BENG 186B: Principles of Bioinstrumentation Design

Lecture 8

Volume Conduction and Biopotentials

References

Webster, Ch. 4 (Sec. 4.2-4.8).

http://en.wikipedia.org/wiki/Electrocardiography

http://en.wikipedia.org/wiki/Electroneuronography

http://en.wikipedia.org/wiki/Electromyography

http://en.wikipedia.org/wiki/Electrooculography

http://en.wikipedia.org/wiki/Electroretinography

http://en.wikipedia.org/wiki/Electroencephalography

— Volume conduction

→ the source of all electrical fields and potentials in and on the body : ECG, EEG, EMG etc.

→ Ohm's law (FIELDS cause CURRENTS) rather than Gauss's law (CHARGE causes FIELD) because charge is zero everywhere in any conductor!

Ohm's law for a volume conductor:

$$\vec{j} = \sigma \cdot \vec{E}$$

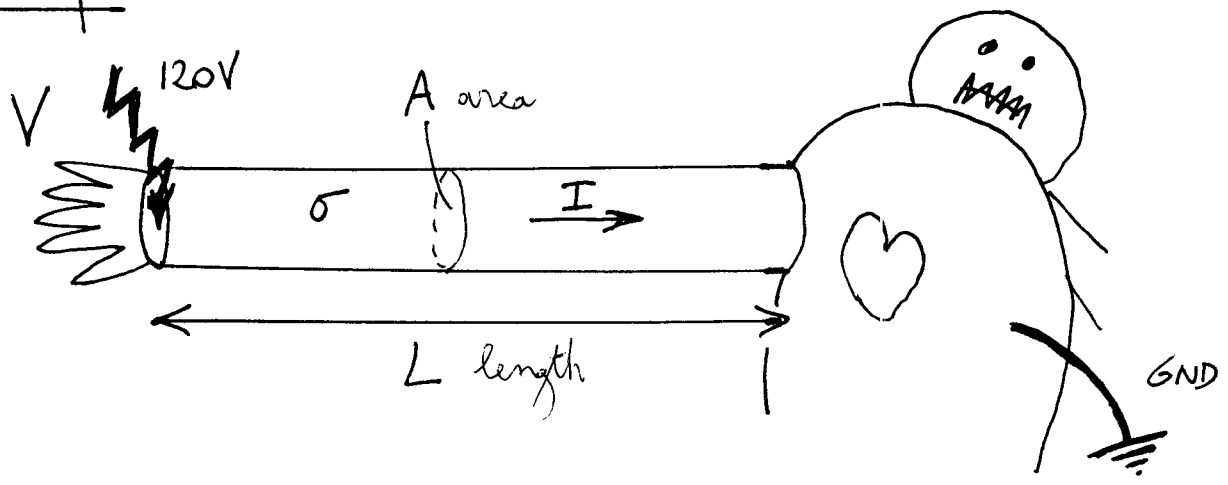
$\vec{j}$	σ	$\vec{E}$
CURRENT DENSITY	VOLUME CONDUCTIVITY	ELECTRIC FIELD
$\left[\frac{A}{m^2}\right]$	$\left[\frac{1}{\Omega m}\right]$	$\left[\frac{V}{m}\right]$

where σ ranges in the body from $0.006\ \Omega^{-1}m^{-1}$ (BONE) to $1.5\ \Omega^{-1}m^{-1}$ (CEREBROSPINAL FLUID).

Volume conduction of the body is important to bioinstrumentation for two main reasons:

1) It allows to measure heart, brain, muscle, etc activity on the SURFACE of the body;
2) It quantifies safety limits on the operation of electrical bioinstrumentation with human subjects

Example :



$$\gamma = \sigma \cdot \mathcal{E}$$

$$\frac{I}{A} = \sigma \cdot \frac{V}{L}$$ constant across (linear gradient)

$$\Rightarrow V = \frac{1}{\sigma}\frac{L}{A} \cdot I = R \cdot I$$ Ohm's Law for a discrete resistor (lump model)

$$R = \frac{1}{\sigma} \cdot \frac{L}{A}$$

$[\Omega]$ $[\Omega m]$ $\left[\frac{m}{m^2}\right]$

$L = 1\ m$

$A = 25\ cm^2 = 0.0025\ m^2$ $\Rightarrow$ $R = 800\ \Omega$

$\sigma = 0.5\ \Omega^{-1}m^{-1}$

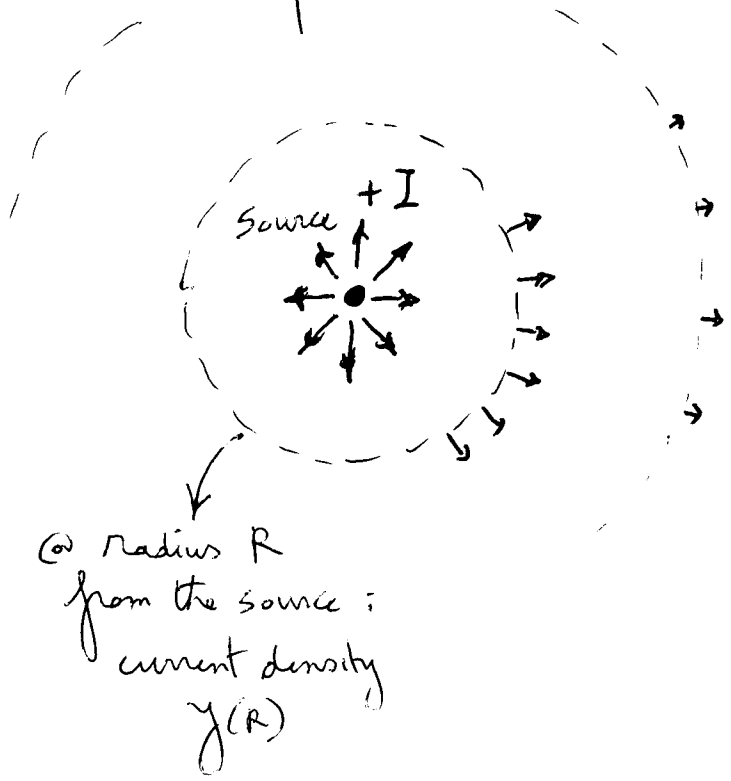
(inside the body)

$$I = \frac{V}{R} = \frac{120V}{800\Omega} = 150\ mA\ !$$

With dry skin, this is much lower, but still possibly lethal.

Biopotentials (EEG, ECG, EMG, ...) result from volume conduction of currents sourced and sunk by collections of electrically active cells (neurons, myocytes, ...) into the extracellular medium.

Current monopole:



Current emanates radially from the source.

Conservation of current (charge) for any R:

$$I = 4\pi R^2 \cdot j(R)$$

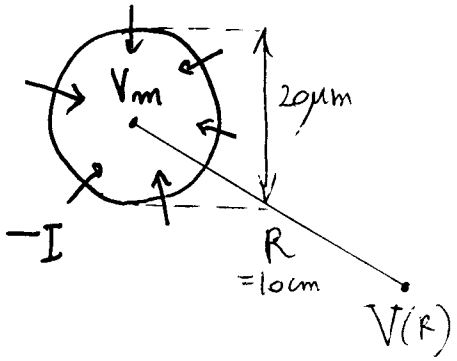
I: total current through sphere with radius R; $4\pi R^2$: total area of sphere; $j(R)$: current density at radius R

$$\Rightarrow j(R) = \frac{I}{4\pi R^2}$$

$$\Rightarrow \mathcal{E}(R) = \frac{1}{\sigma} j(R) = \frac{I}{4\pi\sigma} \cdot \frac{1}{R^2}$$: Field due to volume conduction

$$\Rightarrow V(R) = -\int \mathcal{E}(R)\, dR = \frac{I}{4\pi\sigma} \cdot \frac{1}{R}$$: Potential due to volume conduction of point source +I

Example: A single cell fires a 100 mV action potential in 1 ms. The cell diameter is 20 μm, and its membrane capacitance is 1 μF/cm². What is the amplitude of the extracellular potential at 10 cm distance? Assume $\sigma = 0.1\ \Omega^{-1} m^{-1}$



$$C \frac{dV_m}{dt} = -I$$

$$C = 1\,\mu F/cm^2 \cdot \pi (20\,\mu m)^2 = 4\pi\ pF \approx 12.6\ pF$$

$$\frac{dV_m}{dt} \approx \frac{\Delta V_m}{\Delta t} = \frac{100\,mV}{1\,ms} = 100\ V/s$$

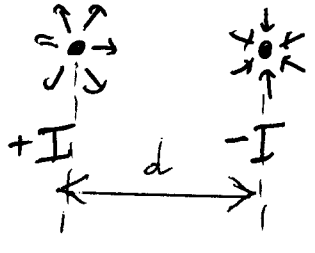
$$\Rightarrow I = -1.26\ nA$$

$$\Rightarrow V(10\,cm) = \frac{I}{4\pi\sigma\, 10cm} = \frac{-1.26\ nA}{4\pi\ 0.1\ \frac{1}{\Omega m} \cdot 0.1\,m} = -10^{-8} V = -10\ nV$$

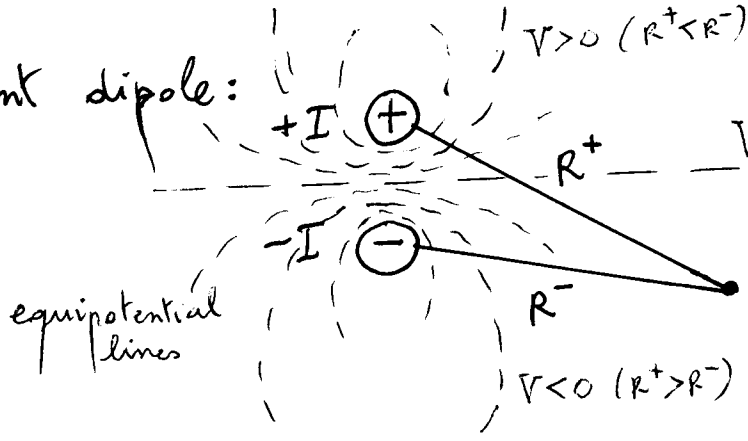
Small! Unless there are millions of these cells firing together (as in the brain, generating EEG signals)

Note: for every source of current in the body, there must be another and matching sink of current, balancing to zero net current for net charge conservation.

The simplest model for this is a DIPOLE:



Current dipole:



$$V = \frac{I}{4\pi\sigma}\left(\frac{1}{R^+} - \frac{1}{R^-}\right)$$

by superposition

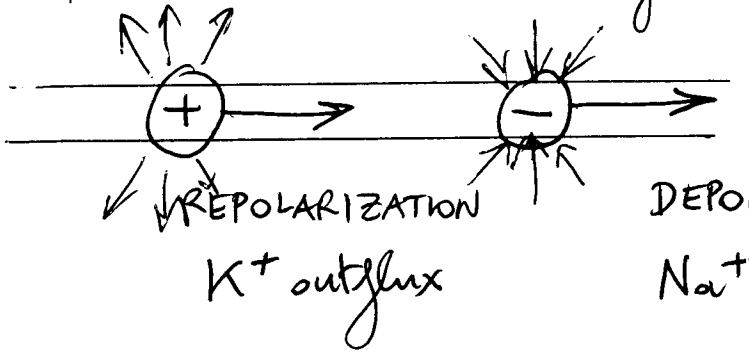
Note: $V = +\infty$ at the source

$V = -\infty$ at the sink

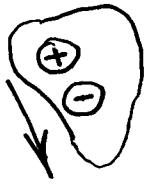
$V = 0$ at the mid-plane between source and sink, and at ∞ distance from source and sink.

Current dipoles are everywhere in the body! e.g.:

- Action potentials traveling along axons in CNS/PNS and muscle (fiber bundles)



- Systolic waves in cardiac myocytes tissue



Same principle: DEPOLARIZATION wavefront followed by REPOLARIZATION

- Excitatory and inhibitory synaptic currents in CNS

⊕ inhibitory synaptic current
⊖ excitatory synaptic current
} with synchronous neural input

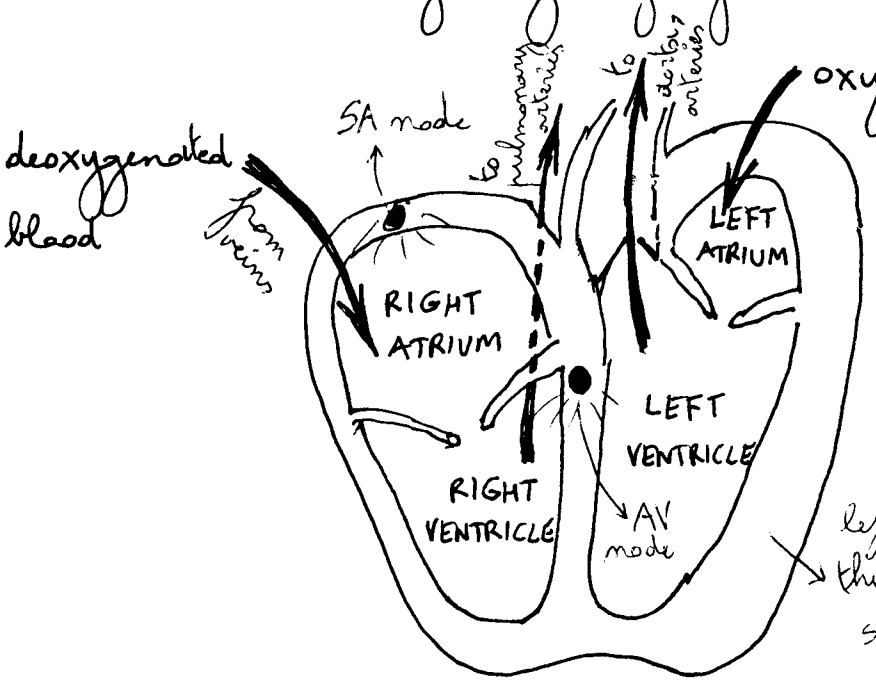
Volume conduction of large numbers of dipoles (each accounting for the collective effect of large numbers of electrically active cells) leads to various BIOPOTENTIALS in the body:

- ENG electroneurogram : PNS somatic nervous system; CNS spinal cord
- EMG electromyogram : skeletal muscle
- ECG (EKG) electrocardiogram : cardiac muscle
- EEG electroencephalogram (on scalp)
  ECoG electrocorticogram (on cortical surface) : CNS brain
- ERG electroretinogram : retina, transient optical response
- EOG electrooculogram : retina - cornea dipole, sustained
- EGG electrogastrogram : smooth muscle in digestive tract

etc... (ExG)

— Electrocardiogram ECG (or EKG): (Sec. 4.6)

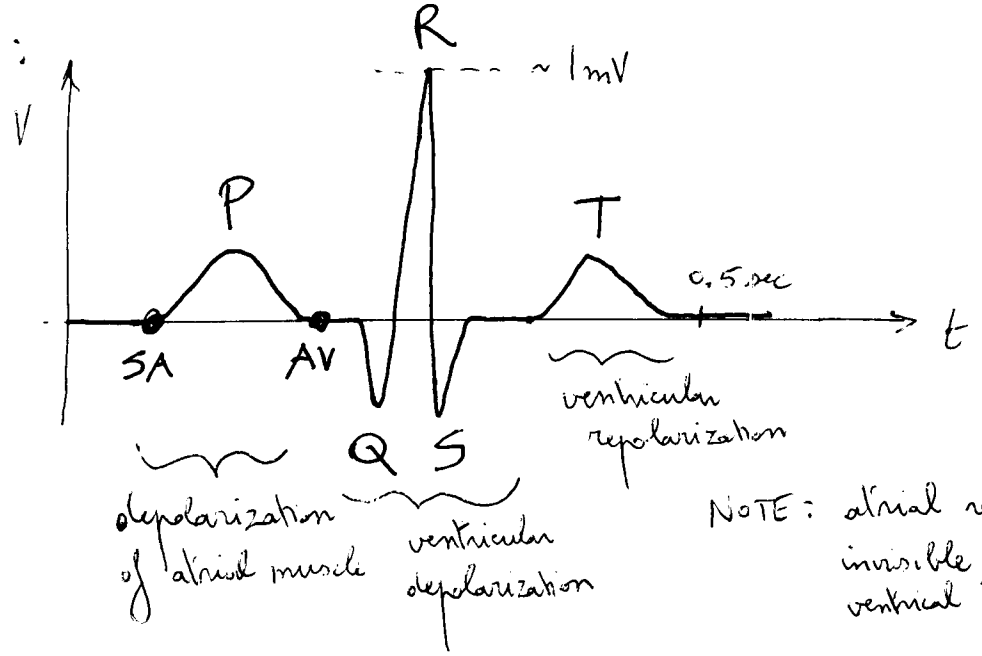
electrical activity originating from cardiac muscle, pumping blood:



left ventricle: thicker walls, and stronger ECG signal, for systemic circulation

- SA node: sinoatrial node: triggers depolarization of atrial muscle to pump blood from ATRIA to VENTRICLES (DIASTOLE)
- AV node: atrioventricular node: relays depolarization of ventrical muscle to pump blood outwards (SYSTOLE)

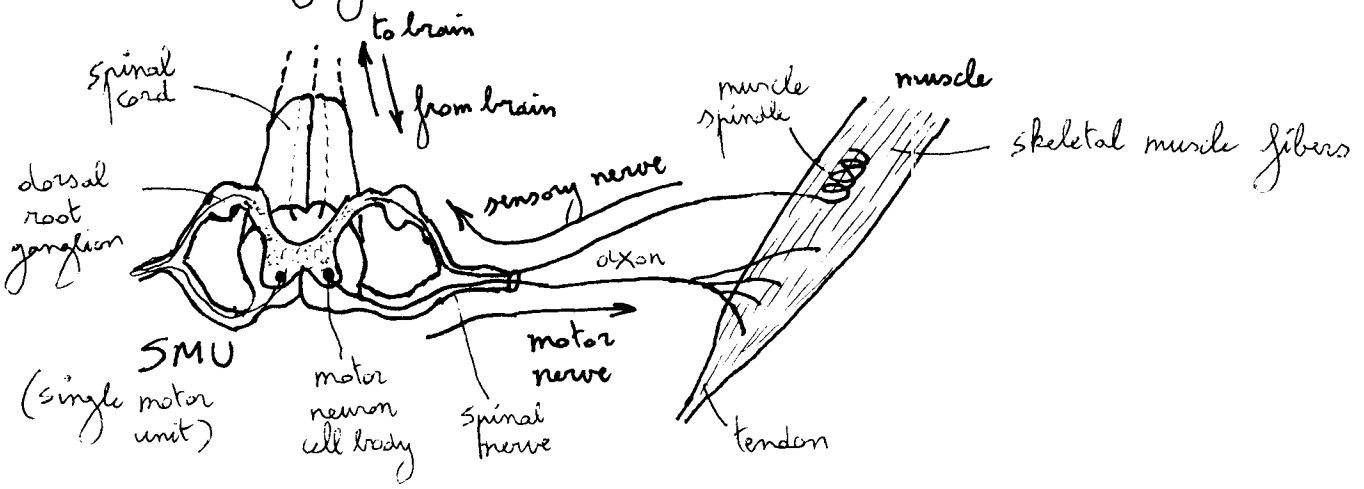
ECG:



NOTE: atrial repolarization is invisible, masked by ventrical depolarization

— Electroneurogram ENG : (Sec 4.3 - 4.4)

and Electromyogram EMG : (Sec. 4.5)



ENG

↓

motor / sensory nerve

axons

↓

small potentials (μV)

↓

recorded internally (invasively)

EMG

↓

muscle

skeletal muscle fibers

↓

large potentials (mV)

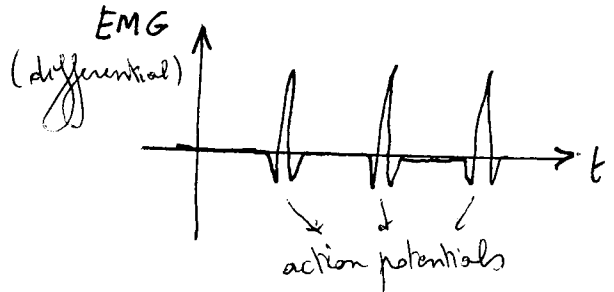
(μV on the skin)

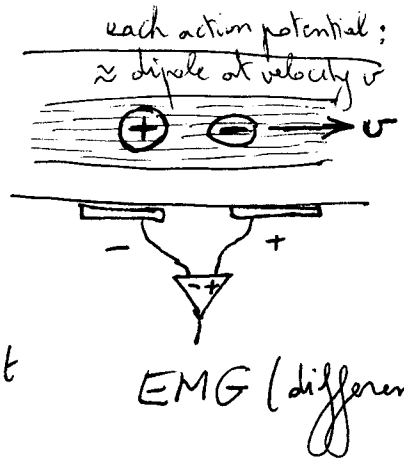
↓

recorded either internally (invasively)

or on the skin (non-invasively)

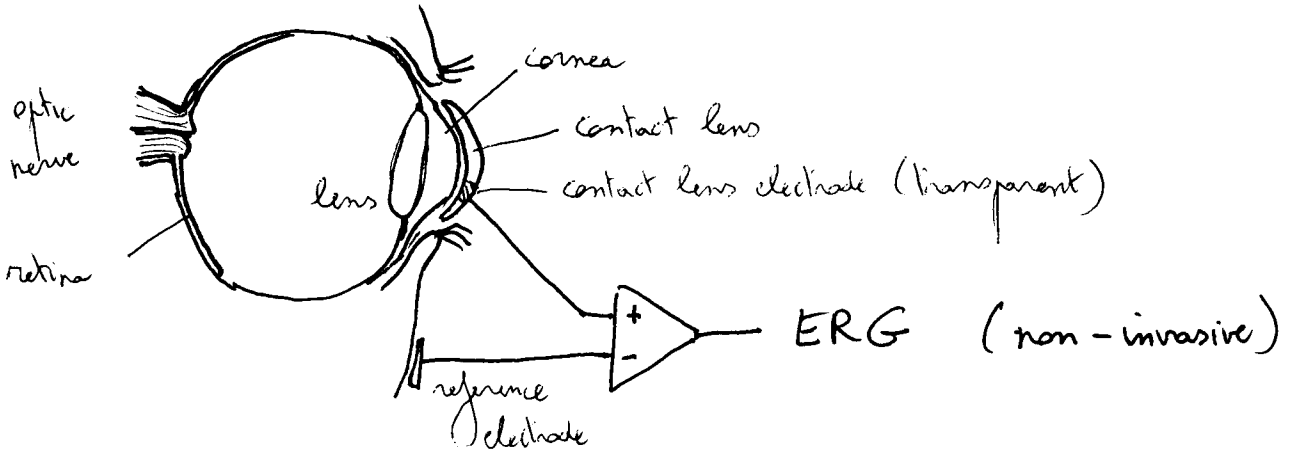
e.g. arm:



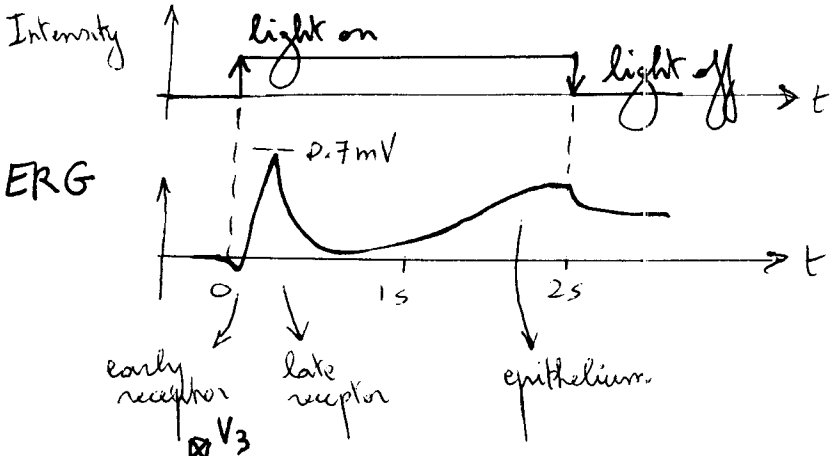


— Electroretinogram (ERG): (Sec. 4.7)
and Electrooculogram (EOG): (Sec. 4.7 pp 162-163)

• ERG:



→ measures transient electrical response of the retina for a flash presentation of light into the eye



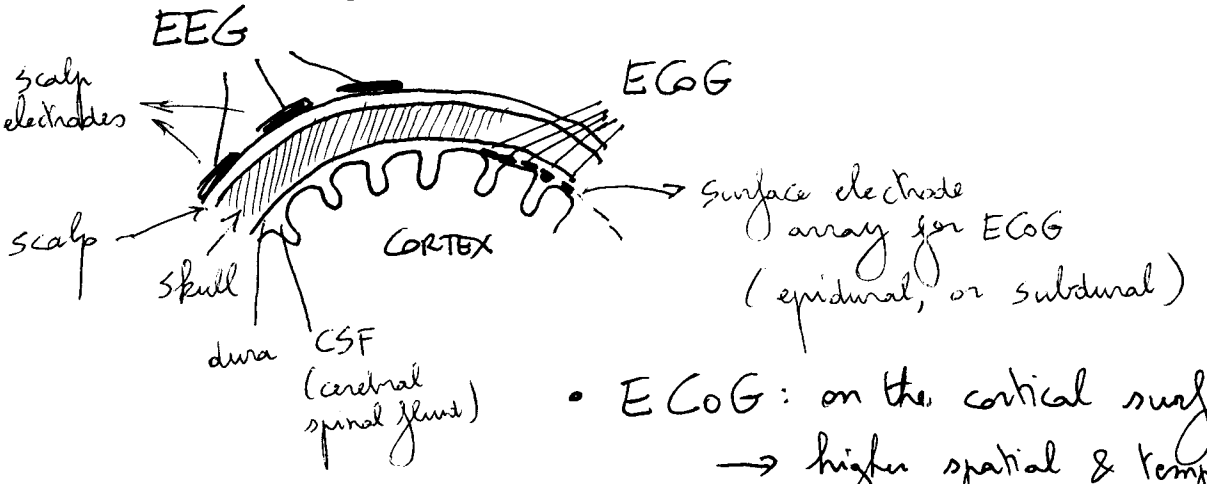
• EOG: (non-invasive)

Two pairs of electrodes for 2-D eye gaze.
$V_1 - V_2$ → azimuth
$V_3 - V_4$ → elevation

→ measures static dipole field due to retina–cornea polarization, tracking the rotation of the eye ball

— Electroencephalogram (EEG) and Electrocorticogram (ECoG) (Sec. 4.8) (also MEG in Section 4.3)

→ measures synchronous collective neural activity in the brain, as the effect of large populations of neurons firing together, mostly in the CEREBRAL CORTEX:



- ECoG: on the cortical surface
  - → higher spatial & temporal resolution (mm; > 100Hz)
  - → more invasive (epilepsy patients)
- EEG: on the scalp
  - → lower spatial & temporal resolution (cm; < 100Hz)
  - → less invasive (brain-computer interfaces)

→ resolves sources of activity in the brain that relate to general cognitive state, expressed in the form of BRAIN WAVES (oscillatory patterns):

(for EEG)

- ALPHA (α) : 8 – 13 Hz , 20 – 200 μV , on occipital lobe (visual cortex)
  - → visual "idle state" and attention
  - → strongest with closed eyes, when not asleep
- BETA (β) : 14 – 30 Hz , 20 – 100 μV , on parietal-frontal lobes
  - → strongest with high activity and concentration
- GAMMA (γ) : 25 – 100 Hz, and > 100 Hz for ECoG!
  - → various mental activity
  - → high-frequency gamma (> 100 Hz, EGG) is highly selective to complex mental constructs, such as arithmetic and language (with the potential for human-computer interfaces)
- DELTA (δ) : < 3.5 Hz , mostly frontal
  - → slow wave sleep
  - → brain injury and neural degeneration, when not asleep
- THETA (ϑ) : 4 – 7 Hz, everywhere!
  - → the brain's "clock"
  - → phase coding in synchrony of neural oscillations
  - → strong during meditation

and many others! (The brain is complex)