BME 501 – Introduction to Biomedical Engineering

Bioelectrical Engineering

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Class notes from: J. Malmivuo and R. Plonsey, *"Bioelectromagnetism,"* Oxford University Press. Also available online at:
http://butler.cc.tut.fi/~malmivuo/bem/bembook/index.htm

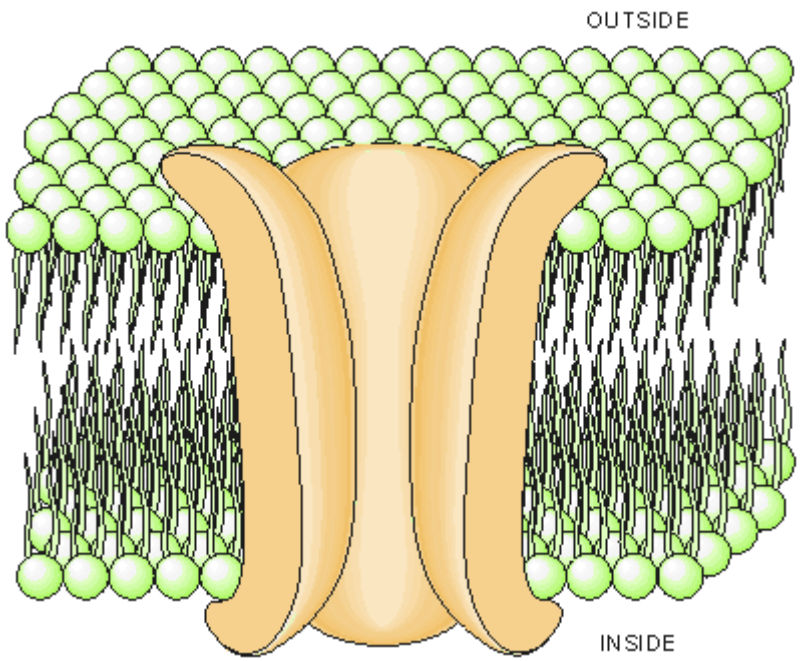
Introduction

- The first documented reference to the nervous system: in ancient Egyptian records*****.
  - The Edwin Smith Surgical Papyrus, a copy (dated 1700 B.C.)
  - a manuscript composed about 3500 B.C.,
  - contains the first use of the word "brain",
  - describes the coverings of the brain which was likened to the film and corrugations that are seen on the surface of molten copper as it cooled,

  ***** (Elsberg, 1931; Kandel and Schwartz, 1985).

- The basic unit of living tissue is the cell.
- Cells are specialized in their anatomy and physiology to perform different tasks.
- All cells exhibit a voltage difference across the cell membrane.
- Nerve cells and muscle cells are excitable (their cell membrane can produce electrochemical impulses and conduct them along the membrane).
- In muscle cells, this electric phenomenon is also associated with the contraction of the cell.
- In other cells, such as gland cells and ciliated cells, it is believed that the membrane voltage is important to the execution of cell function.
- The origin of the membrane voltage is the same in nerve cells as in muscle cells.
- In both cell types, the membrane generates an impulse as a consequence of excitation. This impulse propagates in both cell types in the same manner.

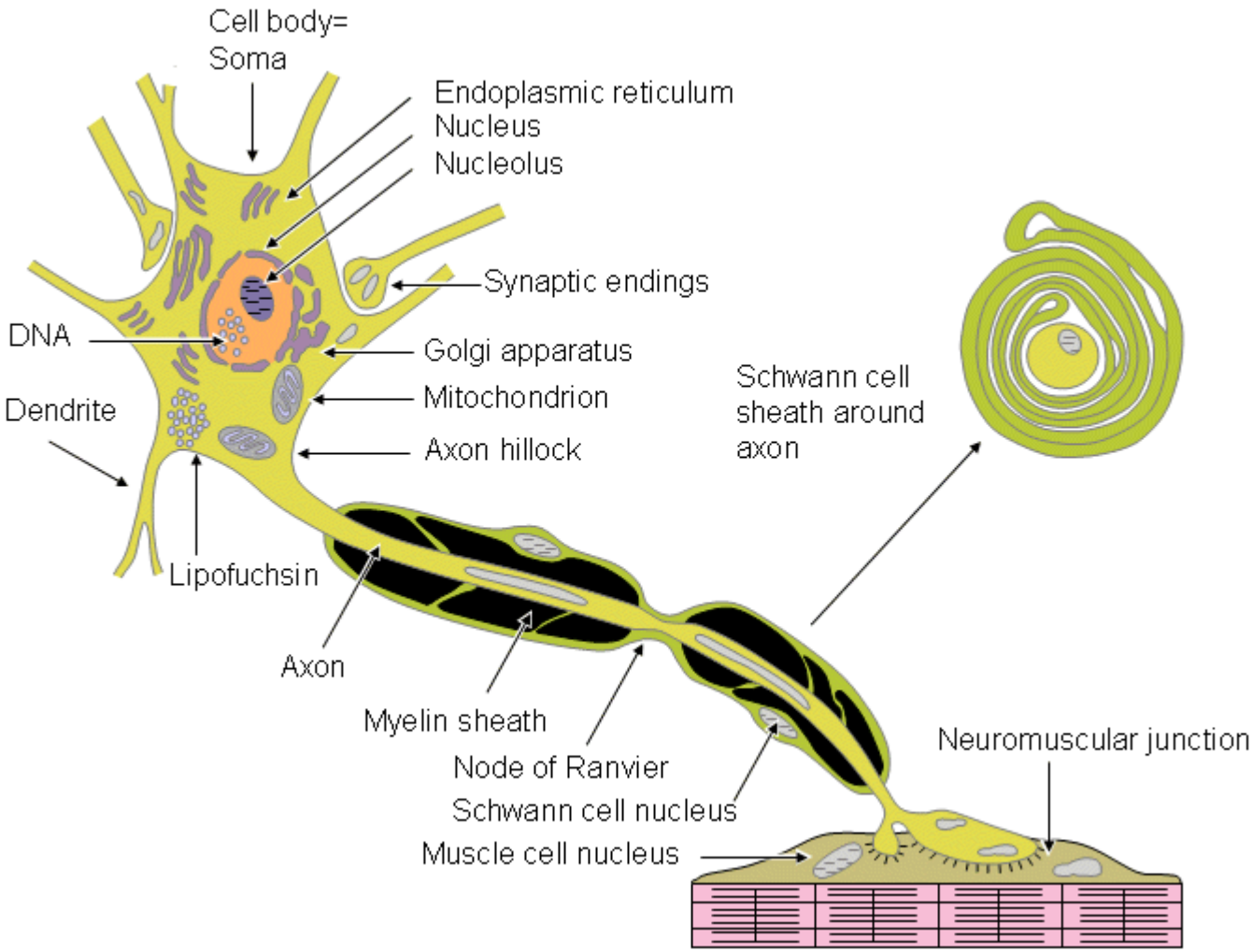
The cell membrane



•Two lipid layers, with the hydrophobic tails pointing inside the membrane (away from the aqueous intracellular and interstitial mediums).

•The macromolecular pores in the cell membrane form the ionic channels through which sodium, potassium, and chloride molecules flow through the membrane and generate the bioelectric phenomena.

The nerve cell



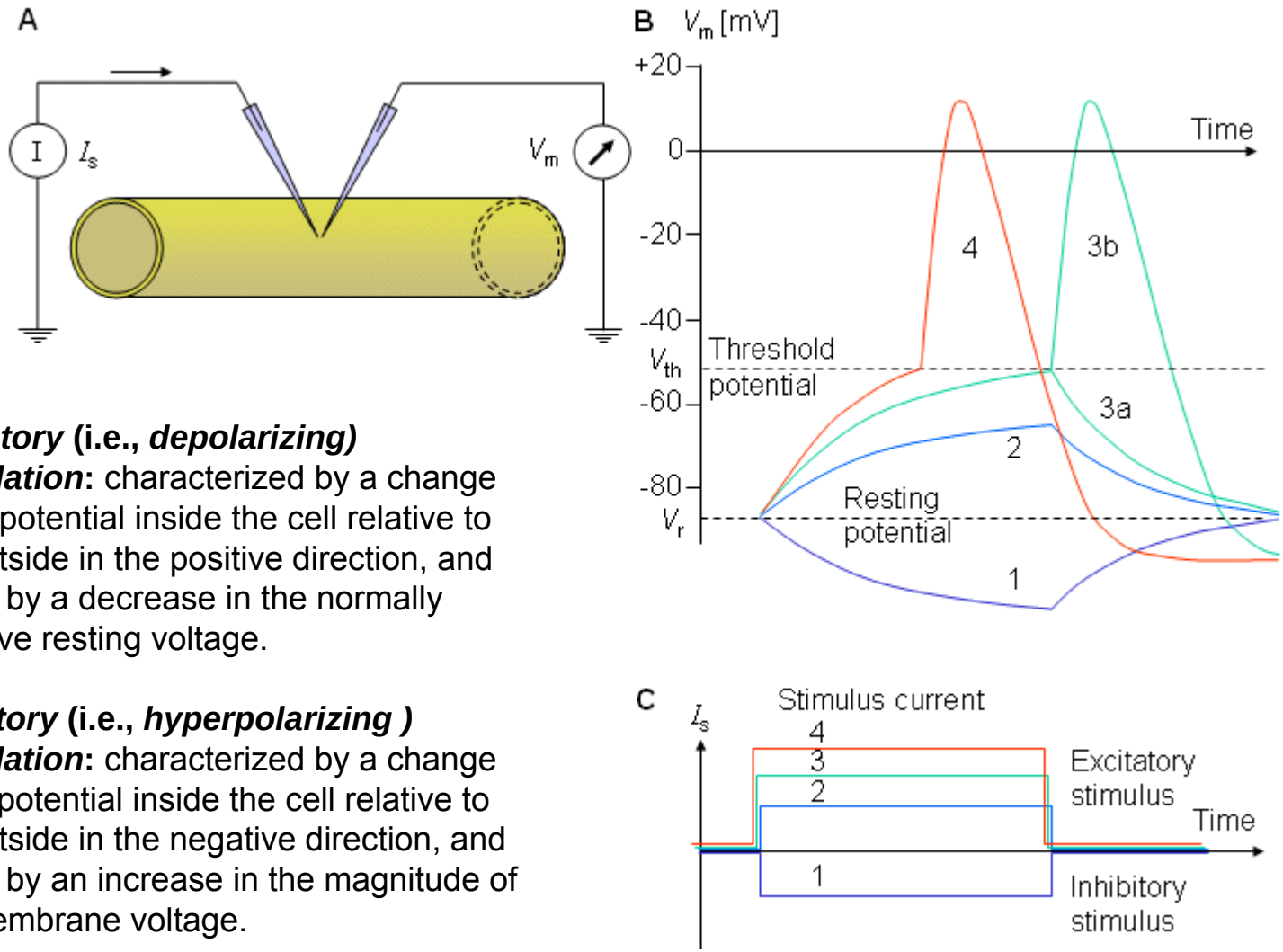
Bioelectric function of the nerve cell

- The *membrane voltage (transmembrane voltage)* (V_m) of an excitable cell: the potential at the inner surface (Φ_i) relative to that at the outer (Φ_o) surface of the membrane:

$$V_m = \Phi_i - \Phi_o.$$

- Classification for nerve cells developed by Theodore Holmes Bullock (1959):
  - a resting potential,
  - potential changes due to activity.

Excitability of nerve cell



***excitatory* (i.e., *depolarizing) stimulation*:** characterized by a change of the potential inside the cell relative to the outside in the positive direction, and hence by a decrease in the normally negative resting voltage.

***inhibitory* (i.e., *hyperpolarizing) stimulation*:** characterized by a change in the potential inside the cell relative to the outside in the negative direction, and hence by an increase in the magnitude of the membrane voltage.

Action Potential

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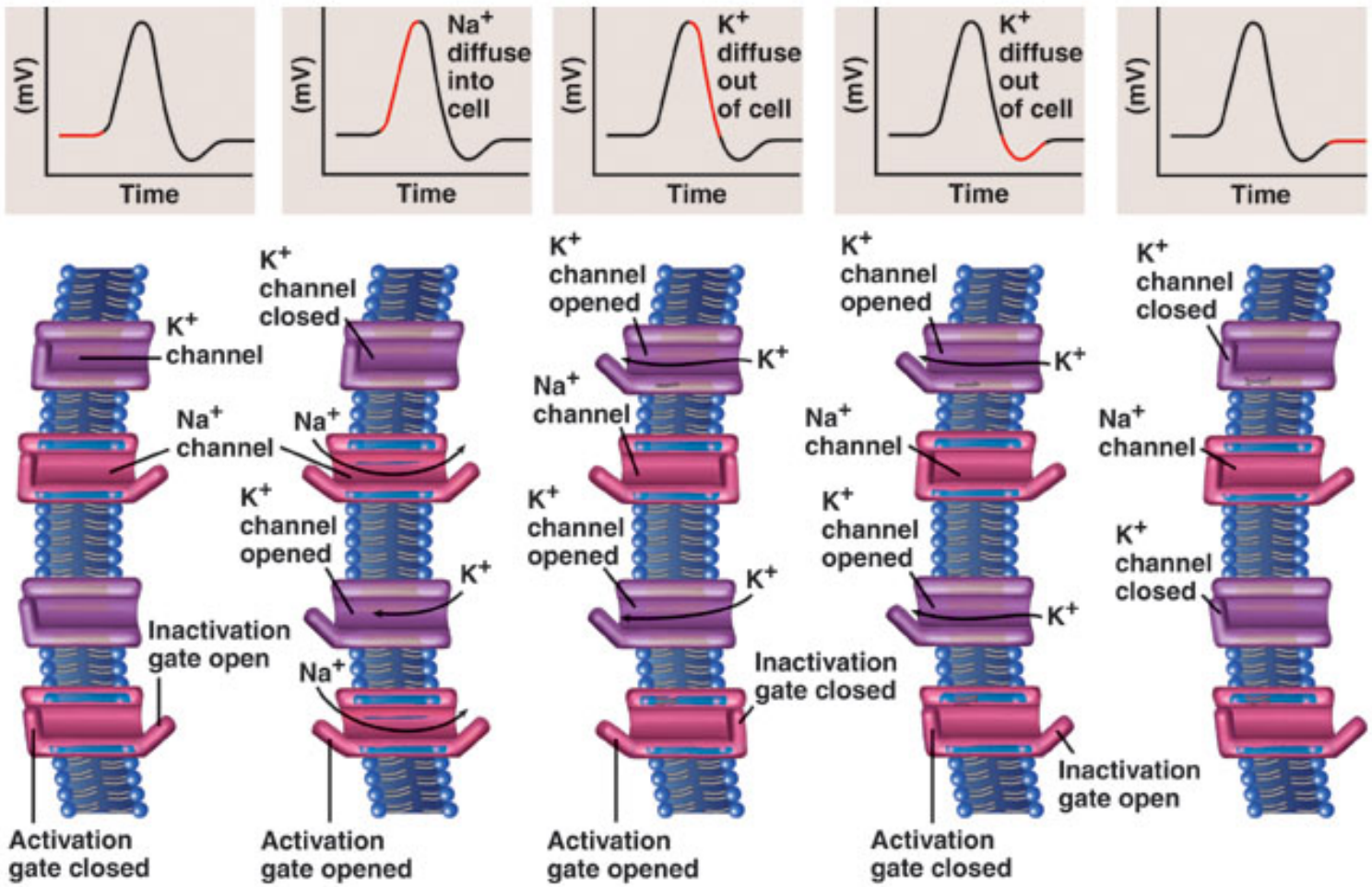
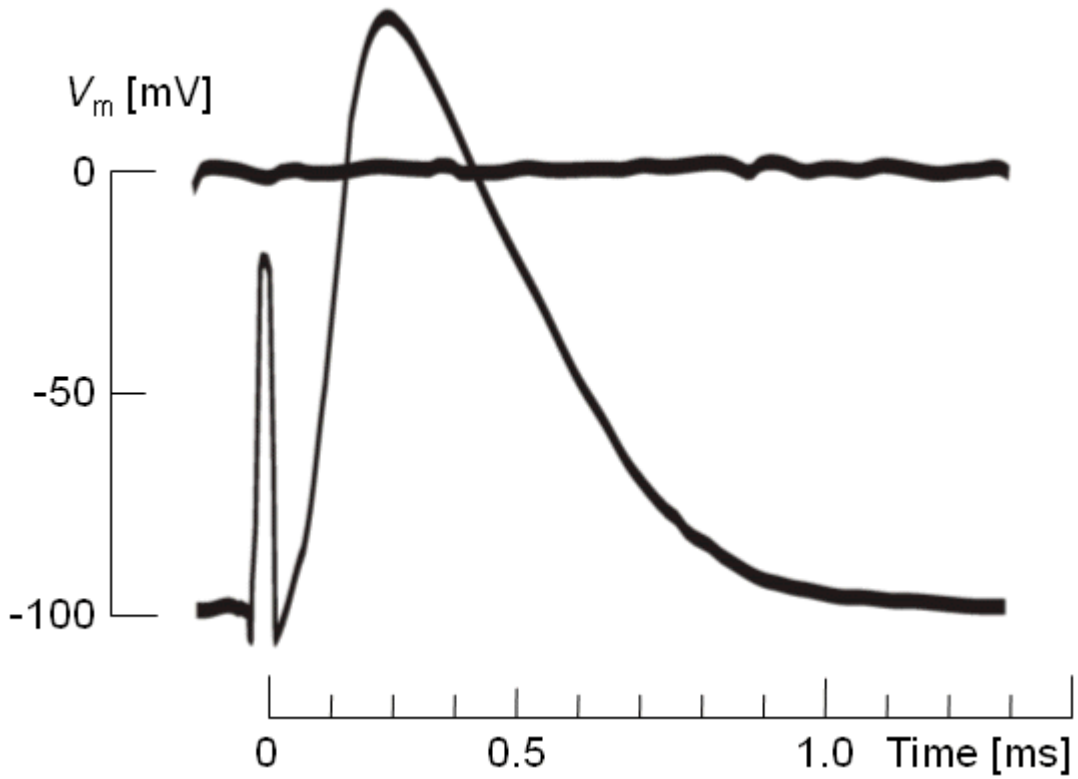


The generation of the activation

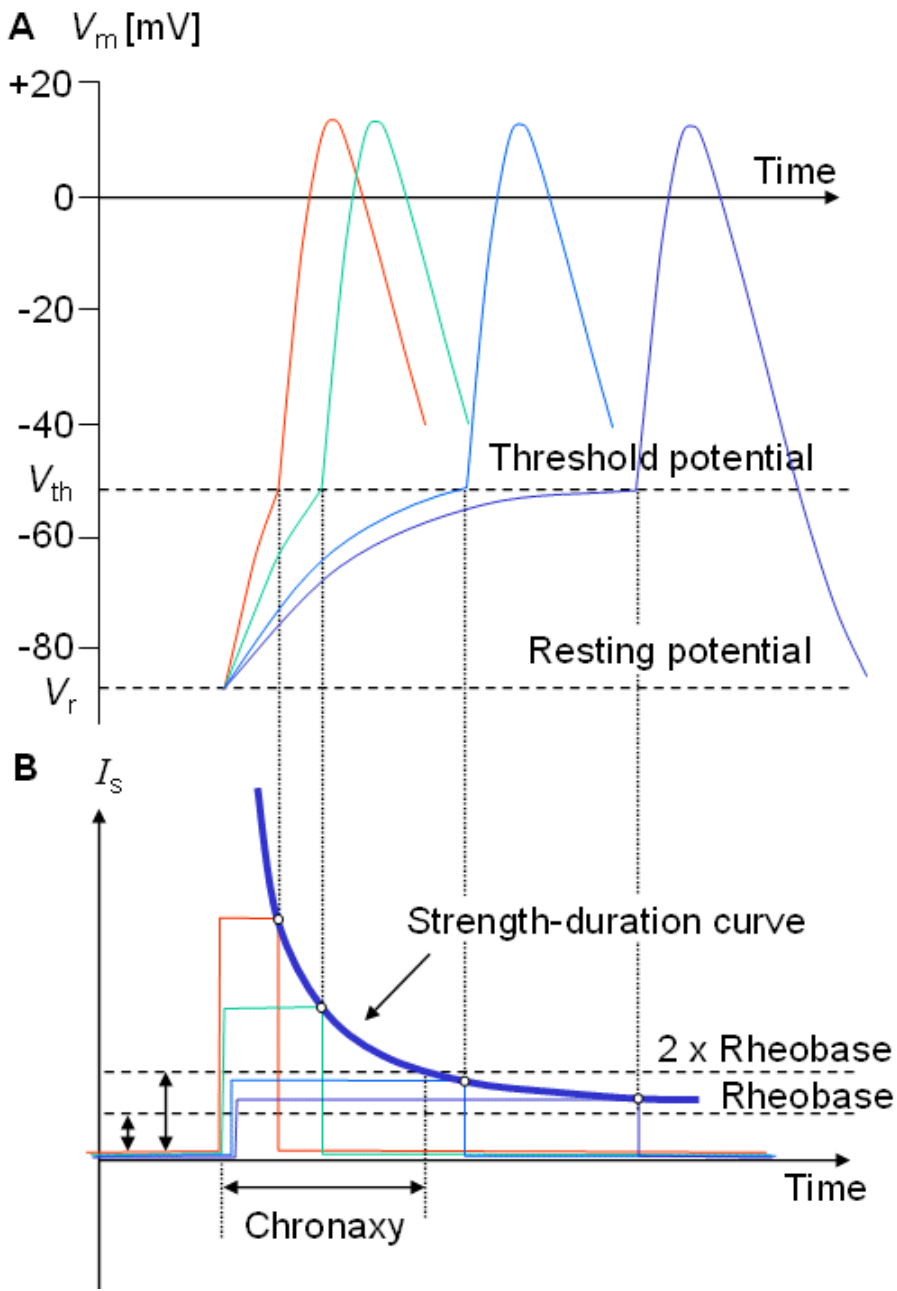
- $[Na+]_{out}$ is about 10 times higher than $[Na+]_{in}$,
- $[K+]_{in}$ is about 30 times higher than $[K+]_{out}$.
- Membrane is stimulated so that the TMP rises and reaches the threshold value
  - The sodium ion permeability increases very rapidly at first, allowing sodium ions to flow from outside to inside, making the inside more positive.
  - The inside reaches a potential of about +20 mV.
  - After that, the more slowly increasing potassium ion permeability allows potassium ions to flow from inside to outside, thus returning the intracellular potential to its resting value.
  - While at rest, following activation, the Na-K pump restores the ion concentrations inside and outside the membrane to their original values.



Nerve impulse recorded from a cat motoneuron following a transthreshold stimulus .

Strength-duration curve

- Represents the relationship between strength and duration of the stimulus
- The smallest current adequate to initiate activation is called the *rheobasic current* or *rheobase*.
- The time needed to excite the cell with twice rheobase current is called *chronaxy*.



Other properties of excitable membranes

- **Accommodation and habituation** denote the adaptation of the cell to a continuing or repetitive stimulus. This is characterized by a rise in the excitation threshold.

- **Facilitation** denotes an increase in the excitability of the cell; correspondingly, there is a decrease in the threshold.

- **Latency** denotes the delay between two events. In the present context, it refers to the time between application of a stimulus pulse and the beginning of the activation.

- **Refractory period:** Once activation has been initiated, the membrane is insensitive to new stimuli, no matter how large the magnitude. This phase is called the *absolute refractory period*. Near the end of the activation impulse, the cell may be activated, but only with a stimulus stronger than normal. This phase is called the *relative refractory period*.

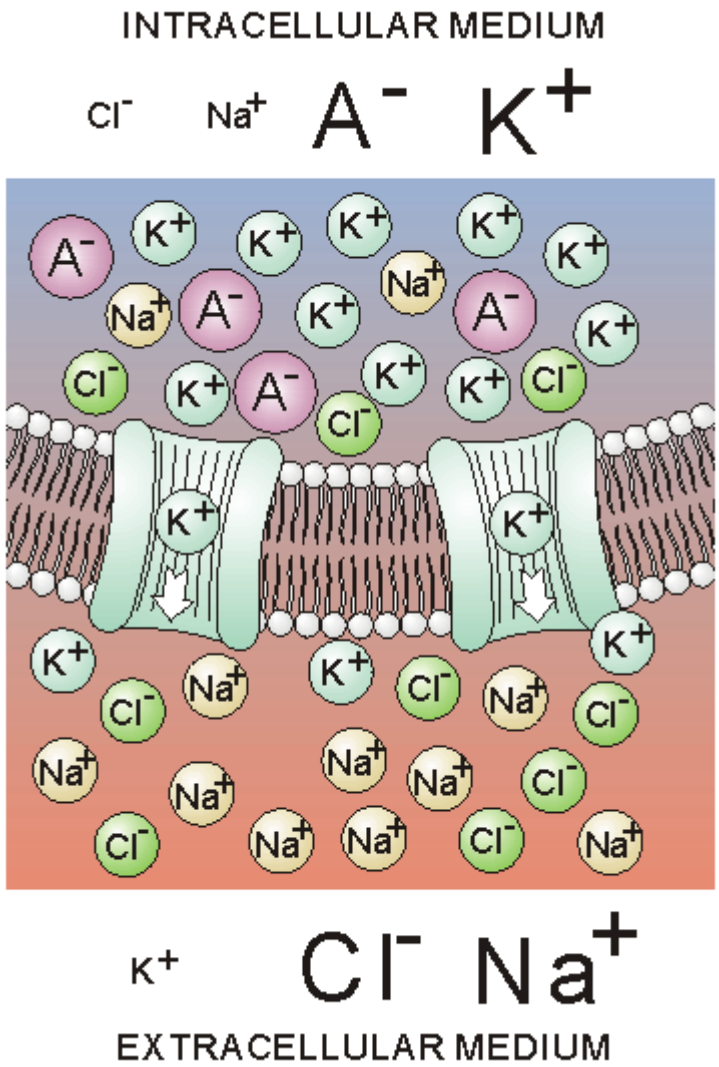
Other properties of excitable membranes

- **Temporal Mapping (Temporal Summation):** Suppose we apply a current pulse which below the threshold of excitation. That is the pulse is not enough to elicit an AP. Following this first pulse if a similar pulse is applied (with not so large a delay), then an AP may appear. This is so because the effect of the first pulse has not vanished yet and the second pulse becomes sufficient to increase the membrane voltage enough to start the positive feedback process which ends up in an AP.

- **Pulse Frequency Modulation:** If a step current is applied (its magnitude must be larger than $I_{rheobase}$), then a continuous series of APs are generated. The frequency of repetition of the APs depends on the magnitude of the current pulse.

- **Anode-Breakdown Excitation:** If a negative current pulse of long duration (or large magnitude) is applied, then at the termination of this current pulse one or more APs may appear.

Subthreshold membrane phenomena



- Ion flow mechanisms:
  - Diffusion
  - Drift (resulting from an electric field force)
- Nernst potential:

$$V_k = -\frac{RT}{z_k F} \ln \frac{c_{i,k}}{c_{o,k}}$$

V_k = equilibrium voltage for the k^{th} ion across the membrane $\Phi_i - \Phi_o$ i.e., the Nernst voltage [V]

R = gas constant [8.314 J/(mol·K)]

T = absolute temperature [K]

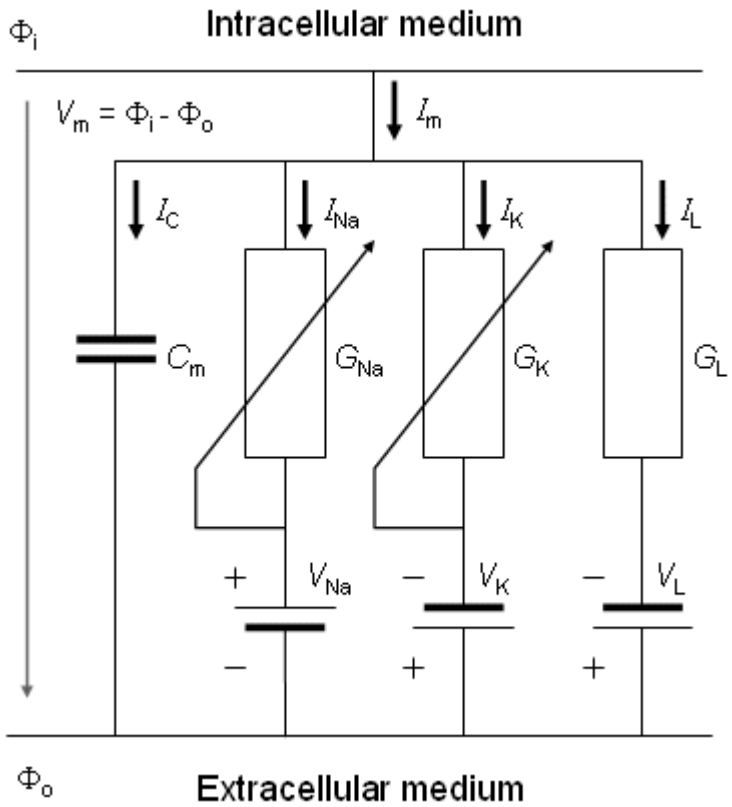
z_k = valence of the k^{th} ion

F = Faraday's constant [9.649 × 104 C/mol]

$c_{i,k}$ = intracellular concentration of the k^{th} ion

$c_{o,k}$ = extracellular concentration of the k^{th} ion

An electric circuit representation of a membrane patch



Hodgkin-Huxley membrane model

- Current carried by sodium ions (G_{Na} function of membrane potential and time)
- Current carried by potassium ions (G_K function of membrane potential and time)
- Current carried by other ions (designated leakage current, constituting mainly from chloride ions)
- Capacitive (displacement) current

At rest: $I_m = 0$.

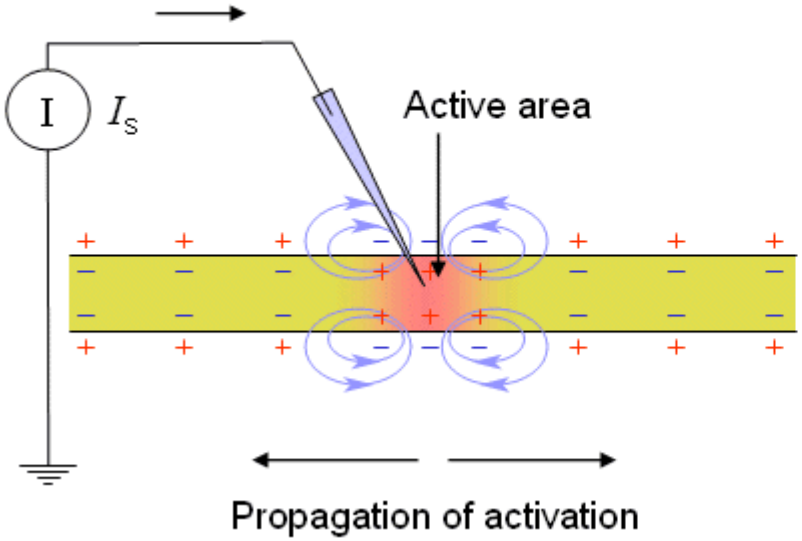
$$V_m = -\frac{RT}{F} \ln \frac{P_K c_{i,K} + P_{Na} c_{i,Na} + P_{Cl} c_{o,Cl}}{P_K c_{o,K} + P_{Na} c_{o,Na} + P_{Cl} c_{i,Cl}}$$

TMP value at rest

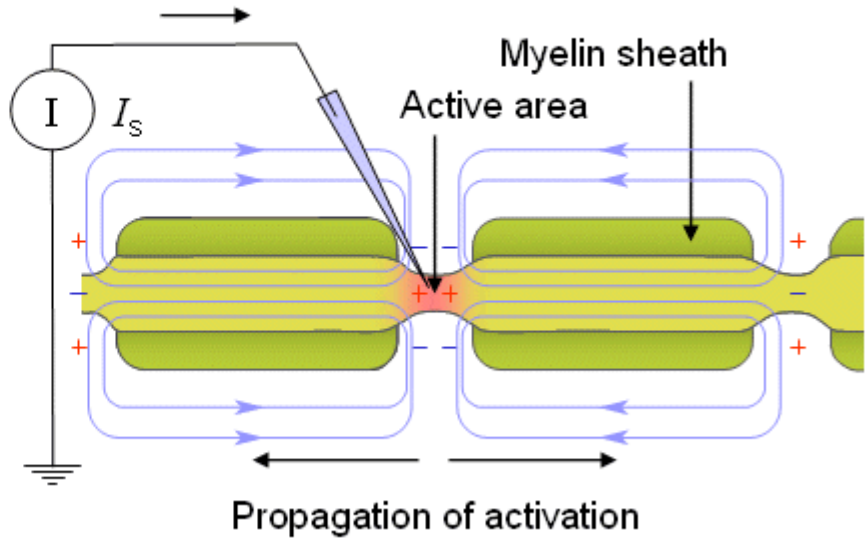
Conduction of the nerve impulse in an axon

- The activation propagates in an axon as an unattenuated nerve impulse (Ludvig Hermann, 1872, 1905)
- Although excitatory inputs may be seen in the dendrites and/or soma, activation originates normally only in the soma.
- Activation in the form of the nerve impulse (action potential) is first seen in the root of the axon (the initial segment of the axon, ie. the axon hillock). From there it propagates along the axon.
- If excitation is initiated artificially somewhere along the axon, propagation then takes place in both directions from the stimulus site.
- The conduction velocity depends on the electric properties and the geometry of the axon.

continuous conduction in an unmyelinated axon



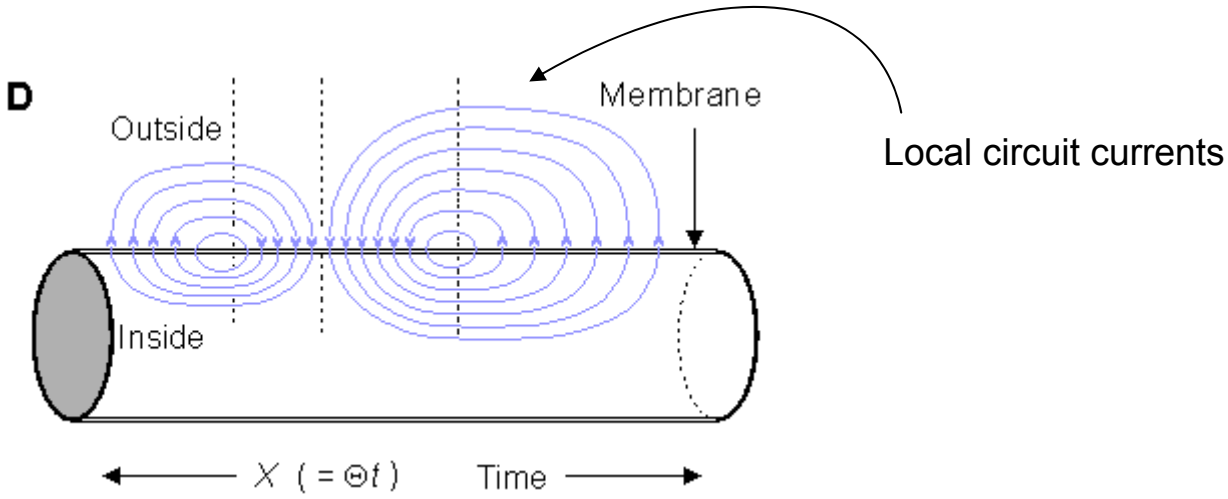
saltatory conduction in a myelinated axon

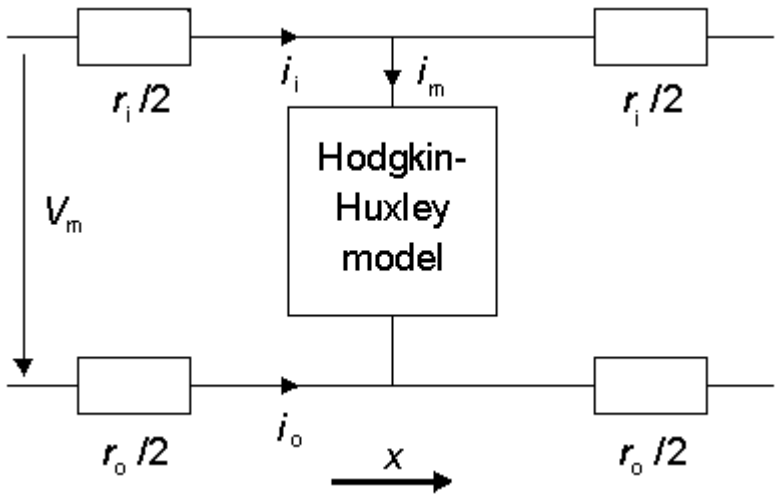


A myelinated axon (surrounded by the myelin sheath) can produce a nerve impulse only at the nodes of Ranvier. In these axons the nerve impulse propagates from one node to another Such a propagation is called *saltatory conduction* (*saltare*, "to dance" in Latin).

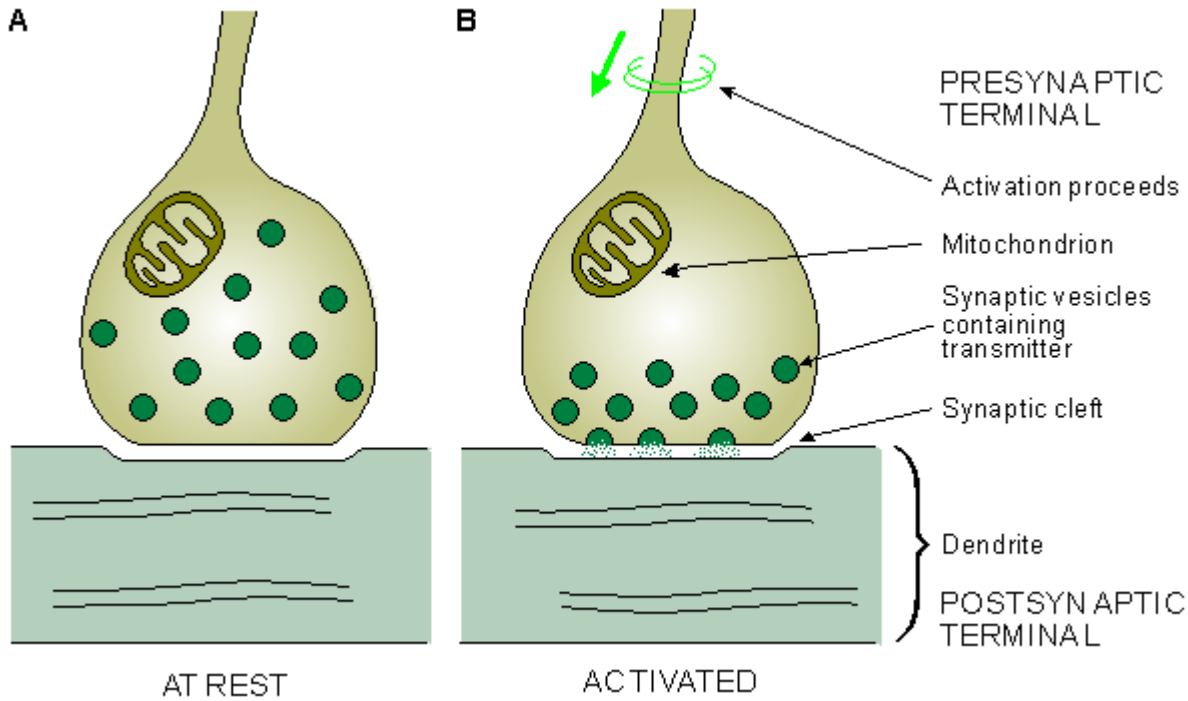
The membrane capacitance per unit length of a myelinated axon is much smaller than in an unmyelinated axon. Therefore, the myelin sheath increases the conduction velocity.

Propagation of nerve impulse





Synaptic transmission



1. The neurotransmitter is manufactured by the neuron and stored in vesicles at the axon terminal
2. When the action potential reaches the axon terminal, it causes the vesicles to release the neurotransmitter molecules into the synaptic cleft
3. The neurotransmitter diffuses across the cleft and binds to receptors on the post-synaptic cell.
4. The activated receptors cause changes in the activity of the post-synaptic neuron
5. The neurotransmitter molecules are released from the receptors and diffuse back into the synaptic cleft
6. The neurotransmitter is re-absorbed by the post synaptic neuron. This process is known as *Reuptake*

Electromyography (EMG)

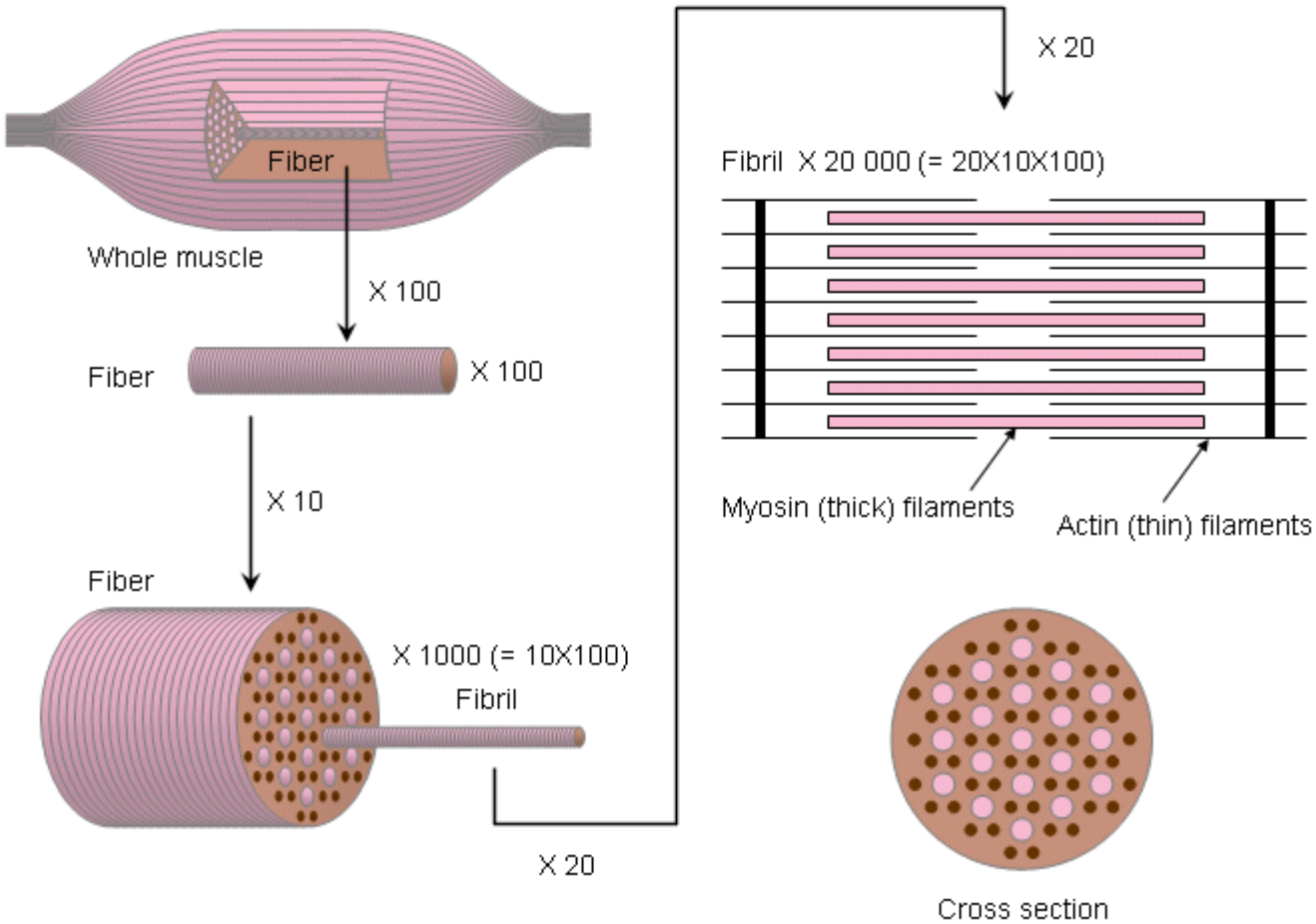
The muscle cell

- *Smooth muscles:* involuntary (i.e., they cannot be controlled voluntarily), found in the digestive tract, in the wall of the trachea, uterus, and bladder. The contraction of smooth muscle is controlled from the brain through the autonomic nervous system.

- *Striated muscles (skeletal muscles):* connected to the bones via tendons. Such muscles are voluntary and form an essential part of the organ of support and motion.

- *Cardiac muscle:* also striated, but differs in other ways from skeletal muscle:
  - It is involuntary,
  - When excited, it generates a much longer electric impulse than does skeletal muscle, lasting about 300 ms. Correspondingly, the mechanical contraction also lasts longer.
  - The electric activity of one muscle cell spreads to all other surrounding muscle cells, owing to an elaborate system of intercellular junctions.

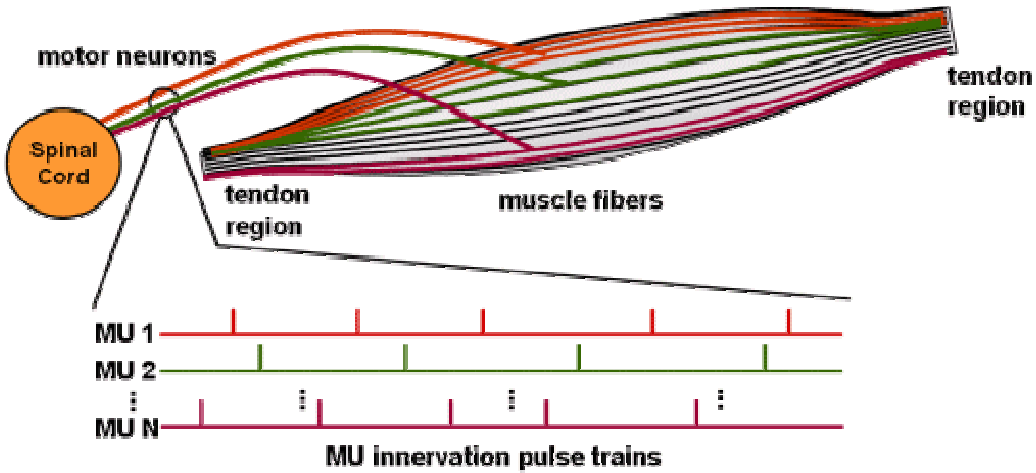
Anatomy of striated muscle



The fundamental physiological unit is the fiber.

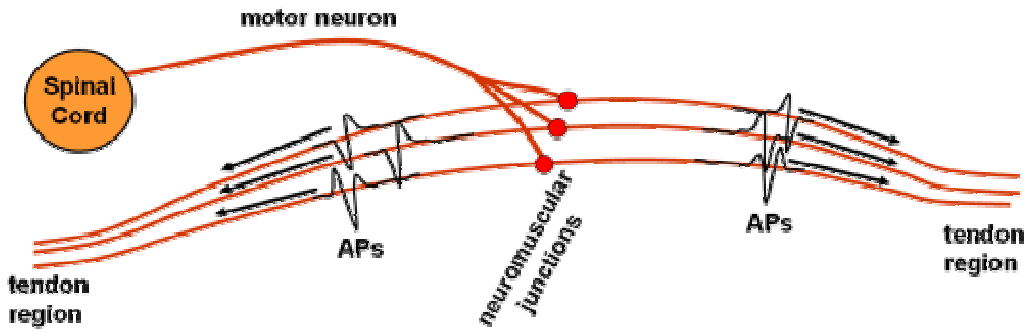
EMG

- detects the electrical potential generated by muscle cells when these cells contract, and also when the cells are at rest.
- EMG signals are composed of up of superimposed motor unit action potentials (MUAPs) from several motor units.
  - A motor unit: one motor neuron and all of the muscle fibers it innervates
- For a thorough analysis, the measured EMG signals can be decomposed into their constituent MUAPs.
- MUAPs from different motor units tend to have different characteristic shapes, while MUAPs recorded by the same electrode from the same motor unit are typically similar.
- MUAP size and shape depend on where the electrode is located with respect to the fibers and so can appear to be different if the electrode moves position.
- EMG decomposition is non-trivial, although many methods have been proposed.



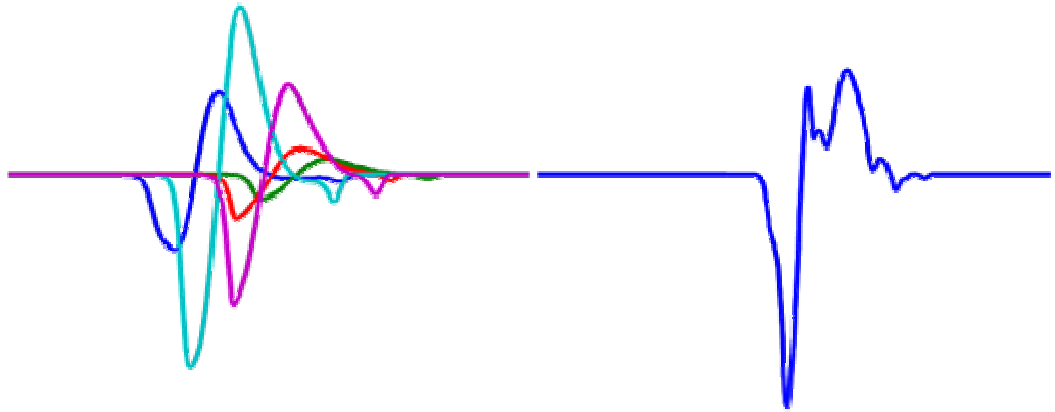
Schematic picture of human muscle with different Motor Units (MU).

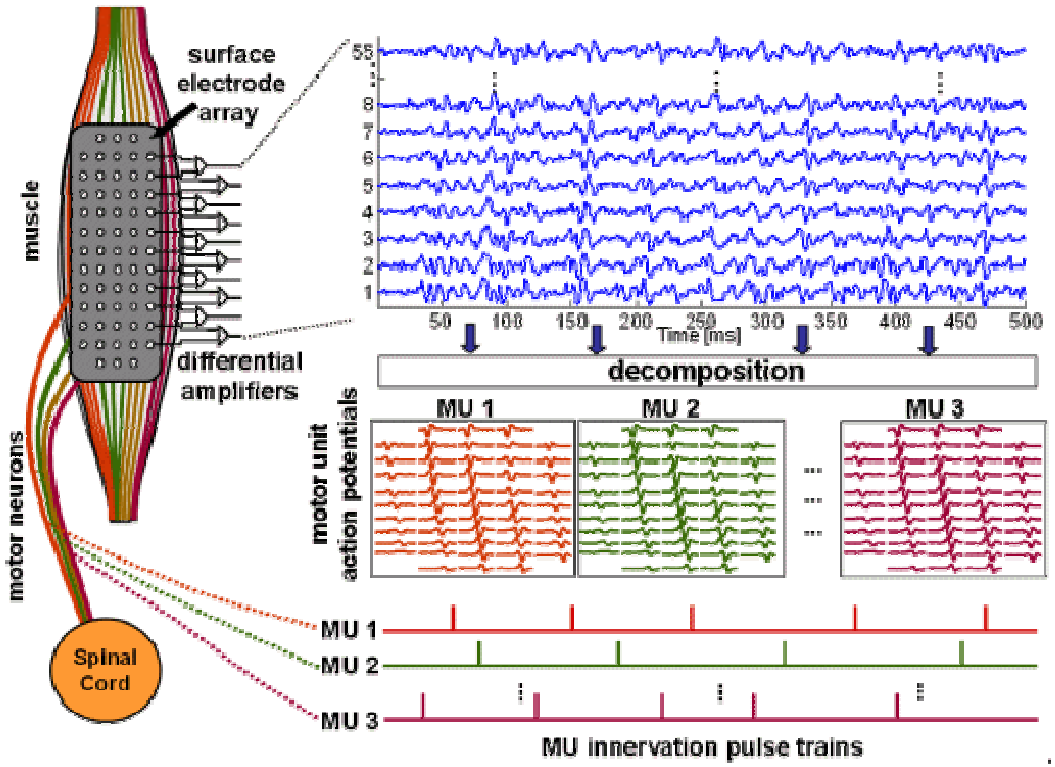
Schematic picture of individual motor unit with traveling Action Potentials (APs).



http://storm.uni-mb.si/semg/index.html

Contributions from individual MUs (left), and their temporal summation (superimposition) as detected by the pick-up electrode (right).





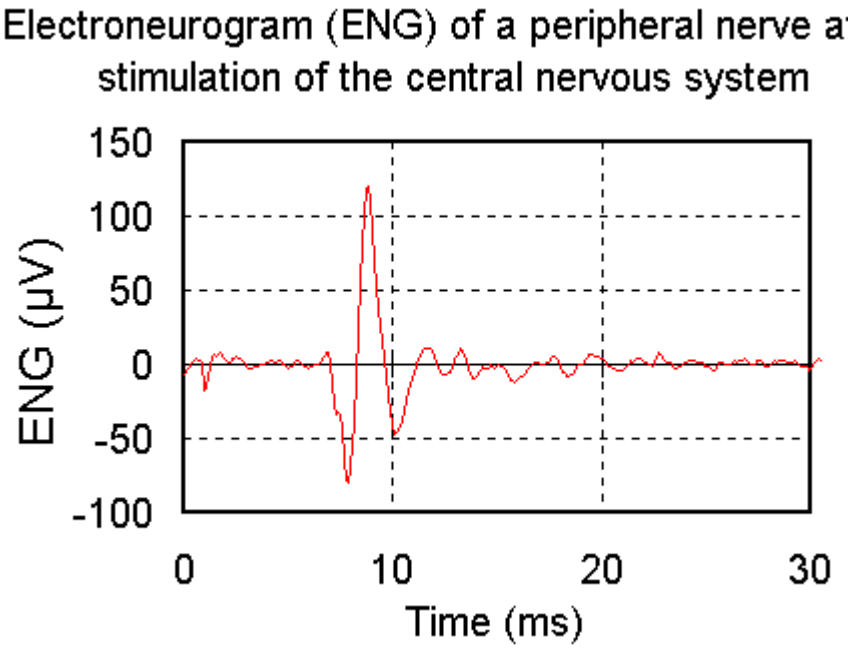
Schematic drawing of surface EMG signals generation (left), acquisition (top) and decomposition (bottom right).

- http://storm.uni-mb.si/semg/index.html

Electroneurography (ENG)

ENG

a method used to visualize directly recorded electrical activity of neurons in the central nervous system (brain, spinal cord) or the peripheral nervous system (nerves, ganglions)



recorded with a monopolar cuff electrode on the ulnaris nerve of a sheep

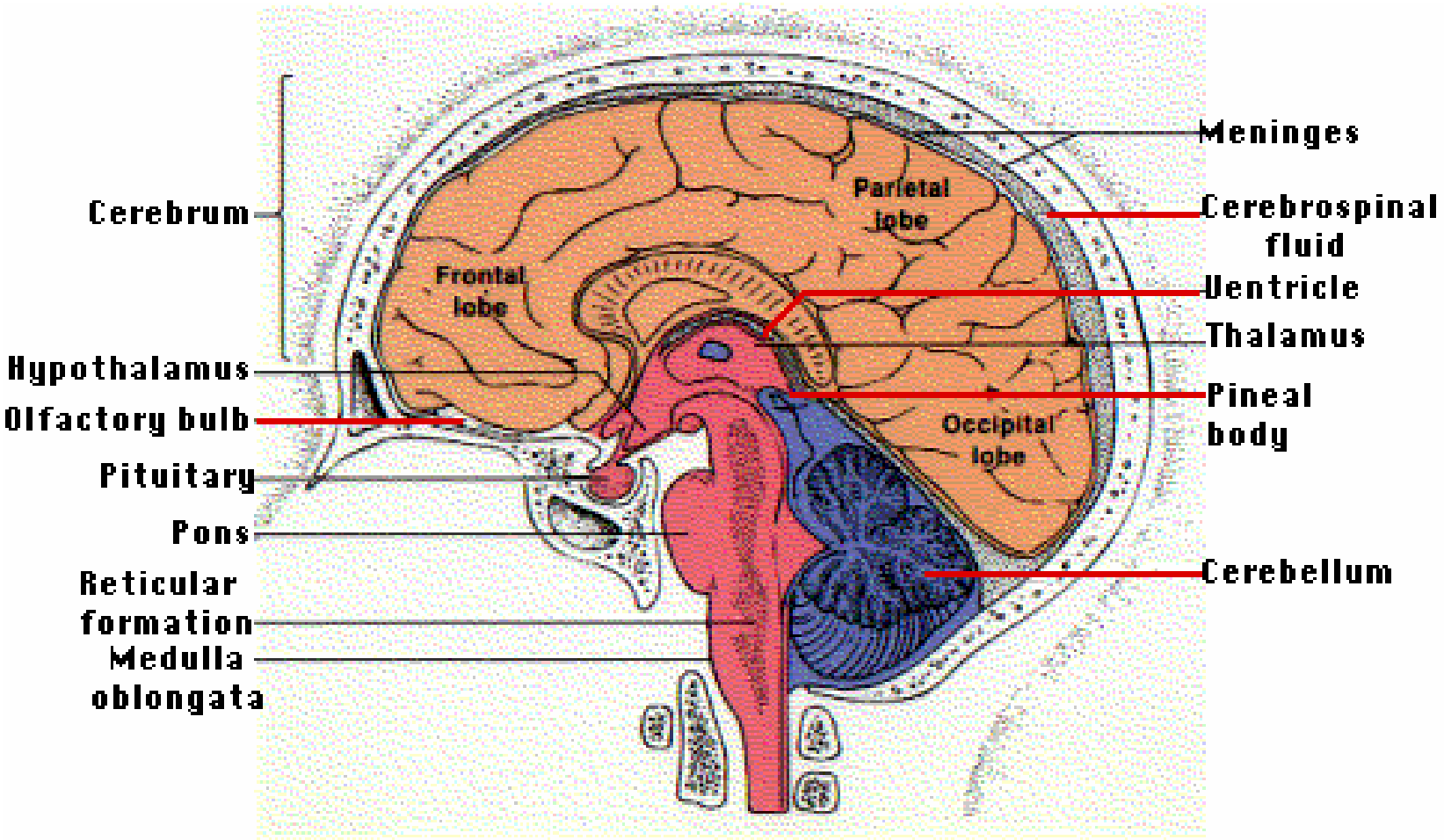
http://www.meduniwien.ac.at/zbmtp/bmt/information/fesdaq/

Electroensephalography (EEG)

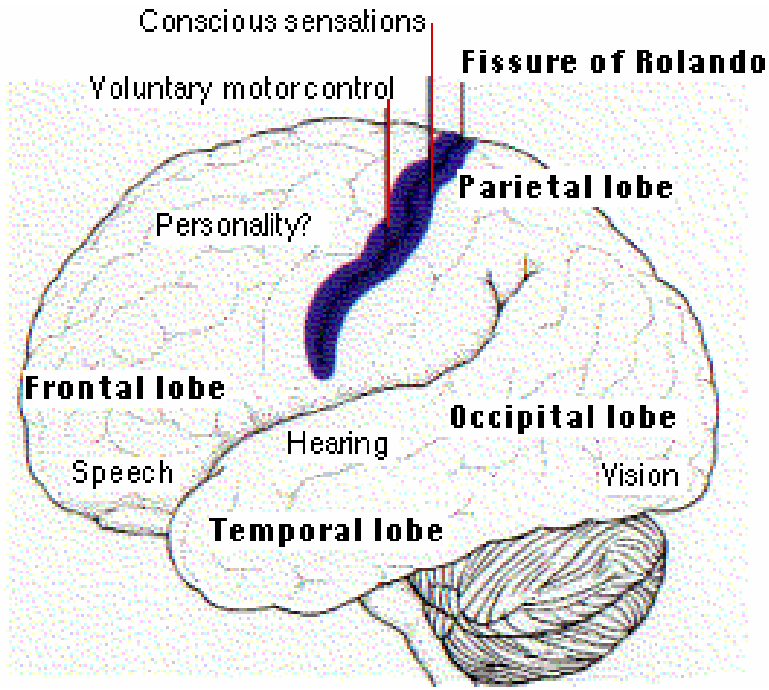
The Brain

- receives sensory input from the spinal cord as well as from its own nerves (e.g., olfactory and optic nerves)
- devotes most of its volume (and computational power) to processing its various sensory inputs and initiating appropriate - and coordinated - motor outputs.

Human Brain


Cerebrum
Hypothalamus
Olfactory bulb
Pituitary
Pons
Reticular formation
Medulla oblongata
Frontal lobe
Parietal lobe
Occipital lobe
Meninges
Cerebrospinal fluid
Ventricle
Thalamus
Pineal body
Cerebellum

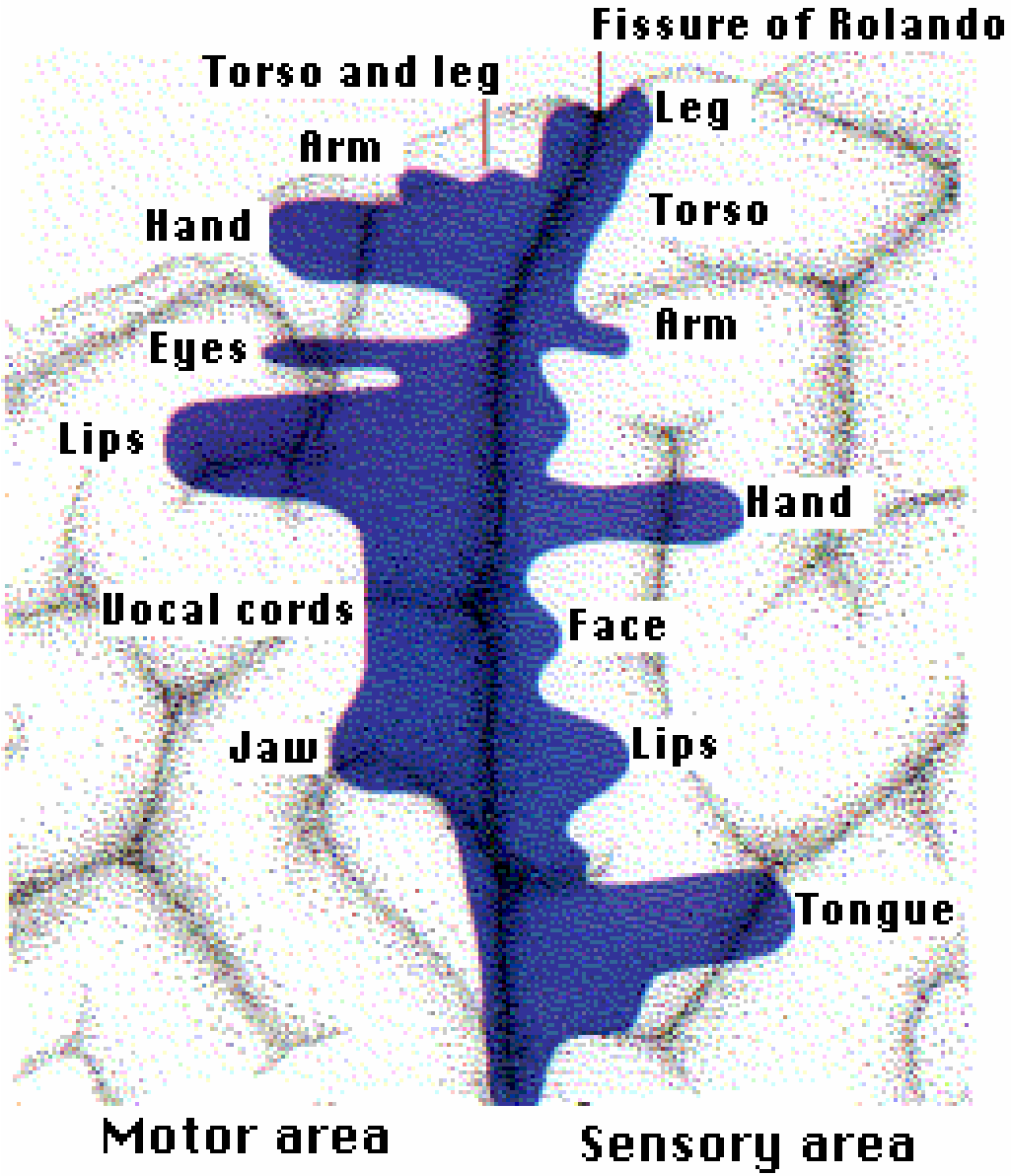
The Cerebral Hemispheres



- frontal lobe
- parietal lobe
- occipital lobe
- temporal lobe

Stimulating the exposed brain with electrodes

- No pain receptors on the surface of the brain
- Stimulation of spots in the motor area causes contraction of the muscles
- The area of motor cortex controlling a body part is not proportional to the size of that part but is proportional to the number of motor neurons running to it
- Stimulation of spots in the sensory area: reports of sensations in a specific area of the body



Mapping the cortex

EEG

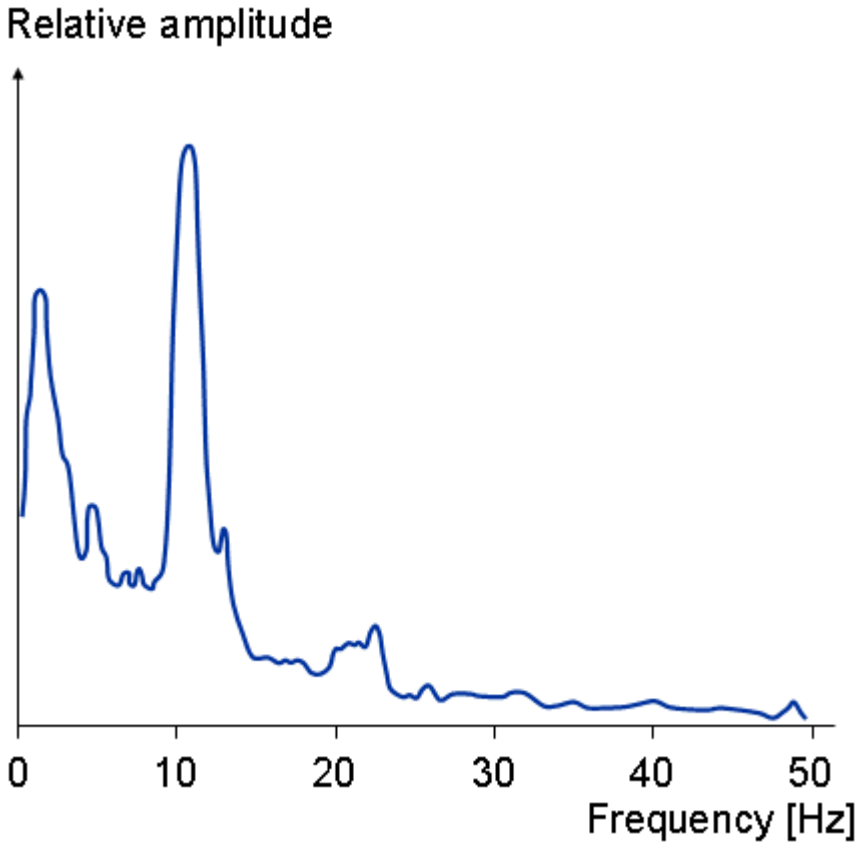
- The first recording of the electric field of the human brain: German psychiatrist Hans Berger in 1924 in Jena.

- ***Spontaneous activity*** is measured on the scalp or on the brain and is called the electroencephalogram. The amplitude of the EEG is about 100 μV when measured on the scalp, and about 1-2 mV when measured on the surface of the brain. As the phrase "spontaneous activity" implies, this activity goes on continuously in the living individual.

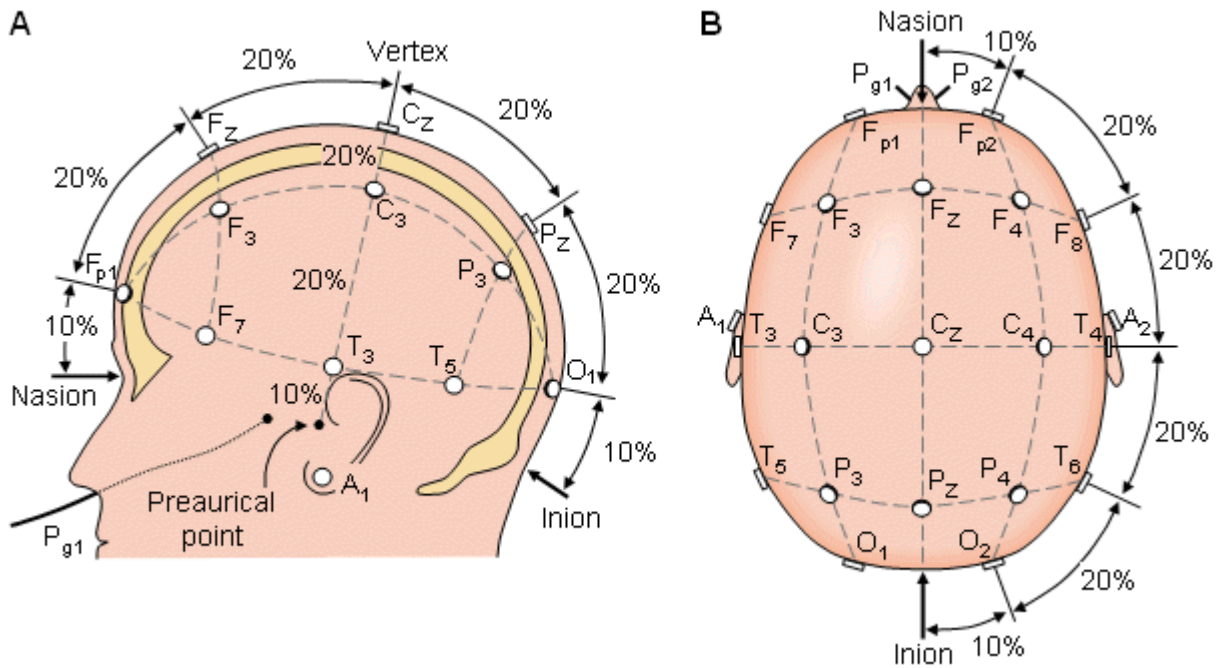
- ***Evoked potentials*** are those components of the EEG that arise in response to a stimulus (which may be electric, auditory, visual, etc.) Such signals are usually below the noise level and thus not readily distinguished, and one must use a train of stimuli and signal averaging to improve the signal-to-noise ratio.

- ***Single-neuron behavior*** can be examined through the use of microelectrodes which impale the cells of interest. Through studies of the single cell, one hopes to build models of cell networks that will reflect actual tissue properties.

Frequency spectrum of normal EEG

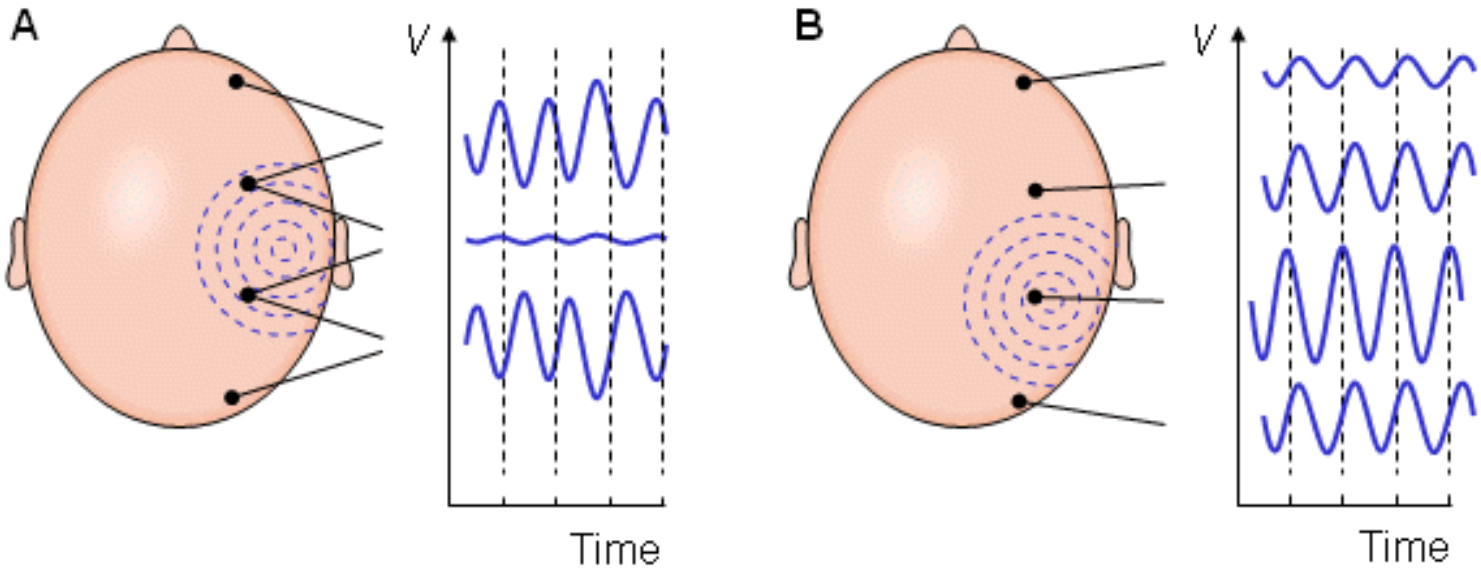


EEG lead system

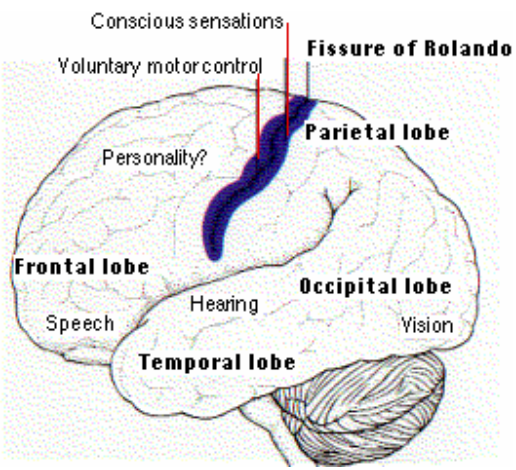


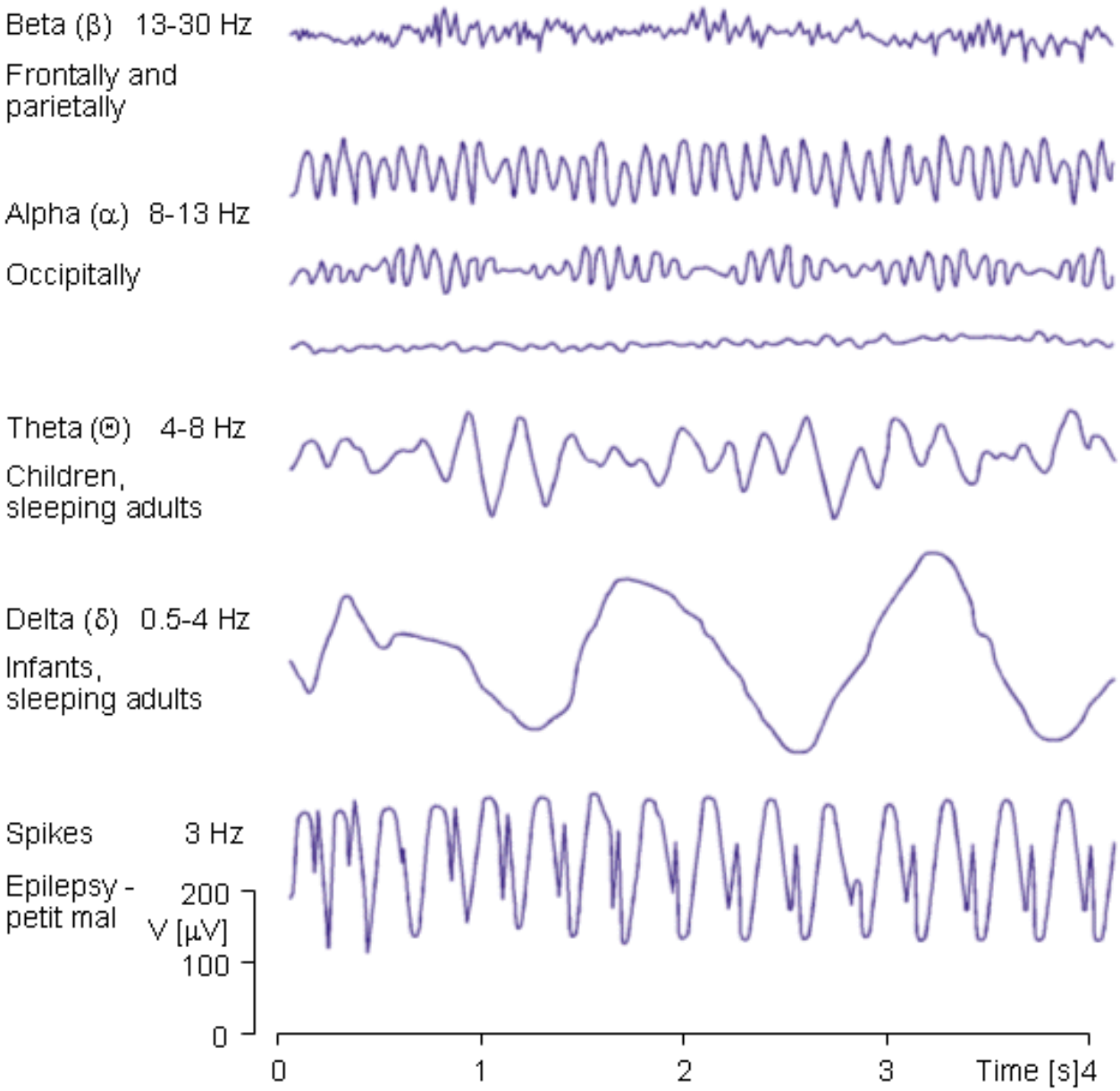
•The internationally standardized *10-20 system*.
•21 electrodes are located on the surface of the scalp
•Reference points are *nasion* (the delve at the top of the nose, level with the eyes) and *inion* (the bony lump at the base of the skull on the midline at the back of the head).
•From the reference points, the skull perimeters are measured in the transverse and median planes. Electrode locations are determined by dividing these perimeters into 10% and 20% intervals.
•Three other electrodes are placed on each side equidistant from the neighboring points.

Bipolar / unipolar measurements

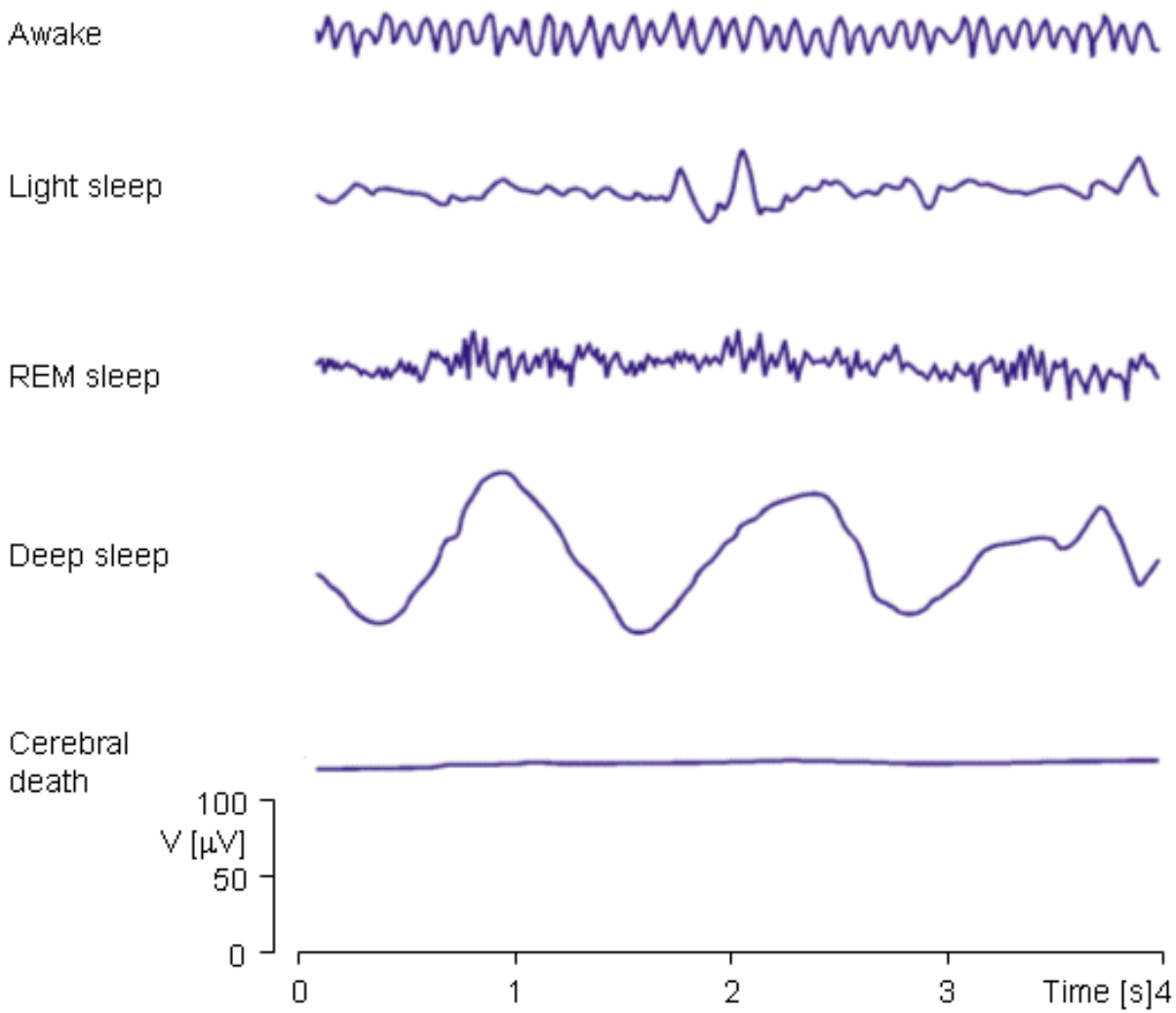


Examples of EEG waves





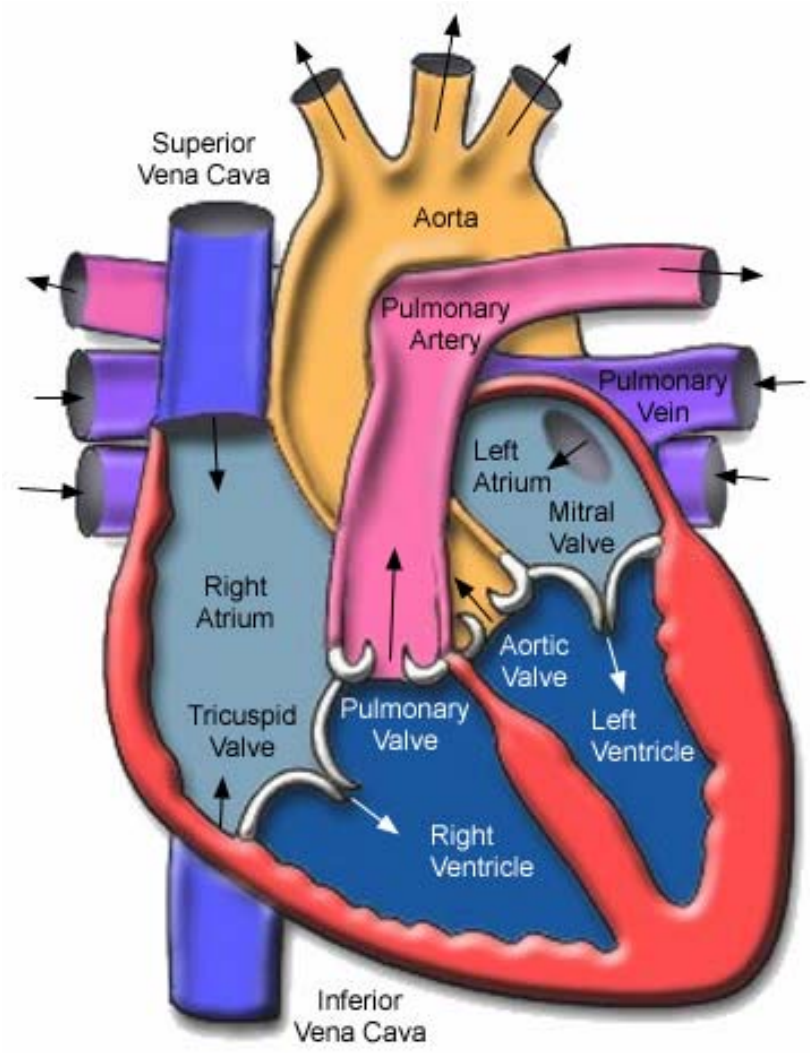
Consciousness and EEG activity relation



As the activity increases, the EEG shifts to higher dominating frequency and lower amplitude.

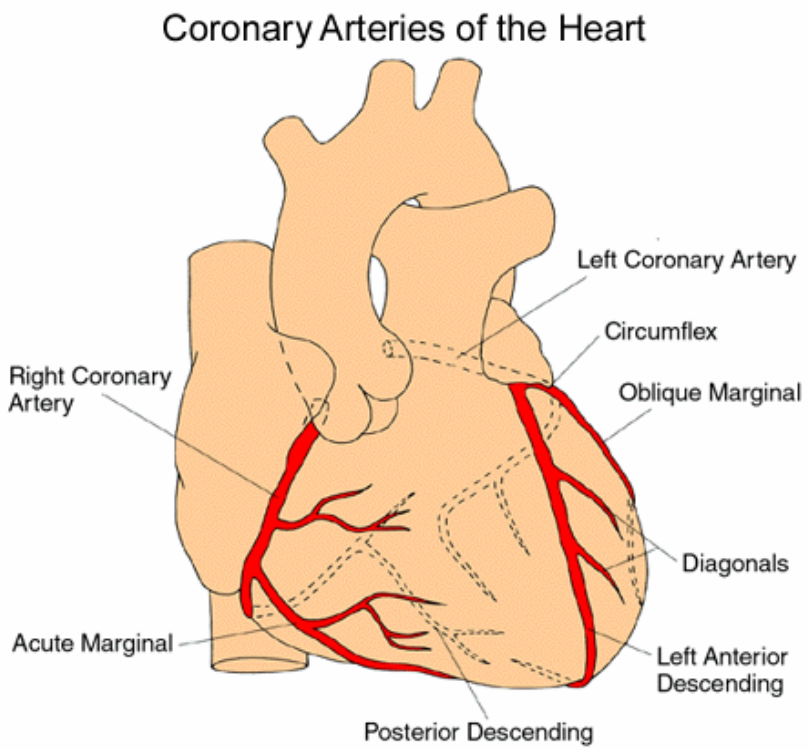
Electrocardiography (ECG)

Anatomy of the Heart



- Weighs 200 to 425 grams
- The average heart beats 100,000 times/day, pumping about 7,571 liters of blood.

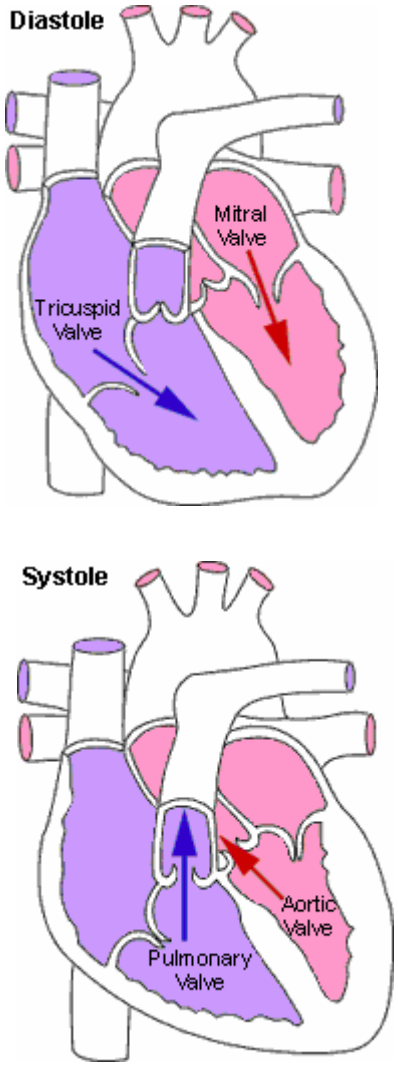
Coronary Arteries/Veins



- The left coronary artery (LCA): ventricles and left atrium.
  - left anterior descending (LAD) artery
  - the circumflex branch
- The right coronary artery (RCA): ventricles, right atrium, and sinoatrial node
  - the right posterior descending artery
  - marginal branch,

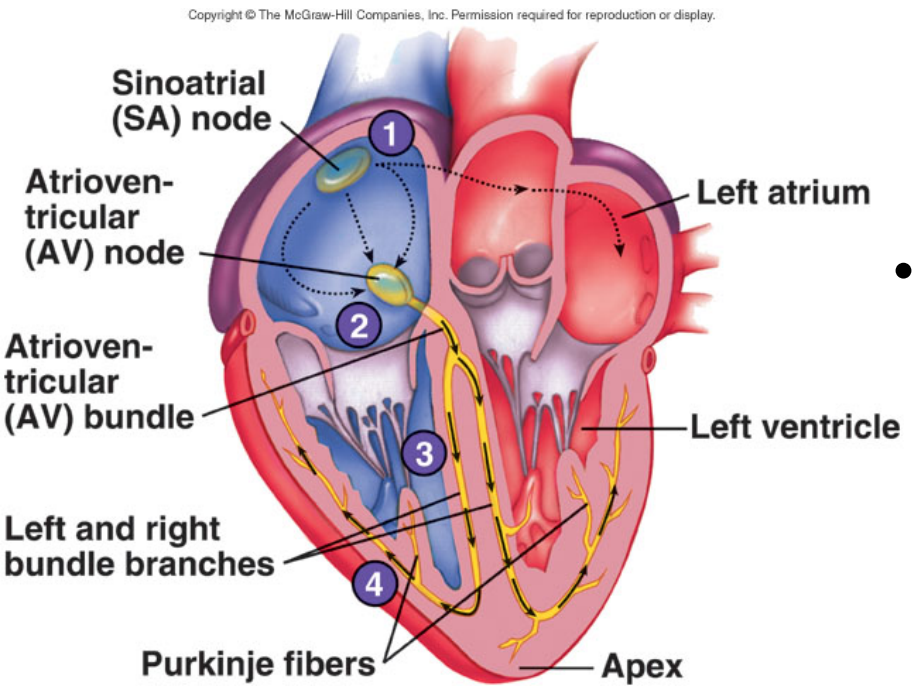
http://www.stanfordhospital.com/healthLib/atoz/cardiac/arteries.html

The Heart Valves



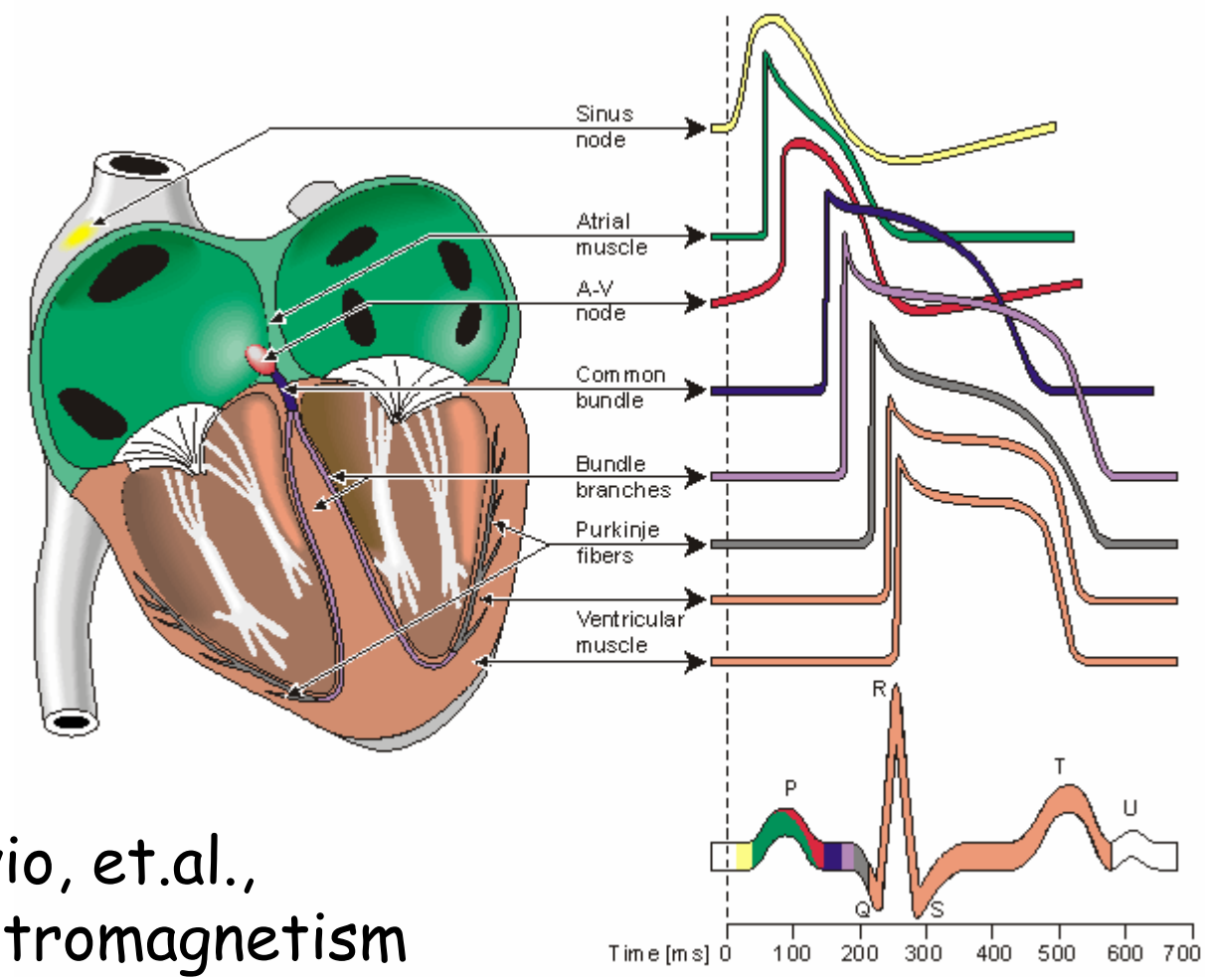
- **The tricuspid valve** regulates blood flow between the right atrium and right ventricle.
- **The pulmonary valve** controls blood flow from the right ventricle into the pulmonary arteries
- **The mitral valve** lets oxygen-rich blood from your lungs pass from the left atrium into the left ventricle.
- **The aortic valve** lets oxygen-rich blood pass from the left ventricle into the aorta, then to the body

Conduction system of the heart



- Electrical signal begins in the sinoatrial (SA) node: "natural pacemaker."
  - causes the atria to contract.
- The signal then passes through the atrioventricular (AV) node.
  - sends the signal to the ventricles via the “bundle of His”
  - causes the ventricles to contract.

Electrophysiology of the heart*



* Malmuvio, et.al., Bioelectromagnetism

Action Potentials in Skeletal and Cardiac Muscle

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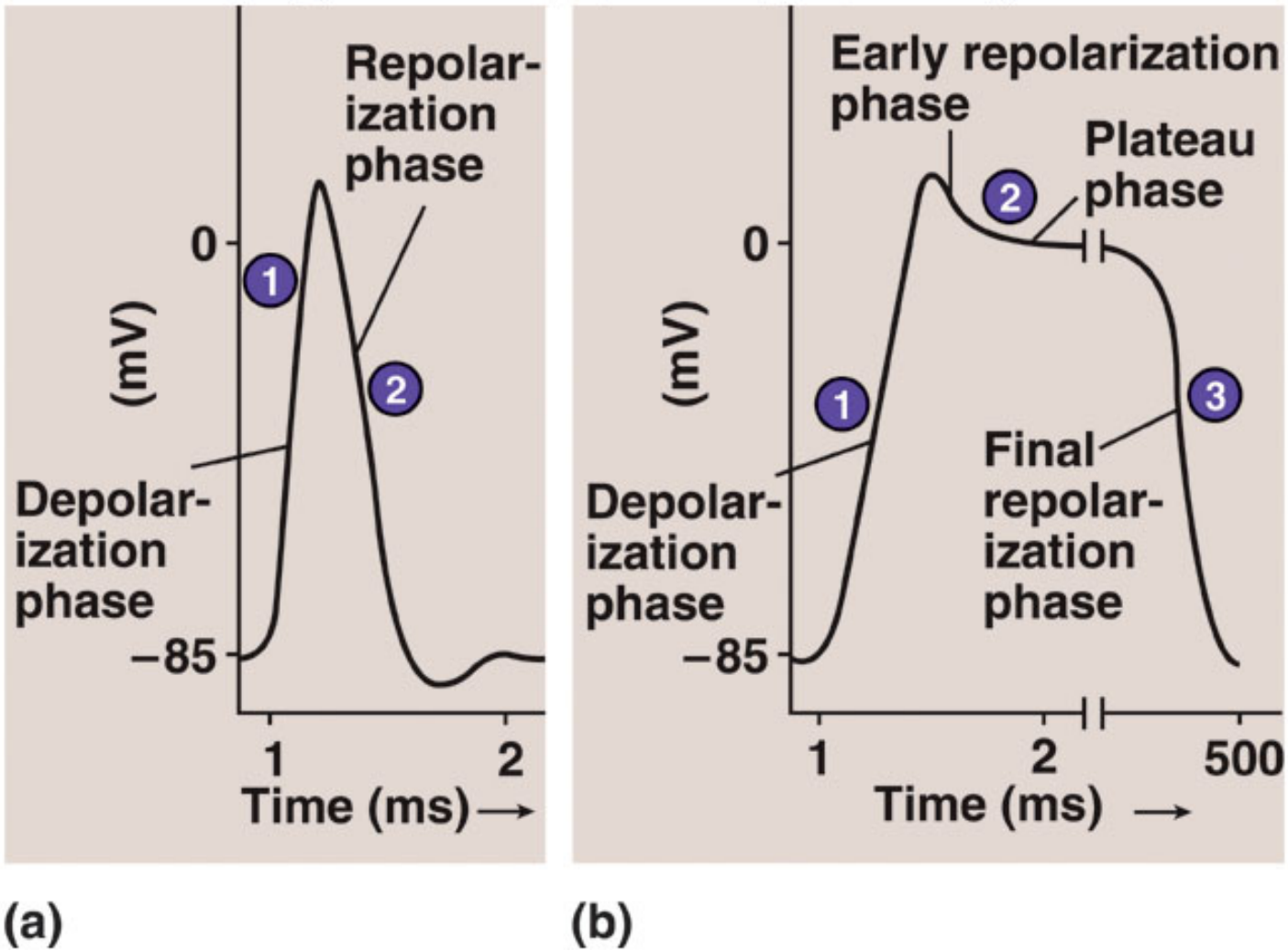

SA Node Action Potential

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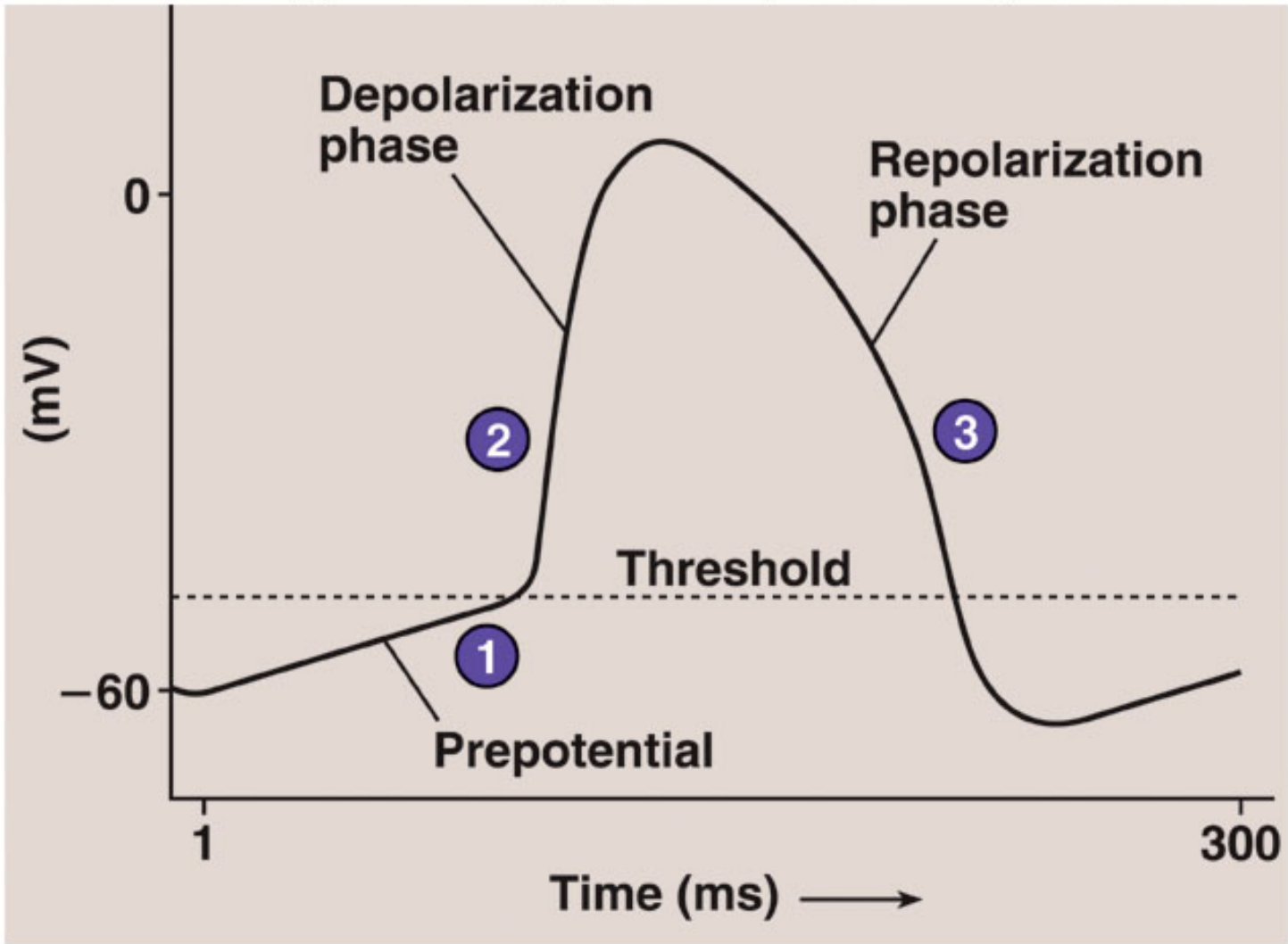
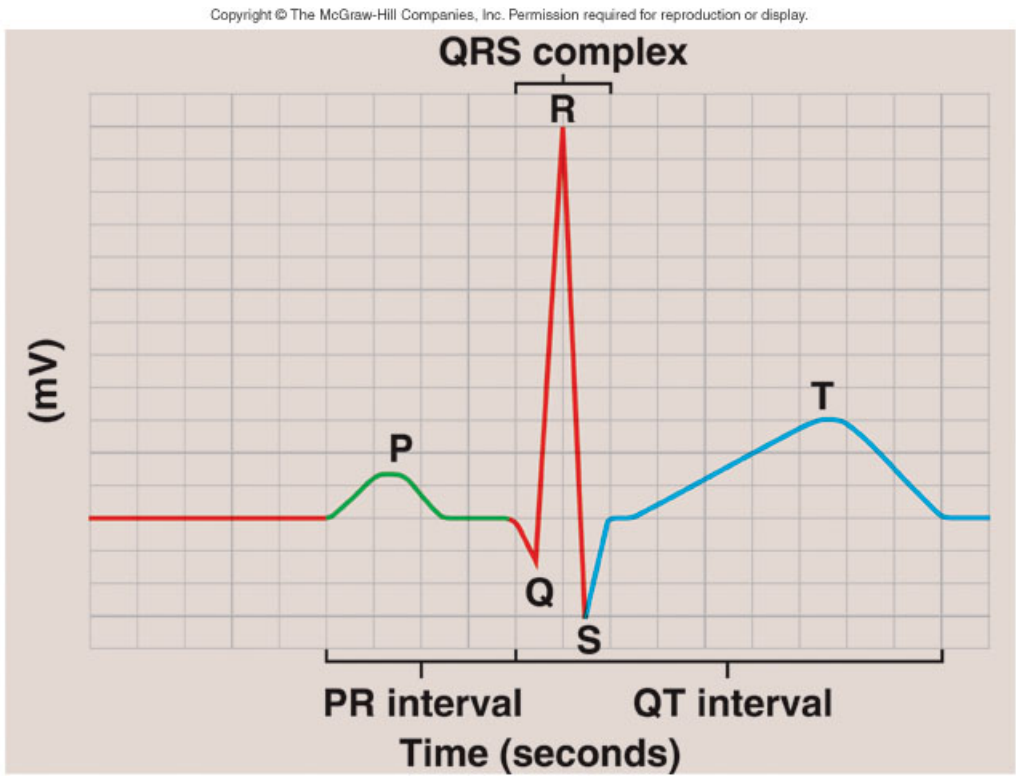
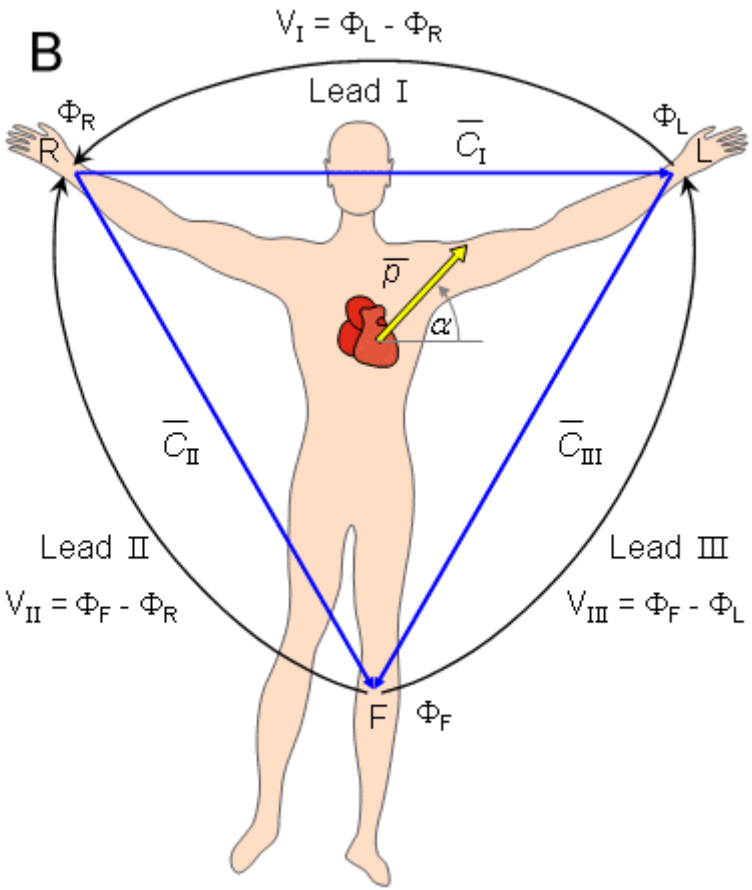


Electrocardiogram



- Action potentials through myocardium during cardiac cycle produces electric currents than can be measured
- Pattern
  - P wave
    - Atria depolarization
  - QRS complex
    - Ventricle depolarization
    - Atria repolarization
  - T wave:
    - Ventricle repolarization

The Einthoven lead system



Lead I: $V_I = \Phi_L - \Phi_R$

Lead II: $V_{II} = \Phi_F - \Phi_R$

Lead III: $V_{III} = \Phi_F - \Phi_L$

V_I= the voltage of Lead I

V_{II}= the voltage of Lead II

V_{III}= the voltage of Lead III

Φ_L= potential at the left arm

Φ_R= potential at the right arm

Φ_F= potential at the left foot

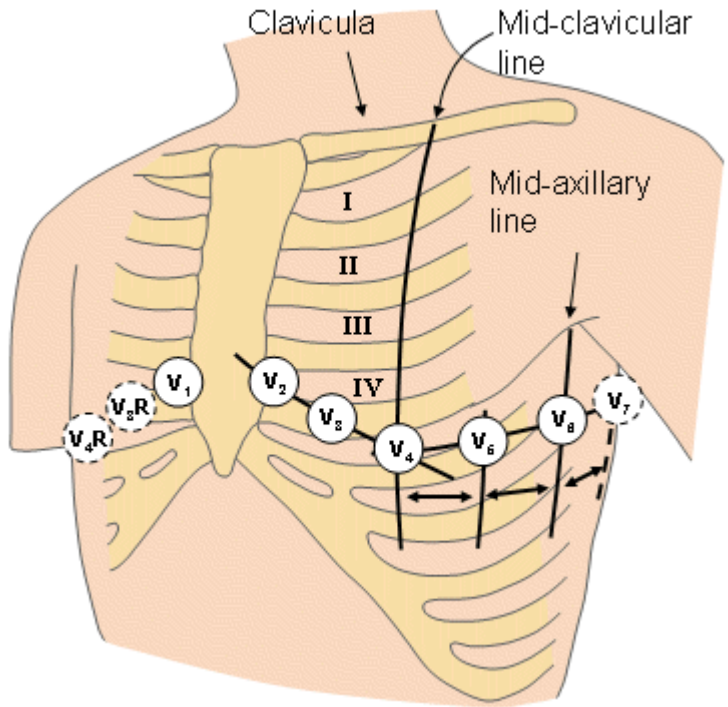
$V_I + V_{III} = V_{II}$ (only two of these three leads are independent)

12 lead ECG system

I, II, III : 2 of them are independent

aV_R, aV_L, aV_F : derived from I, II, III

V_1 – V_6 : precordial leads

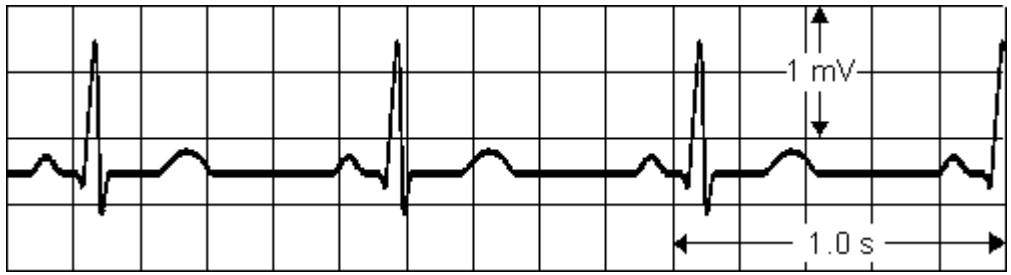


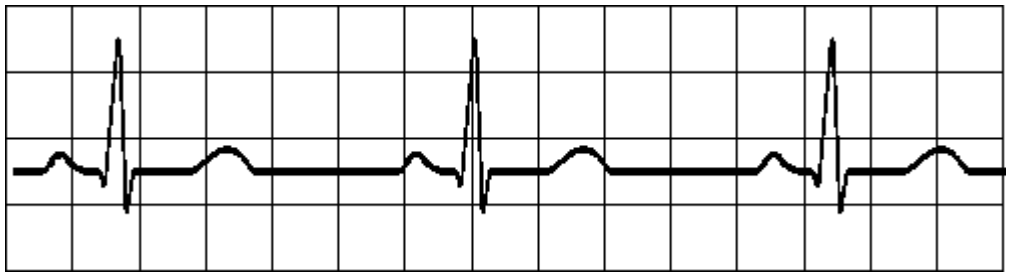
Examples of cardiac arrhythmias

Normal sinus rhythm

Impulses originate at S-A node at normal rate

All complexes normal, evenly spaced
Rate 60 - 100/min





Sinus bradycardia

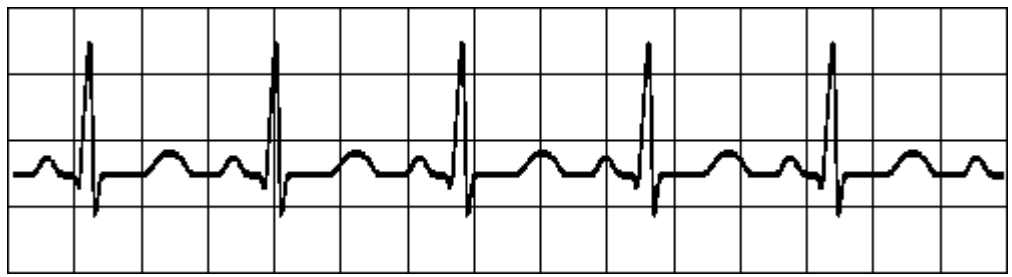
Impulses originate at S-A node at slow rate

All complexes normal, evenly spaced
Rate < 60 - 100/min

Sinus tachycardia

Impulses originate at S-A node at rapid rate

All complexes normal, evenly spaced
Rate > 100/min

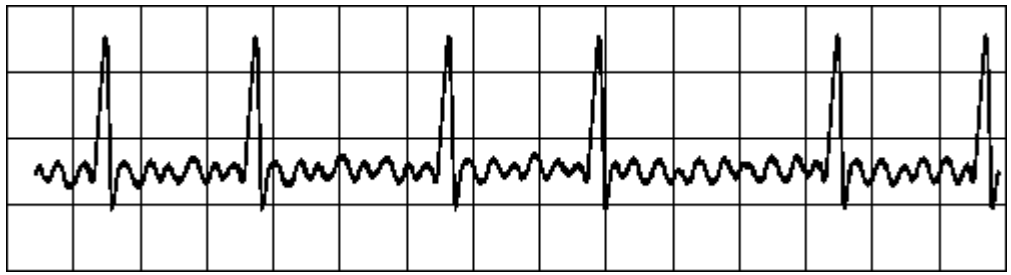


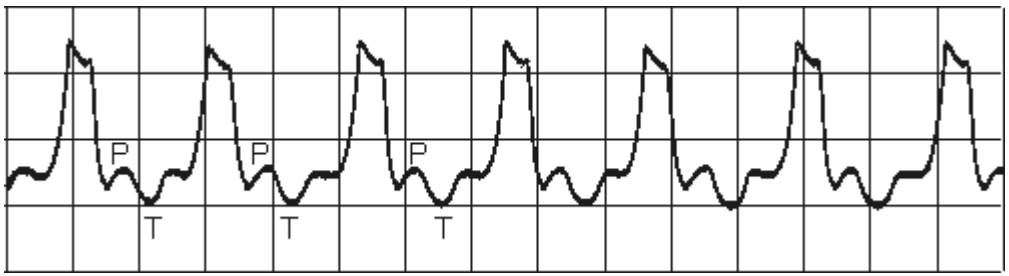
Examples of cardiac arrhythmias

Atrial fibrillation

Impulses have chaotic, random pathways in atria

Baseline irregular, ventricular response irregular

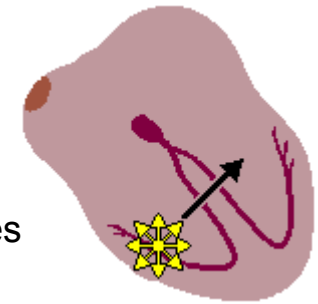


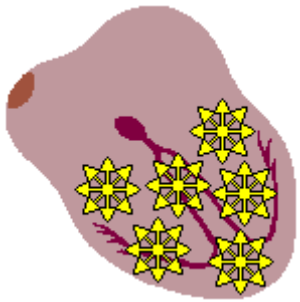


Ventricular tachycardia

Impulses originate at ventricular pacemaker

Wide ventricular complexes
Rate> 120/min





Ventricular fibrillation

Chaotic ventricular depolarization

Rapid, wide, irregular ventricular complexes