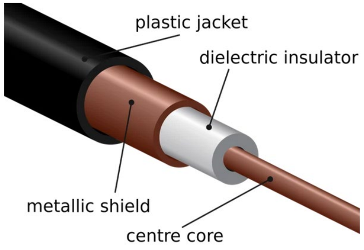
understand:

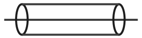
- body surface potential, ExG (e.g., ECG, EEG, EMG, EOG, EGG, EHG, etc.)
- ECG, EKG, P-QRS-T, systole, diastole, 12-lead, fibrillation (AF/VF), ischemia
- ECGi
- EEG

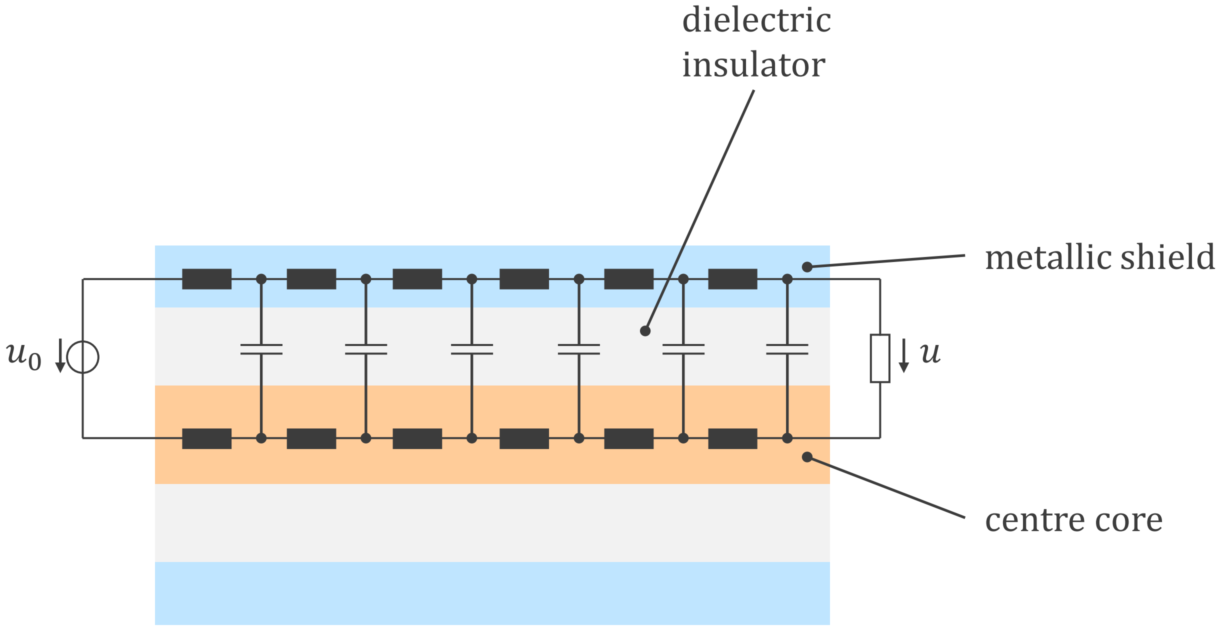
4.2.1 From action potentials to biopotentials

Electrical lines

e.g., coaxial cables





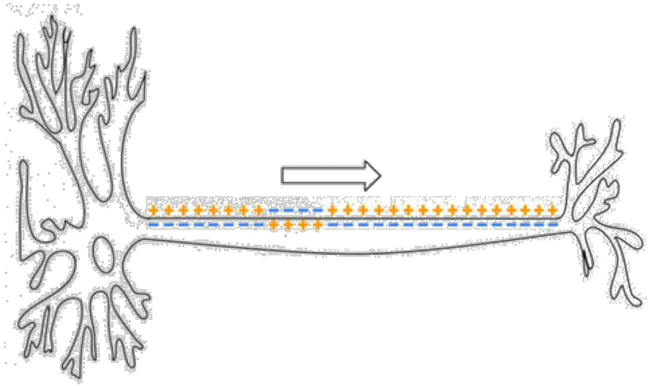


close to speed of light

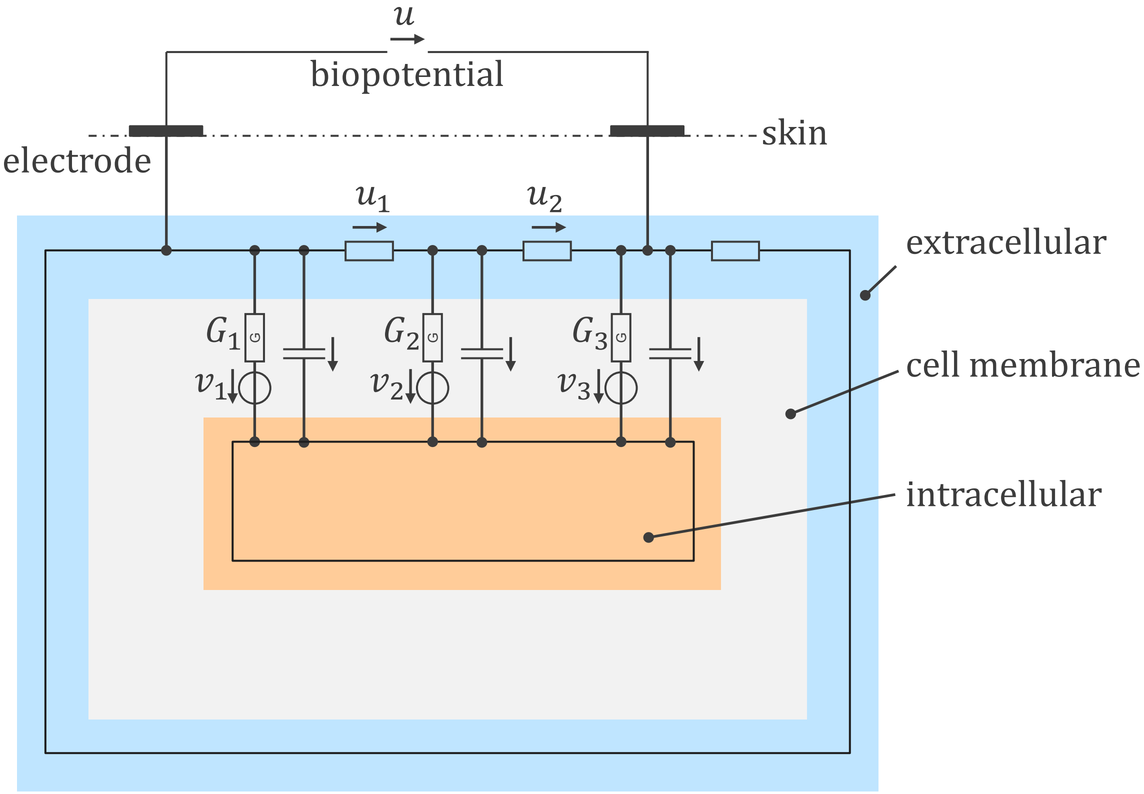
4.2.1 From action potentials to biopotentials (continued)

<u>Cells</u>

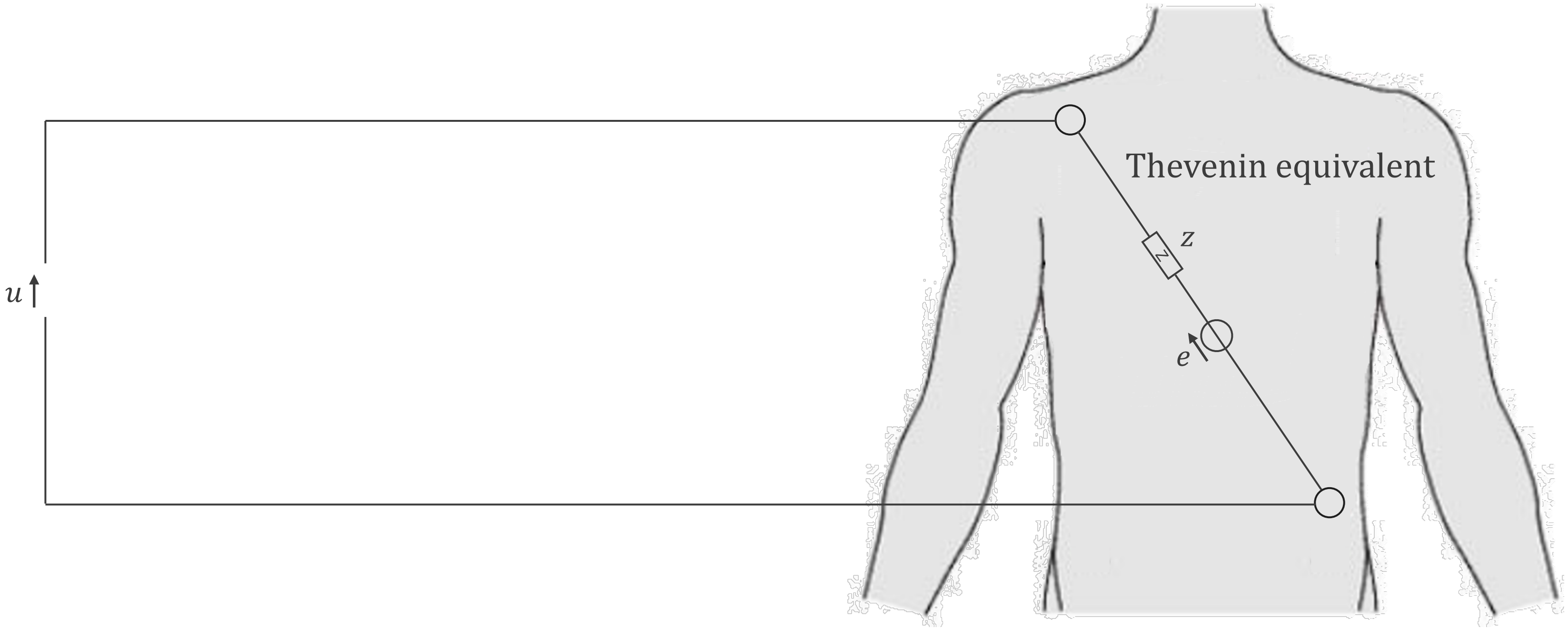
e.g., neuron



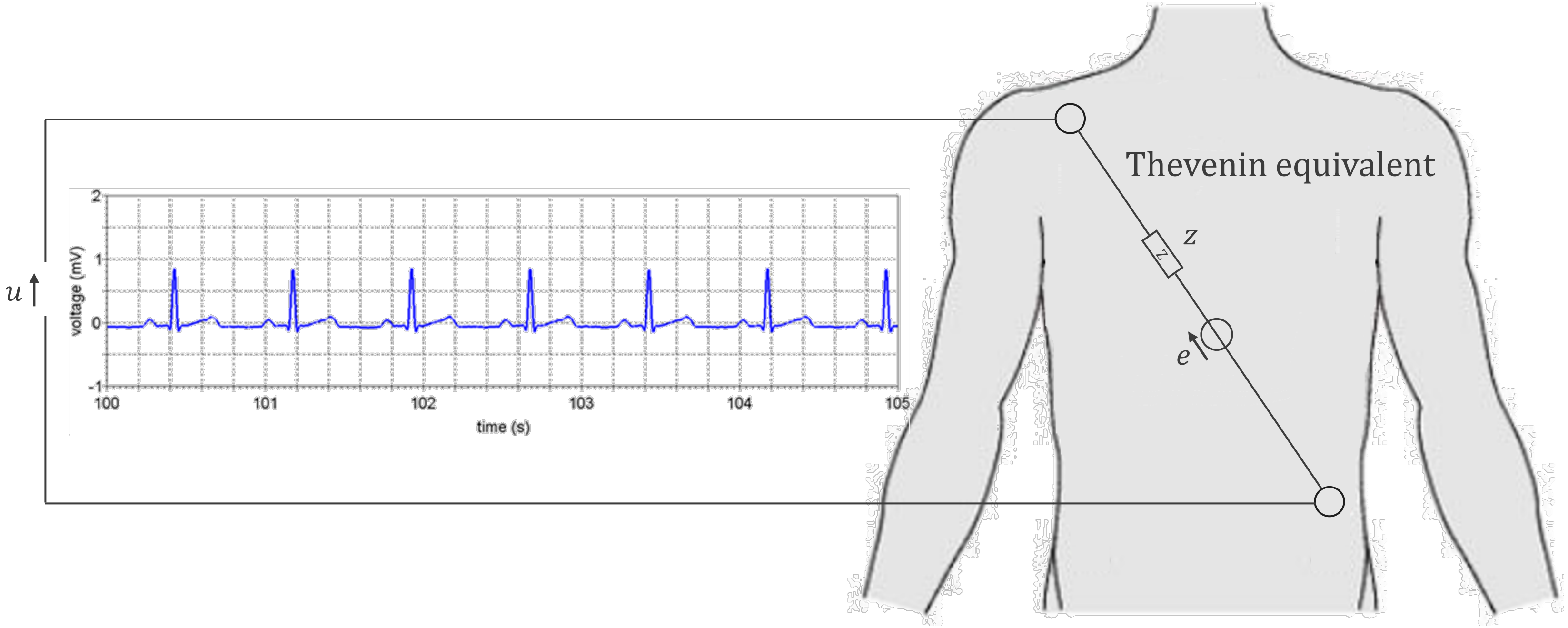
from a few to a few tens of meters per second



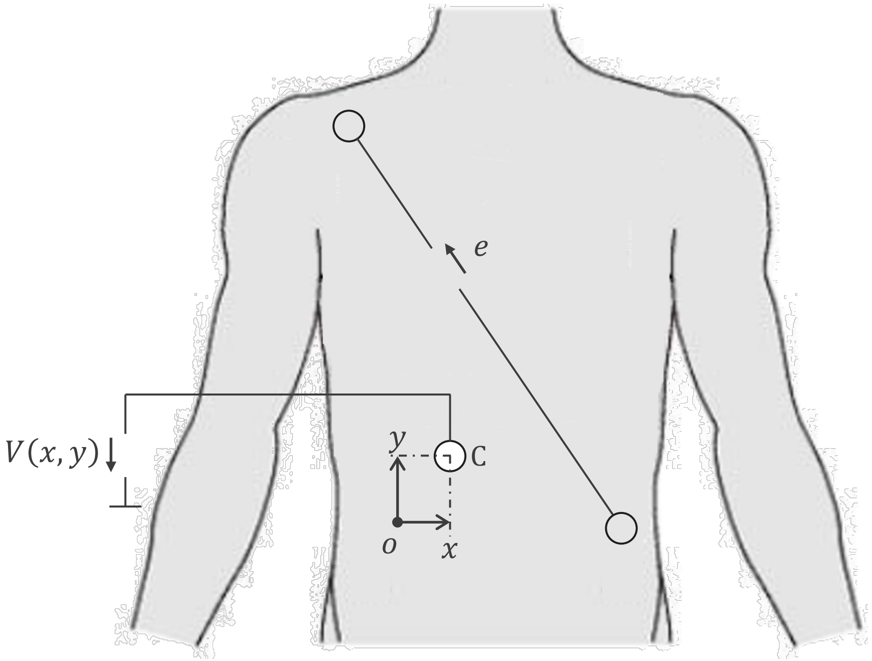
4.2.1 From action potentials to biopotentials (continued)



4.2.2 Electrocardiogram (ECG or EKG)

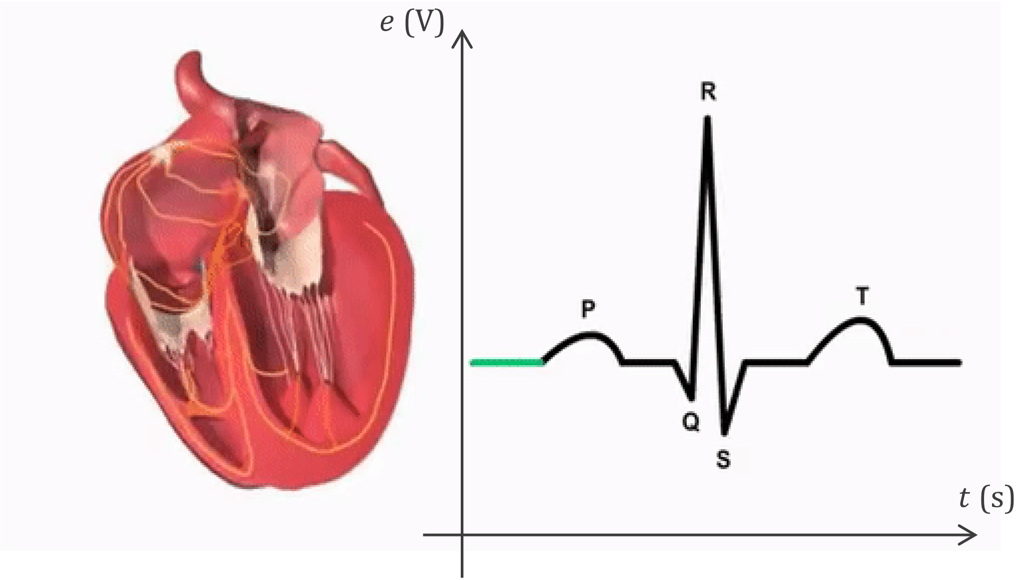


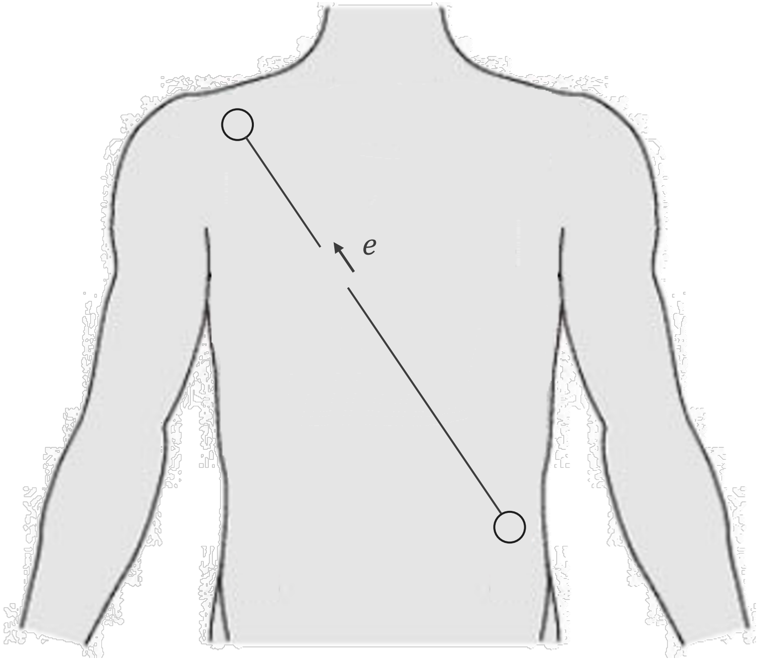
4.2.2 Electrocardiogram (ECG or EKG), continued



4.2.2 Electrocardiogram (ECG or EKG), continued

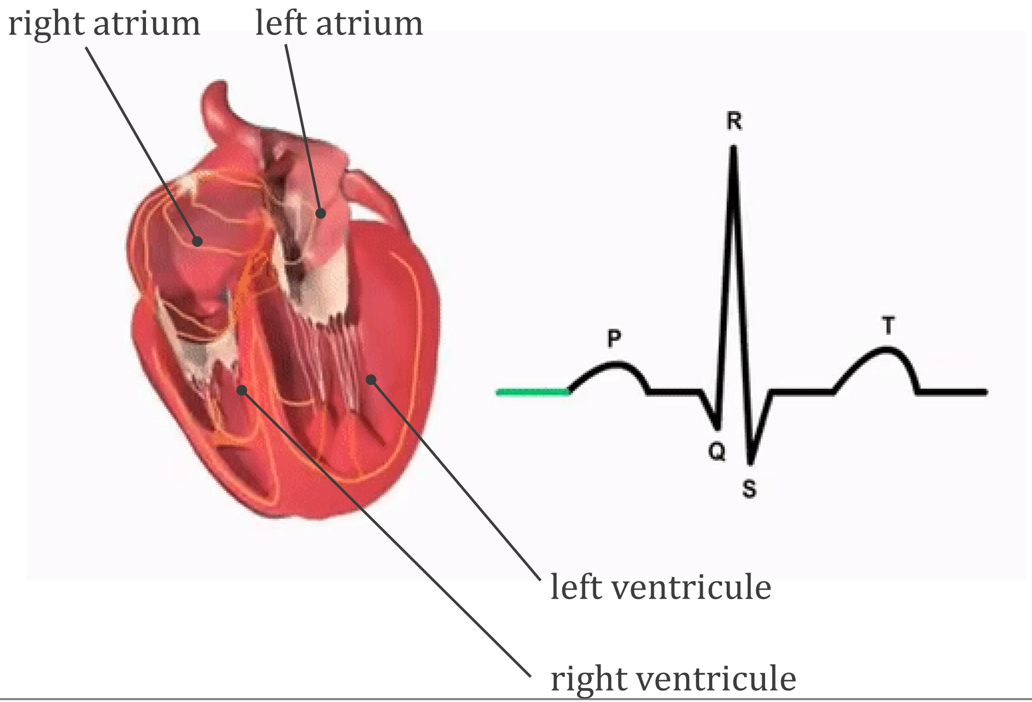
P, QRS, T waves

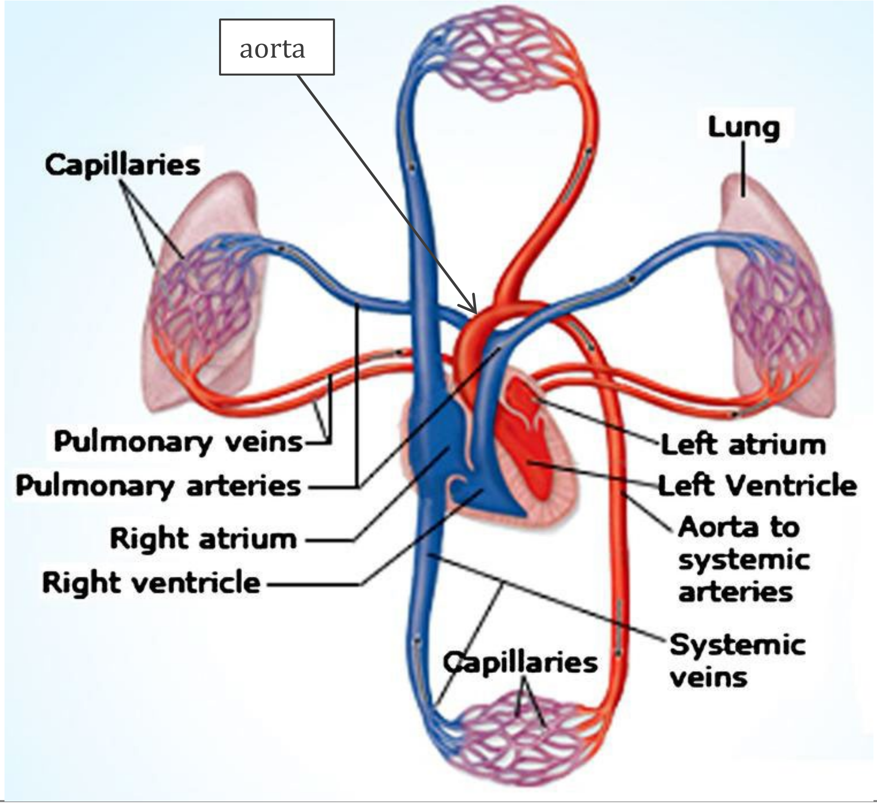




4.2.2 Electrocardiogram (ECG or EKG), continued

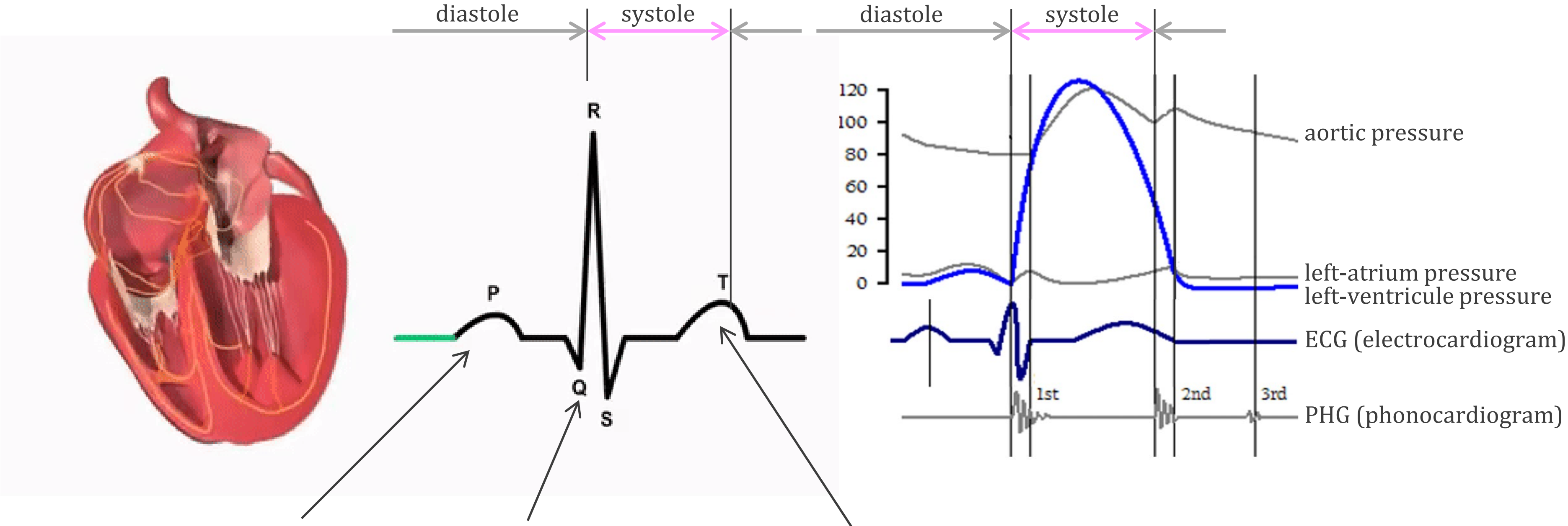
Cardiovascular system





4.2.2 Electrocardiogram (ECG or EKG), continued

Systole and diastole



P-wave: atrial depolarization QRS-complex: ventricular depolarization T-wave: ventricular repolarization

4.2.3 (Einthoven and) Mason-Likar 12-lead ECG system

<u>Bipolar leads (Einthoven)</u>

$$\mathrm{I} = \boxed{\mathrm{L}} - \boxed{\mathrm{R}}$$

$$\mathrm{II} = \boxed{\mathrm{F}} - \boxed{\mathrm{R}}$$

$$\mathrm{III} = \boxed{\mathrm{F}} - \boxed{\mathrm{L}}$$

<u>Augmented leads (Goldberger)</u>

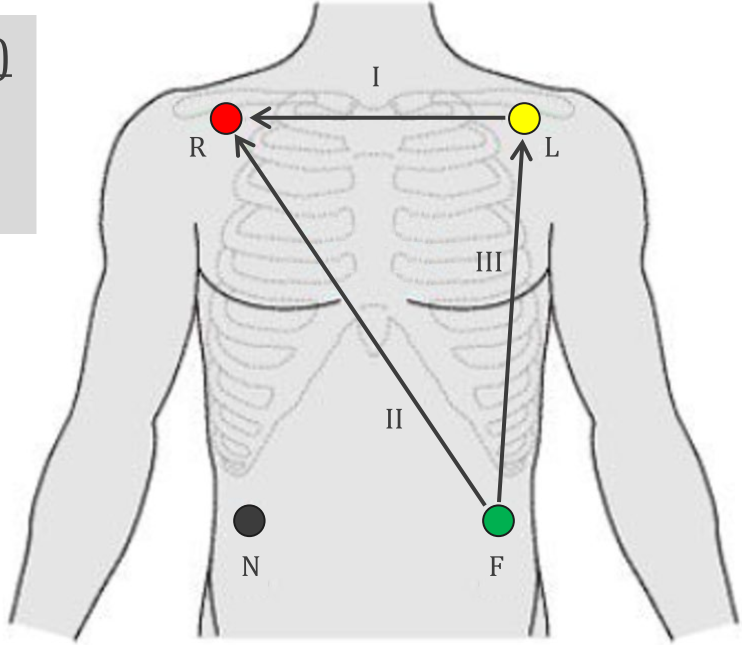
$$\mathrm{aVR} = \tfrac{3}{2}(\boxed{\mathrm{R}} - \mathrm{CT})$$

$$\mathrm{aVL} = \tfrac{3}{2}(\boxed{\mathrm{L}} - \mathrm{CT})$$

$$\mathrm{aVF} = \tfrac{3}{2}(\boxed{\mathrm{F}} - \mathrm{CT})$$

<u>Central terminal (Wilson)</u>

$$\mathrm{CT} = \frac{\boxed{\mathrm{R}} + \boxed{\mathrm{L}} + \boxed{\mathrm{F}}}{3}$$



4.2.3 (Einthoven and) Mason-Likar 12-lead ECG system, cont.

Bipolar leads (Einthoven)

$$\mathrm{I} = \boxed{\mathrm{L}} - \boxed{\mathrm{R}}$$

$$\mathrm{II} = \boxed{\mathrm{F}} - \boxed{\mathrm{R}}$$

$$\mathrm{III} = \boxed{\mathrm{F}} - \boxed{\mathrm{L}}$$

Augmented leads (Goldberger)

$$\mathrm{aVR} = \frac{3}{2}(\boxed{\mathrm{R}} - \mathrm{CT})$$

$$\mathrm{aVL} = \frac{3}{2}(\boxed{\mathrm{L}} - \mathrm{CT})$$

$$\mathrm{aVF} = \frac{3}{2}(\boxed{\mathrm{F}} - \mathrm{CT})$$

Central terminal (Wilson)

$$\mathrm{CT} = \frac{\boxed{\mathrm{R}} + \boxed{\mathrm{L}} + \boxed{\mathrm{F}}}{3}$$

Unipolar leads (Wilson)

$$\mathrm{V1} = \boxed{\mathrm{C1}} - \mathrm{CT}$$

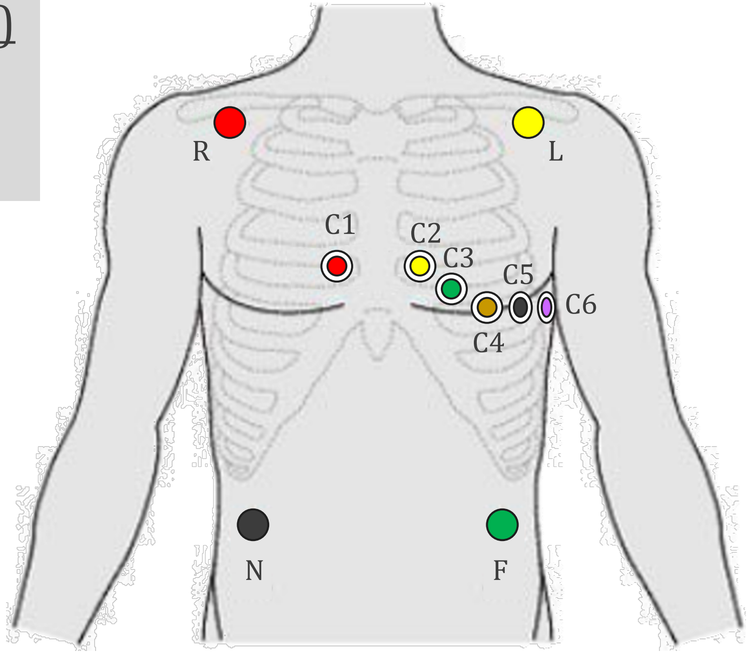
$$\mathrm{V2} = \boxed{\mathrm{C2}} - \mathrm{CT}$$

$$\mathrm{V3} = \boxed{\mathrm{C3}} - \mathrm{CT}$$

$$\mathrm{V4} = \boxed{\mathrm{C4}} - \mathrm{CT}$$

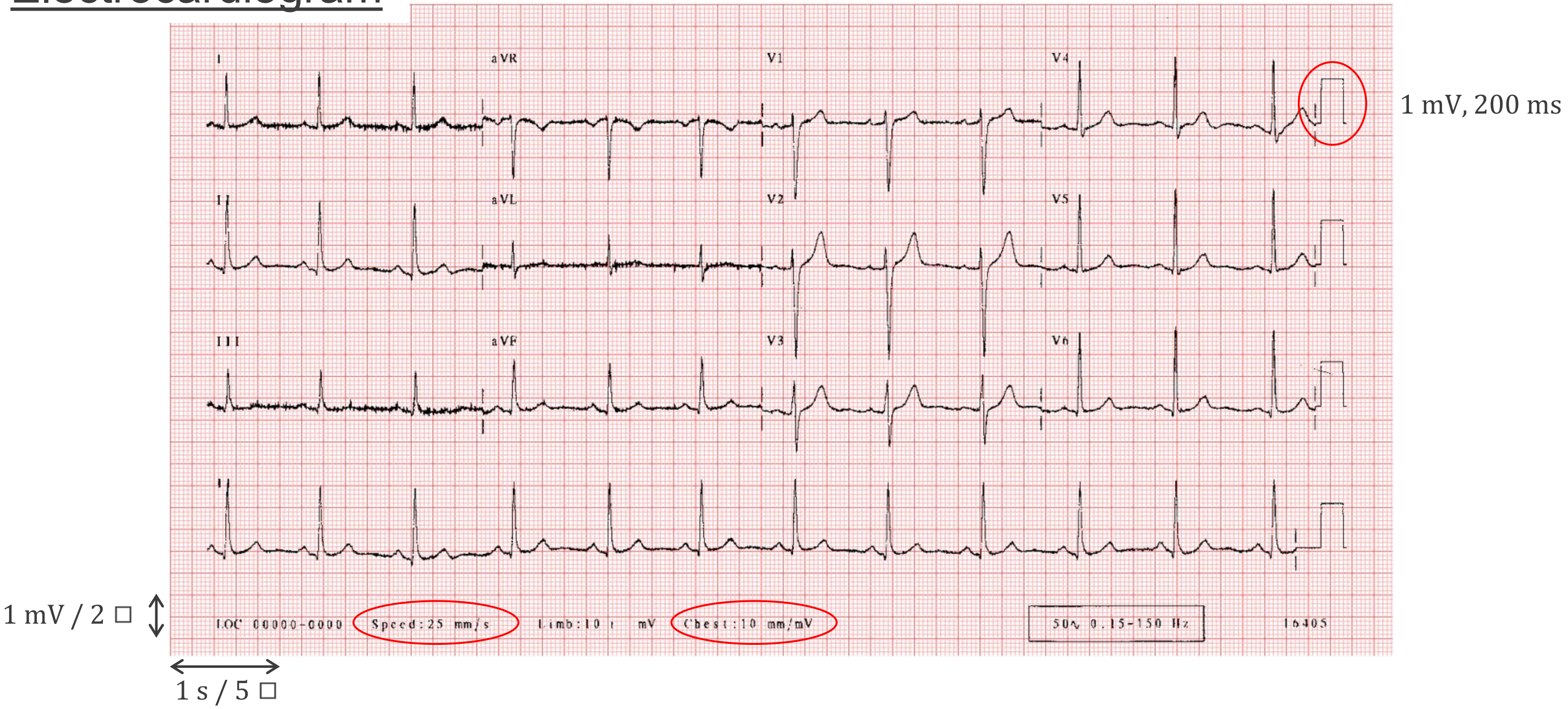
$$\mathrm{V5} = \boxed{\mathrm{C5}} - \mathrm{CT}$$

$$\mathrm{V6} = \boxed{\mathrm{C6}} - \mathrm{CT}$$



4.2.3 Einthoven and Mason-Likar 12-lead ECG system, cont.

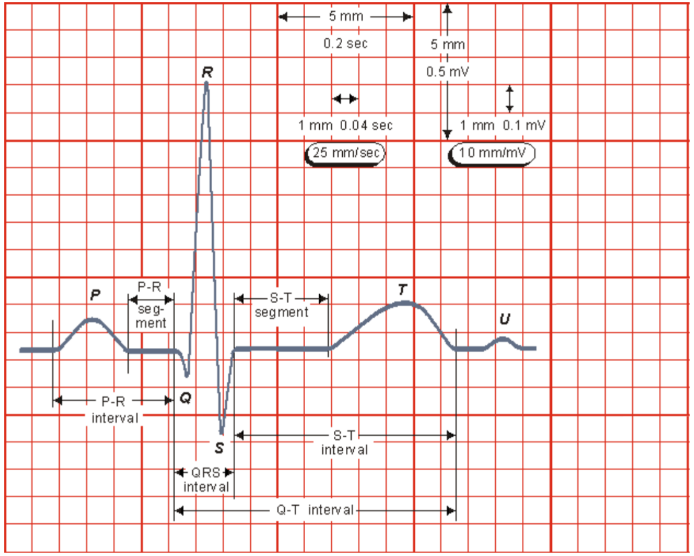
Electrocardiogram



4.2.3 Einthoven and Mason-Likar 12-lead ECG system, cont.

Typical information from ECG

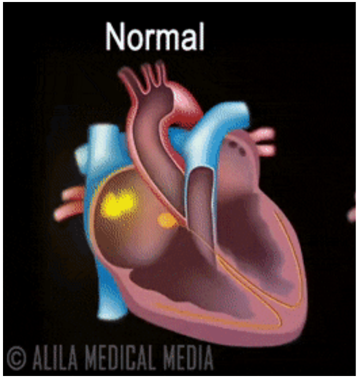
- heartrate (HR): bradycardia, tachycardia, rest and effort heartrates (sports)
- heartrate variability (HRV): linked to autonomic nervous system
  - parasympathetic (rest and digest)
  - sympathetic (fly or fight)
  - respiration
- ST-segment elevation: ischemia
- atrial fibrillation: indirect cause of strokes
- ventricular fibrillation: heart attack

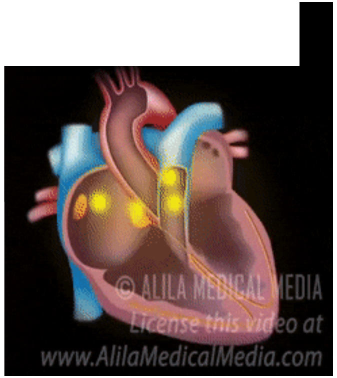


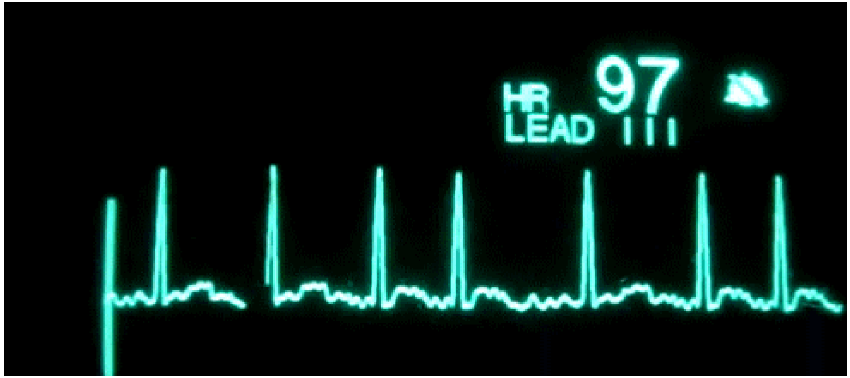
4.2.3 Einthoven and Mason-Likar 12-lead ECG system, cont.

Fibrillation

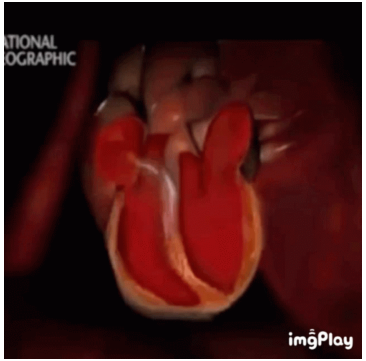
atrial fibrillation:

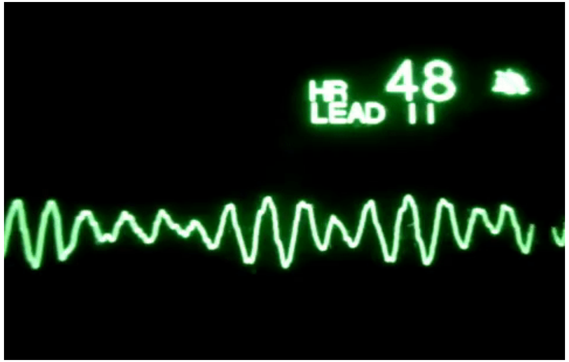




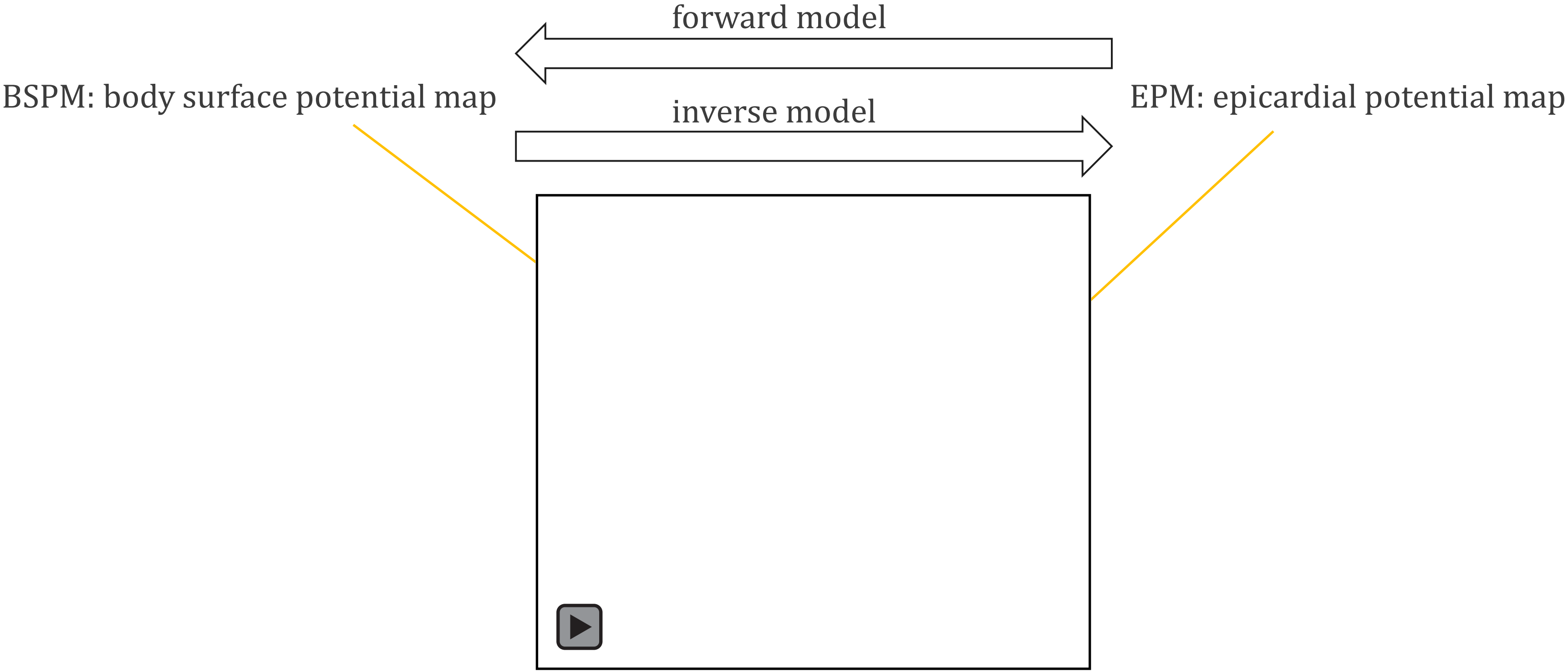


ventricular fibrillation:





4.2.4 Electrocardiographic imaging (ECGi)



4.2.4 Electrocardiographic imaging (ECGi), continued

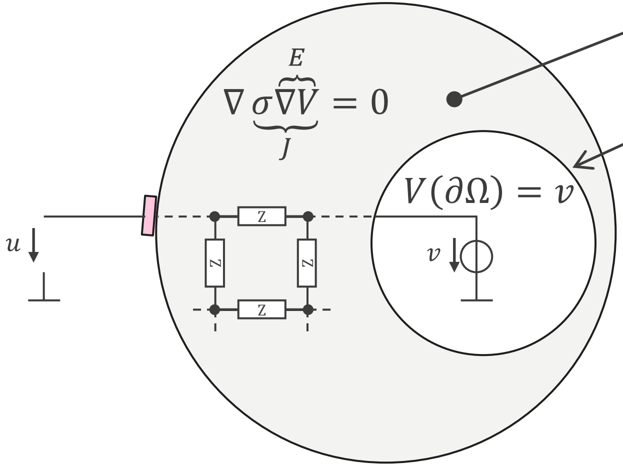
forward model

$u \longleftarrow v$

BSPM: body surface potential map

EPM: epicardial potential map

$$\boxed{u = Av}$$



Ω: domain Ω, i.e., body (except heart)

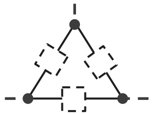
$\partial\Omega$: (inner) border of domain Ω, i.e., epicardium

$V(x, y, z)$: potential (V)
$\sigma(x, y, z)$: conductivity (S/m)
$J(x, y, z)$: current density (A/m^2)
$E(x, y, z)$: electric field (V/m)

<u>Kirchhoff laws</u>

$\nabla \cdot J = 0$

node ($\sum i = 0$)



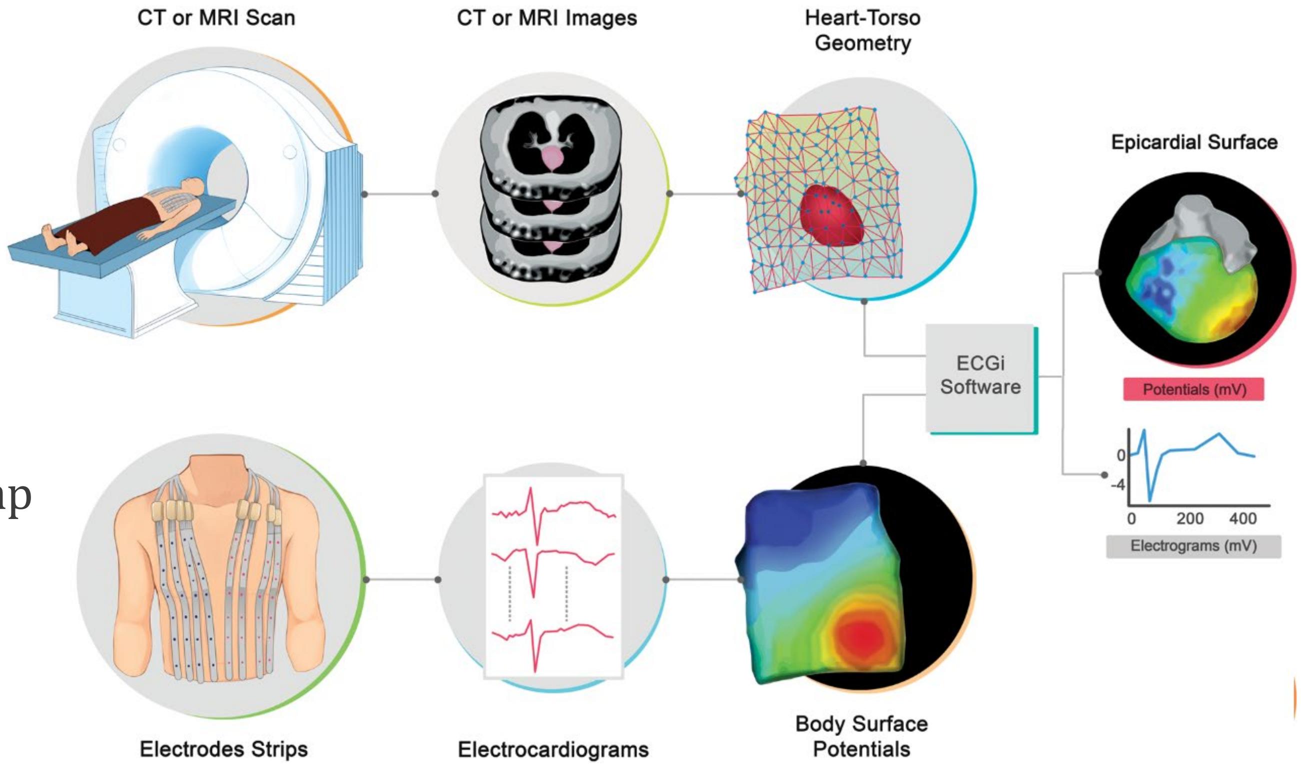
$E = \nabla V \Rightarrow \nabla \times E = 0$

loop ($\sum u = 0$)

4.2.4 Electrocardiographic imaging (ECGi), continued

electrode positions
domain Ω and its
borders ∂Ω
(torso and epicardium)

body surface potential map



4.2.4 Electrocardiographic imaging (ECGi), continued

$$u \xleftarrow{\text{forward model}} v$$

BSPM: body surface potential map

EPM: epicardial potential map

$$u = Av$$

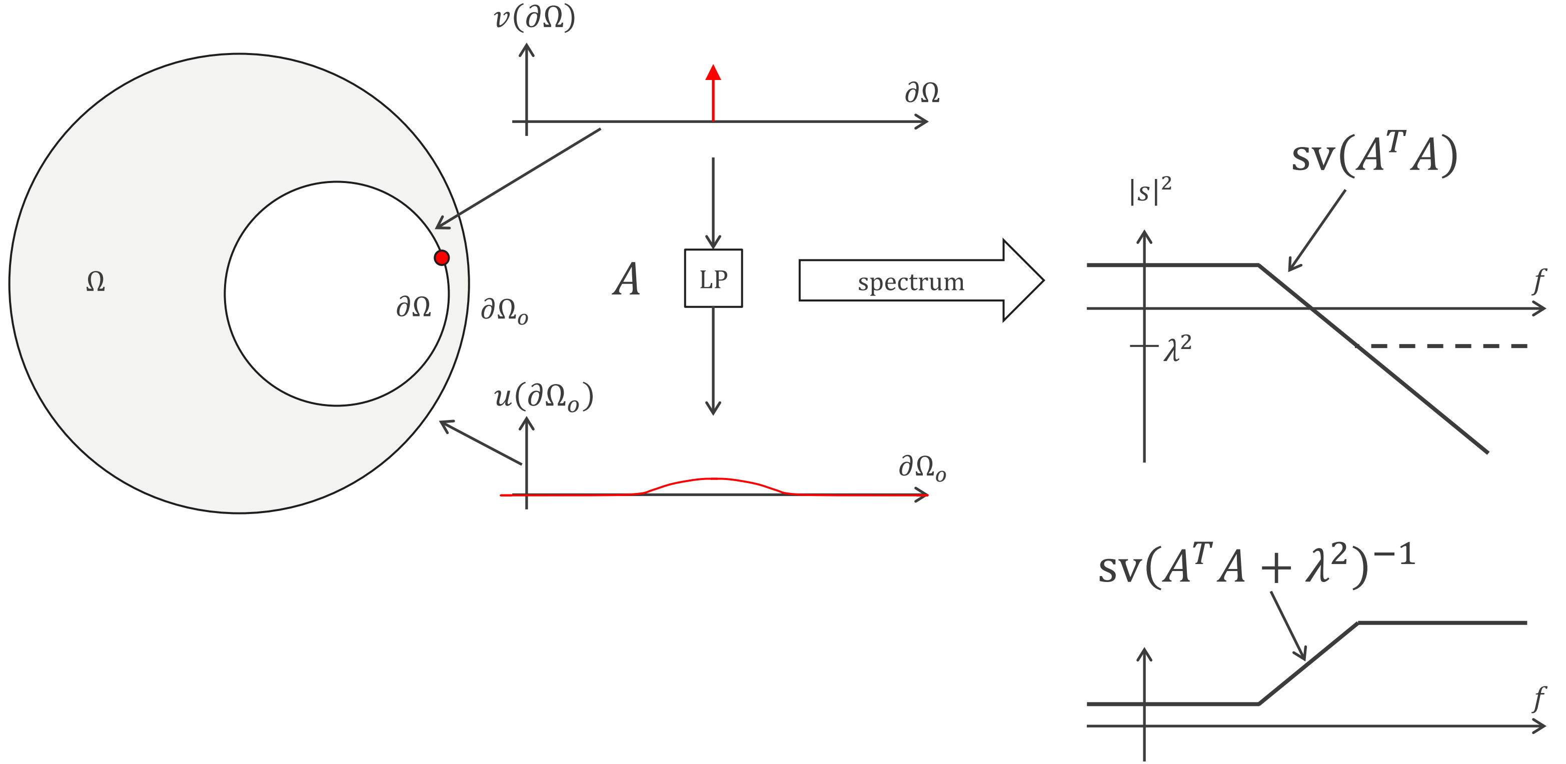
$$u \xrightarrow{\text{inverse model}} v$$

singular

$$v = \min_v\{\|Av - u\|^2\} \qquad (A^T A)v = A^T u$$

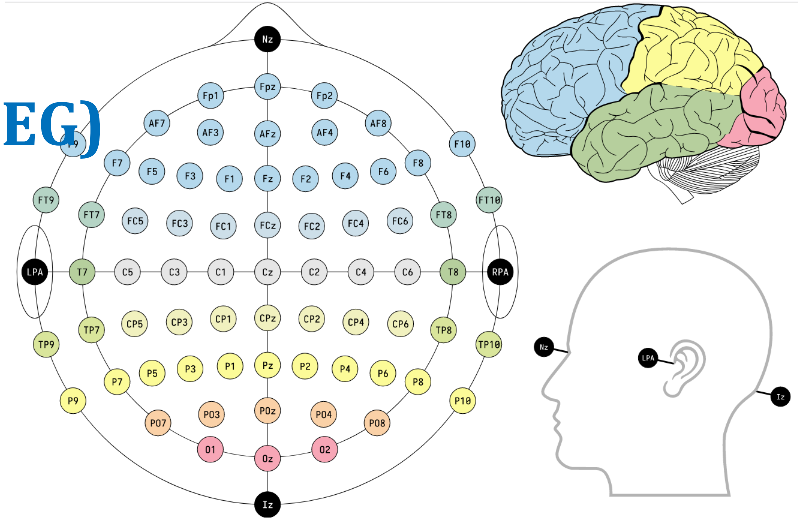
Regularization (Tikhonov) $$v = \min_v\{\|Av - u\|^2 + \lambda^2\|v\|^2\} \qquad \boxed{v = (A^T A + \lambda^2)^{-1} A^T u}$$

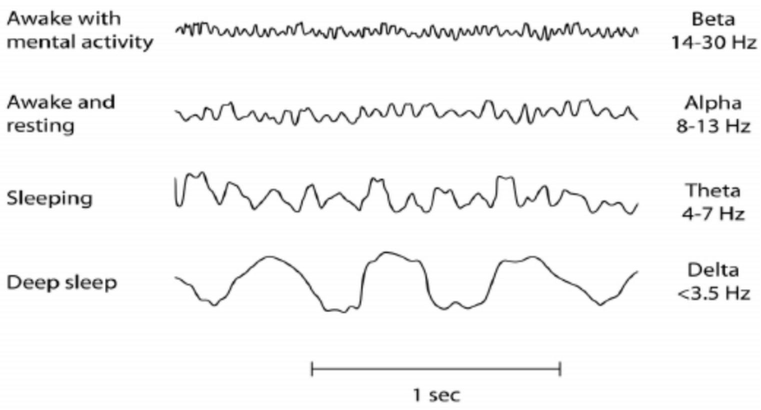
4.2.4 Electrocardiographic imaging (ECGi), continued



4.2.5 Electroencephalogram (EEG)

- epilepsy
- sleep disorders
- stroke
- Creutzfeldt-Jakob disease
- brain death
- level of anesthesia
- etc.





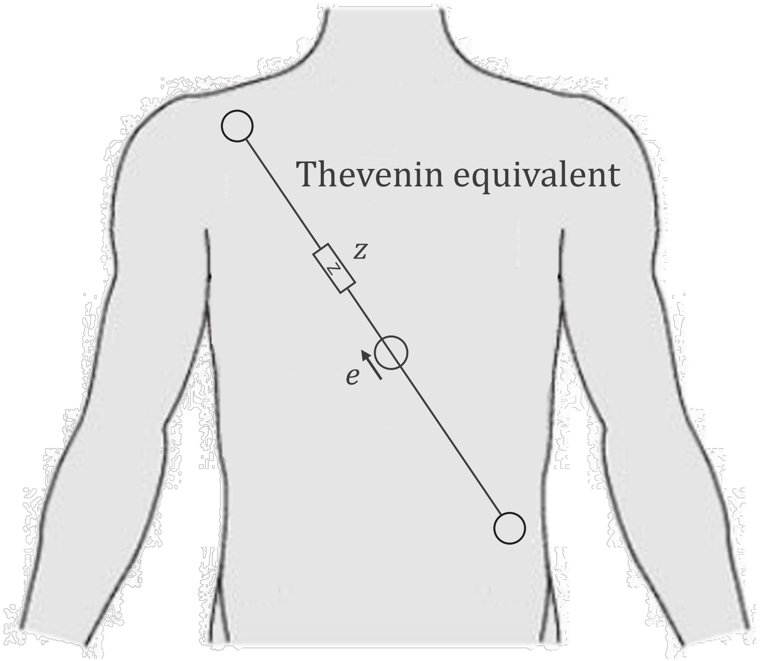
EE-511 Sensors in medical instrumentation
Section 4.3 – Bioimpedances

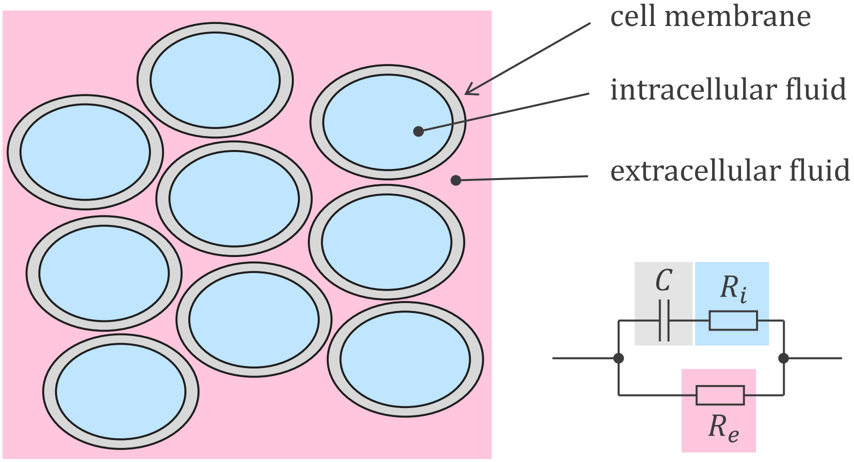
Objectives

understand:

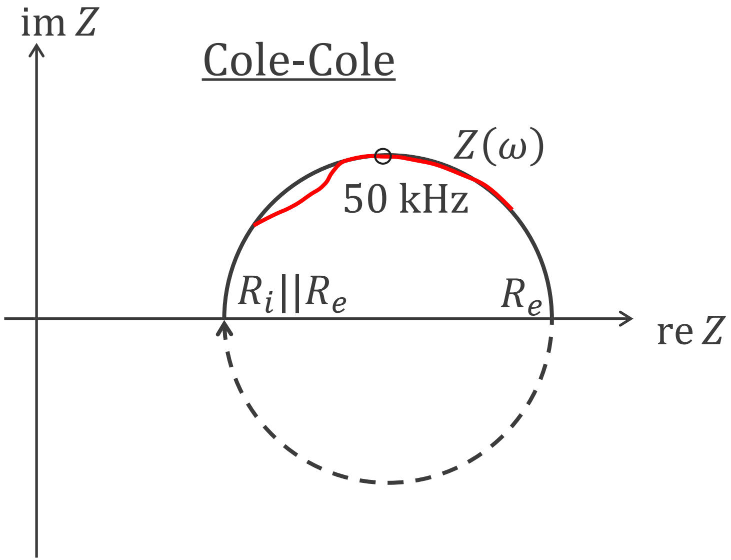
- impedance model, Cole-Cole diagram
- impedance plethysmography
- bioimpedance spectroscopy/analysis, least squares, Bland-Altman plot
- EIT (electrical impedance tomography)
- PAP (pulmonary artery pressure)

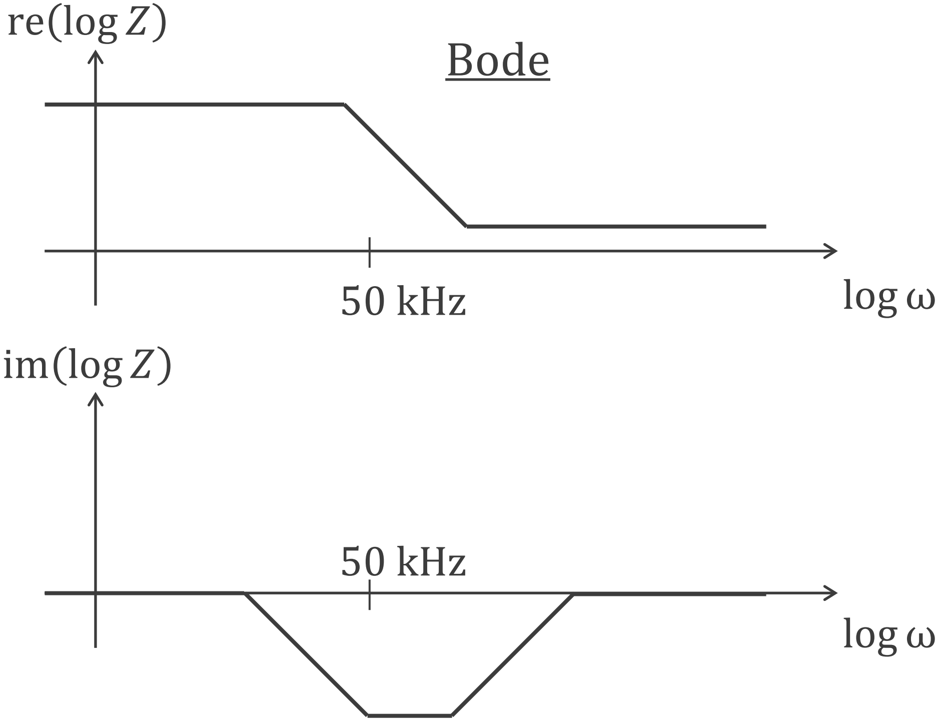
4.3.1 Simple model and Cole-Cole diagram





4.3.1 Simple model and Cole-Cole diagram (continued)



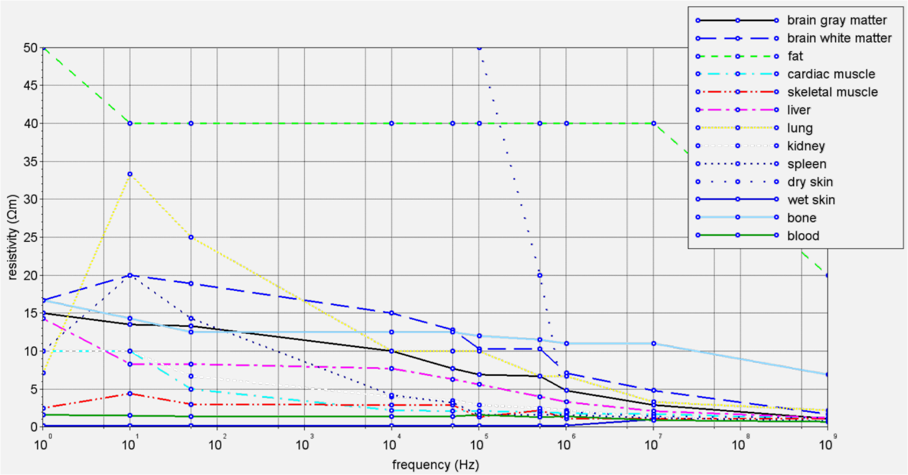


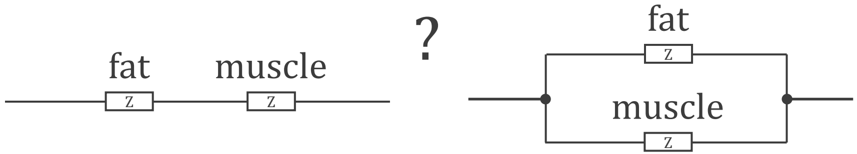
4.3.1 Simple model and Cole-Cole diagram (continued)

Tissue	Resistivity (Ω cm)
Blood	150
Lungs, inspiration	2400
Lungs, expiration	700
Heart muscle, longitudinal	125
Heart muscle, transversal	1800
Skeletal muscle, longitudinal	160–575
Skeletal muscle, transversal	420–5200
Fat	2000–2700
Bone	16 600

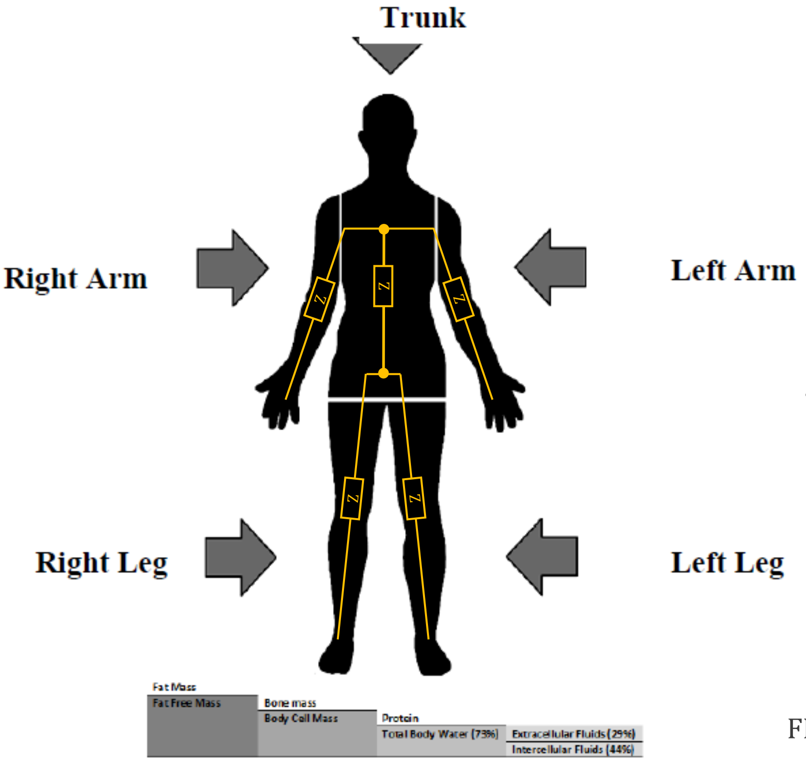
4.3.2 Bioimpedance spectroscopy (BIS)

tissue	0 Hz	10 Hz	50 Hz	10 kHz	50 kHz	100 kHz	500 kHz	1 MHz	10 MHz	1 GHz
brain										
gray matter	15	13.5	13.3	10	7.7	6.9	6.7	4.8	2.9	1.1
white matter	16.7	20	18.9	15	12.8	10.3	10.3	7.1	4.8	1.7
fat	50	40	40	40	40	40	40	40	40	20
muscle										
cardiac	10	10	5	2.2	2.1	2.1	2	1.8	1.7	1.1
skeletal	2.5	4.4	3	2.9	2.9	1.3	2.2	1.1	1.1	1.1
liver	14.3	8.3	8.3	7.7	6.3	5.6	4	3.3	2.1	1.2
lung	7.1	33.3	25	10	10	10	6.7	6.7	3.3	2.2
kidney	10	10	6.7	4	3.5	2.9	2.5	2.2	1.3	0.7
spleen	10	20	14.3	4.2	3.2	1.6	1.6	1.6	1.2	0.8
skin										
dry		5×10^4	3×10^4	1×10^4	5×10^3	50	20	2	1.4	1.2
wet	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1	
bone	16.7	14.3	12.5	12.5	12.5	12	11.5	11	11	6.9
blood	1.6	1.5	1.4	1.4	1.4	1.6	1.3	1.4	0.9	0.7





4.3.3 Bioimpedance analysis (BIA)



W: weight (kg)

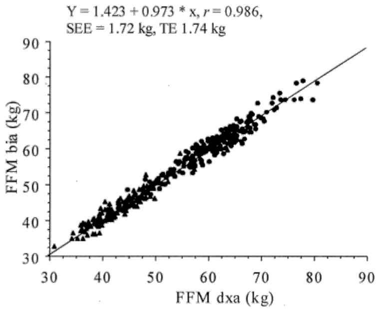
H: height (cm)

FFM: fat free mass (kg)

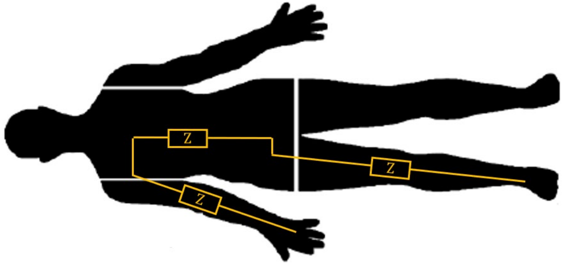
FM: fat mass (kg)

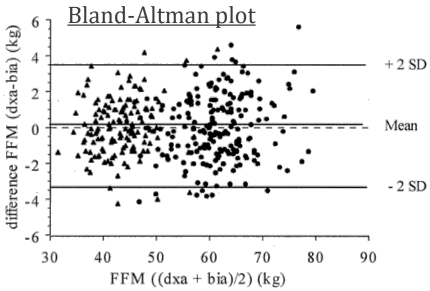
TBW: total body water (kg)

ECF: extra cellular fluids (kg)



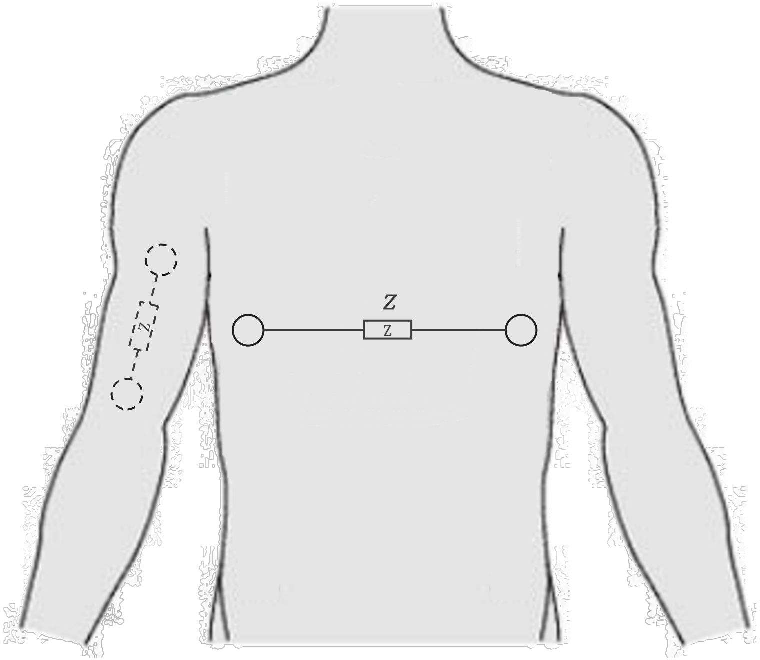
<u>example of empirical equation:</u>



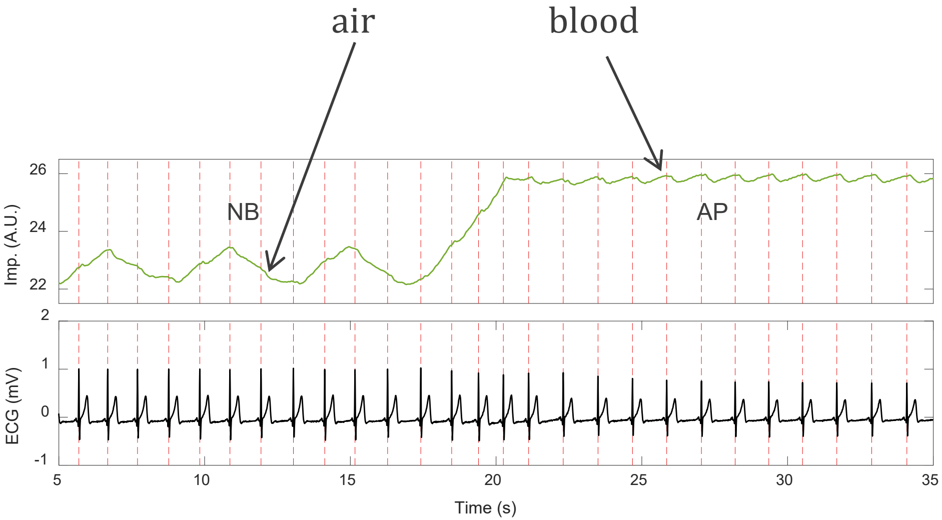


$$\mathrm{FFM} = 0.24\,W + 0.51\,\frac{\mathrm{kg}\,\Omega}{\mathrm{cm}^2}\,\frac{H^2}{R(5\text{ kHz})} + 0.13\,\frac{\mathrm{kg}}{\Omega}\,X(5\text{ kHz}) + \begin{cases} -4.1\text{ kg (woman)} \\ 0.1\text{ kg (man)} \end{cases}$$

4.3.4 Bioimpedance plethysmography



NB: normal breathing, AP: apnea

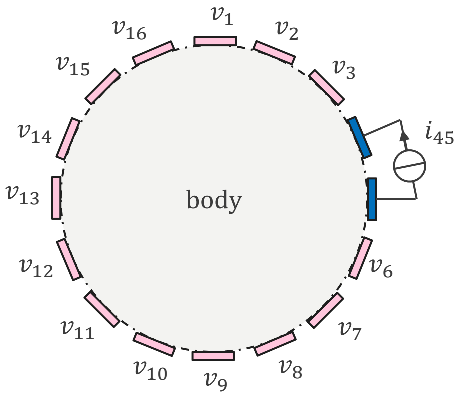


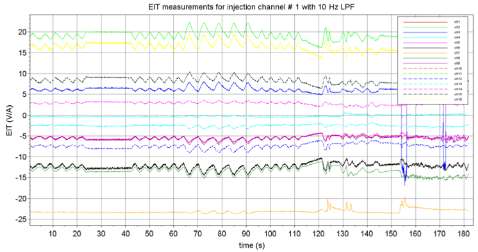
4.3.5 Electrical impedance tomography (EIT)

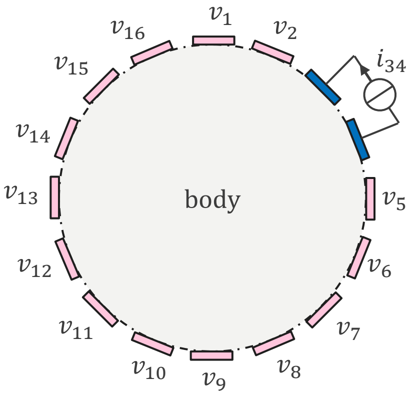
forward model

inverse model

body surface potential for
several current channels

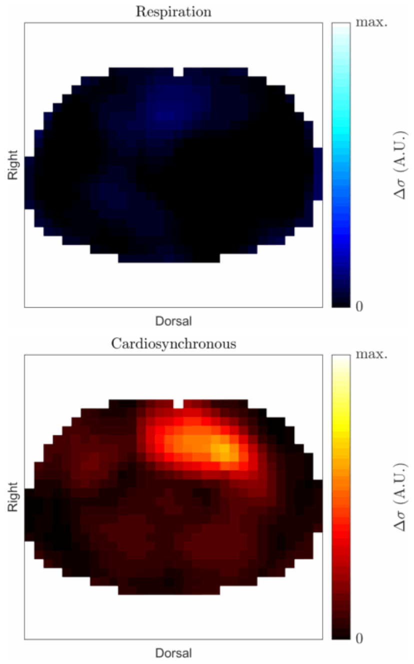






...

conductivity map



4.3.5 Electrical impedance tomography (EIT), continued

body surface potential for several current channels

$$v \xleftarrow{\text{forward model}} \sigma(\Omega)$$

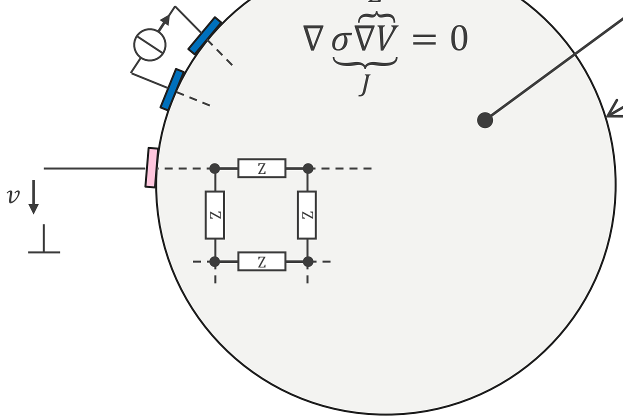
conductivity map

$$f\colon \sigma(\Omega), J(\partial\Omega) \mapsto v$$

$$\boxed{f_J\colon \sigma(\Omega) \mapsto v}$$

$$\sigma \nabla V n = J_n$$

$$\nabla \underbrace{\sigma \overbrace{\nabla V}^{E}}_{J} = 0$$



Ω: domain Ω, i.e., body

∂Ω: border of domain Ω, i.e., body skin

$V(x, y, z)$: potential (V)
$\sigma(x, y, z)$: conductivity (S/m)
$J(x, y, z)$: current density (A/m^2)
$E(x, y, z)$: electric field (V/m)
n: unit vector normal to ∂Ω

4.3.5 Electrical impedance tomography (EIT), continued

body surface potential for several current channels

$$v \xleftarrow{\text{forward model}} \sigma(\Omega)$$

conductivity map

$$\boxed{f_J : x = \sigma(\Omega) \mapsto v} \qquad \Delta f_J \simeq \frac{\partial f_J}{\partial x}(x_0) \cdot \Delta x$$

$$v \xrightarrow{\text{inverse model}} \sigma(\Omega)$$

singular

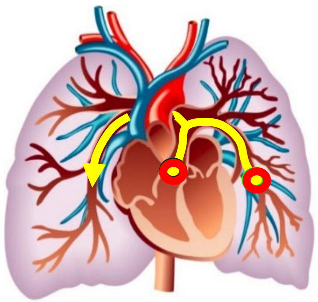
$$\Delta x = \min_{\Delta x} \left\{ \left\| A \Delta x + \Delta f_J - v \right\|^2 \right\} \qquad (A^T A) \Delta x = A^T \left(v - \Delta f_J \right)$$

Regularization (Tikhonov) $\Delta x = \min_{\Delta x} \left\{ \left\| A \Delta x + \Delta f_J - v \right\|^2 + \lambda^2 \| \Delta x \|^2 \right\}$ $\qquad \Delta x = (A^T A + \lambda^2)^{-1} A^T \left(v - \Delta f_J \right)$

(Time) difference EIT $\qquad \boxed{\Delta \sigma(\Omega) = (A^T A + \lambda^2)^{-1} A^T \Delta v}$

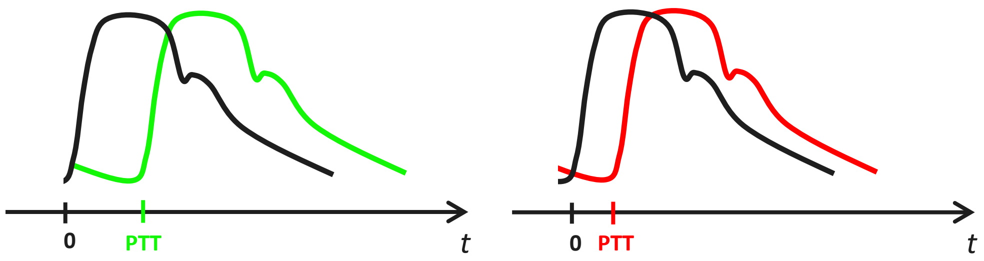
4.3.6 Pulmonary artery blood pressure (PAP)

Pulmonary Pulse Transit Time (PTT)



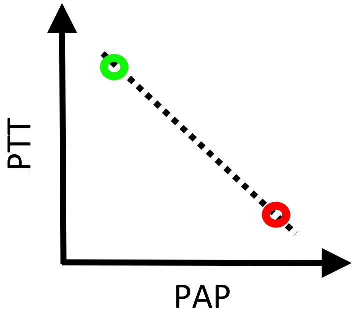
Low PAP → High PTT

High PAP → Low PTT

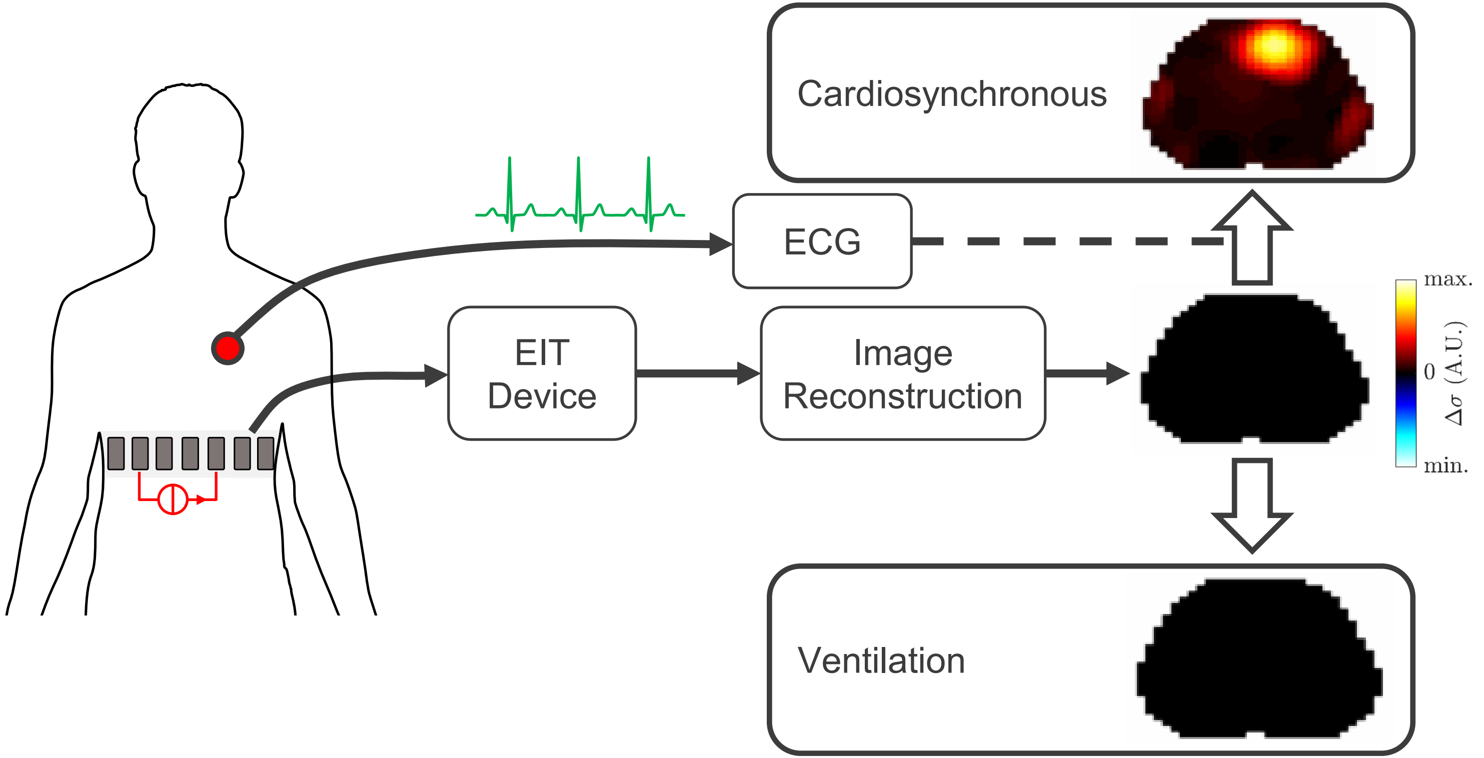


PAP: pulmonary artery pressure
PTT: pulse transit time

Estimate PAP via **pulmonary PTT** with EIT



4.3.6 Pulmonary artery blood pressure (PAP), continued



EE-511 Sensors in medical instrumentation

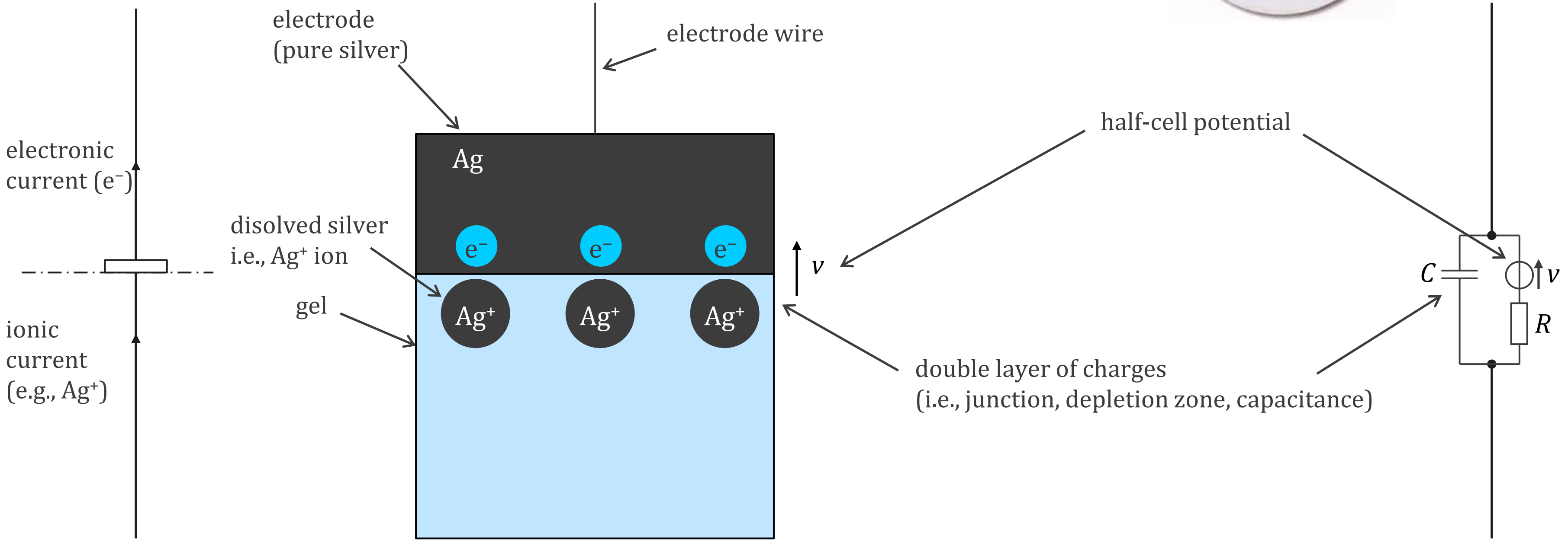
Section 4.4 – Electrodes

Objectives

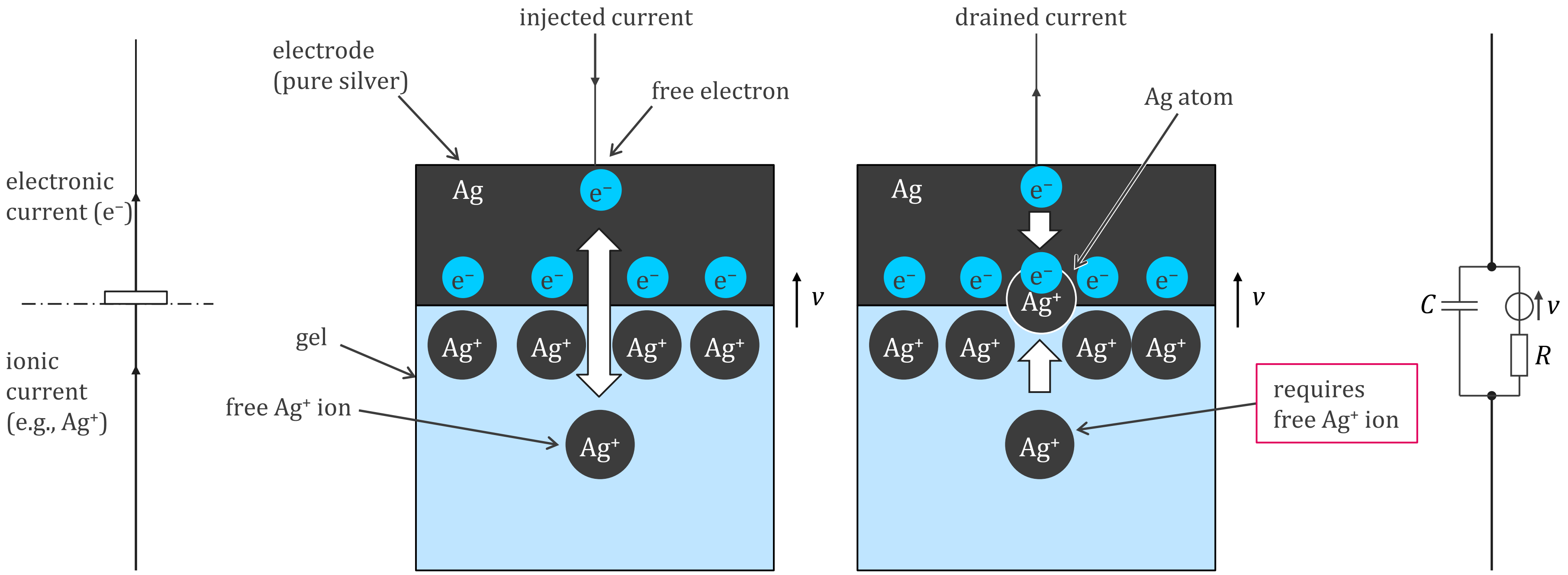
understand:

- contact, electrode
- electrode model, electrode potential, polarized, non-polarized electrode
- motion artefacts
- galvanic, capacitive electrode, noise
- stratum corneum, dry electrode
- potential electrode, current electrode

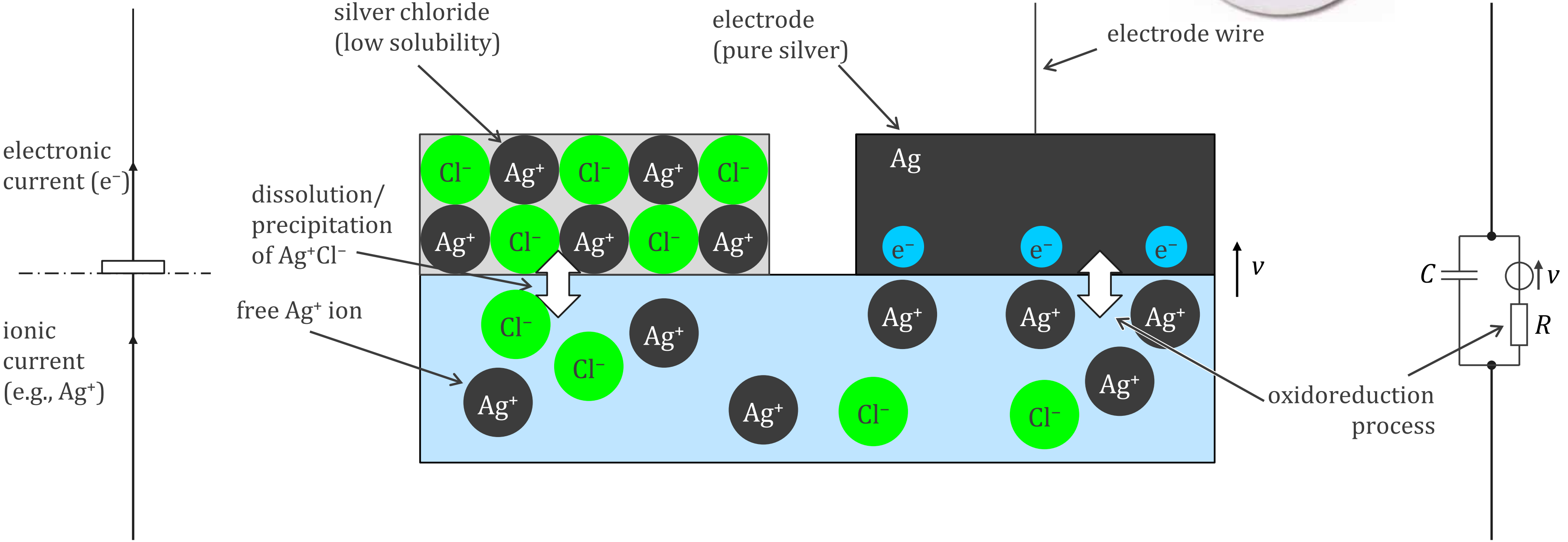
4.4.1 Half-cell potential



4.4.2 Electron-ion transducer and electrode model



4.4.3 Ag/Ag⁺Cl⁻ electrode



<u>Definition:</u>

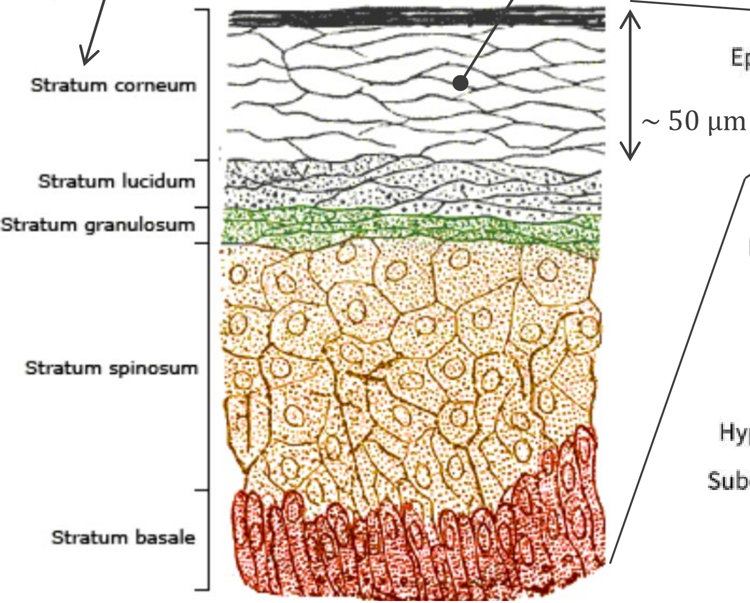
polarized electrode: $R \to \infty$ (e.g., Pt)

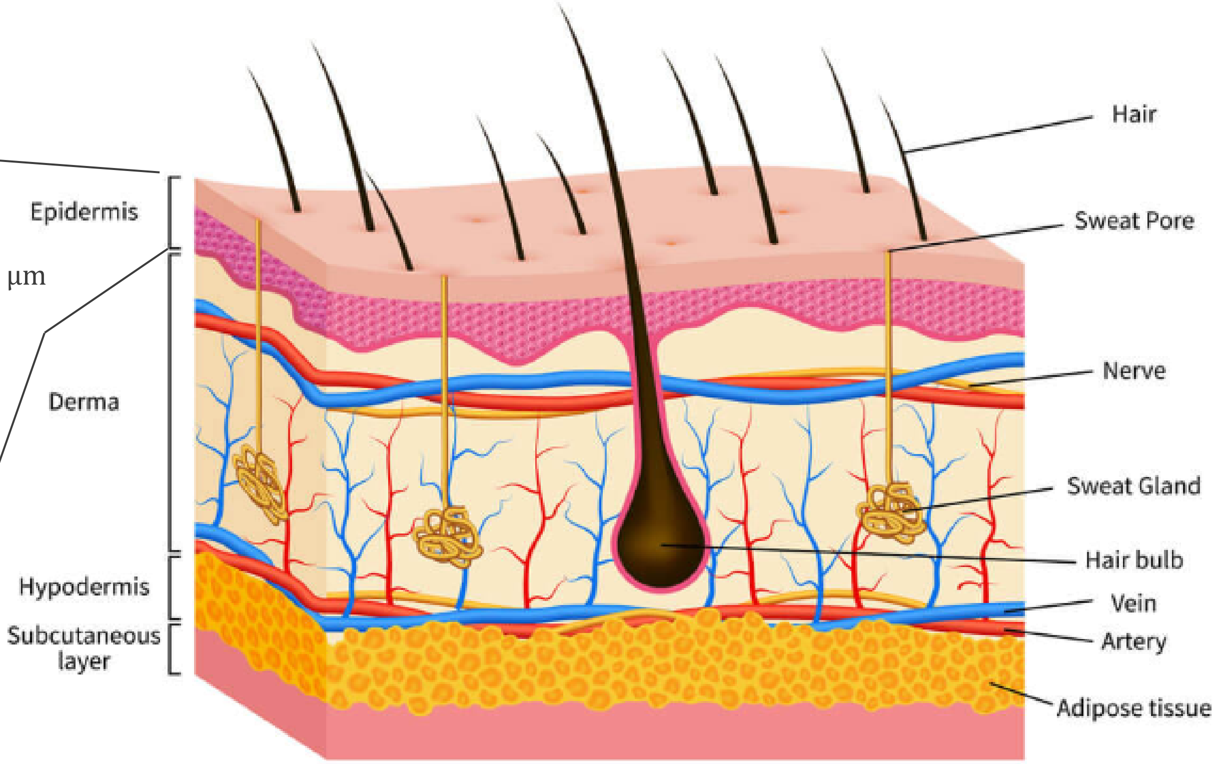
non-polarized electrode: $R \to 0$ (e.g., Ag/Ag⁺Cl⁻)

4.4.4 Skin

used to be removed
with sandpaper
before applying gel electrode

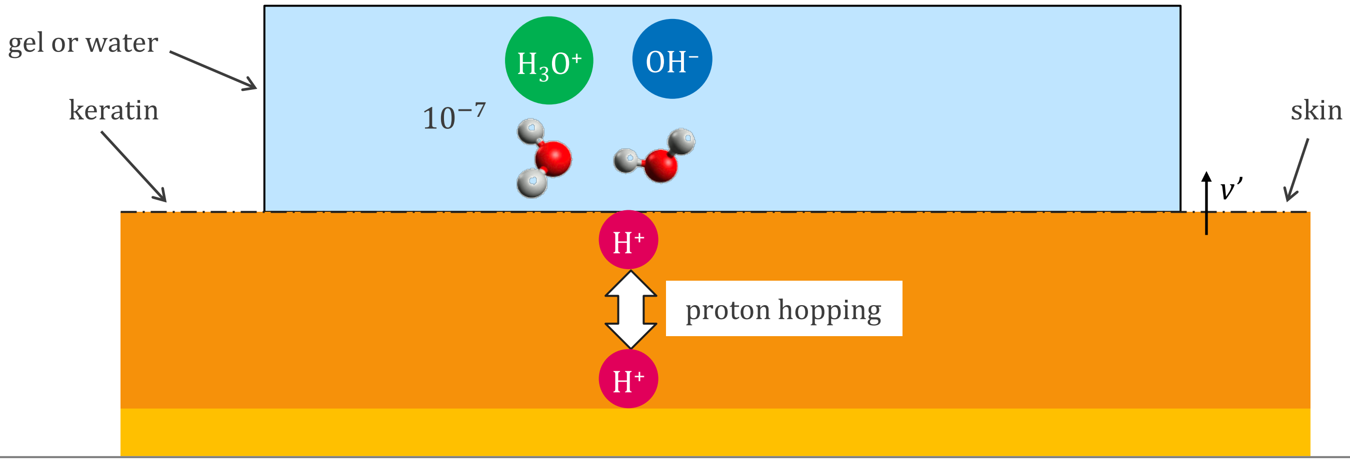
keratin



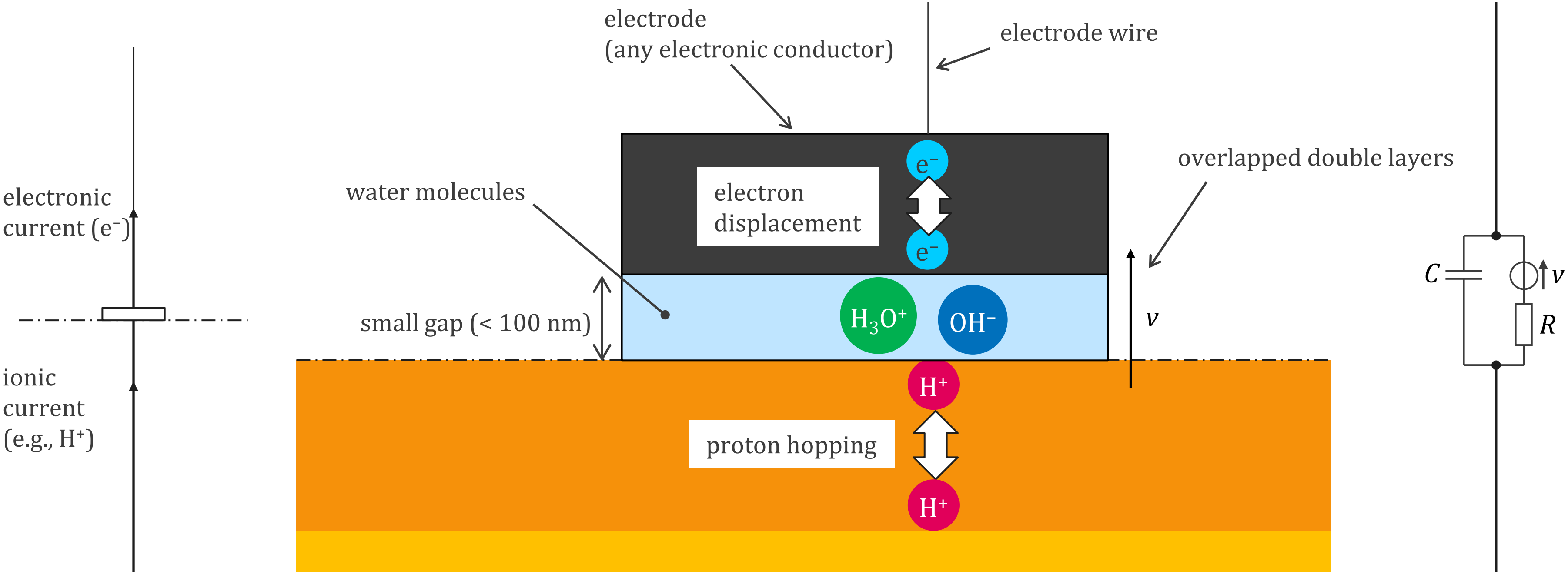


4.4.4 Skin

Proton hopping in keratin



4.4.5 Dry electrodes

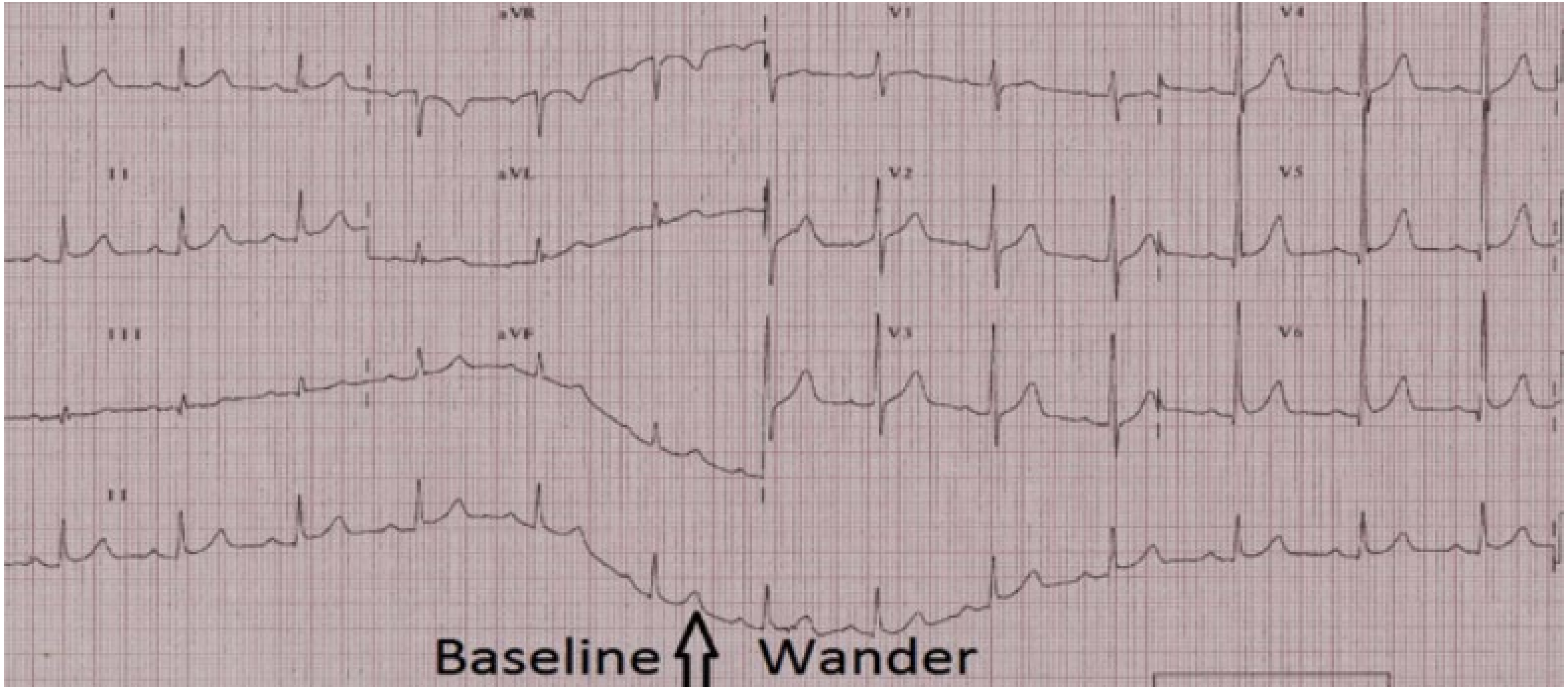


4.4.5 Dry electrodes

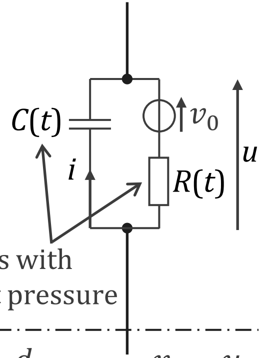
Dry electrodes versus gel electrodes

- Dry electrodes
  - have a lower effective contact area
  - have a higher impedance (at least an order of magnitude)
  - which is also more variable with changes of pressure (gel/water makes a cushion)

4.4.7 Motion artefact

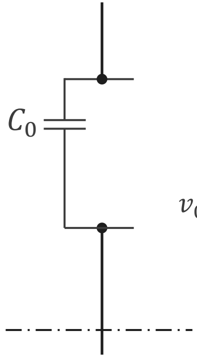


4.4.7 Motion artefact (continued)



changes with
contact pressure

$$\frac{d}{dt}\underbrace{(uC)}_{q} = \underbrace{\frac{v_0 - u}{R}}_{i}$$

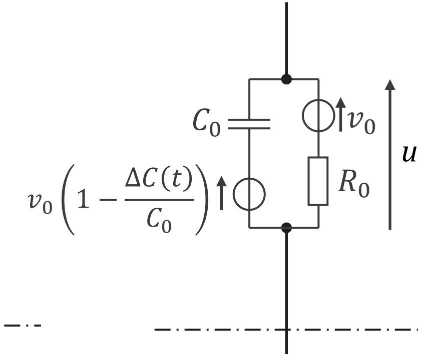


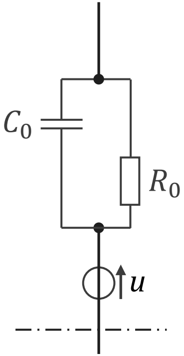
charges are conserved:

$$q = v_0 C_0 = vC$$

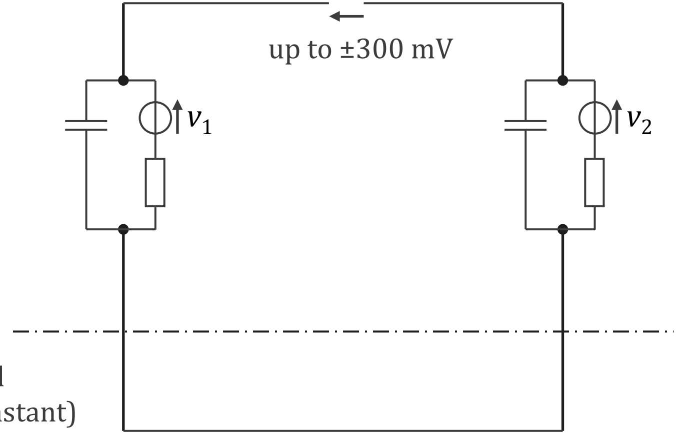
$$\Rightarrow v = \frac{v_0 C_0}{C} \simeq v_0\left(1 - \frac{\Delta C}{C_0}\right)$$

Taylor expansion



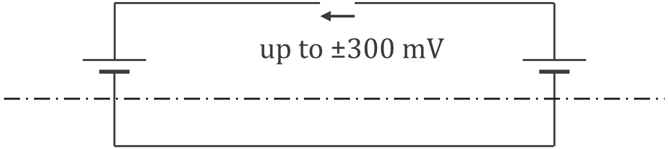


simplified model
(assuming C and R constant)

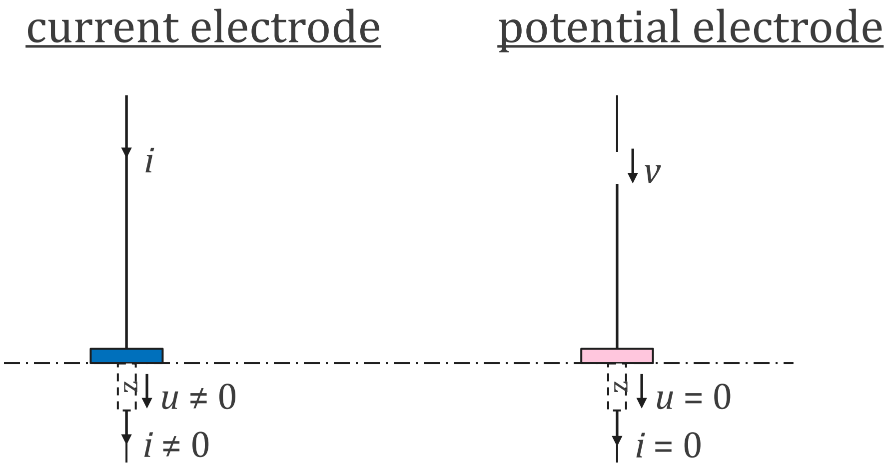


$$\boxed{u = v_0\left(1 - \frac{R_0 s}{1 + R_0 C_0 s}\Delta C(t)\right)}$$

small $R_0|C_0$ is good
($\sim 1/A|A$)



4.4.6 Potential and current electrodes

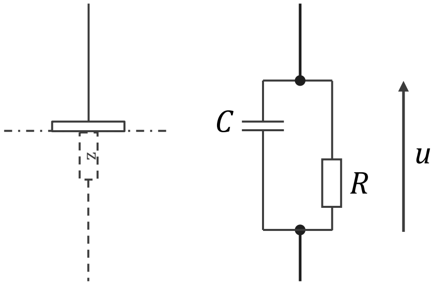


note: an electrode can be of a given type for a channel (e.g., frequency band or time slot) and of another type for another channel

4.4.8 Galvanic and capacitive electrodes

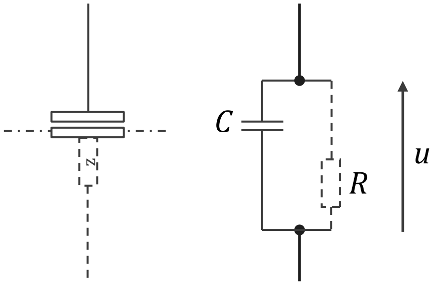
galvanic electrodes

- too much thermal noise when $R > 1\ \mathrm{M\Omega}$



capacitive electrodes

- too much thermal noise when $R < 300\ \mathrm{T\Omega}$



$$u = \sqrt{\frac{k_B T}{C(1 + 2\pi f_L R C)}}$$

f_L: high-pass cut-off frequency

Quiz

Electrodes N and RL are

- ☐ averaged for Wilson CT potential
- ☐ negative and right-lead electrodes
- ☐ white and purple electrodes
- ☐ two names for the same electrode

Atrial fibrillation may cause

- ☐ brain stroke
- ☐ heart attack
- ☐ heart failure
- ☐ ischemia

The stratum corneum is

- ☐ a good electrical conductor
- ☐ about 1 mm thick
- ☐ made of keratin
- ☐ made of living cells and fat

Cells transmit signals with an

- ☐ electron current
- ☐ ion current
- ☐ action potential wave
- ☐ electromagnetic wave

Quiz

The 12-lead ECG system is a set of

- ☐ independent signals
- ☐ standardized signals
- ☐ 12-electrode potentials
- ☐ signals displayed for 12 s

Systole is the period defined by high

- ☐ right ventricle pressure
- ☐ left ventricle pressure
- ☐ right atrium pressure
- ☐ left atrium pressure

A current electrode is

- ☐ not for potential measurement
- ☐ for current measurement
- ☐ ideally a polarized electrode
- ☐ for defibrillation

$Ag/Ag^{+}Cl^{-}$ electrodes

- ☐ are made of three materials
- ☐ are non-polarized electrodes
- ☐ do not have half-cell potential
- ☐ are best for dry electrodes