Biopotentials

各種電生理訊號

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Review: membrane potential

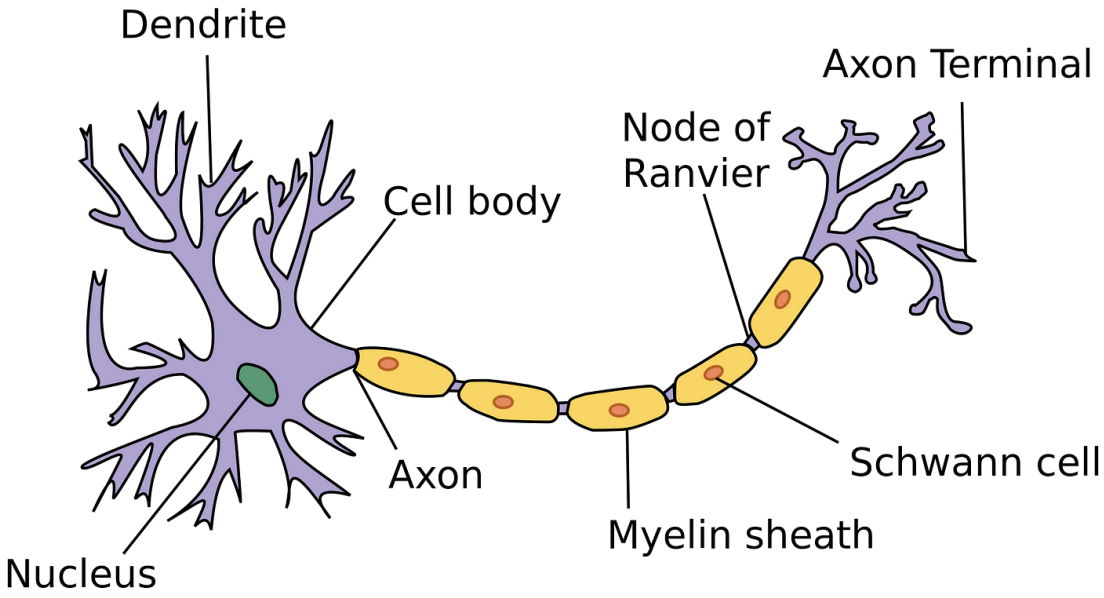
- Resting and action potential
  - Permeability of ion channels
- Propagation of action potential

- Biopotential: bioelectric potential reflecting physiological activity of a certain tissue or organ.
  - We'll focus on ENG, EMG, ECG, and EEG.

Electroneurography (ENG, ENoG)

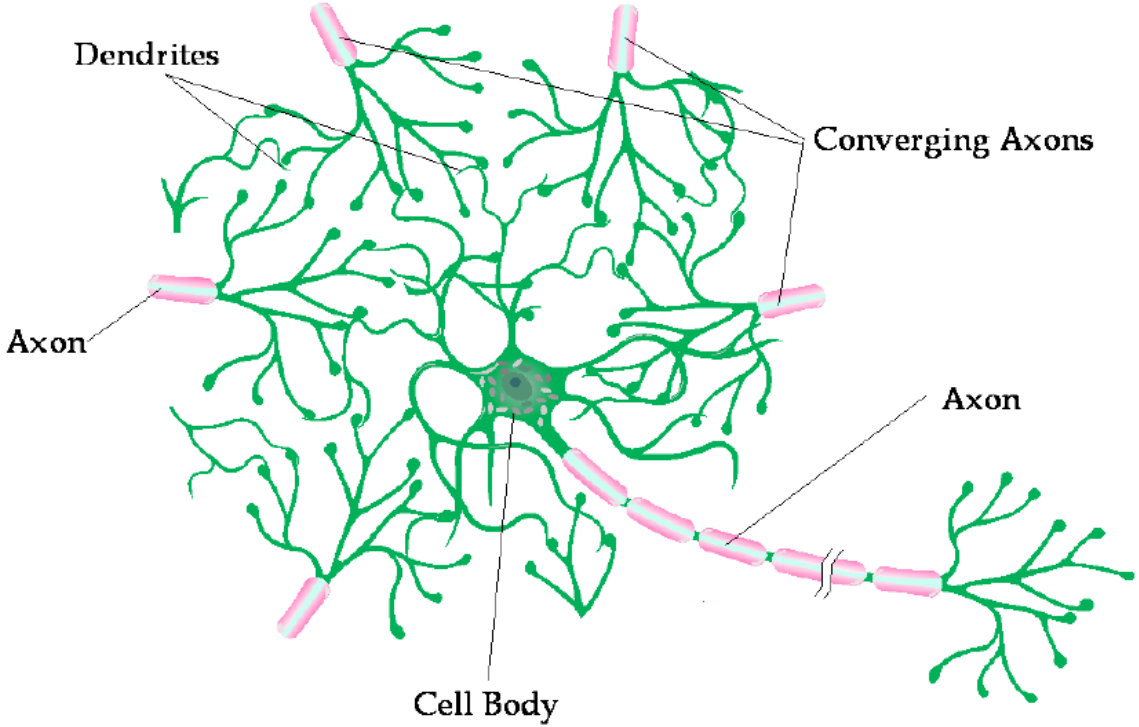
- Recording of the biopotential of a specific nerve after stimulation
  - Sensory nerve or motor nerve
- Clinical application: diagnosis of peripheral nerve disorder
  - Based on waveform and nerve conduction velocity
  - Ex: facial nerve

Neuron

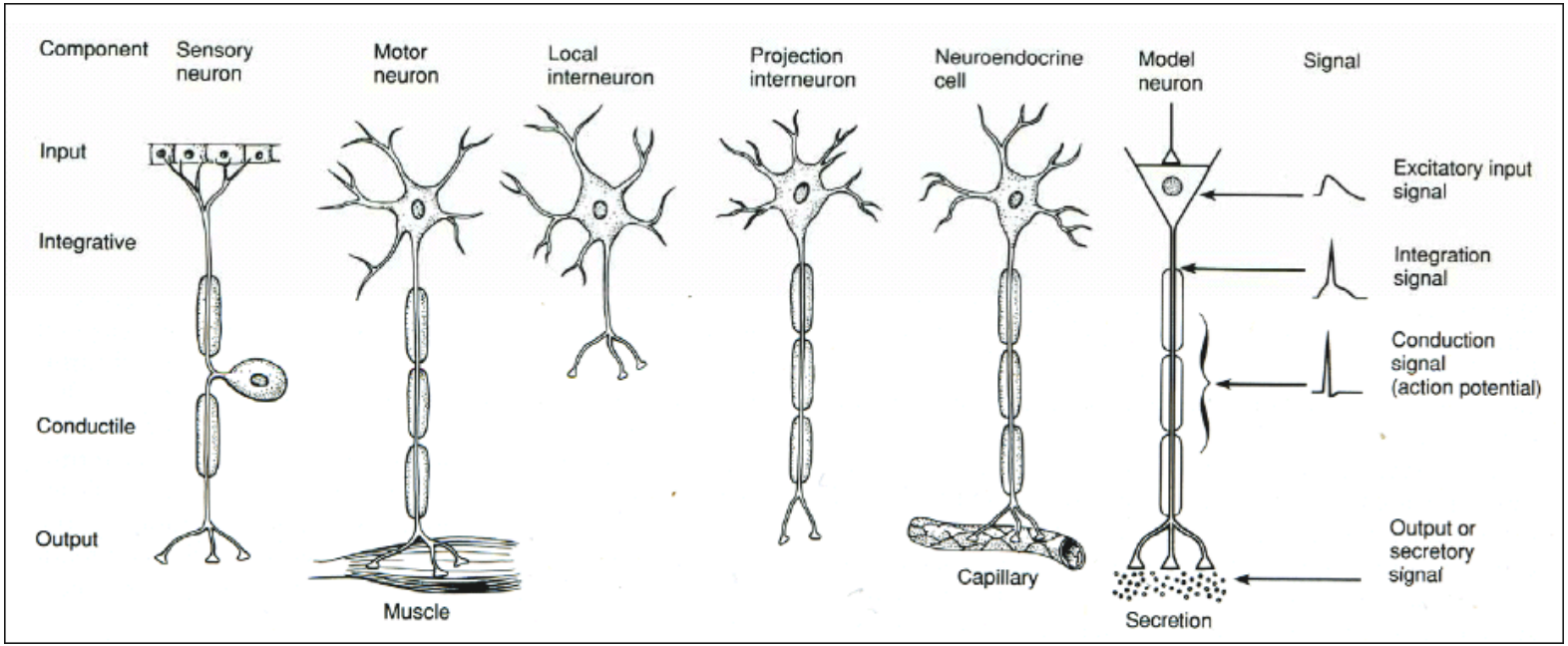


Structure of a neuron

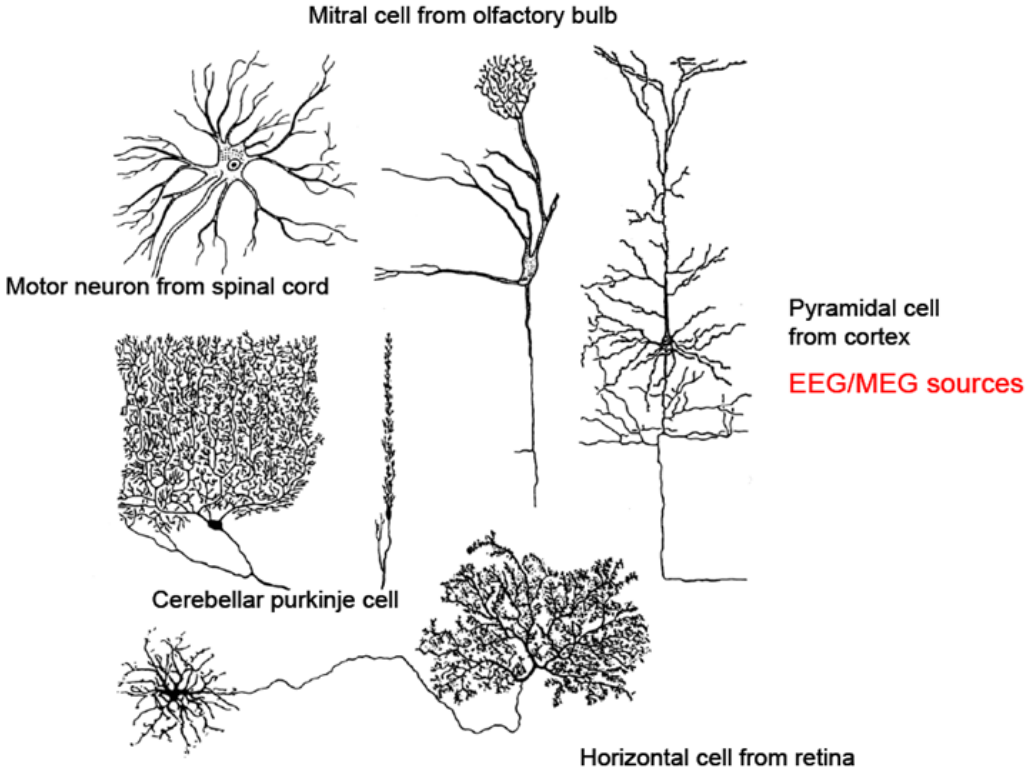
Connection of neurons



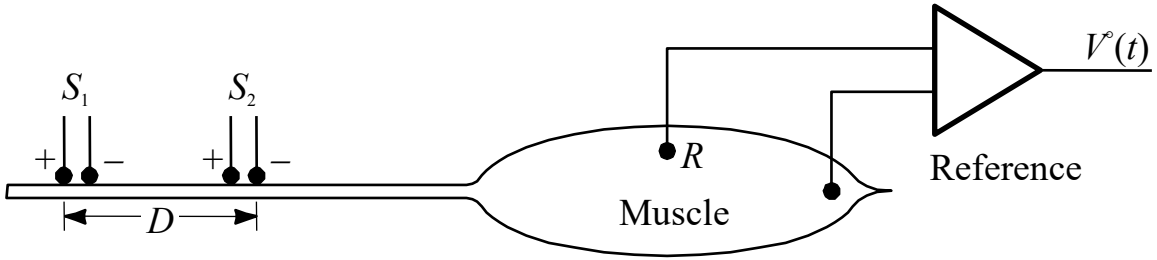
Various types of neurons

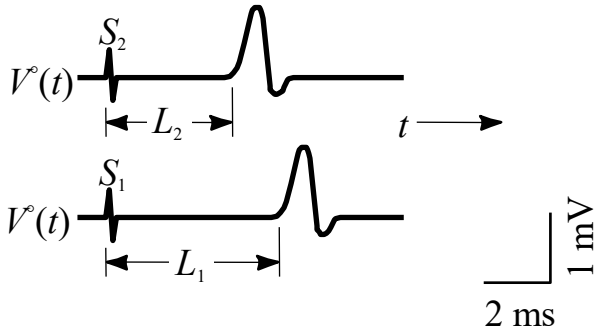


And more…


Mitral cell from olfactory bulb
Motor neuron from spinal cord
Pyramidal cell
from cortex
EEG/MEG sources
Cerebellar purkinje cell
Horizontal cell from retina

ENG: conduction velocity

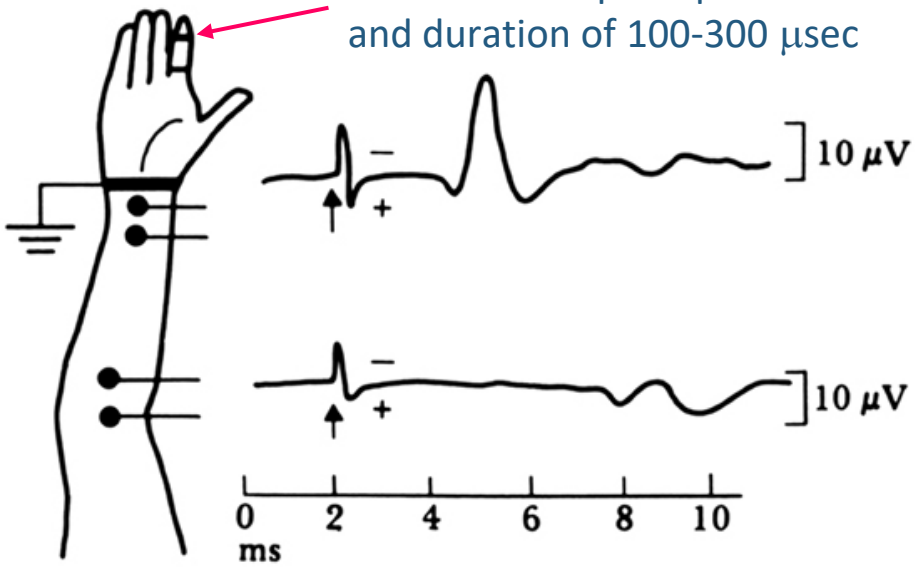




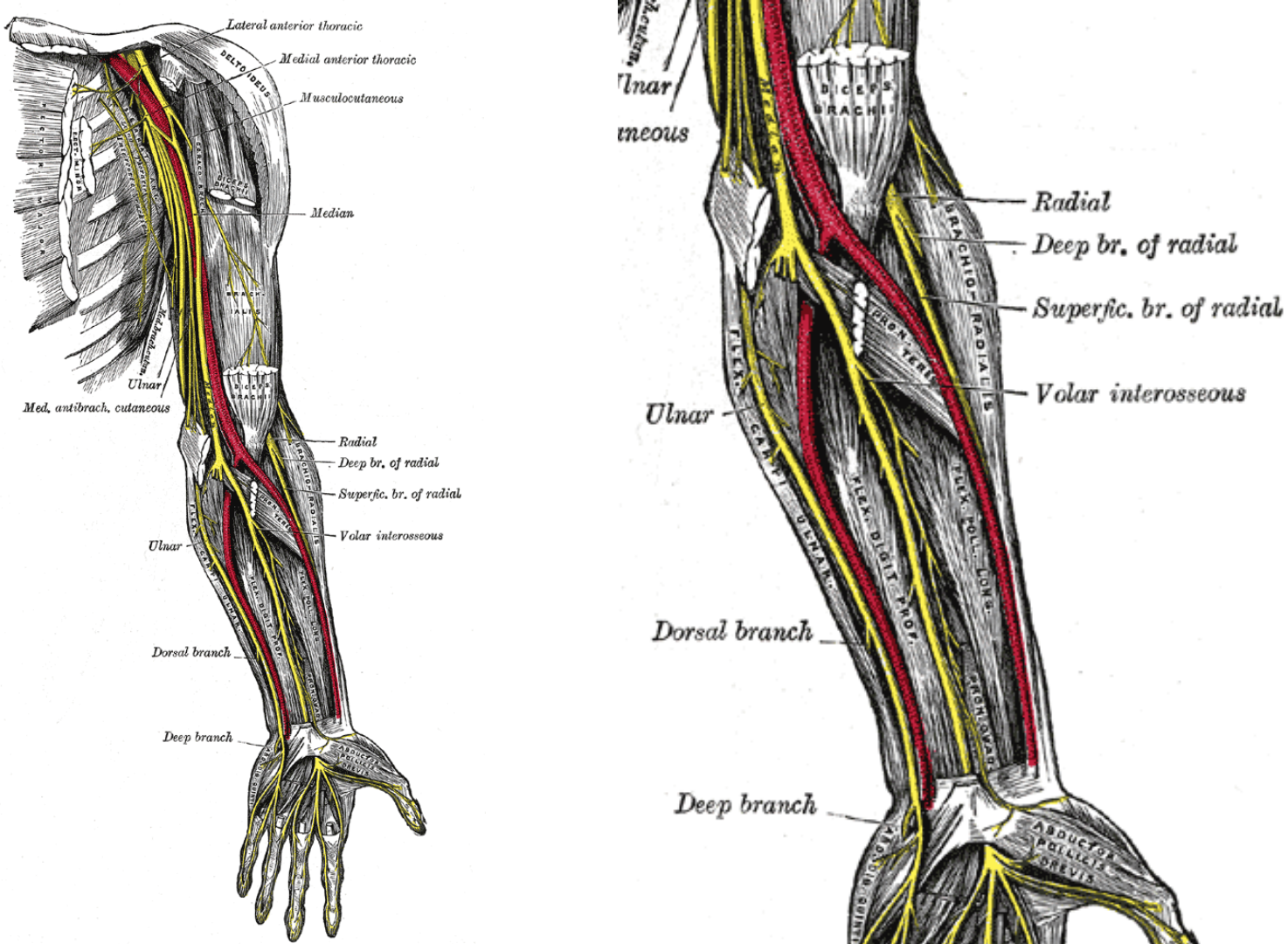
$$\text{Velocity} = u = \frac{D}{L_1 - L_2}$$

ENG: waveform

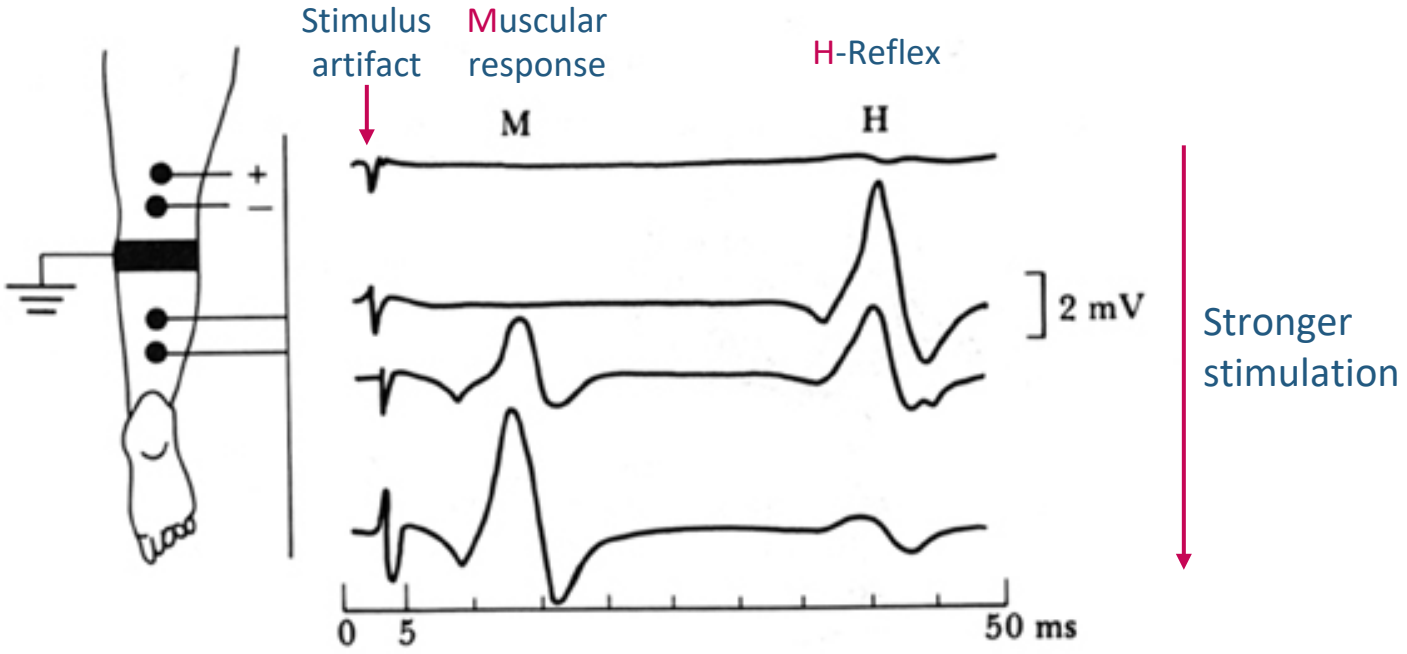
Stimulation: square pulse with 100-V amplitude and duration of 100-300 μsec



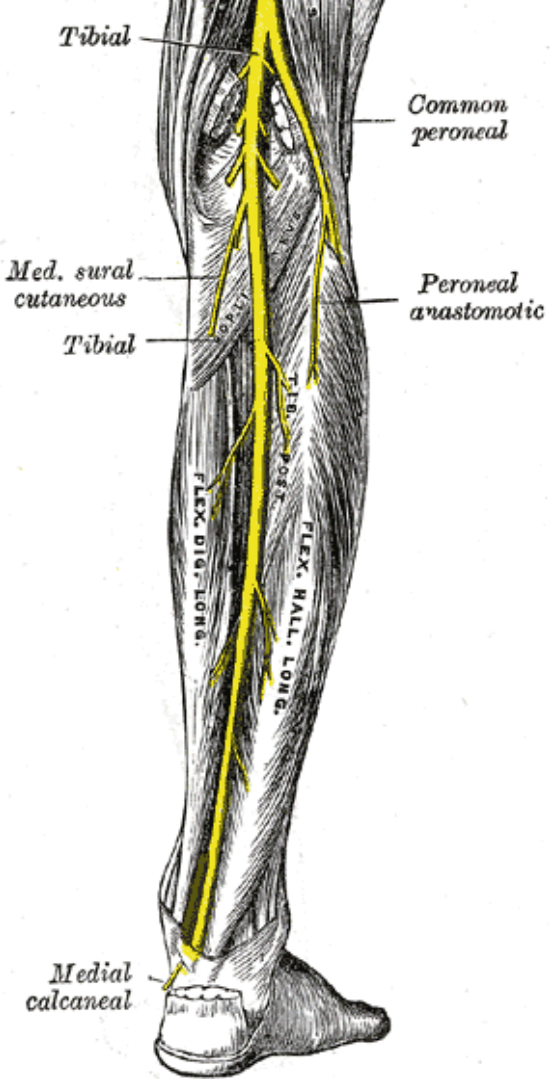
ENG of median nerve at wrist (up) and elbow (down)

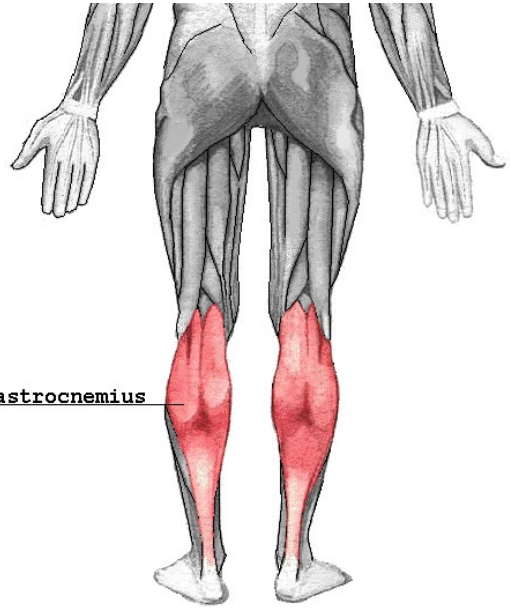

Lateral anterior thoracic
Medial anterior thoracic
Musculocutaneous
Median
Ulnar
Med. antibrach. cutaneous
Radial
Deep br. of radial
Superfic. br. of radial
Volar interosseous
Ulnar
Dorsal branch
Deep branch
Radial
Deep br. of radial
Superfic. br. of radial
Volar interosseous
Ulnar
Dorsal branch
Deep branch

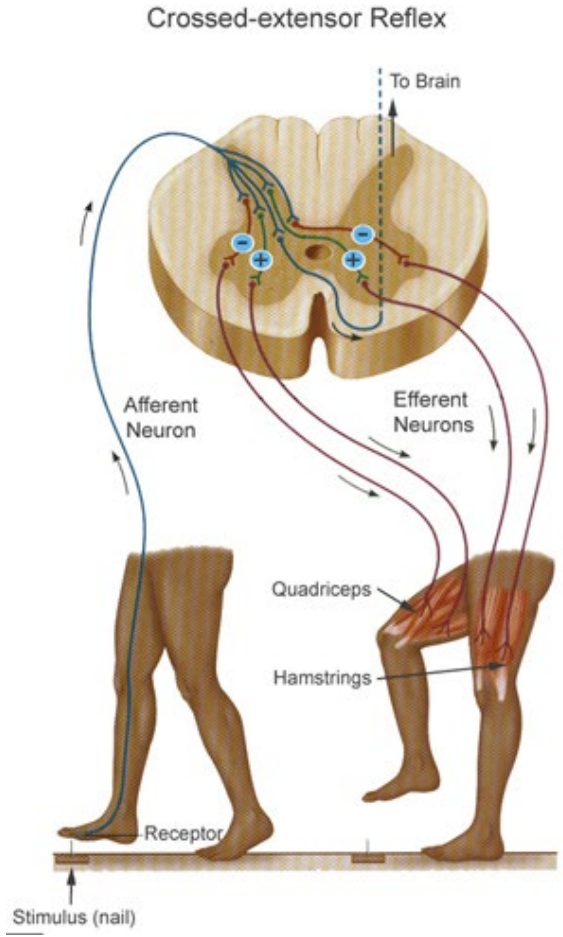
The H reflex



Stimulation: posterior tibial nerve; Recording: triceps sural muscle


Tibial
Common peroneal
Med. sural cutaneous
Peroneal anastomotic
Tibial
FLEX. DIG. LONG.
FLEX. HALL. LONG.
Medial calcaneal


Gastrocnemius


Crossed-extensor Reflex
To Brain
Afferent Neuron
Efferent Neurons
Quadriceps
Hamstrings
Receptor
Stimulus (nail)

ENG

- ENG is used to examine nerve conduction and impulse propagation along a specific nerve.
- Relatively weak in amplitude
- Dysfunctional side v.s. normal side

EMG

Electromyography (EMG)

- When the signal on a motor neuron reach the muscle, an action potential is triggered on muscle fiber to induce muscle contraction.
  - Twitch contraction
- EMG: recording the electrical activity produced by skeletal muscle

Muscle and motor control

- Skeletal muscle consists of elongated and multi-nucleate muscle cells called muscle fibers.
- Each fiber is innervated by one motor neuron, and a typical muscle is controlled by hundred motor neurons.

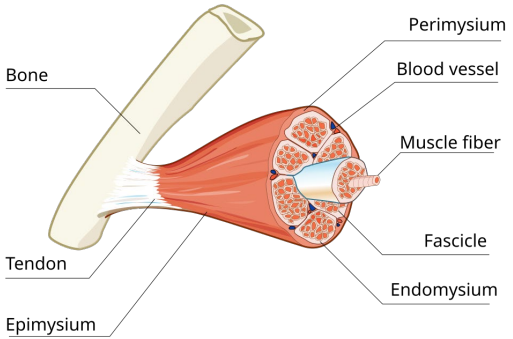


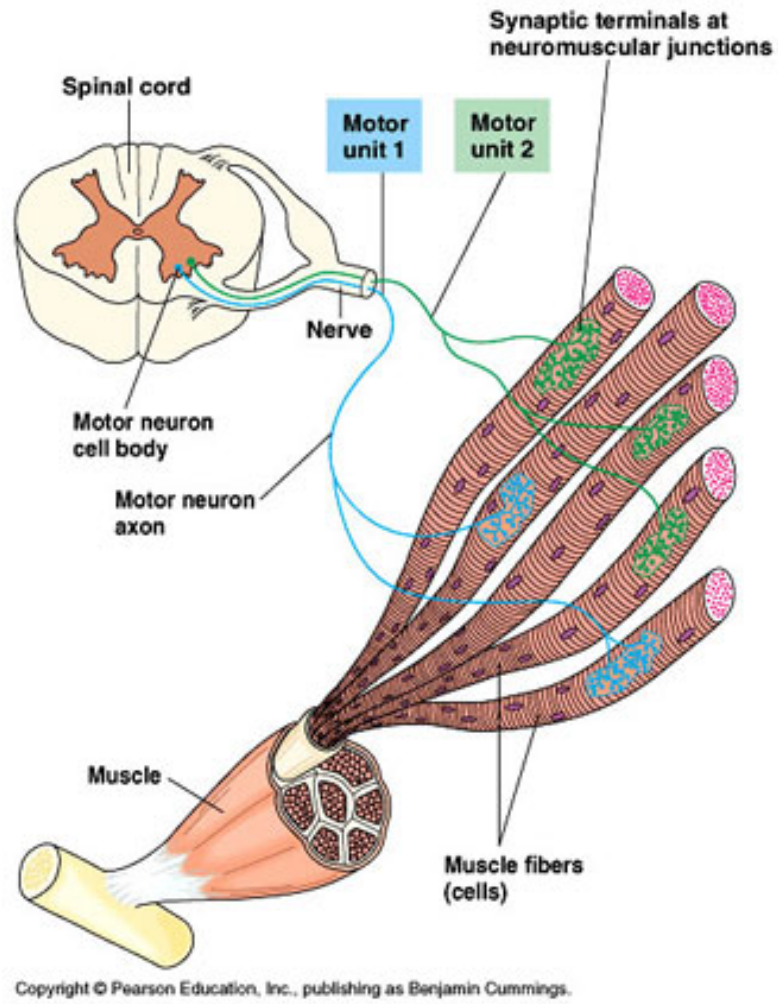
Photo credit: Wikipedia (Muscle fascicle)

Motor unit

- A motor neuron and the muscle fibers it innervates are known as a motor unit.
  - The basic fundamental unit of motor control
  - The number of muscle fibers in one motor unit (innervation number) ranges from <10 (eye muscle) to >1000 (leg muscle).

Motor unit

- Each muscle fiber is innervated by one motor neuron.
- One motor neuron controls multiple fibers.

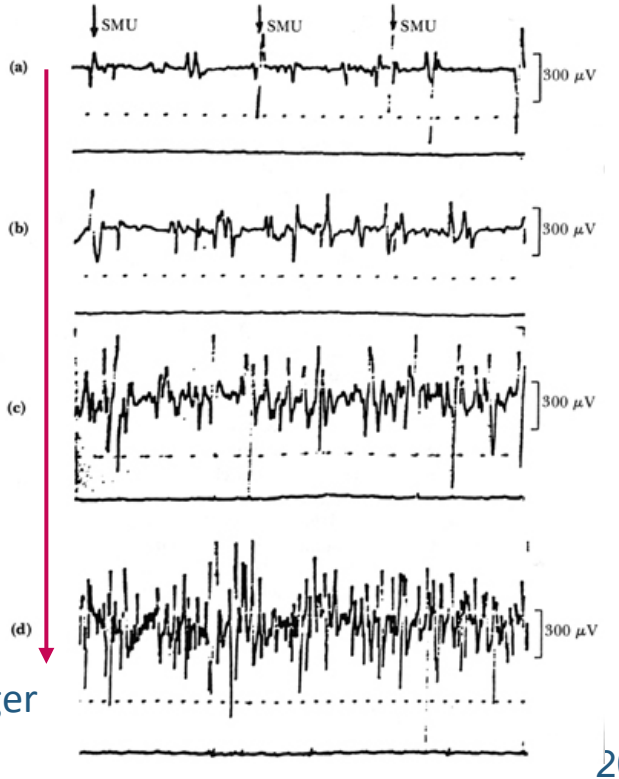


What is measured by EMG?

- EMG measures the electrical activity of muscle.
- EMG waveform is not only related to the motor units that are activated (in different muscles) during contraction, but also their contraction time and speed.

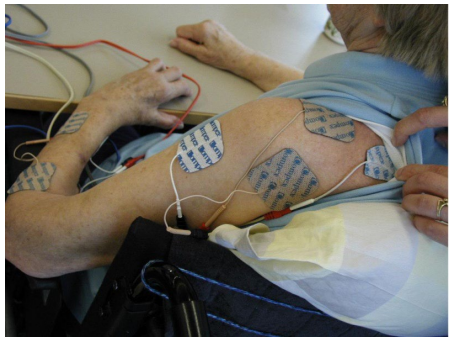
EMG and forces

- Stronger force comes with more motor units being recruited and faster discharge rate.
- Evoked potential of a single MU:
  - Contraction time: 3-15 ms
  - Amplitude: 20-2000 µV
  - Discharge rate: 6-30 cycles/sec



How to measure EMG?

- Invasive: needle electrode
  - EMG of a specific (group of) muscle
  - Stronger signals, especially for deep muscles
  - Uncomfortable, higher risk of infection
- Non-invasive: (adhesive) skin electrode
  - EMG of superficial muscles beneath skin
  - Convenient and safe

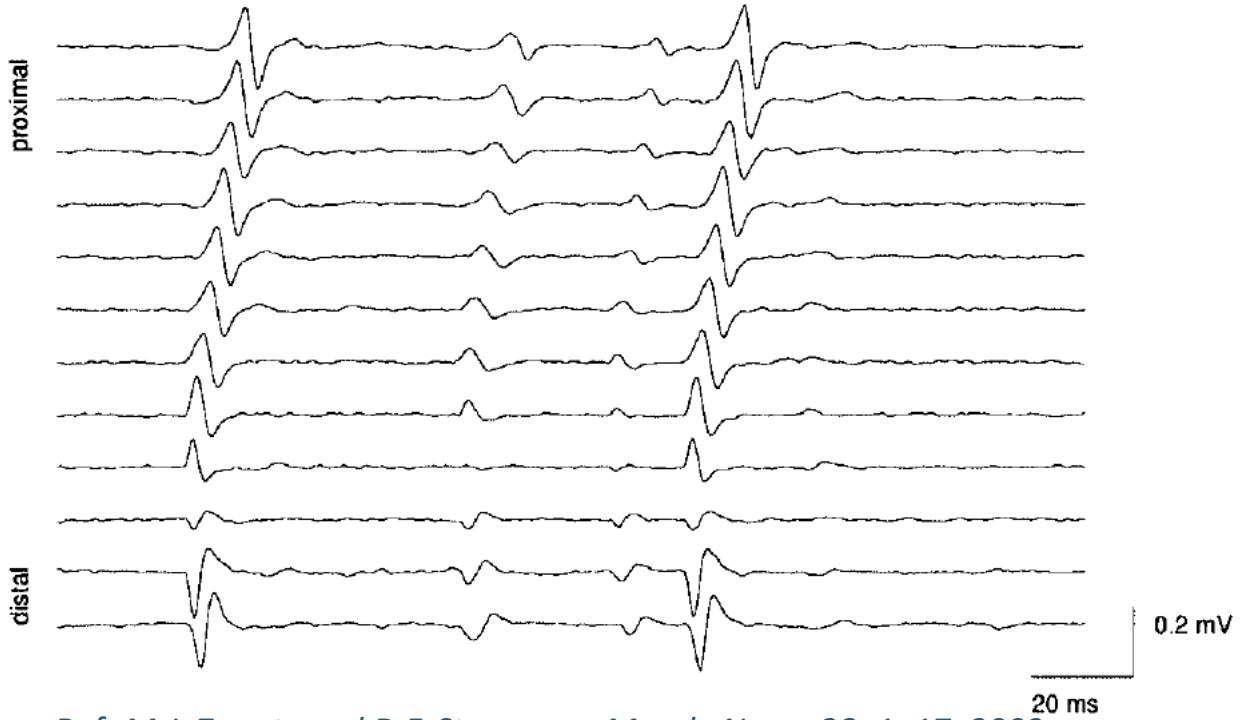


Skin electrode array/grid

A 126-channel high-density electrode grid

Ref: *M.J. Zwarts and D.F. Stegeman, Muscle Nerve 28: 1–17, 2003*

EMG measured by the array



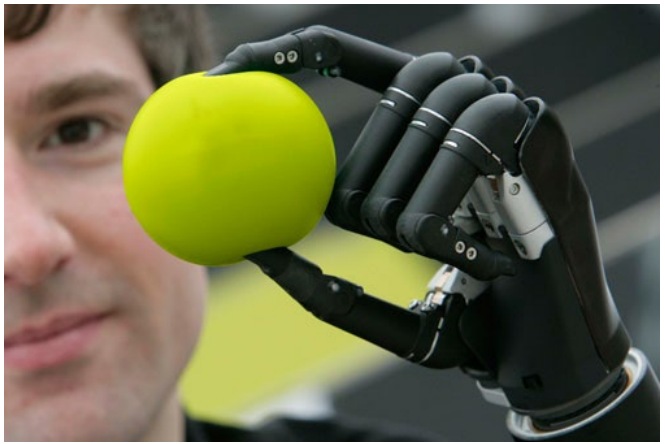
Ref: *M.J. Zwarts and D.F. Stegeman, Muscle Nerve 28: 1–17, 2003*

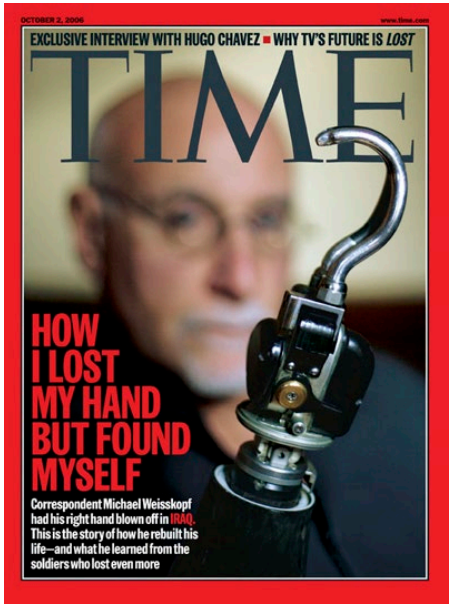
EMG

- EMG is the recording the electrical activity produced by muscle contraction.
- EMG waveform is related to the motor units being recruited and their contraction profiles.
  - Can we tell the motion from EMG?
  - Spatial information can be provided by multi-channel EMG

Applications of EMG

- Diagnosis of neuromuscular diseases
- Control of prosthetic limbs
  - Utah arm
  - i-Limb

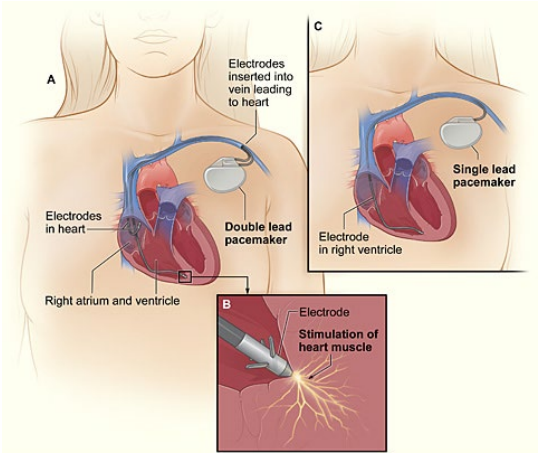




To induce muscle contraction?

- How to control someone's arm with your brain? (TED)
- Functional electrical stimulation
- Pacemaker

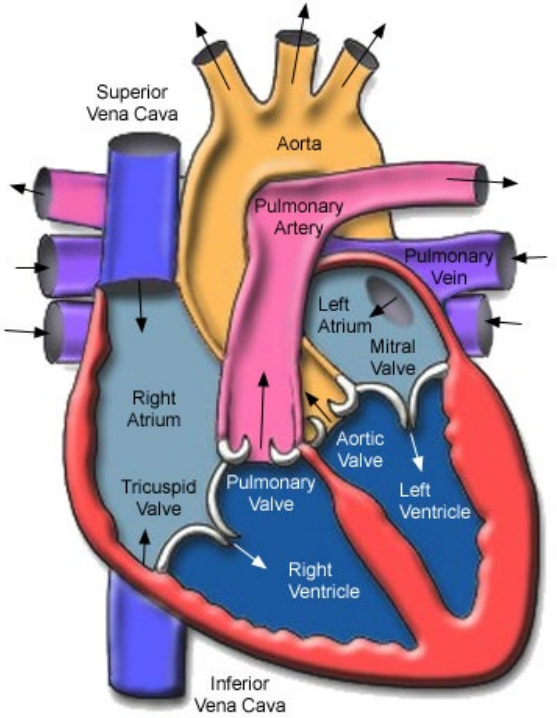
Photo credit: *www.nhlbi.nih.gov/*



ECG/EKG

Fundamentals of heart

- Driving force of the circulatory system
  - Beating 2-3 billion times in you life
  - Pumping out ~10000 liters of blood everyday
- Four chambers: L/R atrium and L/R ventricle
  - Systematic circulation
  - Pulmonary circulation
  - Direction of blood flow?



Fundamentals of heart

- Cardiac muscle
  - The order of contraction?
  - The strongest chamber?

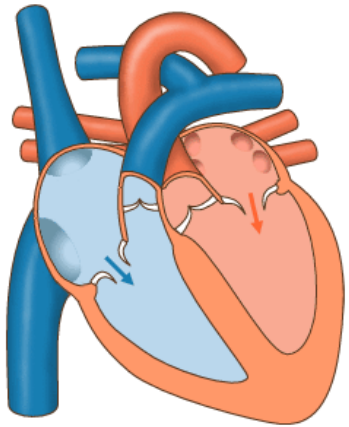
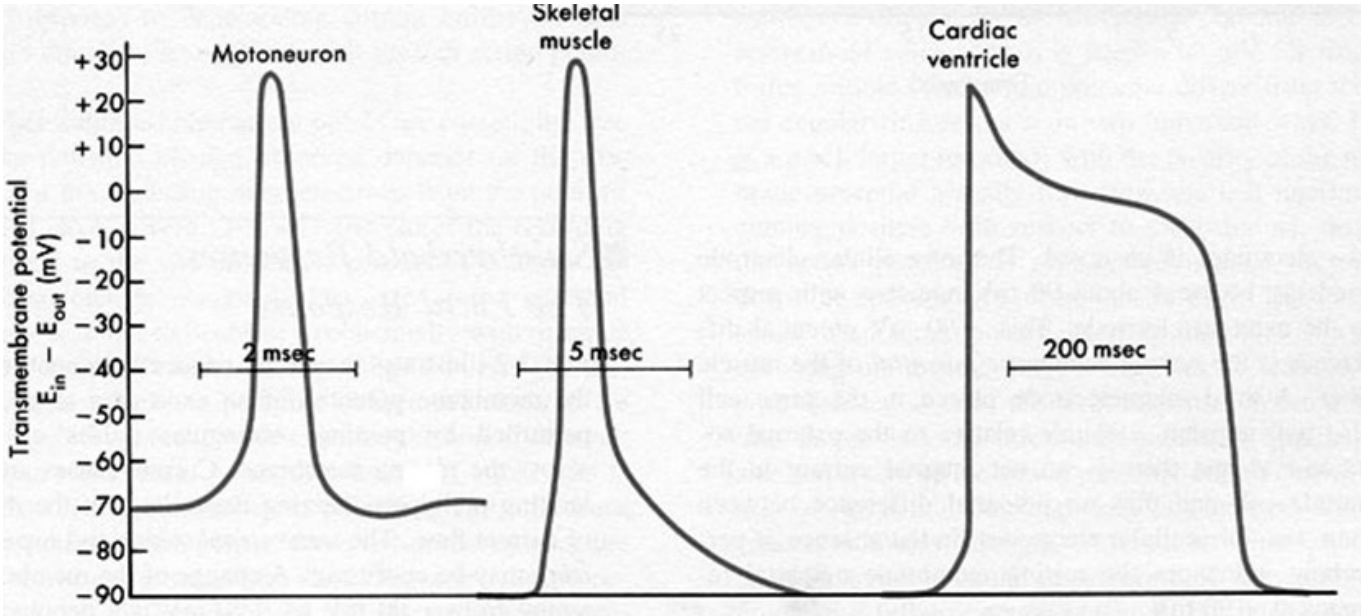


Photo credit: Wikipedia (Heart)

- Cardiovascular diseases: the most common cause of death globally (~30%)

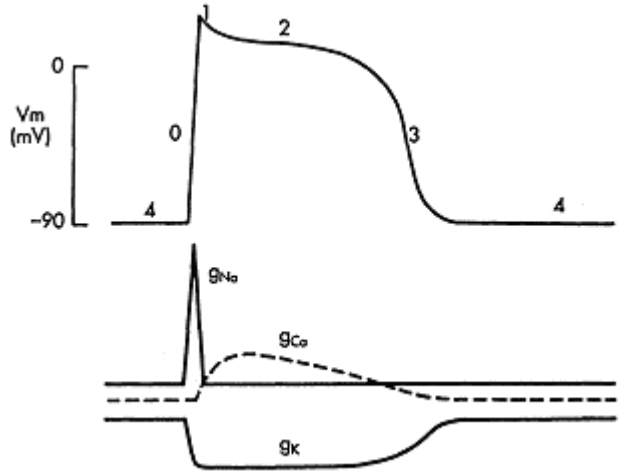
Review: action potential



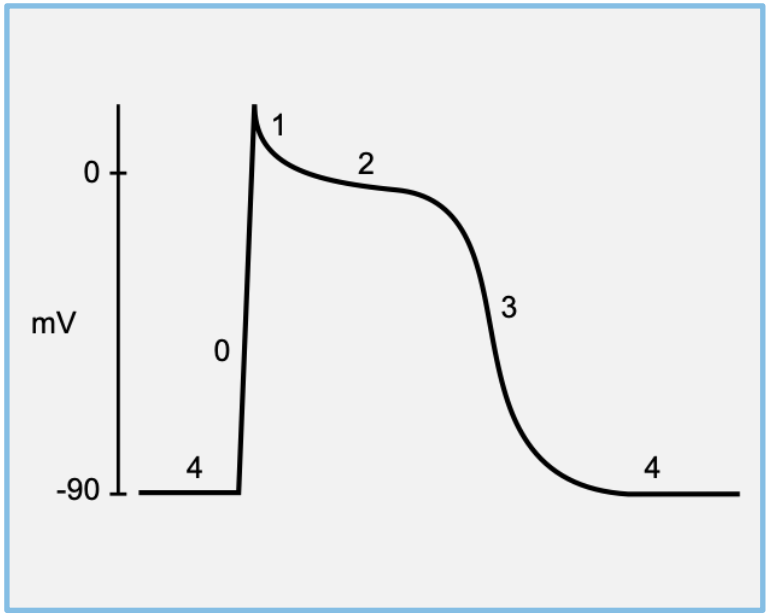
Action potential of different cells

Action potential of cardiac ventricle

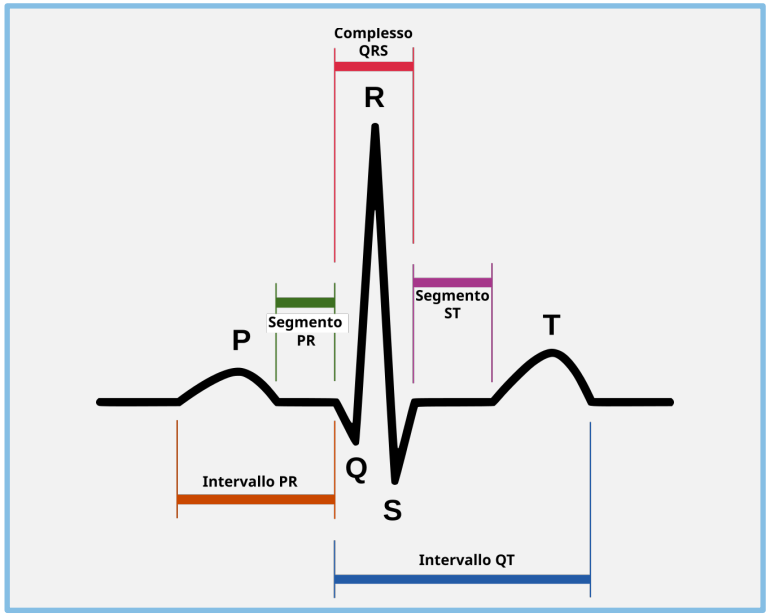
- **0** Depolarization phase
- **1** Transient repolarization phase
- **2** Plateau phase (Ca^{2+} inflow)
- **3** Repolarization phase
- **4** Resting phase



Cardiac AP vs Normal ECG



AP of cardiac ventricle



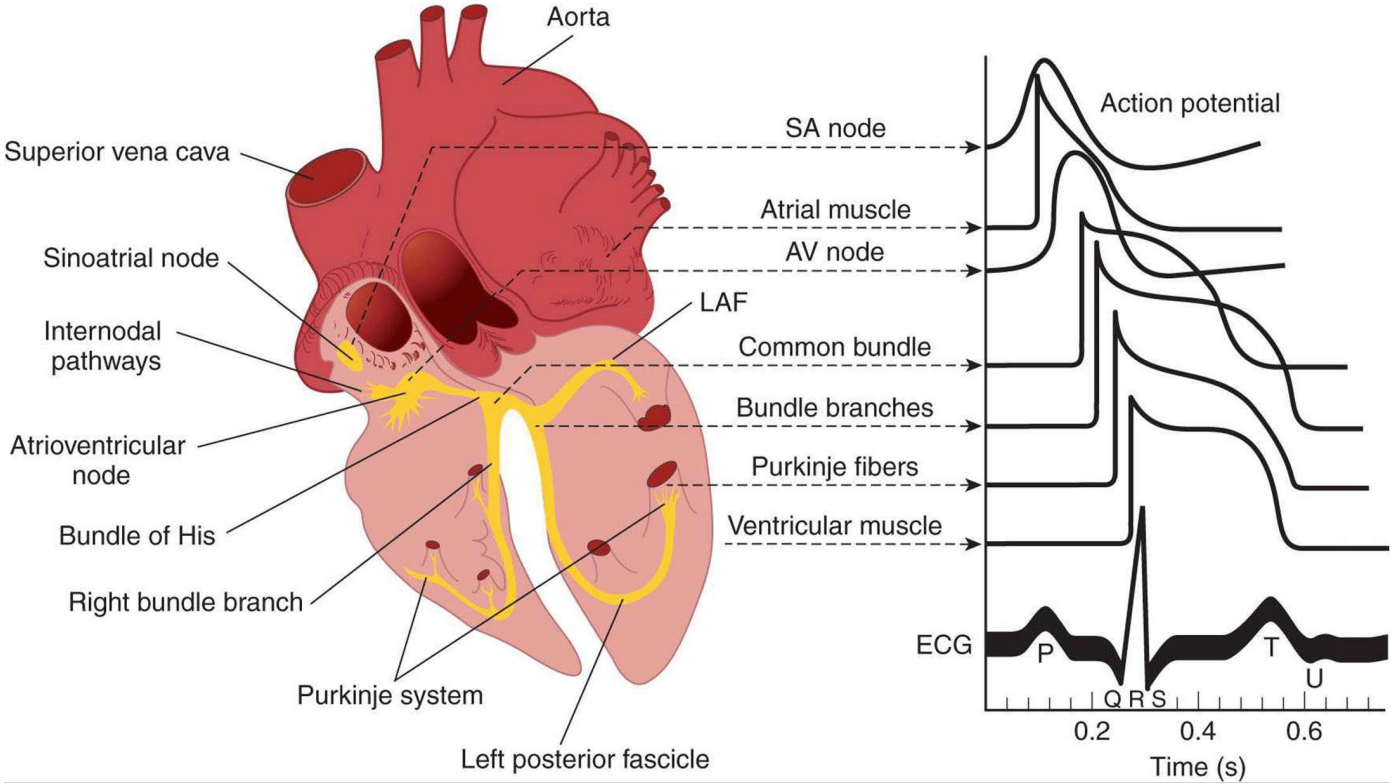
ECG: PQRST pattern

Photo credit: Wikipedia (Electrocardiography)

Why are they so different?

- The PQRST pattern doesn’t look like cardiac AP in any way!?
- ECG: recording of the heart’s electrical activity through repeated cardiac cycles
  - Summation of the electrical activity from all cardiac cells

PQRST wave of ECG



Ref: Barret KE, Barman SM, Yuan J, Brooks HL. Ganong's Review of Medical Physiology, 25th Edition

Conduction of AP: pacemaker cells

- Sinoatrial (SA) node → **Atrial contraction**

  Atrioventricular (AV) node → (AV node delay)

  Bundle of His →

  Bundle branches →

  Purkinje fiber network → **Ventricular contraction**

Electrical conduction system

- Rhythm: the automatic and regular impulses generated by pacemaker cells
  - Set the pace of muscle contraction and blood pumping
  - Control the heart rate

SA node →

AV node →

Bundle of His →

Bundle branches →

Depolarization of ventricle (Contraction) →

Repolarization of ventricle (Relax)

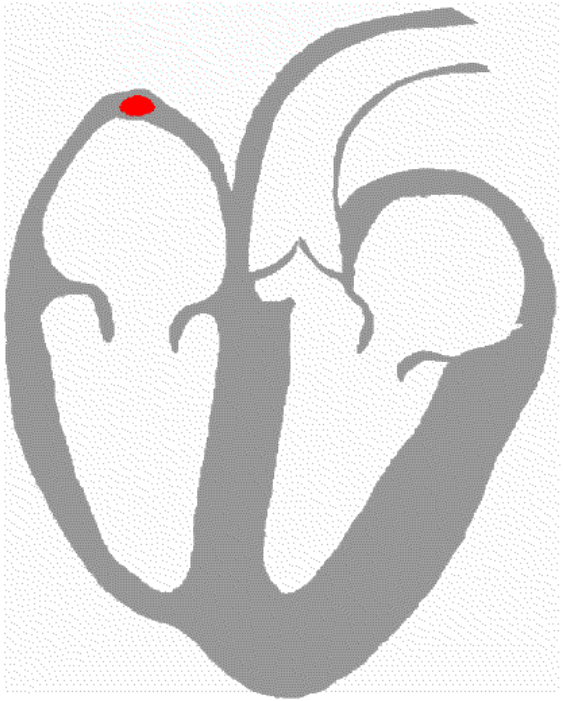


Photo credit: Wikipedia (Electrocardiography)

ECG and cardiac contraction

- ECG: summation of cardiac electrical activity
- P wave: contraction of atria
- PR interval: impulse delay (~0.1s) at AV node
- QRS complex: contraction of ventricles
- T wave: relax of ventricles

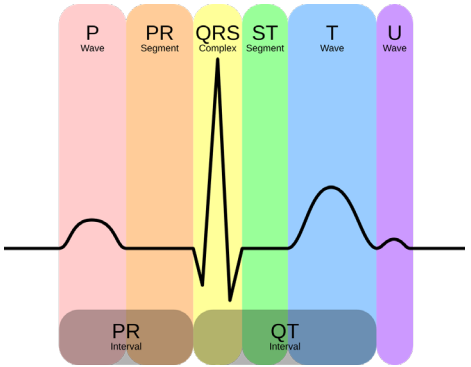
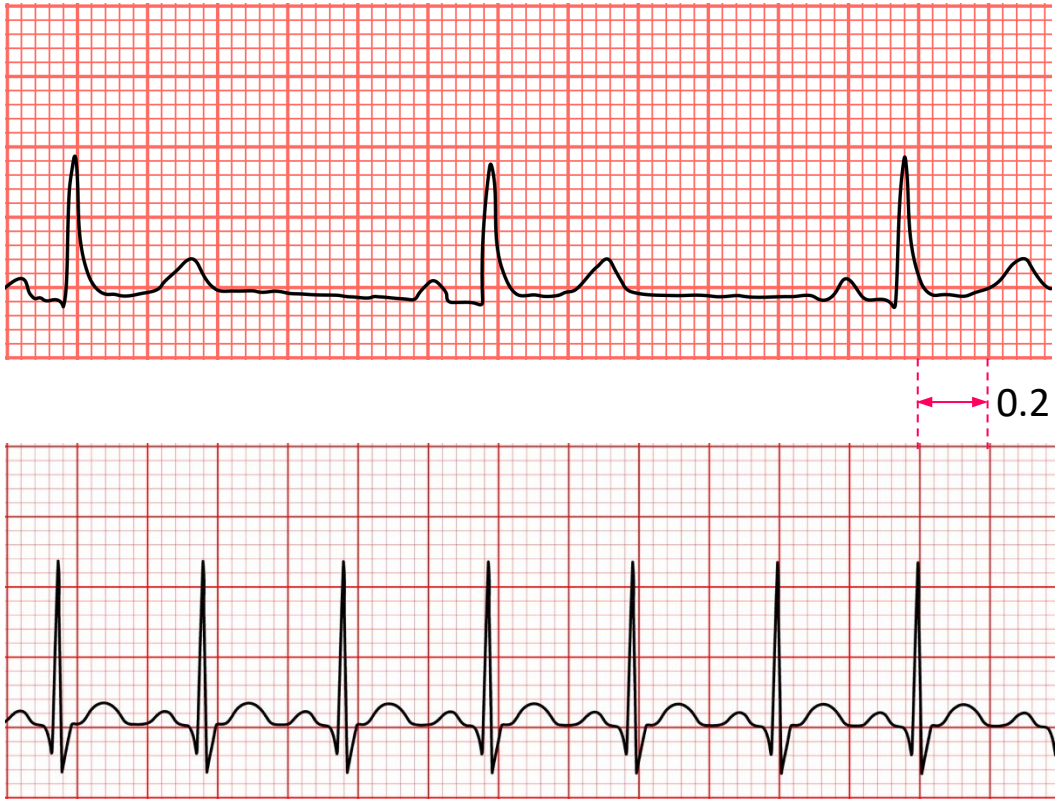


Photo credit: Wikipedia (Electrocardiography)

ECG

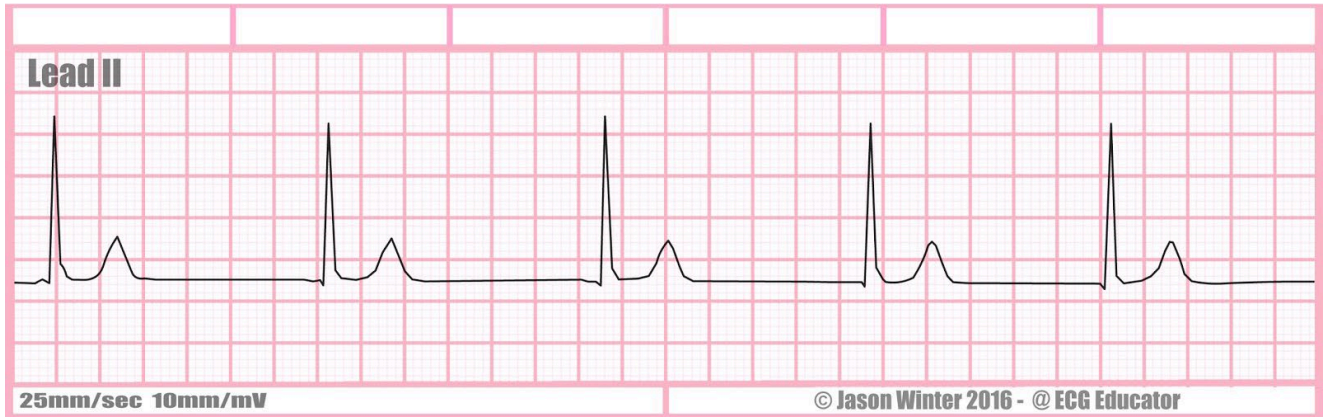
- In general, ECG is interpreted as electrical functioning of the heart, and the pattern of its waveform reflects muscular function.
  - Timing and amplitude
- Abnormal cardiac contraction can be diagnosed by ECG.
  - Ex: arrhythmia, myocardial infarction, …



Normal PQRST pattern shows a sinus rhythm:
Sinus bradycardia (upper) and sinus tachycardia (lower)

Cardiac rhythm

- The rhythmic contraction can be initiated by
  - SA node (primary pacemaker): 60-100 bpm
  - AV node (secondary pacemaker): 40-60 bpm
  - Bundle branches and Purkinje fibers: 30-40 bpm
- Who takes the lead?
  - The one with the quickest rate of depolarization



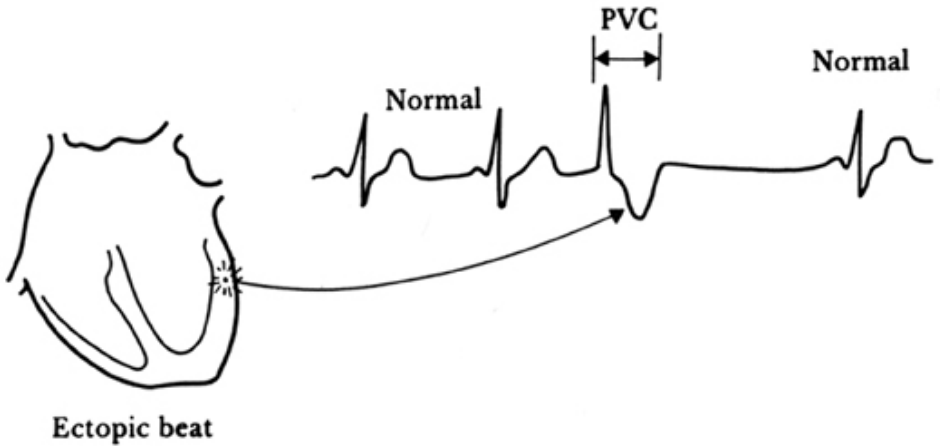
HR: ~47 bpm

Bradycardia (47 bpm) with P wave missing

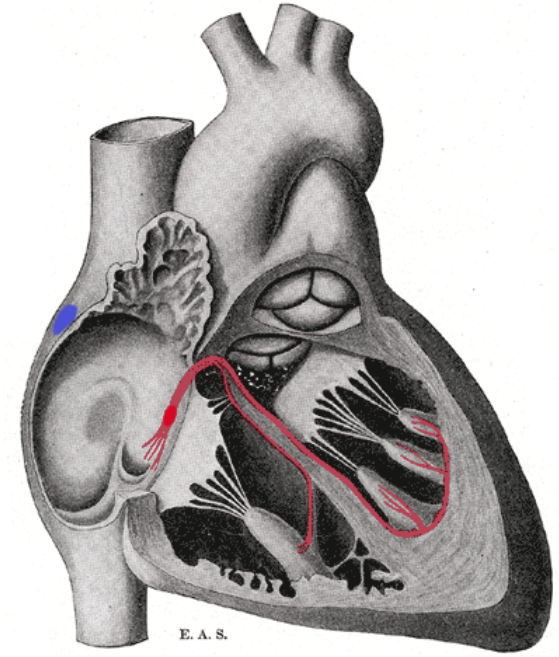
→ The rhythm is initiated by AV node (AV nodal bradycardia)

Premature ventricular contraction

- PVC (or VPC) is a common event where the heartbeat is initiated by Purkinje fibers in the ventricles.
  - Ectopic focus
  - Feel like a "skipped beat"



Sinus rhythm and PVC



Normal conduction of impulse

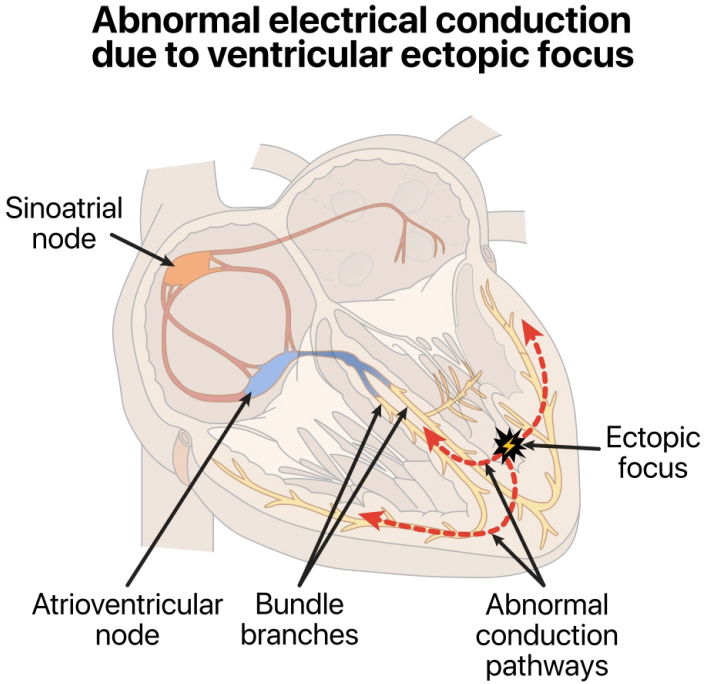


Photo credit: Wikipedia (Cardiac pacemaker)

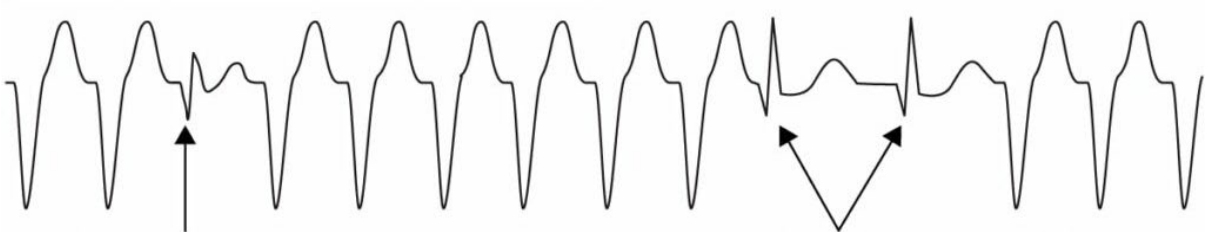
PVC

- Less effective pumping of blood
- PVC is a common type of irregular heartbeat (arrhythmia).
- Possible causes include hypertension, hypercapnia, intake of caffeine, stress, lack of sleep…
  - Remember those days before final exam?

Ventricular tachycardia

- Frequent or consecutive PVC might induce ventricular tachycardia or even ventricular fibrillation.
  - VT: may occur without symptoms, or present with palpitations, shortness of breath, and chest pain

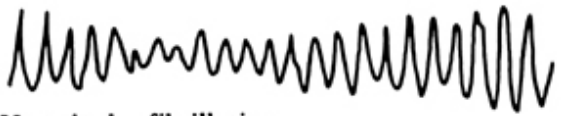
Ventricular tachycardia



Ventricular fibrillation

- Disorganized/random cardiac contraction
- Fail in pumping blood
- Life threatening!

(b)

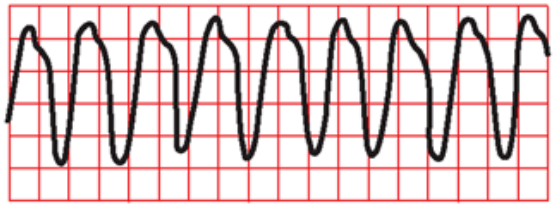


Ventricular fibrillation

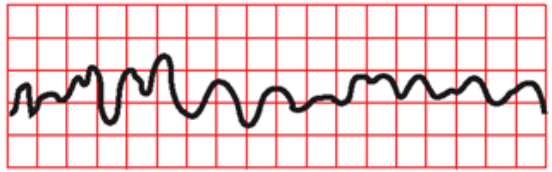
ECG of PVC, VT, and VF

Premature ventricular contractions (PVC)

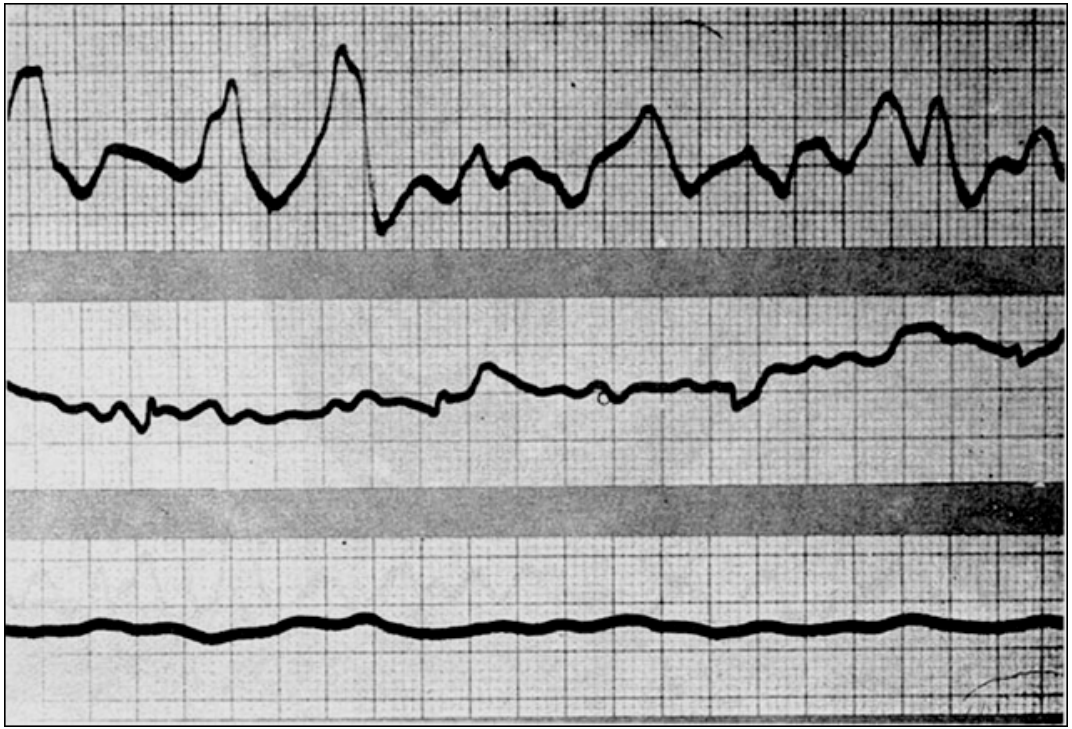
Ventricular tachycardia



Ventricular fibrillation



Scene in the Emergency room



What should we do now?

Defibrillation

- Defibrillation: a delivery of a strong electric shock to depolarize most of cardiac muscle, ending the arrythmia.
  - Re-establish the normal sinus rhythm (temporarily)
- Automated external defibrillator (AED) in public places

AED and its electrodes

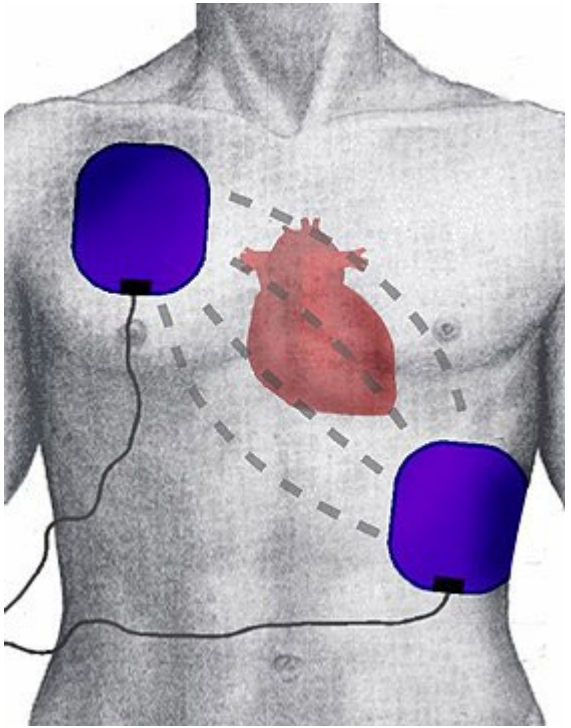
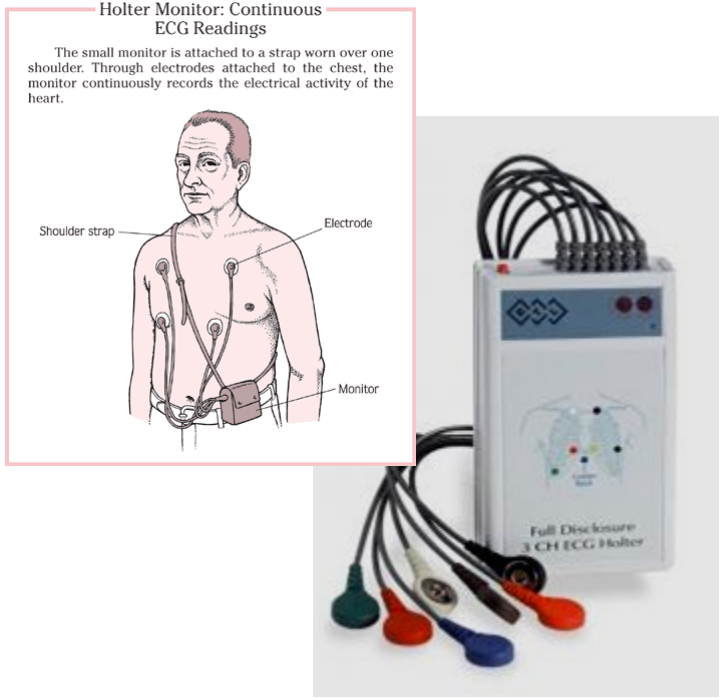


Photo credit: Wikipedia (Defibrillation)

ECG for diagnosis

- Atrial fibrillation 心房震顫
- Heart block 心臟阻滯
- Arrhythmia 心律不整
- Ischemia, infarction, and a lot more…
  心肌缺血 心肌梗塞
- One of the most widely used tools in cardiology

Clinical use of ECG



Holter monitor ECG

Exercise stress test

ECG monitoring in daily life

KardiaMobile, AliveCor

Apple watch

EEG

Human brain

- Central nervous system
- Responsible for most of the activities of the body, processing and integrating the information, and decision making.
- Cerebrum, cerebellum, and brainstem

大脳　　小脳　　脳幹

Brain: structure and function

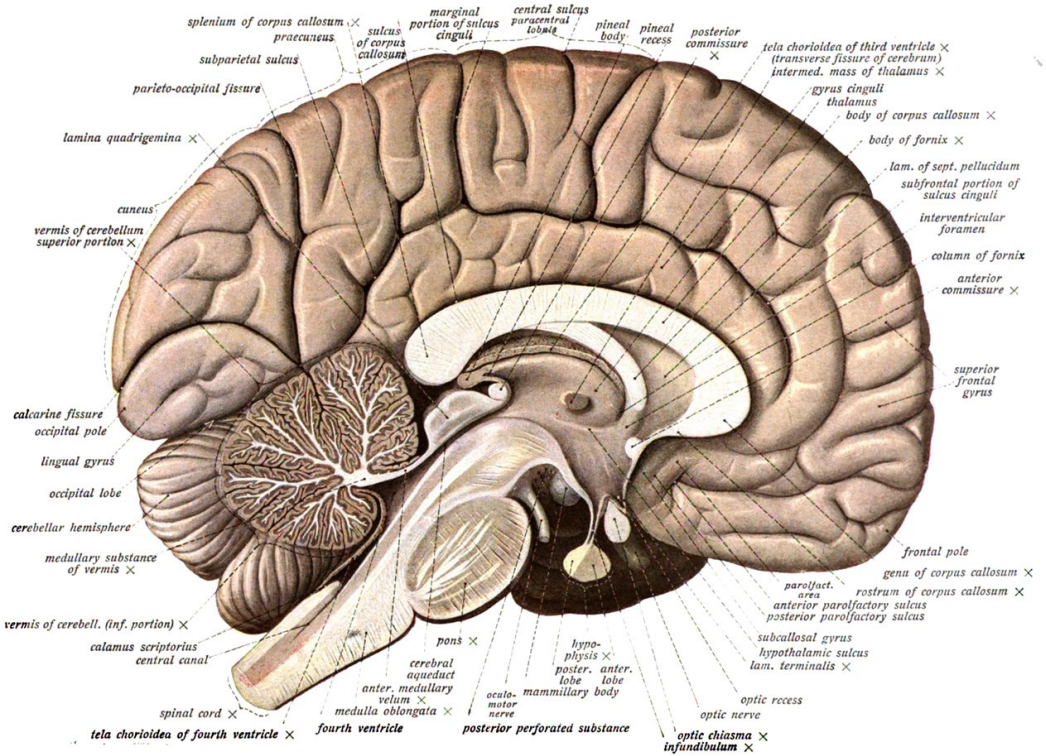
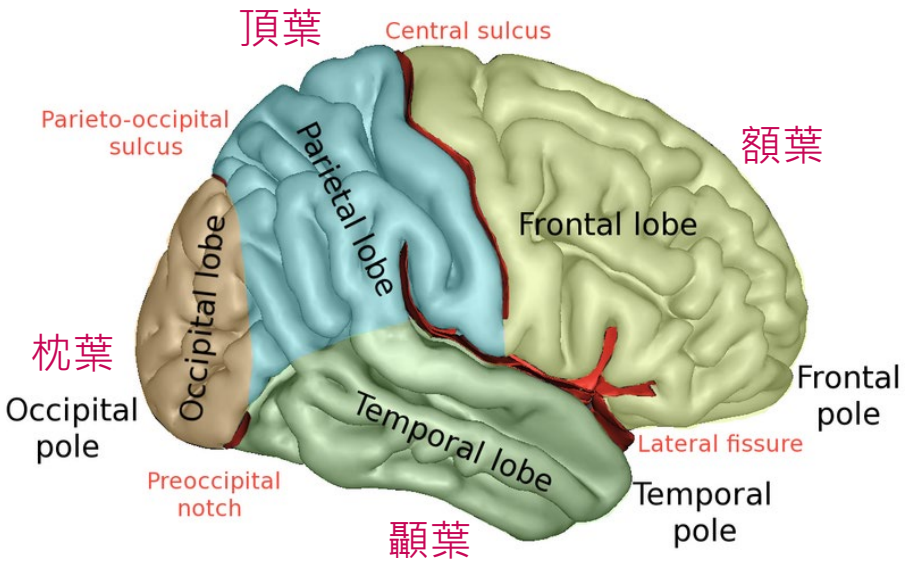


Photo credit: Wikipedia (Human brain)

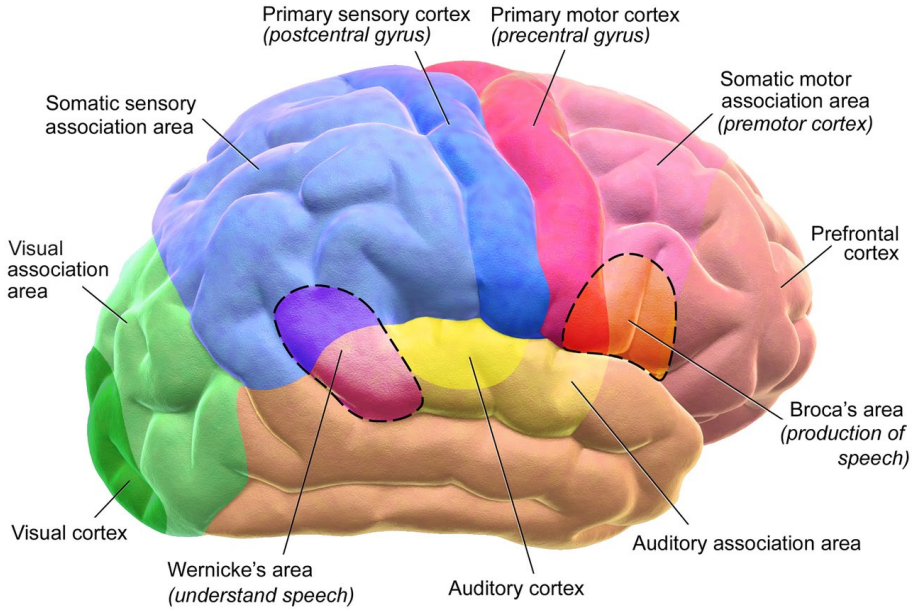
Cerebrum

- L/R hemispheres
- Brain tissues: gray matter and white matter
  - Cerebral cortex: outer layer of GM, highly folded (neuron cell bodies)
  - Underlying WM (neural fiber tracts)
  - Subcortical structures (deep GM nuclei)
- Control sensations, emotions, execution, memory,…

Cerebrum: structure and function



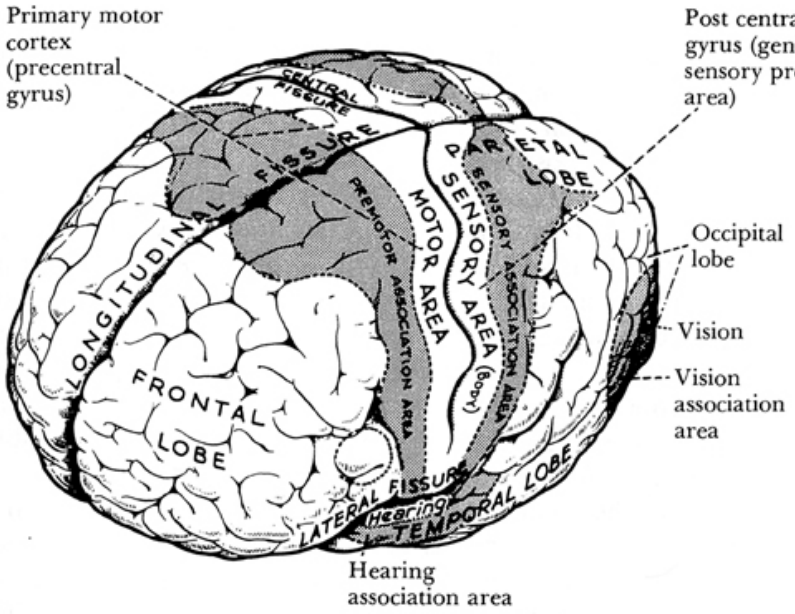
Four lobes of the brain

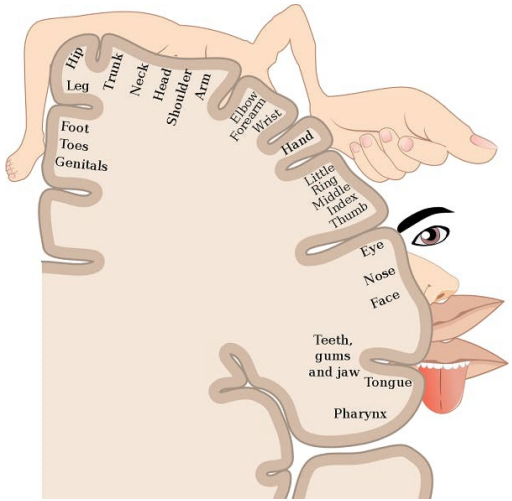


Functional maps

Photo credit: Wikipedia (Human brain, Lobes of the brain)

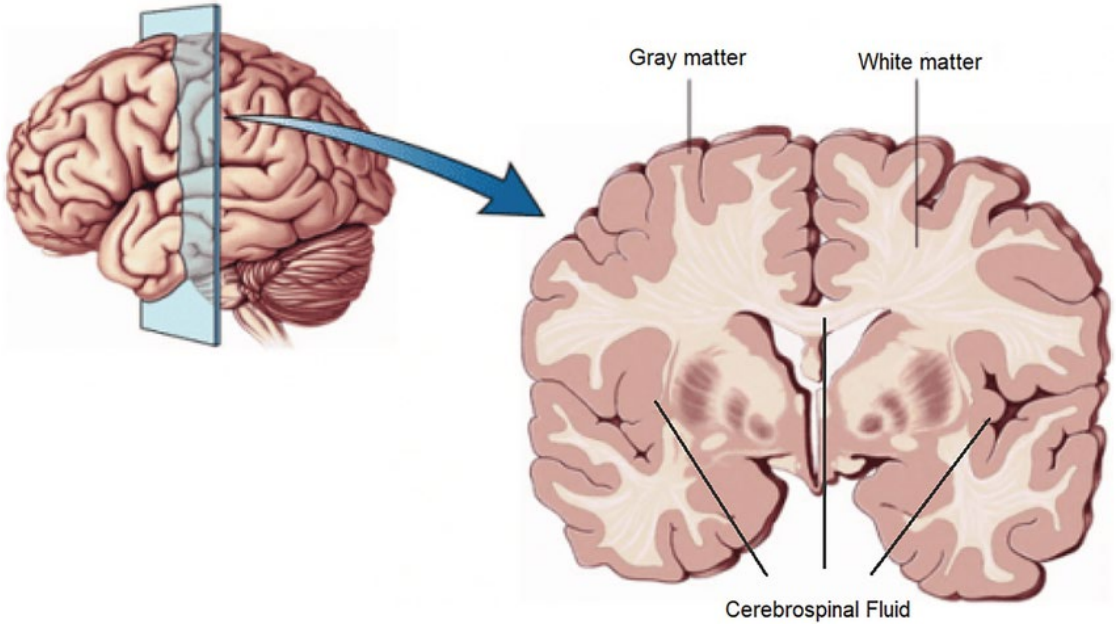
Functional anatomy

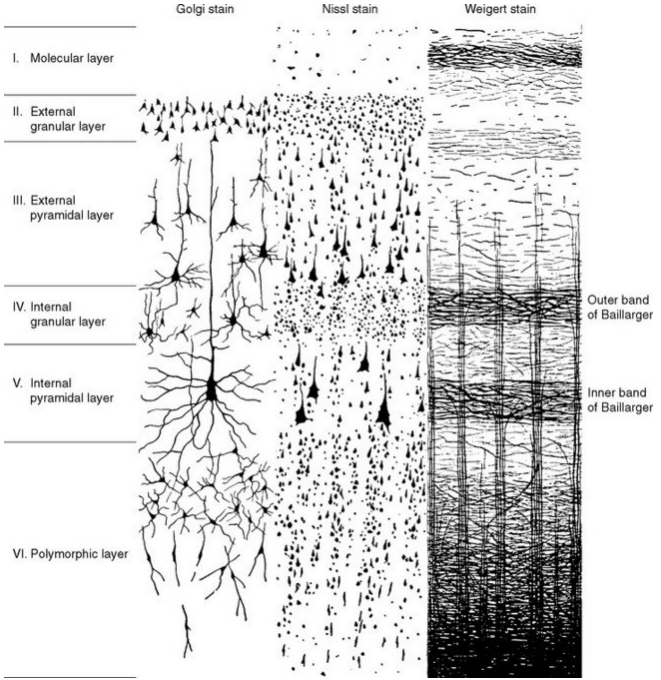




Homunculus of somatosensory cortex

Cerebral cortex



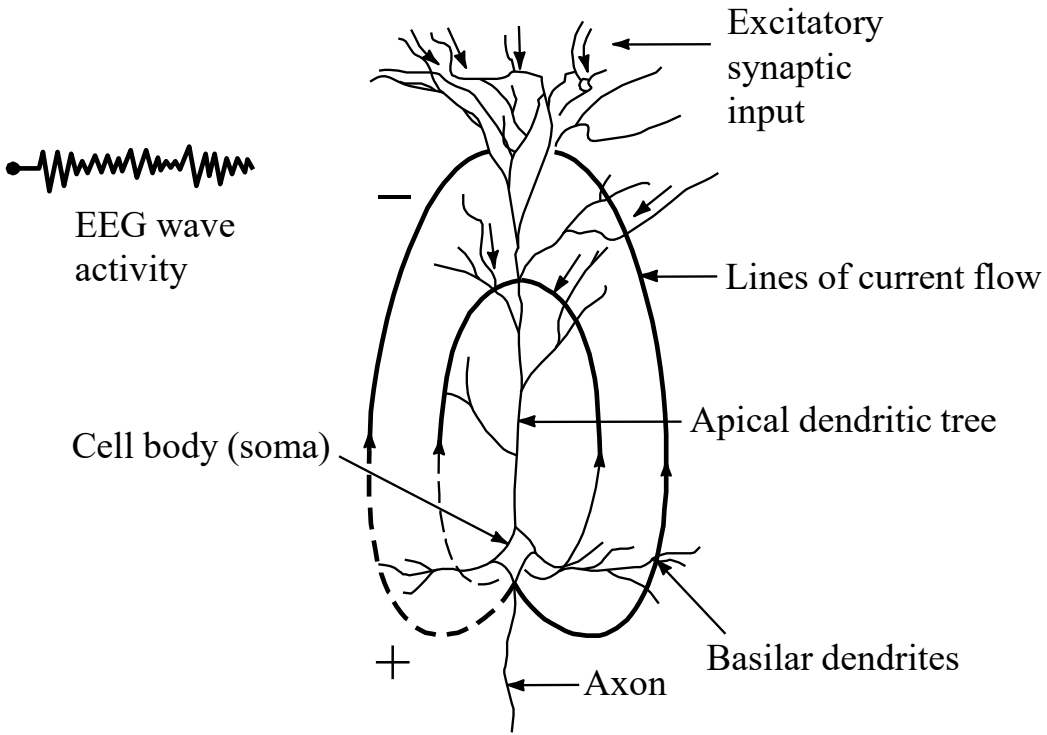


6 layers of cerebral cortex and pyramidal cells

Activation of cortex

- Activation potentials pass through pyramidal cells, which are well-aligned and vertically-oriented to the cortical surface, to transmit signals.
- A group of pyramidal cells firing AP simultaneously can generate larger electrical activity.

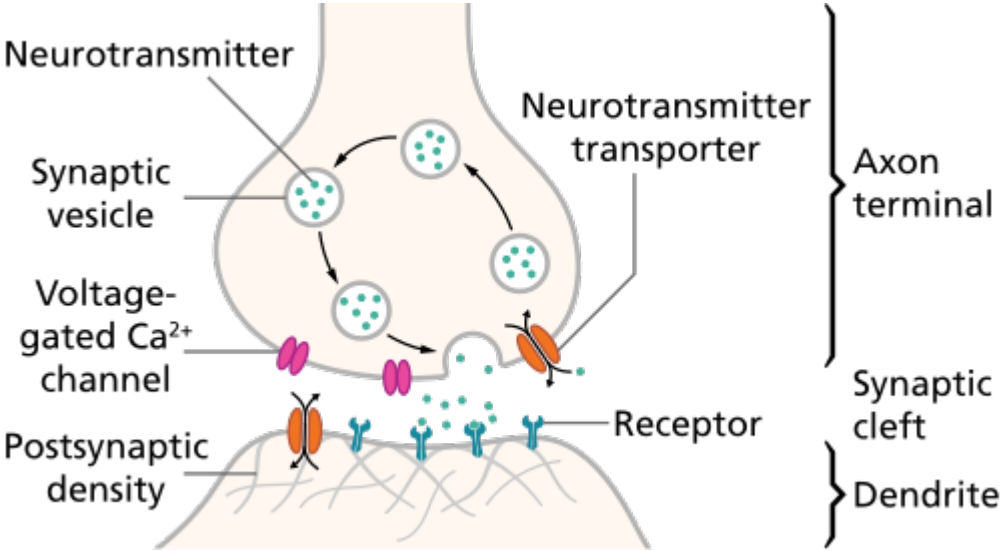
Pyramidal cell



ElectroEncephaloGraphy (EEG)

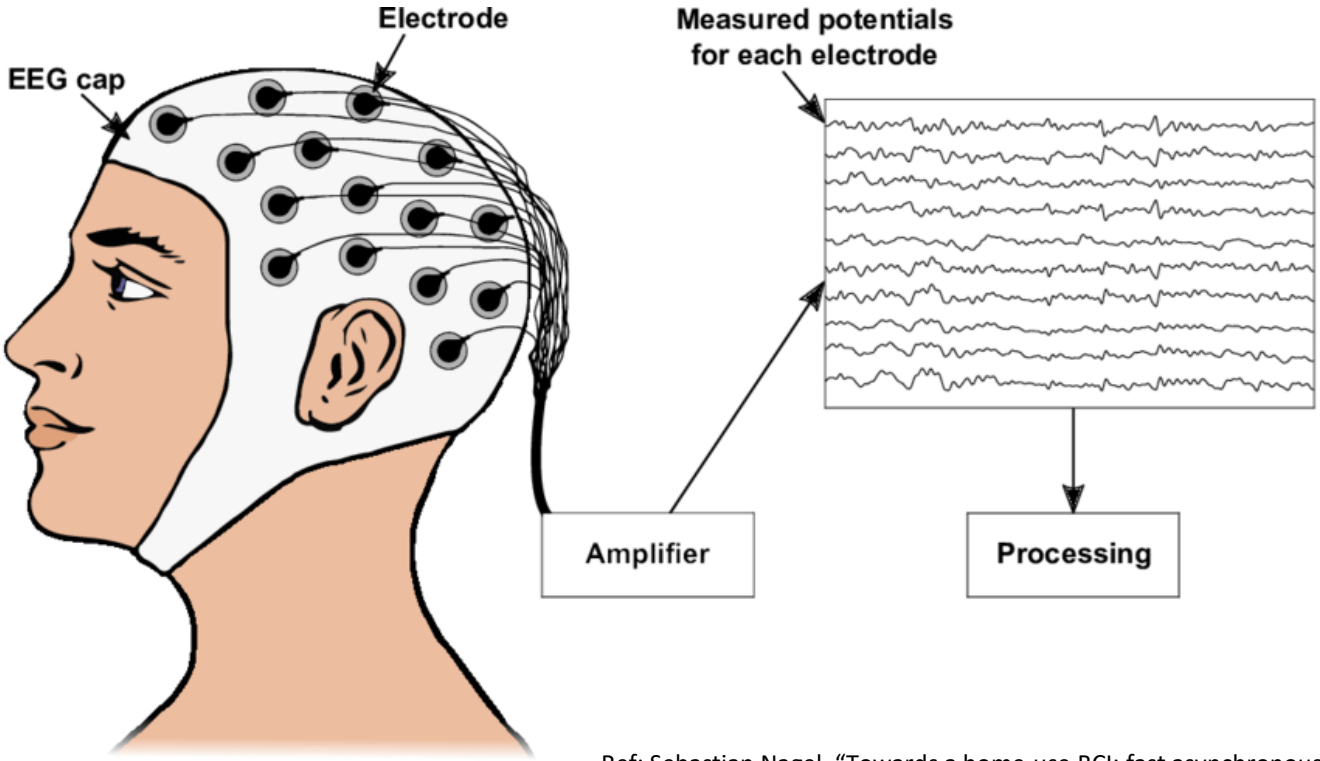
- Measurement of the electrical activities of the brain
- Non-invasive measurement
  - Using electrodes attached on subject's scalp
- Mainly representing the post-synaptic potentials/currents due to synchronous activation or suppression of a regional cortex

Action potential and synapses



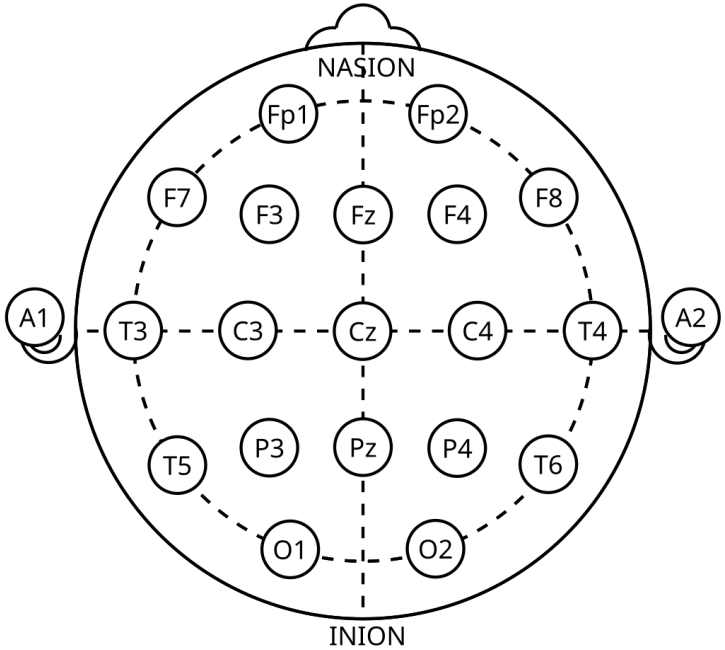
Release of neurotransmitters at the synapse is trigger by action potential and leads to activation of ion channels in post-synaptic membrane (dendrite).

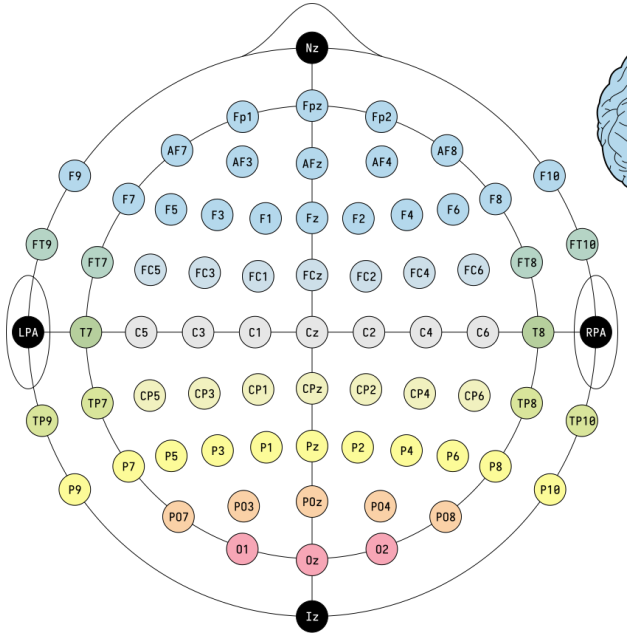
EEG

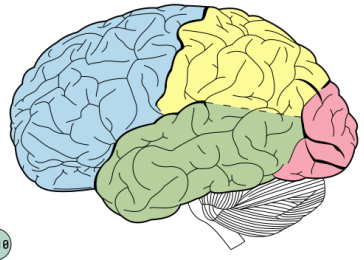


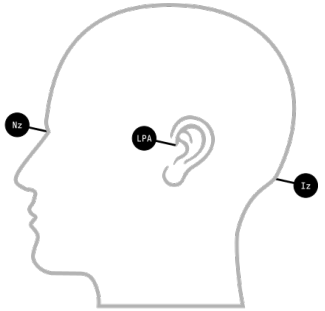
Ref: Sebastian Nagel, “Towards a home-use BCI: fast asynchronous control and robust non-control state detection.”, 2019,

Standard EEG electrode location









Fp: prefrontal, F: frontal, C: central, T: temporal, O: occipital.

Photo credit: Wikipedia (10-20 system EEG)

EEG?

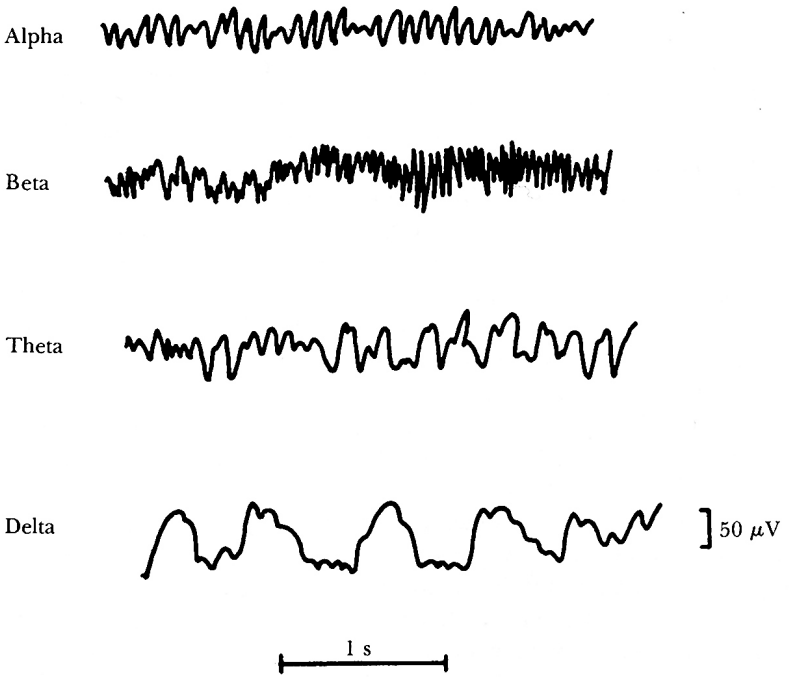
Random noise?

Photo credit: Wikipedia (Electroencephalography)

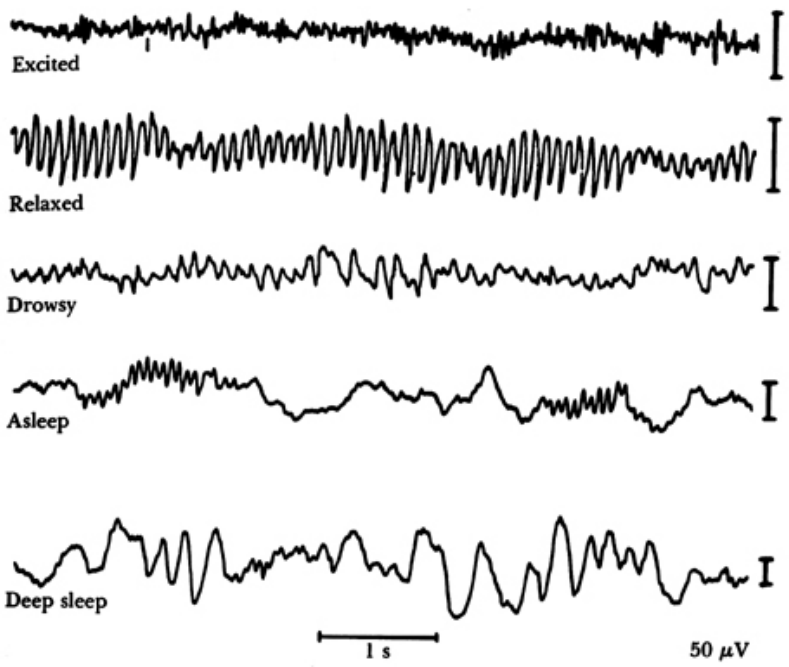
Patterns of EEG

- Reflect one's state of wakefulness
- Classification by its frequencies:
  - Alpha waves (8-13 Hz): awake and relax
  - Beta waves (14-30 Hz): intense activity
  - Theta waves (4-7 Hz): drowsiness
  - Delta waves (< 4 Hz): deep sleep

Patterns of EEG



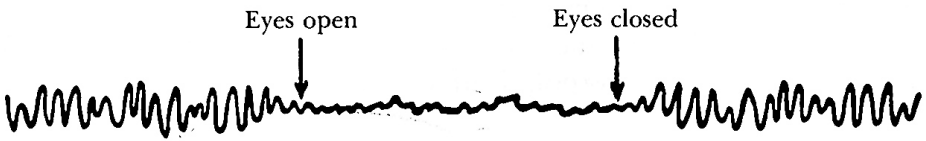
Normal EEG waves



EEG at various awake conditions

Properties of EEG

- Relatively weak in signal intensity
  - Usually no more than 100 μV
- Prone to electrical interferences
  - Even a blink of eyes



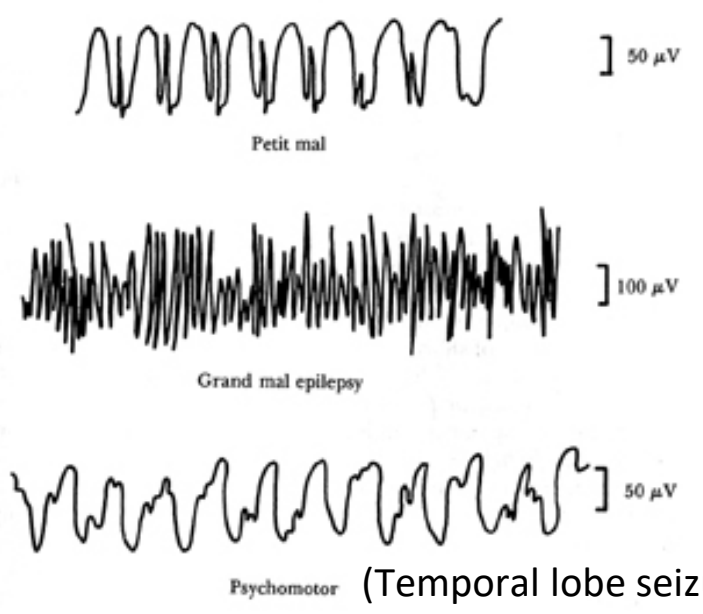
Webster et al. Medical Instrumentation: Application and Design, 3E (2020)

Applications of EEG

- Diagnosis of sleep disorder, coma, brain death, epilepsy…
- Research in neuroscience
  - Event-related potentials
  - Brain-computer interface

Abnormal EEG of epilepsy

- Epilepsy: an abnormal, excessive, and synchronized electrical discharge in neurons of a localized region or the whole brain.

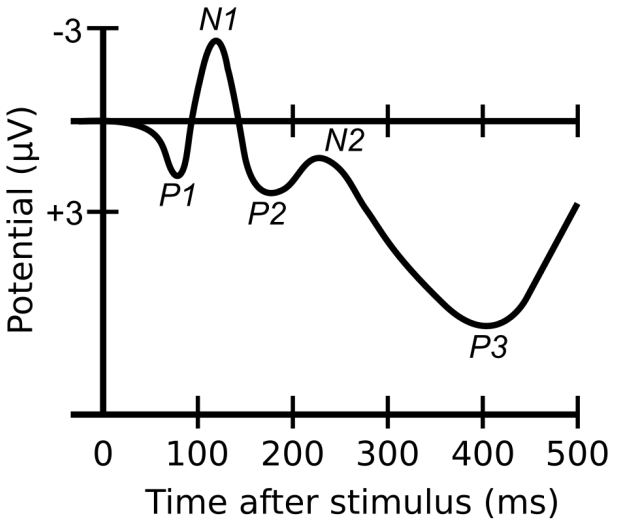


(Temporal lobe seizure)

Webster et al. Medical Instrumentation: Application and Design, 3E (2020)

Event-related potentials

- The electric response to a specific sensory, cognitive, or motor event.
  - Brain functional mapping



Brain-computer interface

- Tell what you're thinking from EEG?
  - To control the cursor (on the screen) and the robot arm.
- Brain-computer interface:
  - A communication link between the brain's electrical activity and an external device
  - EEG is one of the non-invasive BCIs

MagnetoEncephaloGraphy

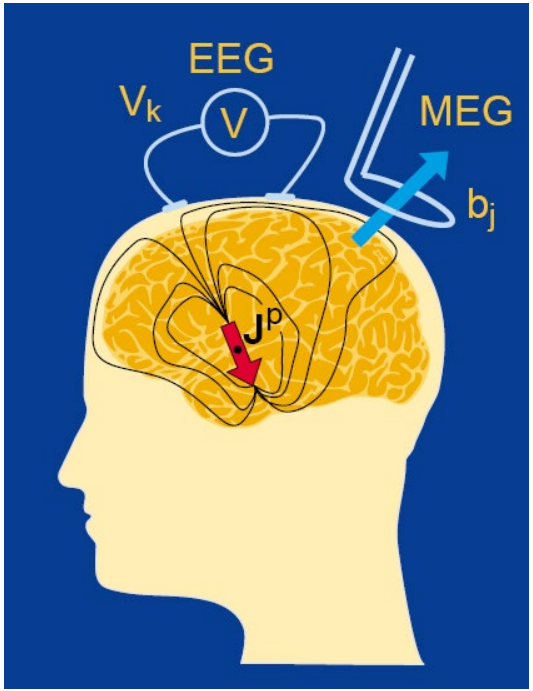
MEG

Reference:
MEG tutorials by Matti Hämäläinen,
MGH NMR Center, Charlestown, MA

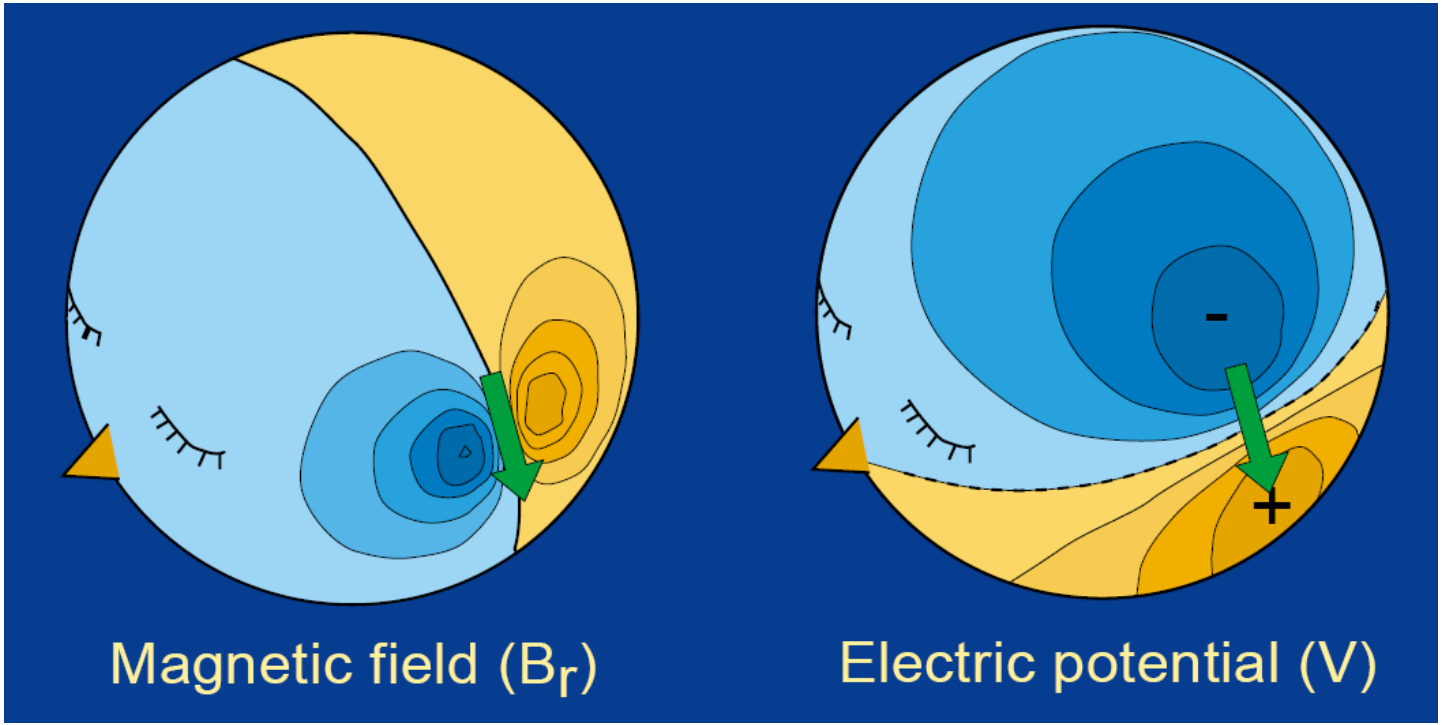
Electric activities produce magnetic field?

- Activation of neurons → weak electrical currents in cerebral cortex
  - Electric potential signals (EEG)
  - Magnetic field signals (MEG)
- Biot-Savart law

$$\vec{B}(\vec{r}) = \frac{\mu}{4\pi}\int_G \vec{J}(\vec{r})\frac{\vec{R}}{R^3}dV\,,\vec{R} = \vec{r} - \overrightarrow{r'}$$



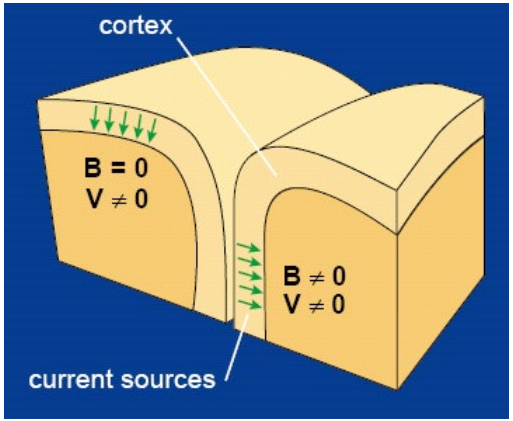
Ionic currents of neurons

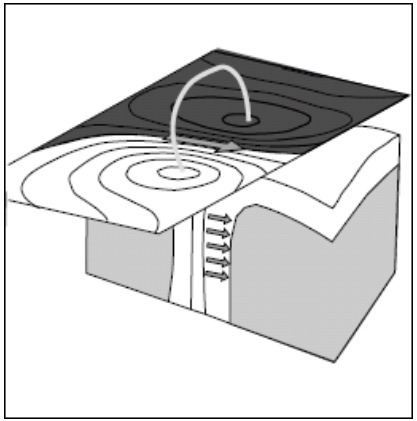


Green arrow: electric dipole inside the brain

Challenges of MEG

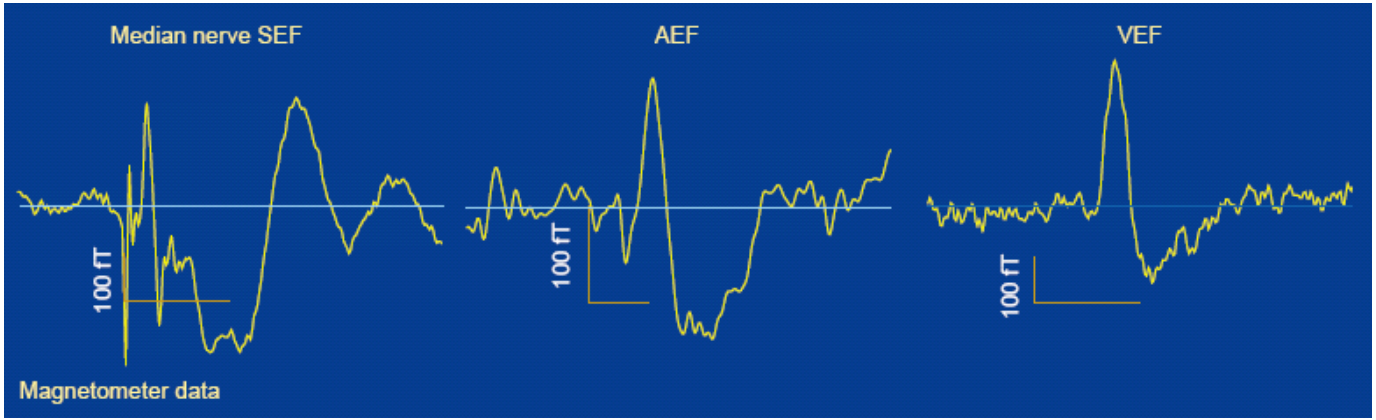
- Direction of most electric dipoles (aligned with pyramidal cells) is vertical to the cortical surface.
- The magnetic field (B) generated by radial components of electric dipoles (at gyri) are hardly detected.





More challenges of MEG

- Extremely weak magnetic field
  - $B < 10^{-9}$ Tesla for cortical activation
  - Earth's magnetic field ~ 5×10^{-5} Tesla

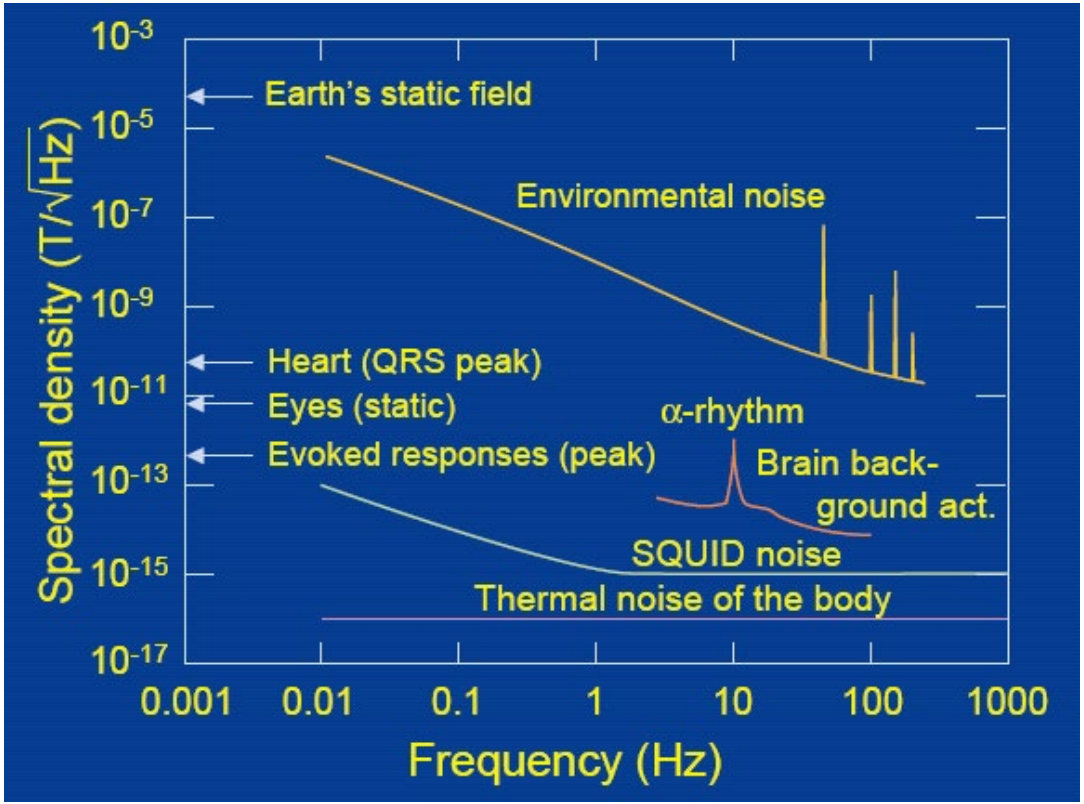


Somatosensory evoked field

Auditory evoked field

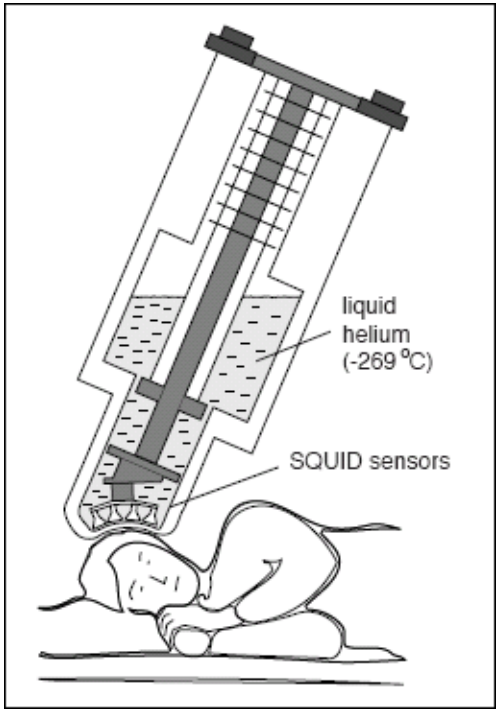
Visual evoked field

Field strength of MEG and interferences



Measurement of MEG

- Magnetically shielded room
- SQUID (superconducting quantum interference device)
  - Superconducting coil
  - Operate at 4 K (temperature)



Modern MEG scanner

Photo credit: Wikipedia (Magnetoencephalography, National Institute of Mental Health, National Institutes of Health, Department of Health and Human Services)

MEG vs EEG

- Both present signal from neural activities in high temporal resolution.
- EEG is more sensitive to the electric interferences. (Ex: static potential at scalp)
- MEG only detects tangential currents at sulci.
- Cost: MEG >> EEG

Summary

- Electroneurography
- Electromyography
- Electrocardiography
- Electroencephalography
  - Magnetoencephalography

生醫工程導論：電生理訊號

Reference chapters:

Chapter 4: The origin of biopotentials, “Medical Instrumentation: Application and Design”, John G. Webster.

MEG reference:

Matti Hämäläinen, Riitta Hari, RJ Ilmoniemi, Jukka Knuutila, and OV Lounasmaa, “Magnetoencephalography – theory, instrumentation, and applications to noninvasive studies of working human brain”, Review of modern physics, Vol.65, No.2, 1993