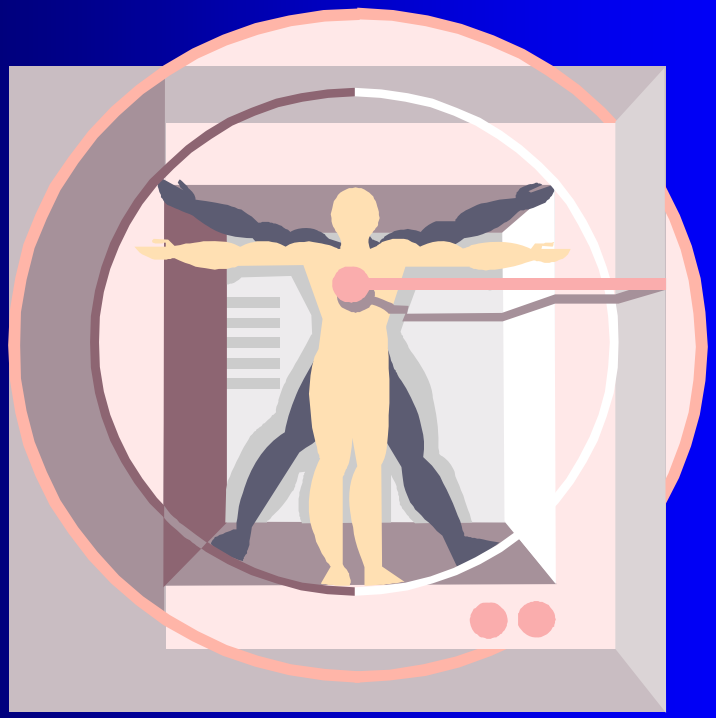
Biomedical Signal Processing & Modeling

ECE 09.402.03 / 09.504.03

Fall 2006



Polikar

Lecture 1

Introduction:

Characterization of Biomedical Signals

Biomedical Signal Processing & Modeling (3)
0909.504.03 / 0909.402.03
Fall 2006

Class Homepage: engineering.rowan.edu/~polikar/CLASSES/ECE504

Welcome

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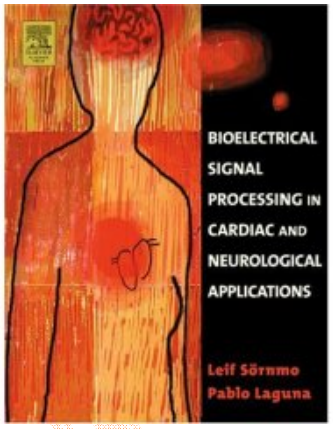
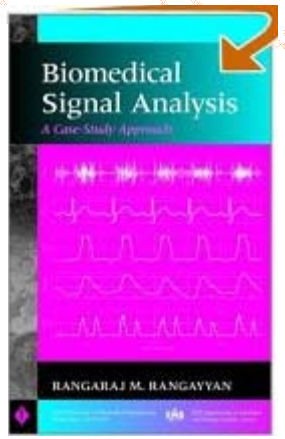
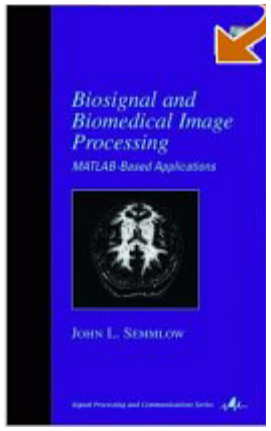
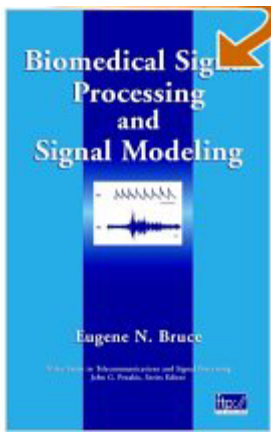
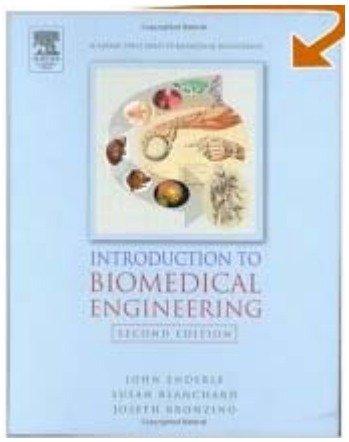
Class Meeting:	**????**
References	Bioelectrical Signal Processing in Cardiac & Neurological Applications, Sörnmo Biomedical Signal Analysis, Rangayyan, Wiley 2002. Biosignal and Biomedical Image Processing, Semmlow, Marcel Dekker, 2004. Biomedical Signal Processing & Signal Modeling, Bruce, Wiley, 2001 Introduction to Biomedical Engineering, 2/e Enderle, Elsevier, 2005

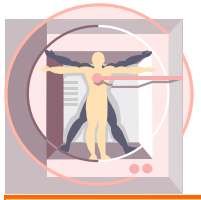












BSP & M

Tentative Syllabus

Week of		Material to be uncovered
September	6	Introduction - the nature of biological signals - ECG, EEG, EMG,. ExG, ETC. (the last one is not a biological signal!!!)
	13	The origin of biopotentials - where do electrical signals of biological origin come from…? The story of action potentials
	20	DSP fundamentals: Sampling, filtering, frequency domain analysis…fun, fun,fun…!
	27	Time-frequency analysis for biological signals: Wavelets - the new kid in the DSP block that unseated the DFT from its previously undisputed throne
October	4	Processing of random and stochastic signals - spectral estimation: What to do when you cannot expect the expected…?
	11	Adaptive and optimal filtering - Part I: What to do when signal and noise spectra overlap and traditional filtering collapses…?
	18	Adaptive and optimal filtering - Part II: Some advanced topics
	25	Modeling with biological signals - if I were a box generating biological signals, what would be in me…?
November	1	Detection theory: detecting biological signals in noise - how to find the fetal ECG if it is buried in mother's ECG…?
	8	Independent component analysis: Cocktail party problem applied to EEG signals
	15	Classficiation of biological signals: Your EEG says, you are having an epileptic seizure, no..wait... your ECG says you are about to have an heart
	22	Bootstrapping techniques in signal processing & classification: How to cheat when you have very little data without getting a ticket from the DSP police
	29	Cardiovascular applications - ECG processing
December	6	Neurological applications - EEG processing
	13	Other topics / Biomedical imaging
	20	Finals week - Project presentations

From the Tiniest Molecule

Chemical Level

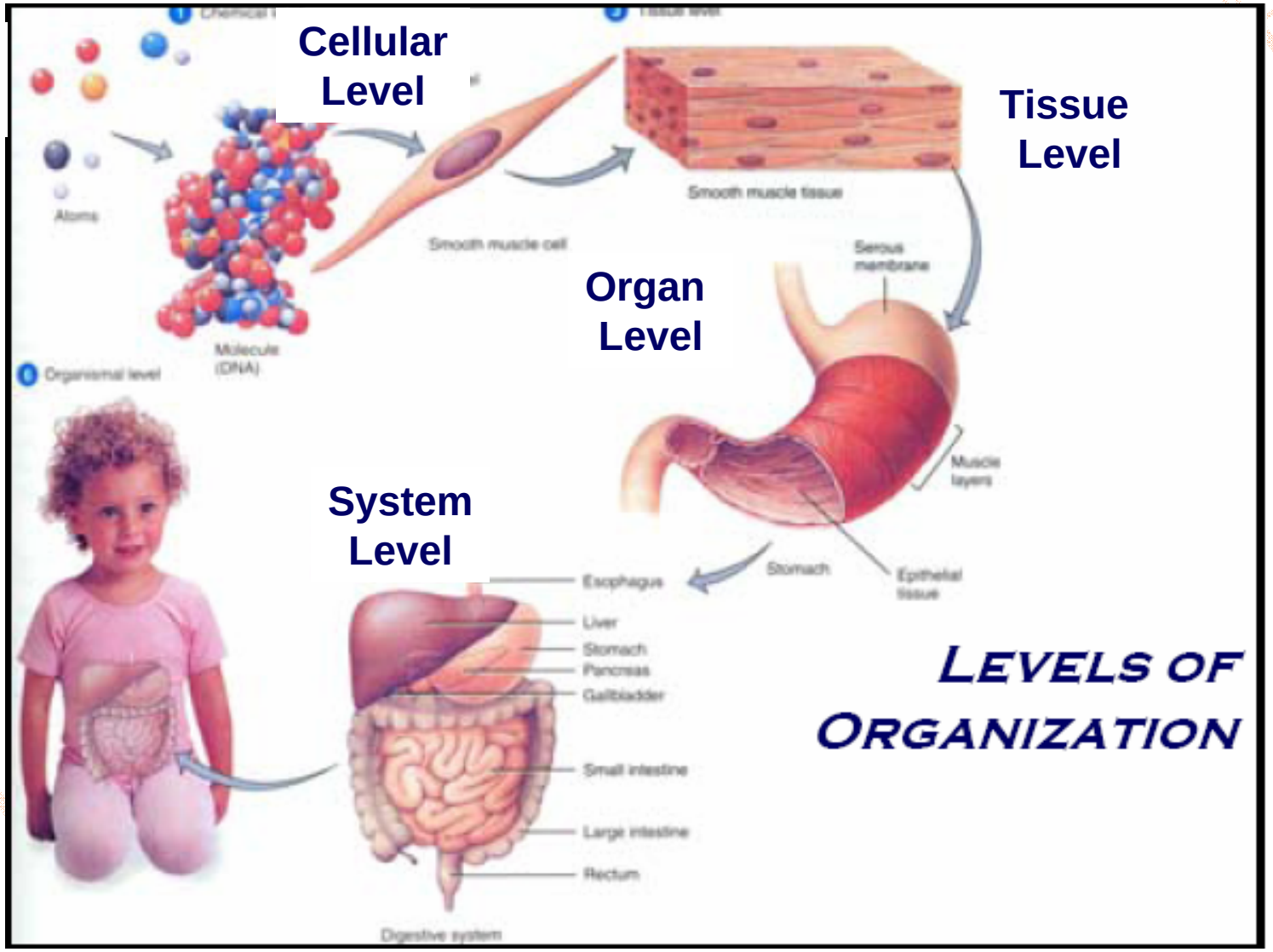
Cellular Level

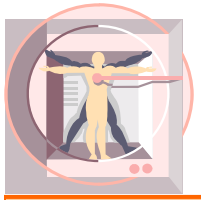
Tissue Level

Organ Level

System Level

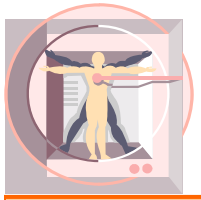
Organizational Level





Nature of Biomedical Signals

- Living organisms are made of many systems – e.g. human body:
  - Nervous, cardiovascular, gastrointestinal, endocrine, respiratory, etc.
  - Each system is made of subsystems (organs, tissues, etc.) that are responsible for certain physiological processes
    - Cardiovascular system pumps blood to deliver nutrients to the body
- Each physiological process is associated with certain types of signals that reflect their nature and activities
  - Such signals can be of different types:
    - Biochemical → hormones, neurotransmitters
    - Electrical → potentials, currents
    - Mechanical → pressure, temperature
- Any deviation of these signals from their normal parameters typically represents a disease / disorders → pathological condition
  - Observing these signals and comparing them to their known norms, we can often detect these pathological conditions



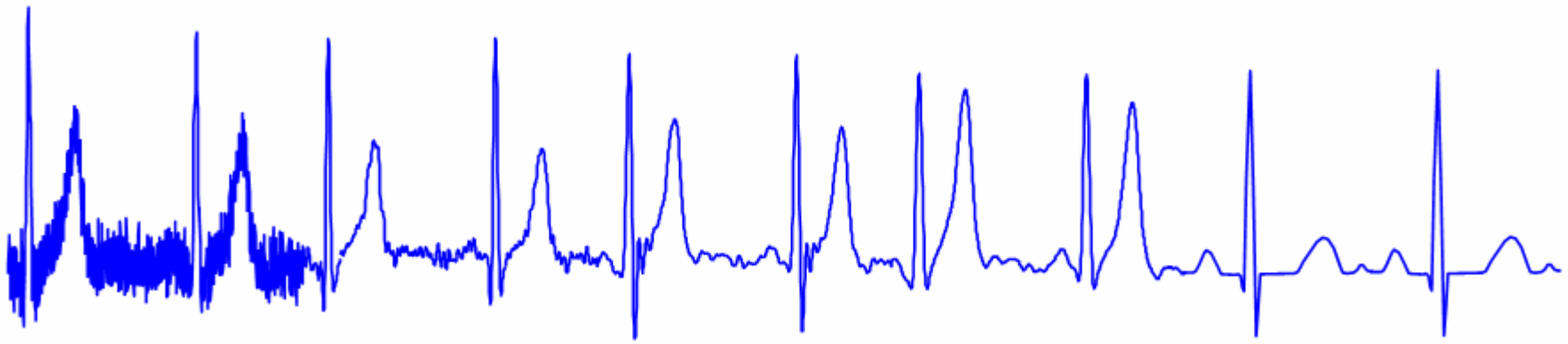
Nature of Biomedical Signals

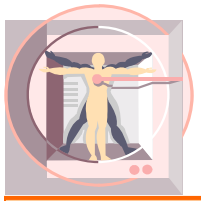
- For example:
  - Most infections → an increase in body-core temperature
  - Cardiovascular disorders → arrhythmias in electrocardiogram (ECG), or changes in blood pressure
  - Certain neurological disorders (such as epilepsy) → electroencephalogram (EEG)
- Each quantity may also be measured quantitatively or qualitatively
  - Increase in body temperature
    - Inside of the palm (crude)
    - Mercury based thermometer under arm or …. Well, you know where…(better)
    - Termistor based thermometer in the artery using a catheter (best)
- When such measurements are observed over a period of time, a one-dimensional time-series is obtained → this is a physiological signal

1-D Signals

- Typical female core body temperature variation over one-month

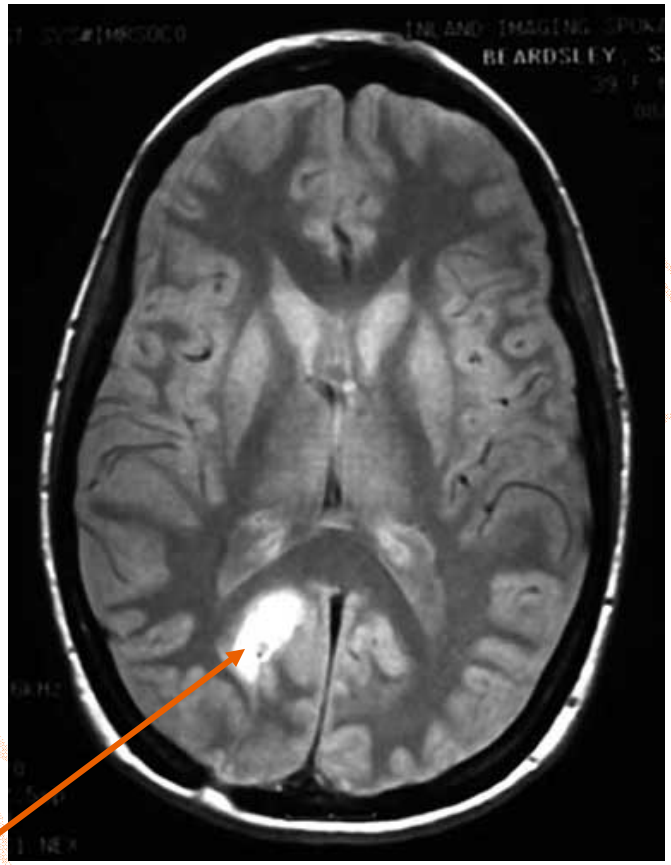
- An ECG that is progressively been cleaned from noise



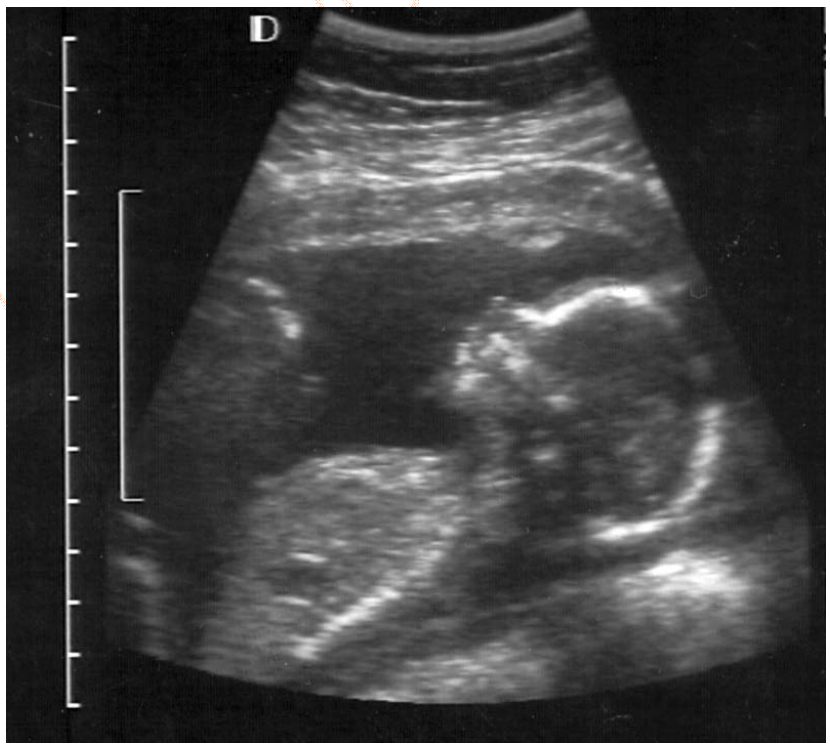


2-D Signals

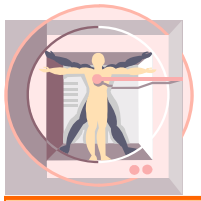
- Images are also used very often in medicine – these are simply two-dimensional signals



MRI that shows a tumor



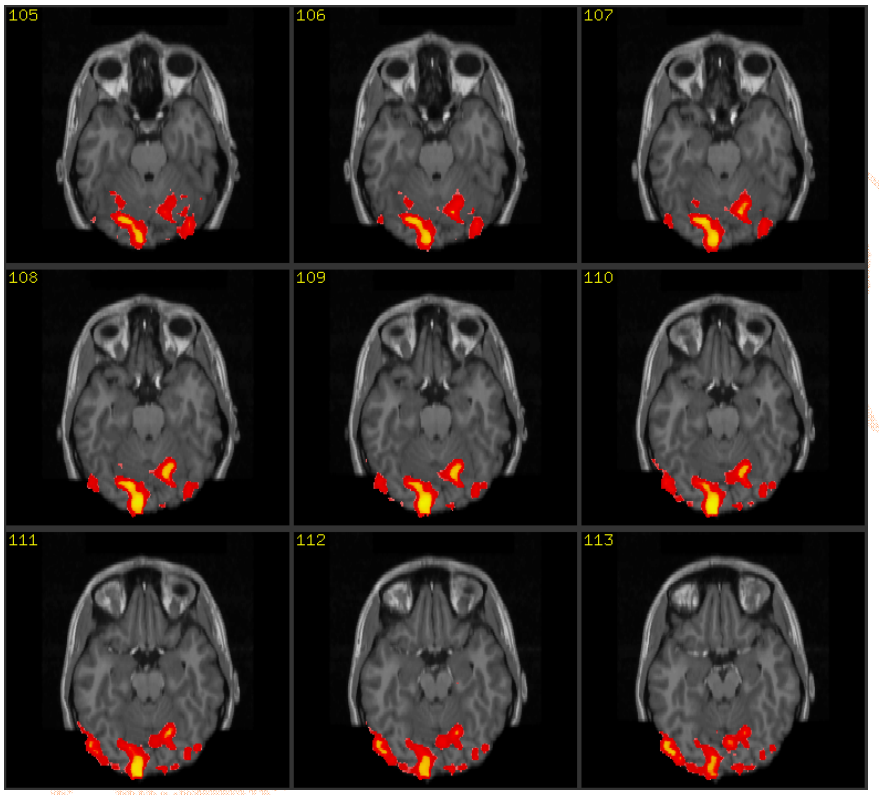
Fetal ultrasound

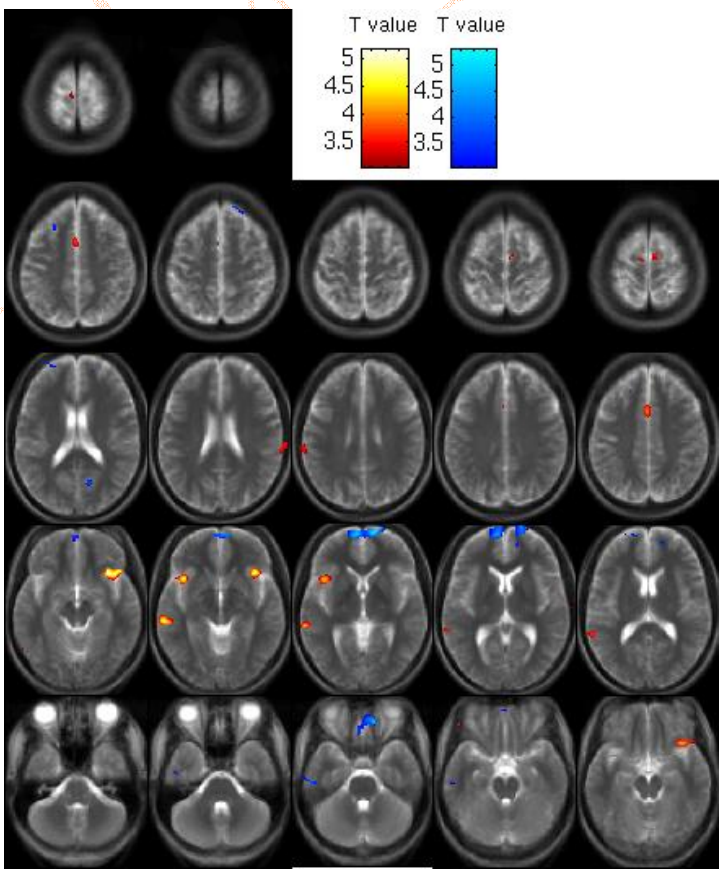


3-D Signals

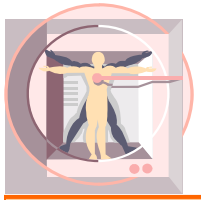
- More recently, 3-D signals, in the form of movies or series of 2-D images have also become common in bioimaging

http://www.fmrib.ox.ac.uk/fmri_intro/fusion.gif



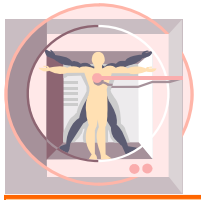


Functional MRI (fMRI)



Some Commonly Used Biomedical Signals

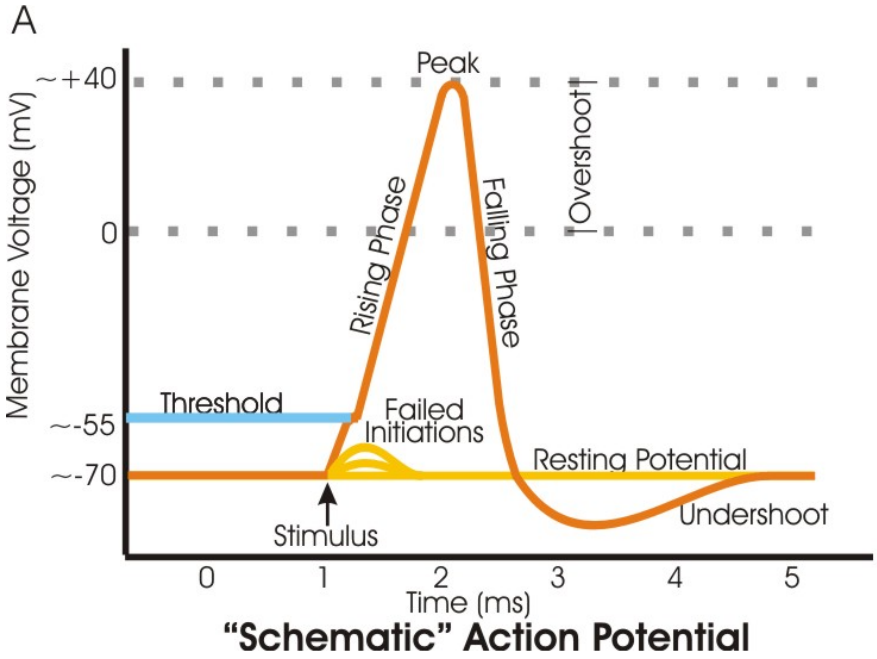
- The action potential – mother of all biological signals
- The electroneurogram (ENG) – propagation of nerve action potential
- The electromyogram (EMG) – electrical activity of the muscle cells
- The electrocardiogram (ECG) – electrical activity of the heart / cardiac cells
- The electroencephalogram (EEG) – electrical activity of the brain
- The electrogastogram (EGG) – electrical activity of the stomach
- The phonocardiogram (PCG) – audio recording of the heart's mechanical activity
- The carotid pulse (CP) – pressure of the carotid artery
- The electoretinogram (ERG) – electrical activity of the retinal cells
- The electrooculogram (EOG) – electrical activity of the eye muscles



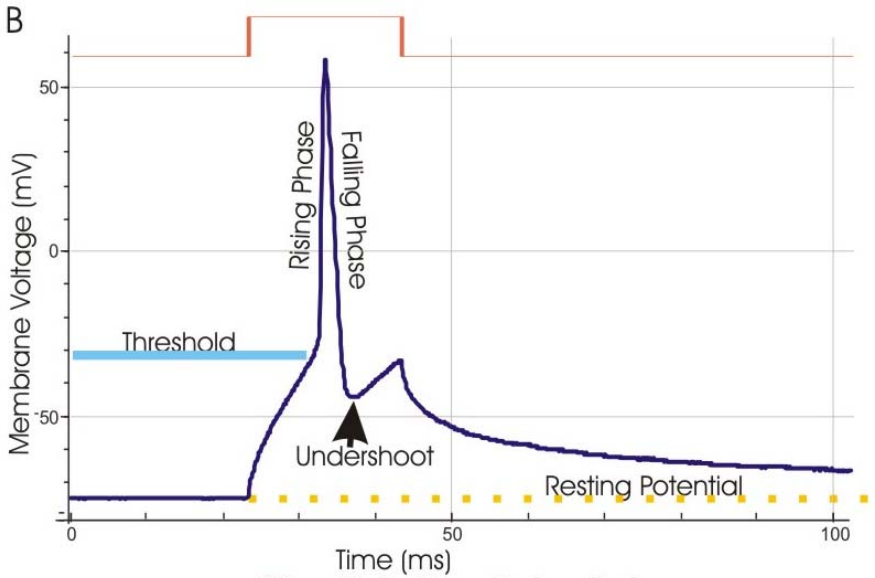
The Action Potential

- The action potential is the origin of all biopotentials
  - All biological signals of electrical origin are made up from integration of many action potentials
- The AP is the electrical signal that is generated by a single cell when it is mechanically, electrically or chemically stimulated
  - It is the primary mechanism through which electrical signals propagate between cells, tissues and organs
  - It is due in part, to an electrochemical imbalance across the cell membrane, and in part, due to selective permeability of the membrane to certain ions
    - At resting state, the cell membrane is permeable to K^+ and Cl^-, but not to Na^+
    - Lots of Na^+ trapped outside make the intracellular region electrically more negative, with a resting membrane potential of -60 ~-80 mV
    - When the cell is disturbed, ion channels across the membrane open up and allow an influx of Na^+ : depolarization → inside of the cell becomes more positive: +20mV
    - However, the channels close soon after, forcing the membrane potential back to its resting stage: repolarization
    - The change in membrane potential is the AP, which itself then stimulates the neighboring cell, and starts the transmission of the APs

The Action Potential

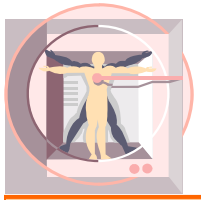


"Schematic" Action Potential



"Real" Action Potential

- Recording an AP requires the isolation of a single cell.
  - Microelectrodes (with tips a few μm across) are used to stimulate and record the response. A typical AP is 2-4ms long with an amplitude of about 100mV
- More about action potentials next week!
  - http://www.blackwellpublishing.com/matthews/channel.html
  - http://www.blackwellpublishing.com/matthews/nmj.html



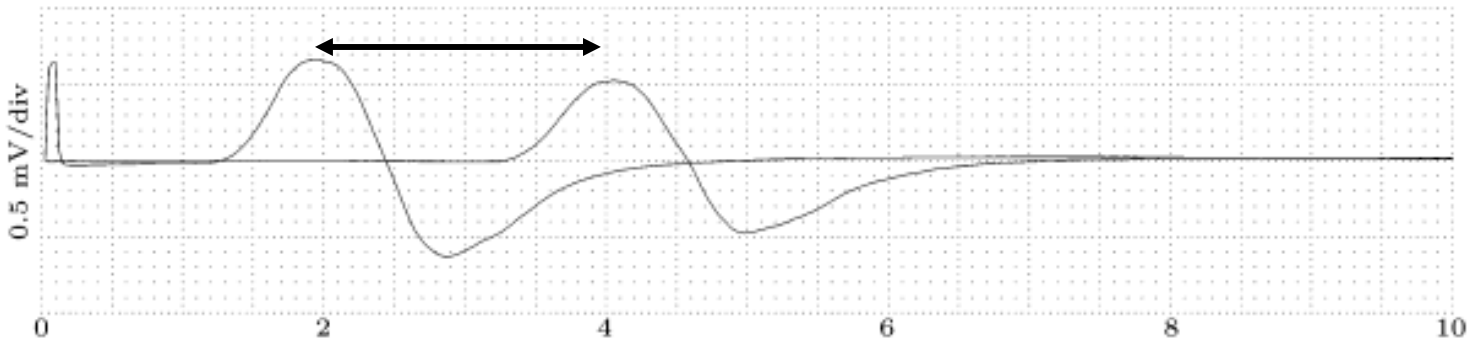
READ ALL ABOUT IT

- In preparation of next week's class, research and read about the action potentials. Wikipedia is a good place to start, but do search other sites as well.
- In particular look for the following:
  - Depolarization, repolarization, hyperpolarization, overshoot
  - All-or-none behavior of the AP
  - Voltage gated and ligand gated Na^+ and K^+ channels
  - Ion pumps
  - Absolute and relative refractory periods of the AP
  - Propagation of the AP: saltatory conduction
  - Goldman equation, Donnan equilibrium

- Why should we care?
  - As we will see again and again in the future, the AP is the basic component of all bioelectric signals – ECG, EEG, etc. are all integration of many, many APs, and understanding the AP will therefore be most useful for characterizing and processing other signals.

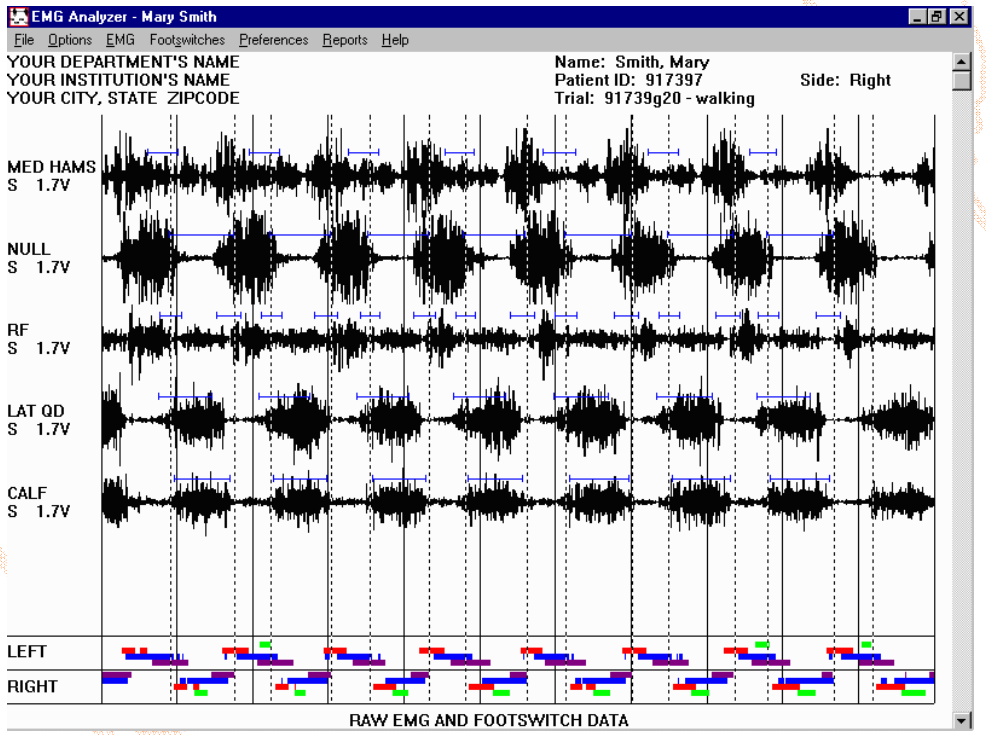
ELECTRONEUROGRAM - ENG

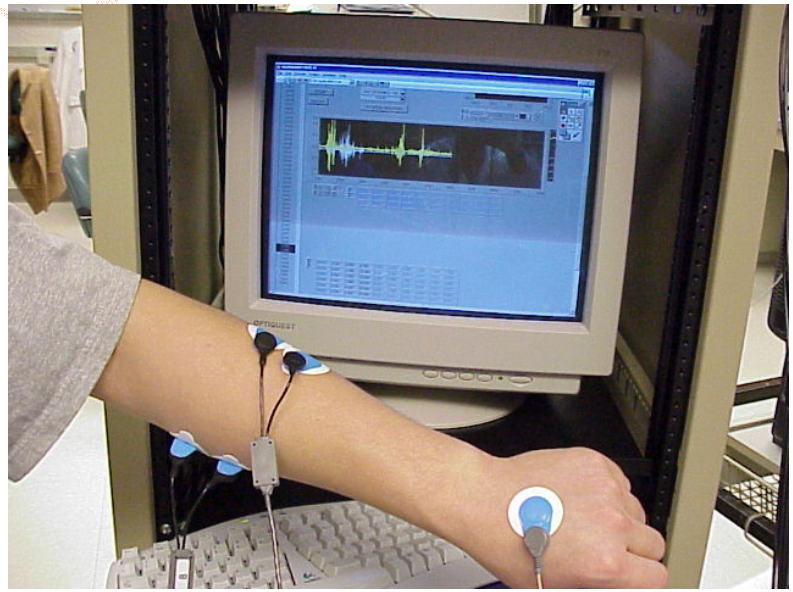
- ENG is the response of a (peripheral) nerve cell when it is stimulated with an electrical shock.
  - Acquired using needle electrodes
  - Used to determine the conduction velocity of the nerve
    - If the nerve does not respond quickly enough, or does not respond at all, it signifies a nerve injury.
    - The conduction velocity is measured by placing two electrodes at close-by locations and recording the ENG at both locations. The temporal difference between the two ENG can then be used to obtain conduction velocity.



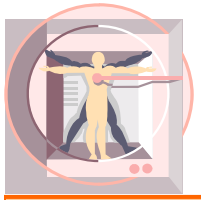
The Electromyogram - EMG

- The EMG is the graphic representation of the electrical activity of the skeletal muscles – either during resting stage, or in response to stimulation
  - Unlike AP which is measured on the cellular level, the EMG is a surface signal obtained through surface and/or needle electrodes
    - It is the collection / integration / amalgamation of millions of muscle APs as measured from the skin surface





http://www.pitt.edu/~zmli/handlab/image/EMG.JPG

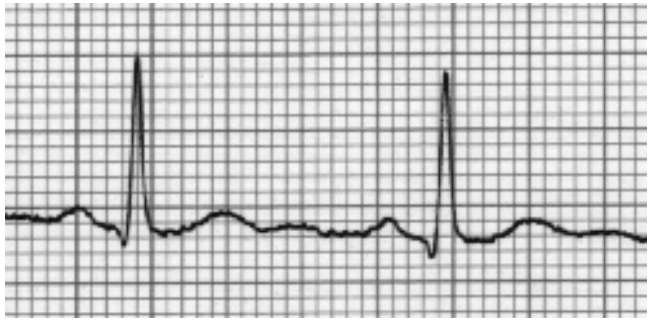


The Electromyogram

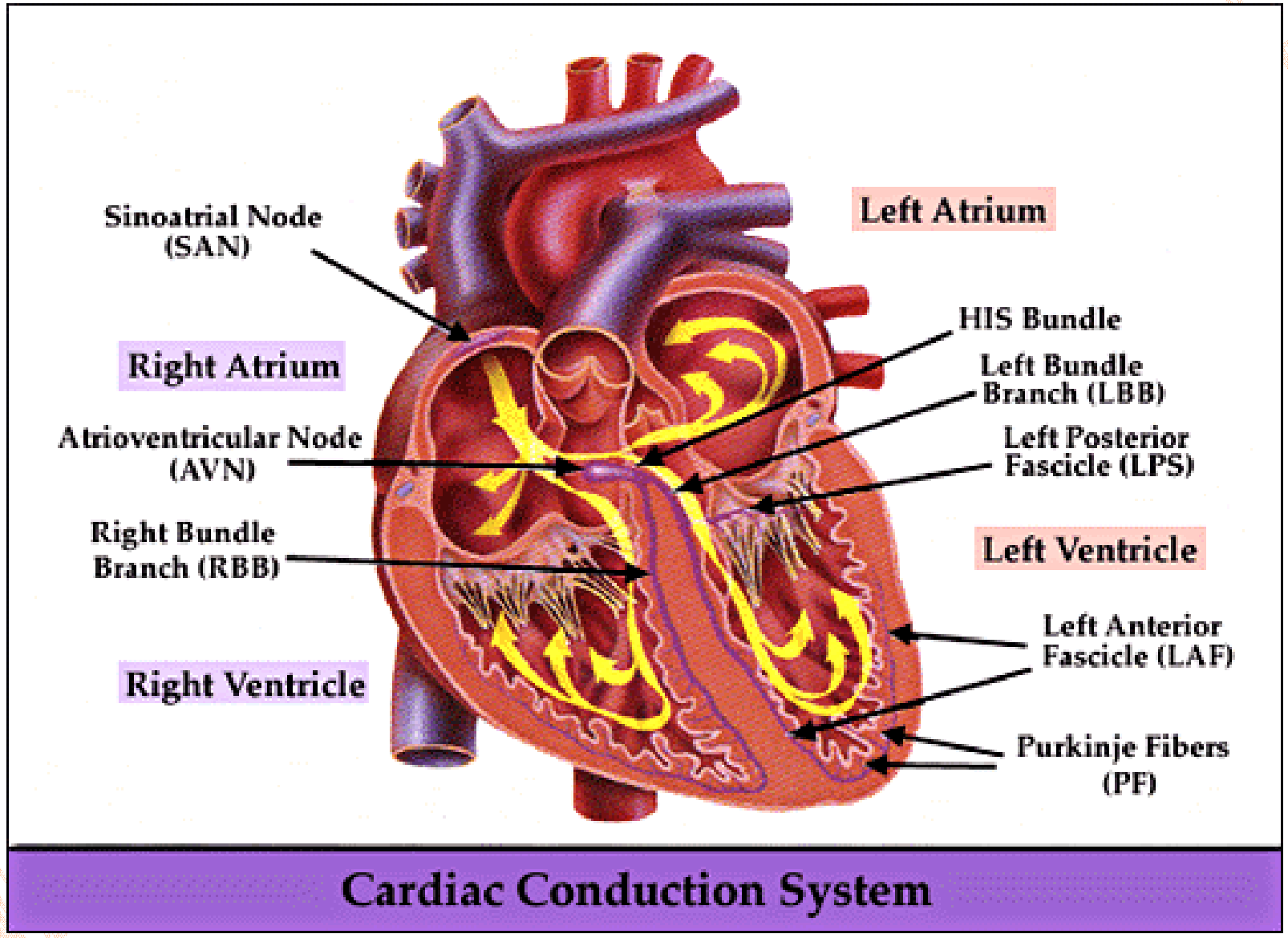
- Practical use…? Not always pleasant!
  - The EMG is used to determine whether a person's perceived muscle weakness is caused by a disease within the muscle or by a problem in a nerve supplying the muscle. This is an invasive test; it is performed by inserting needles into muscles and measuring their responsiveness to electrical stimulation. Risks may include pain during needle insertion, bleeding, or infection. Bleeding or infection occurs infrequently. The patient will feel electrical shocks in the muscles that are tested during the EMG. If the patient understands the test and wants to proceed, he or she should indicate willingness by completing a consent form.
  - **A typical EMG lasts between 15 and 90 minutes. (Ouch!)**
    - The patient is positioned on an exam table with the muscles to be tested at rest.
    - An antiseptic is used to cleanse the skin at the planned needle insertion points and a metal plate is positioned under the muscle(s) being tested.
    - Several needle electrodes are then inserted through the skin and into the muscle.
    - The muscle's electrical activity is measured at rest and with voluntary contraction.
    - The electrical activity will be audible over an audio-amplifier. It is also visible on an oscilloscope and recorded on graph paper.
    - Following the test, the patient may take a mild analgesic and/or apply warm compresses to the muscles for soreness. Needle insertion sites should be observed and the patient's primary health care provider notified if bleeding, a hematoma, or signs of infection are noted.

The Electrocardiogram - ECG

- ECG is the graphical recording of the electrical activity of the heart
  - It is by far the most easily recognized biological signal, and it is also the one that is most commonly used for clinical diagnosis
    - It is routinely used in clinical settings for checking the vital signs of a patient, or the cardiovascular health of a patient
    - The existence of ECG (hence the existence of the pulse) single handedly indicates the presence of life
  - ECG can be obtained easily using surface electrodes.
  - As with other electrical signals of biological origin, it is the combination of many APs from different regions of the heart that makes up the ECG
    - Its characteristic shape is widely recognized.
    - It consists of a large peak (QRS) indicating the main contraction of the ventricular muscles, along with several other peaks representing the contaction and relaxation of different cardiac mucle groups.

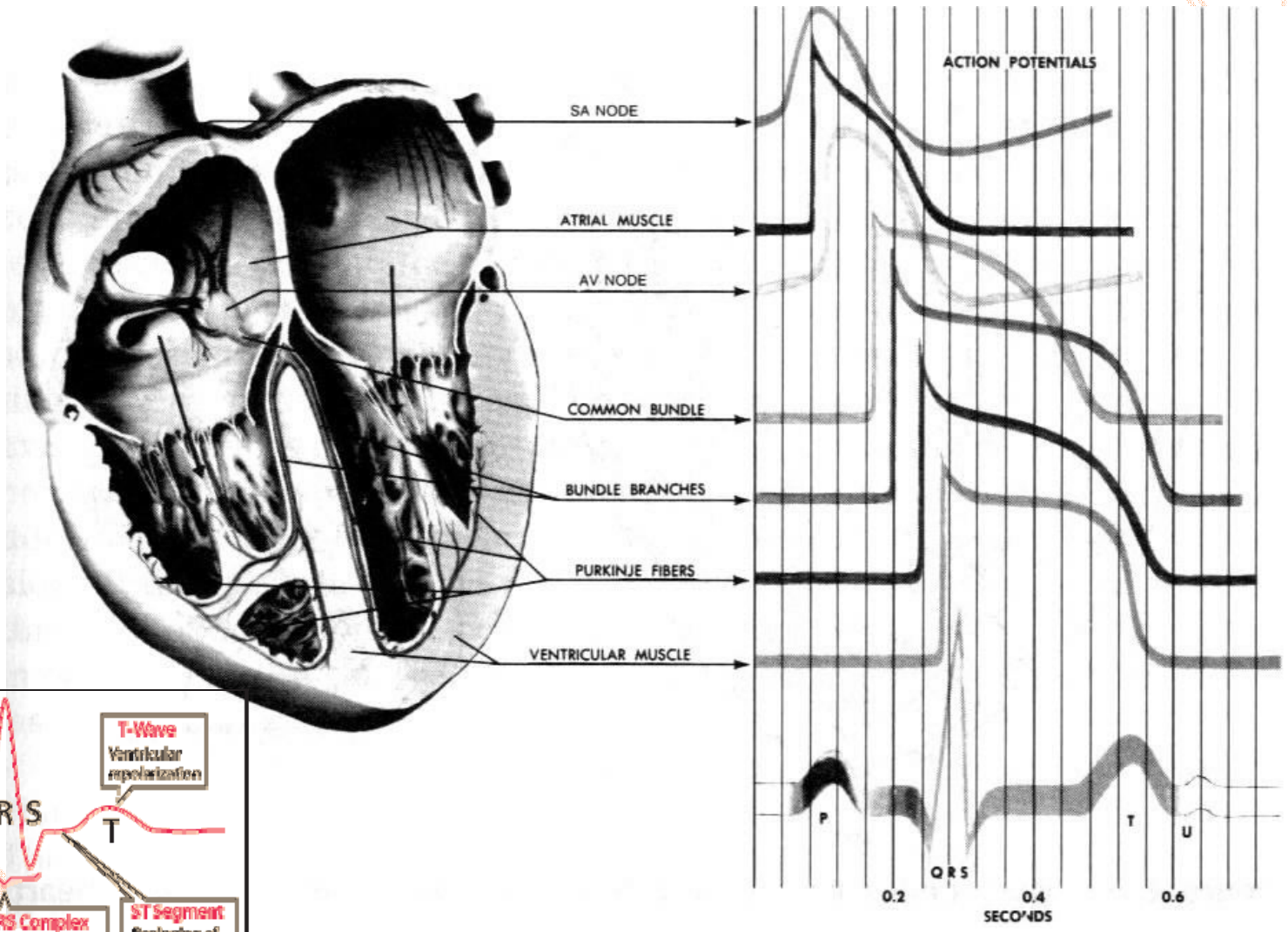


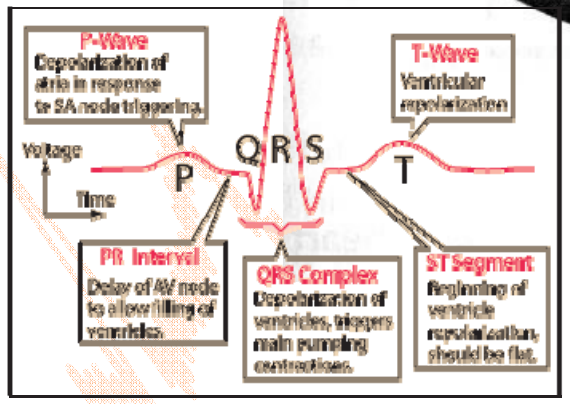
Cardiac Conduction System



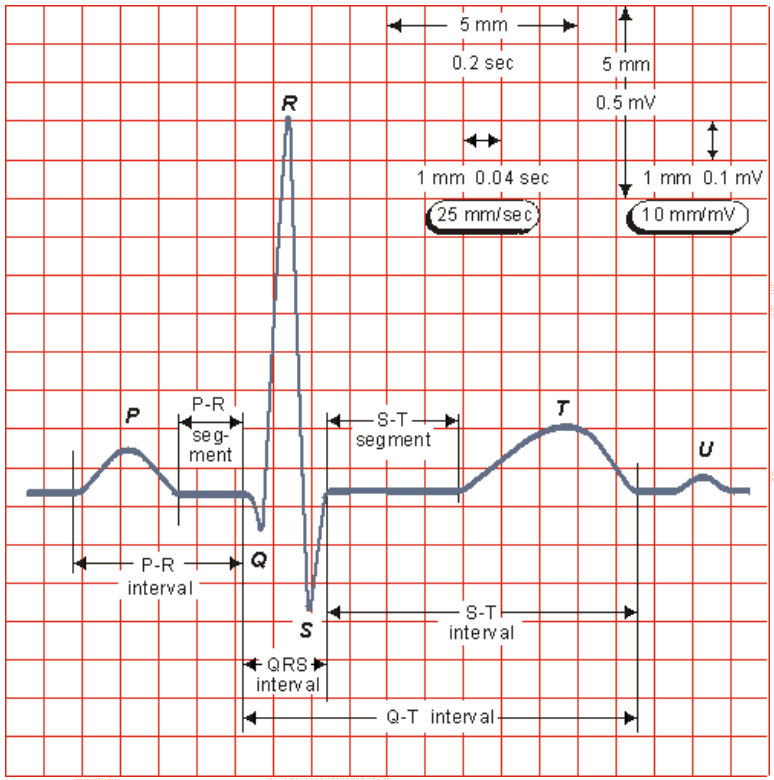
Cardiac Conduction System

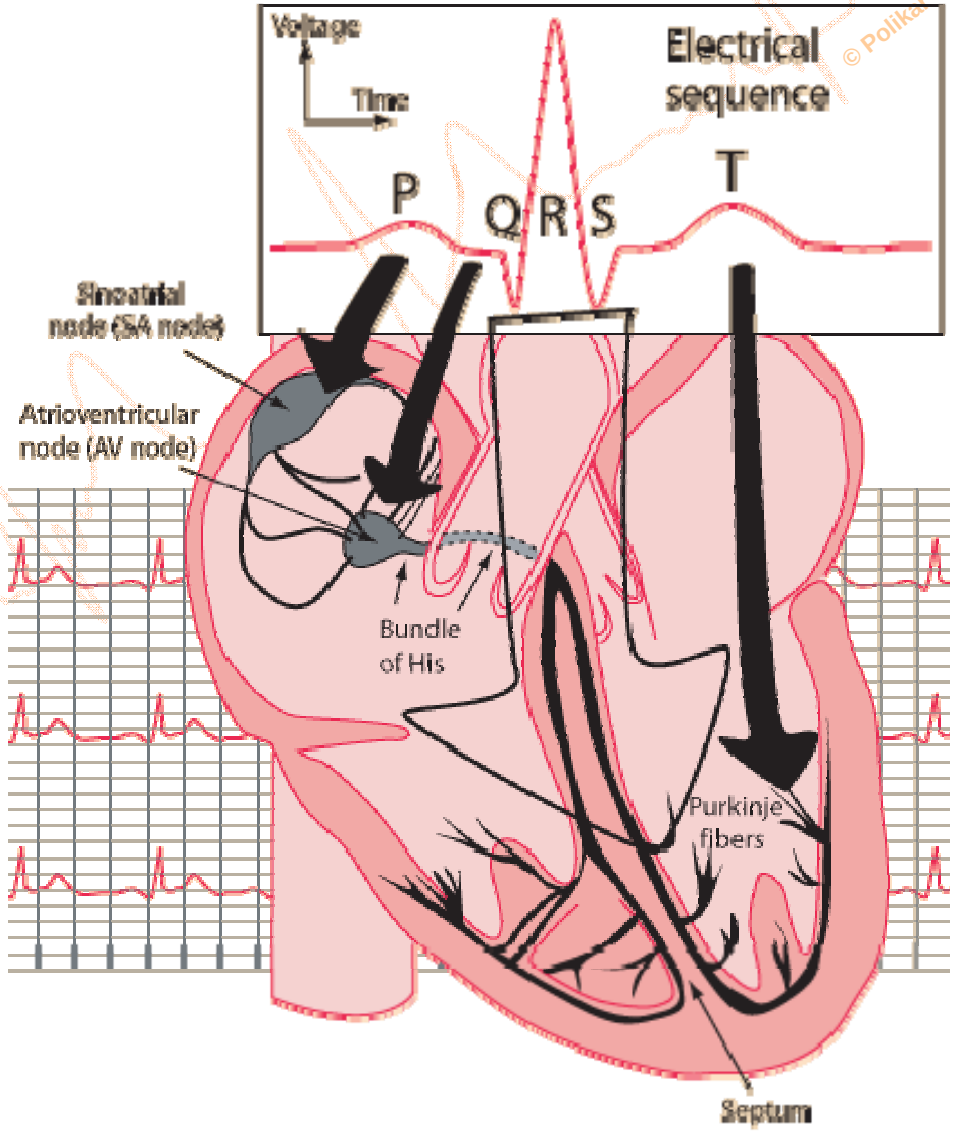
The Electrocardiogram





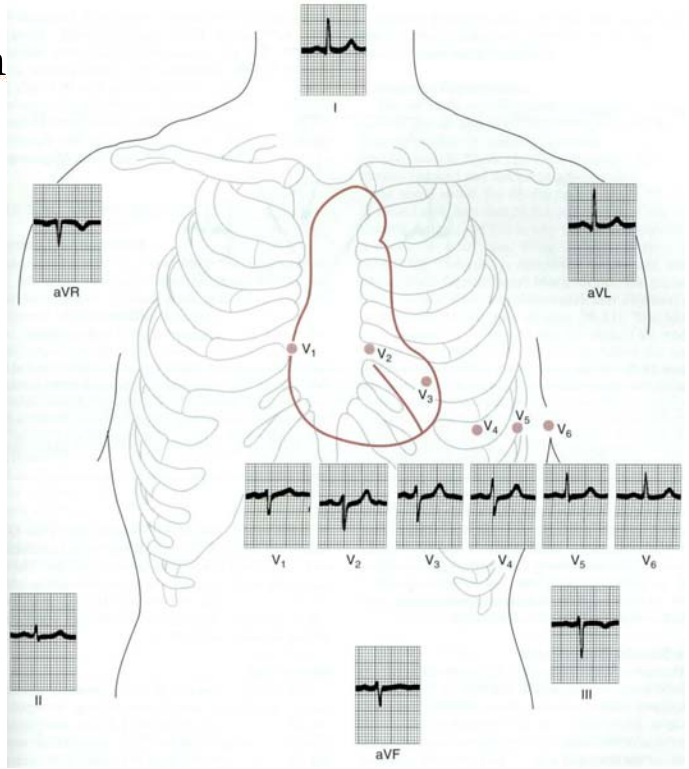
The Electrocardiogram





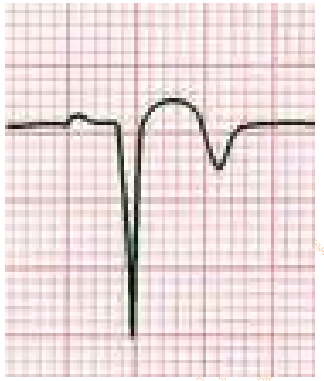
The Electrocardiogram

- The cardiac dynamics that generate the ECG is quite fascinating
  - Highly recommend that you read about the physiological chain of events that take place for each heart beat and how that relates to the ECG
- The ECG is often obtained from several electrode configurations, called the ECG leads.
  - We will revisit the ECG lead configuration throughout the semester.

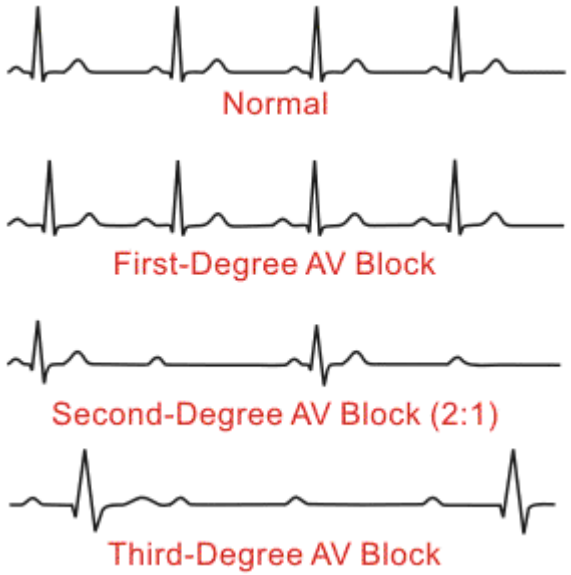


ARRHYTHMIAS

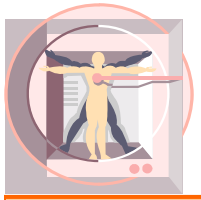
- Any abnormality in the cardiovascular dynamics manifests itself as an arrhythmia in the ECG
  - By analyzing the ECGs, the cardiologist can typically make a diagnosis.
  - Automated diagnosis based on ECG analysis using signal processing and pattern recognition techniques have been very popular recently.



ST-segment elevation
may indicate myocardial infarction



http://cvpharmacology.com/

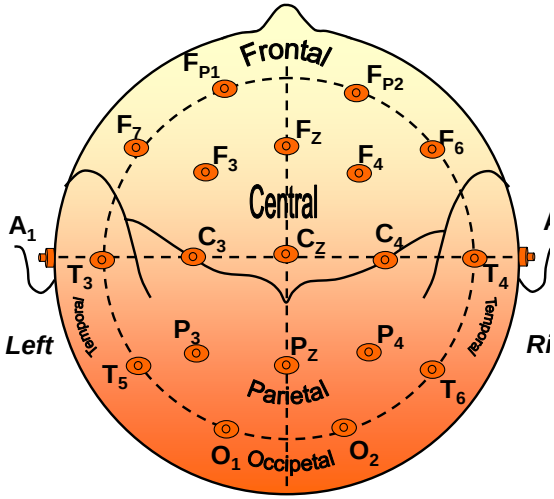


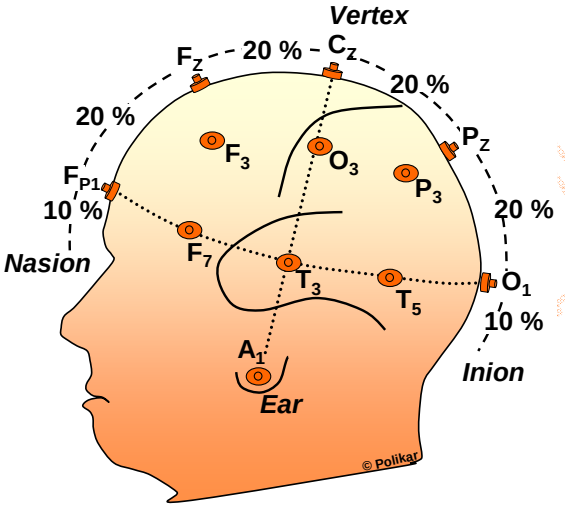
The Electroencephalogram
EEG

- EEG is the graphical representation of the electrical activity of the brain
  - Very commonly used to diagnose certain neurological disorders, such as epilepsy
  - More recently, also investigated whether it can detect various forms of dementia or schizophrenia
- EEG is the specific recording obtained using the scalp electrodes from the surface of the skull
  - During surgery, electrodes may also be placed directly on the cortex. The resulting signal is then ***electrocorticogram*** (ECoG).
  - Just like ECG, EEG is also obtained using several different electrodes places on different regions of the head / brain

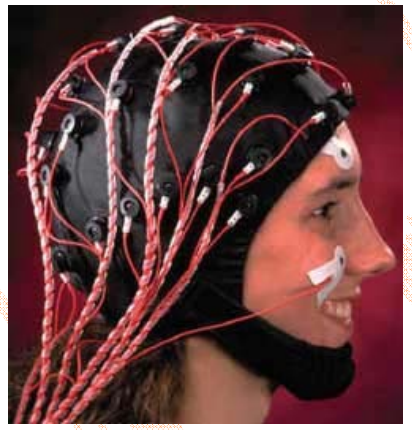
10-20 International Electrode Placement

- Traditionally, electrodes are placed at standard locations





- However, recently electrode-caps allowed additional (64-128) electrodes to be used.

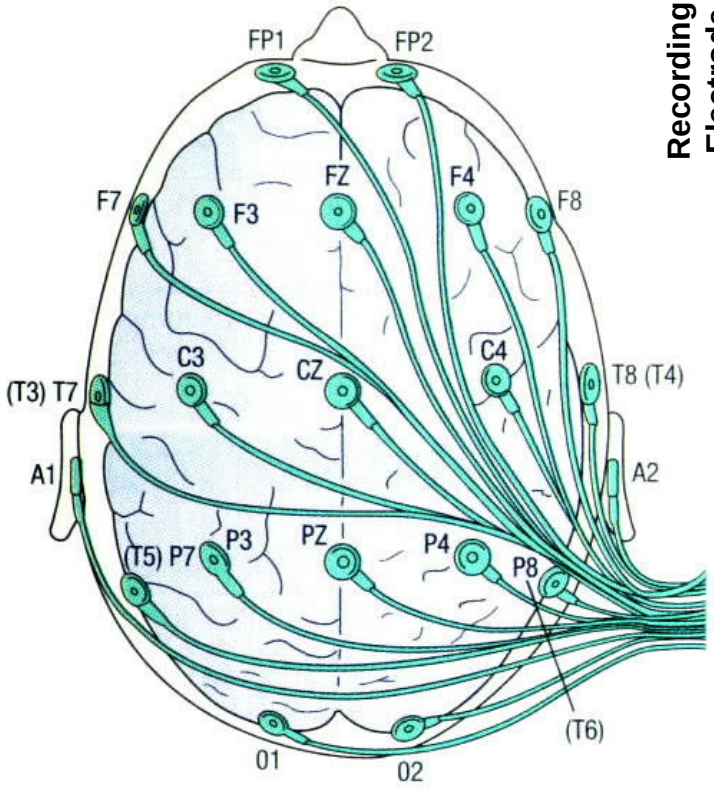


http://www.shifz.org/race/eeg2.htm

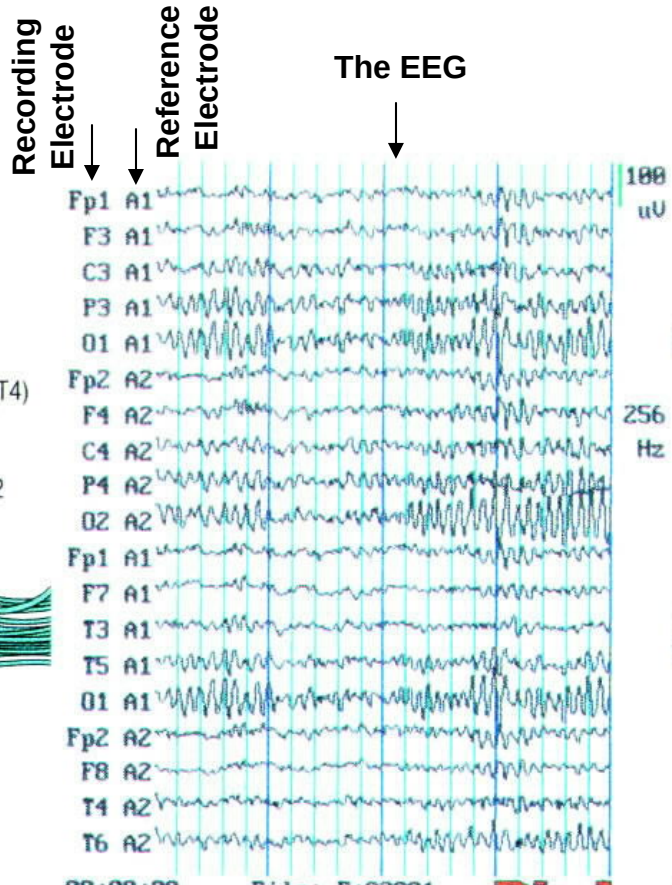
http://ieng9.ucsd.edu/~phammon/

http://local.wasp.uwa.edu.au/~pbourke/other/eeg/

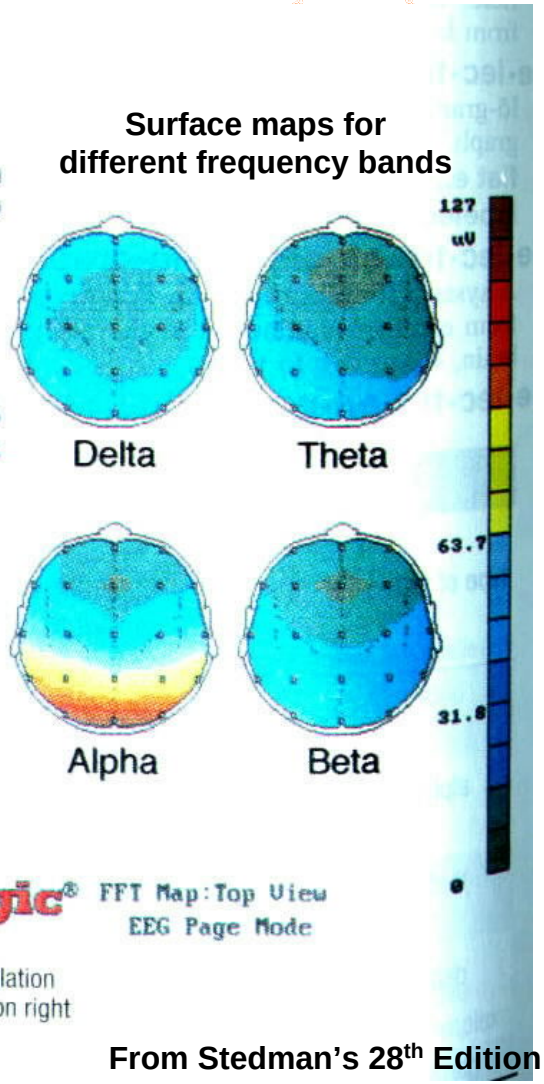
The EEG Signals



position of electrodes



normal EEG wave forms shown on left and computer compilation of frequency bands (delta, theta, alpha, and beta) mapped on right



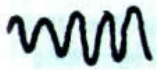
electroencephalography

From Stedman's 28th Edition

THE EEG SIGNALS

- EEG signals are of extremely small amplitude – typically in the μV range
  - Often analyzed in four frequency bands that are associated with certain activities:
    - δ: 0.5 – 4 Hz
    - θ: 4 – 8 Hz
    - α: 8-13 Hz
    - β: 13 - 30 Hz

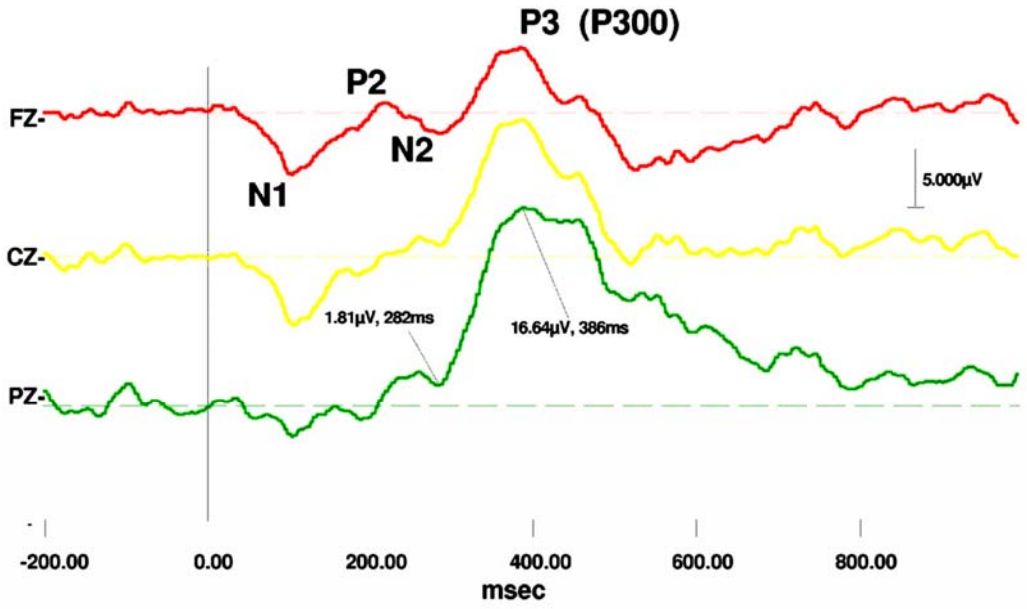
electroencephalogram

type of wave	shape	frequency per sec.	amplitude in μV	physiologic variations of potential in waking EEG: adult	in waking EEG: child	in sleeping EEG: all ages
beta		14–30	5–50	frontal and precentral prominent, in clusters	seldom prominent	beta-activity ("spindles") sign of light sleep
alpha		8–13	20–120	predominant activity	predominant activity, age 5 and above	not a sign of sleep
theta		4–7	20–100	constant, not prominent	predominant activity, from 18 mos. to 5 yrs.	normal sign of sleep
delta		0.5–3	5–250	not prominent	predominant activity until 18 mos.	concomitant sign of deep sleep
gamma	—	31–60	–10	laws governing predominance and localization not fully known		

From Stedman's 28th Edition

The Event Related Potentials - ERPs

- ERPs are really EEGs obtained under a specific protocol that requires the patient to response to certain stimuli – hence event related potentials.
  - Also called ***evoked potentials*** these signals can be used to diagnose certain neurological disorders such as dementia, and they can also be used as a lie-detector
    - ***The oddball paradigm***
    - ***The guilty knowledge test***

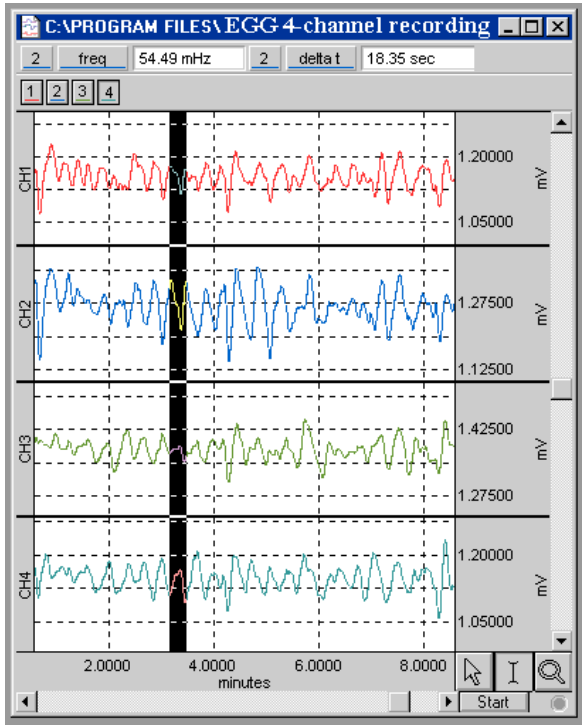


http://www.bnl.gov/neuropsychology/ERPs_al.asp

The Electrogastogram - EGG

- The EGG is the graphical representation of the electrical activity of the stomach
  - Created by the rhythmic depolarization and repolarization of the underlying smooth muscle cells of the stomach
  - Just like the EEG, the EGG activity is always present and it is not in response to specific contractions of the stomach muscle.
    - EGG is also obtained using surface electrodes.

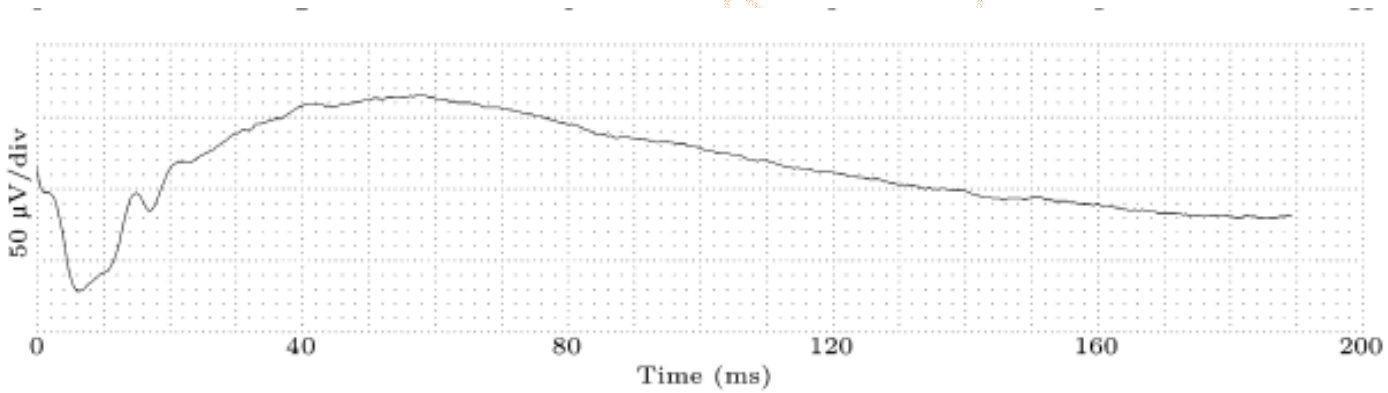
http://lbibi.chez-alice.fr/Site_SBB_ESA/parabolic_flight/results/point1.htm

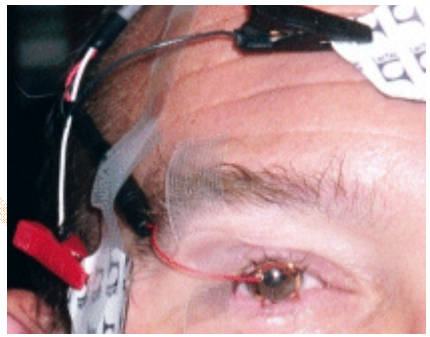


http://www.biopac.com/

ELECTRORETINOGRAM
ERG

- The ERG is the record of the retinal action currents produced by the retina in response to a light stimulus.
  - It measures the electrical responses of the light-sensitive cells (such as rods and cones). The stimuli are often a series of light flashes or rotating patterns
  - The ERG is recorded using contact lens electrode that the subject wears while watching the stimuli.

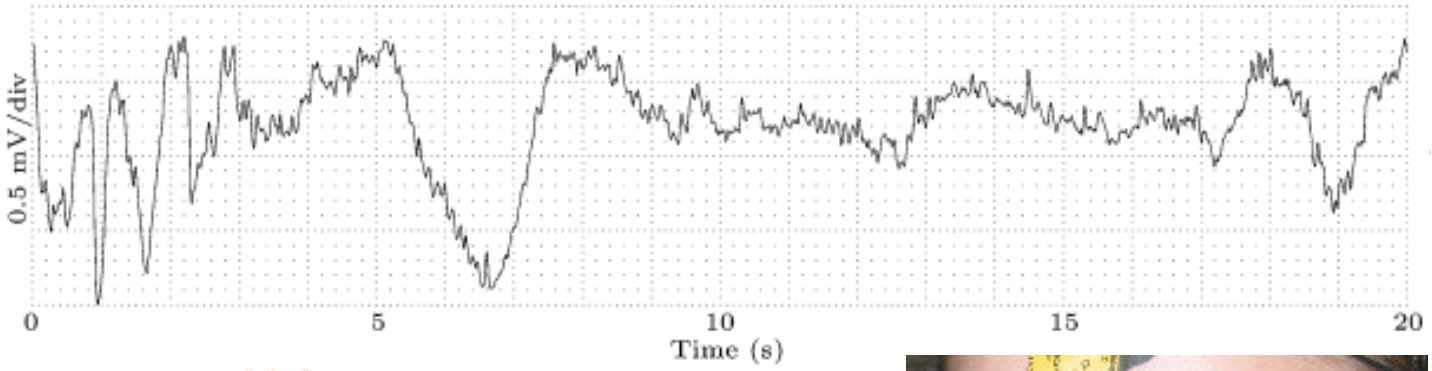


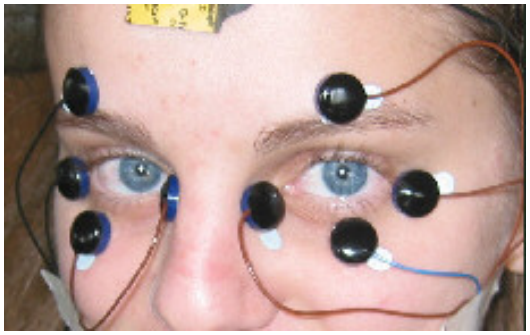


http://www.metrovision.fr/mv-electrodes-im01.gif

The Electrooculogram
EOG

- The EOG measures the resting potential of the retina. Unlike ERG it is not recorded in response to a stimulus.
  - The EOG is often used in recording the eye-movements (such as in VR applications, or as a reference in EEG applications to remove eye-blink artifacts)
  - EOG is also used in diagnosing certain sleep disorders, where the active REM can easily be recorded using the EOG

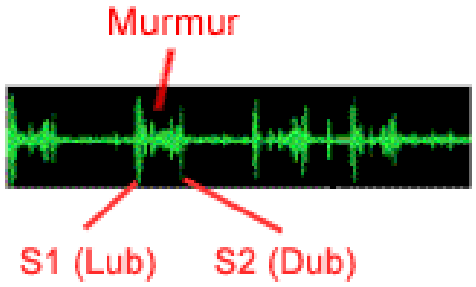




http://www.metrovision.fr/

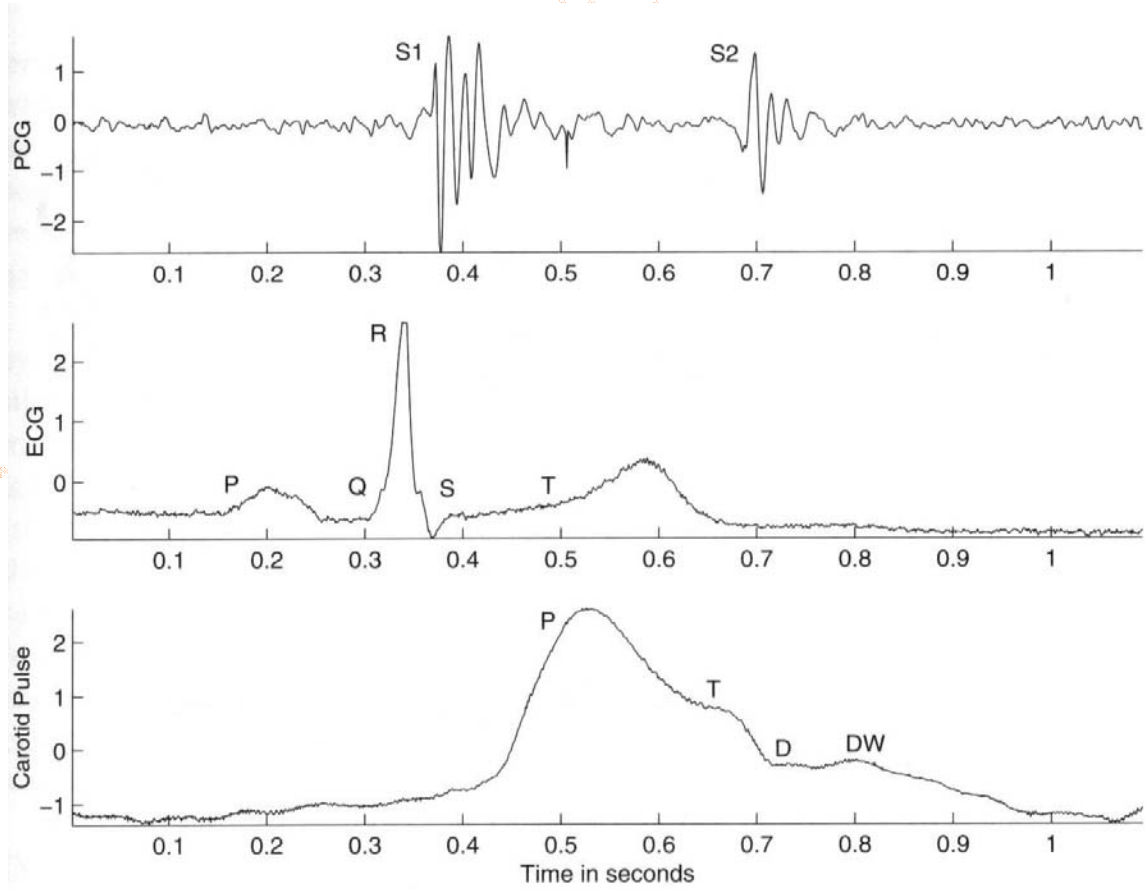
PHONOCARDIOGRAM - PCG

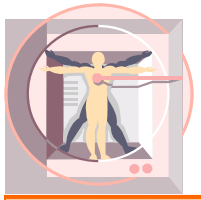
- The PCG is the graphic record of the heart sounds and murmurs. It is thus a mechanical / audio signal, rather than an electrical signal
  - Can be easily heard using a stethoscope
  - Or can be converted into an electrical signal using a transducer
  - Typically used to determine the disorders related to the heart valve, since their routine opening and closing create the well-known sounds.
    - S_1 sounds: First heart sounds – ventricular contractions move blood into atria closing of the AV (mitral and tricuspid) valves, then semilunar valves open and blood ejected out of ventricles – immediately follows the QRS complex
    - S_2 sounds: Second heart sounds – Closure of semilunar (aortic and pulmonary) valves
    - Any unexpected sound may indicate a malfunctioning valve that causes the blood flow into / out of a chamber when it should not. Also called heart murmurs.



The Carotid Pulse (CP)

- CP is a mechanical signal measured using pressure transducer over the carotid artery
  - Provides the pulse signal indicating the changes in arterial blood pressure / volume with each heart beat – usually measured together with PCG and ECG.
  - While it closely resembles the actual pressure, it does not measure the pressure itself directly.
  - Its components:
    - P: percussion wave
      Ejection of blood from the left ventricle
    - T: Tidal wave
      Pulse returning from upper body
    - D: Dicrotic notch
      Closure of the aortic valve
    - DW: Dicrotic wave
      Pulse reflected from lower body



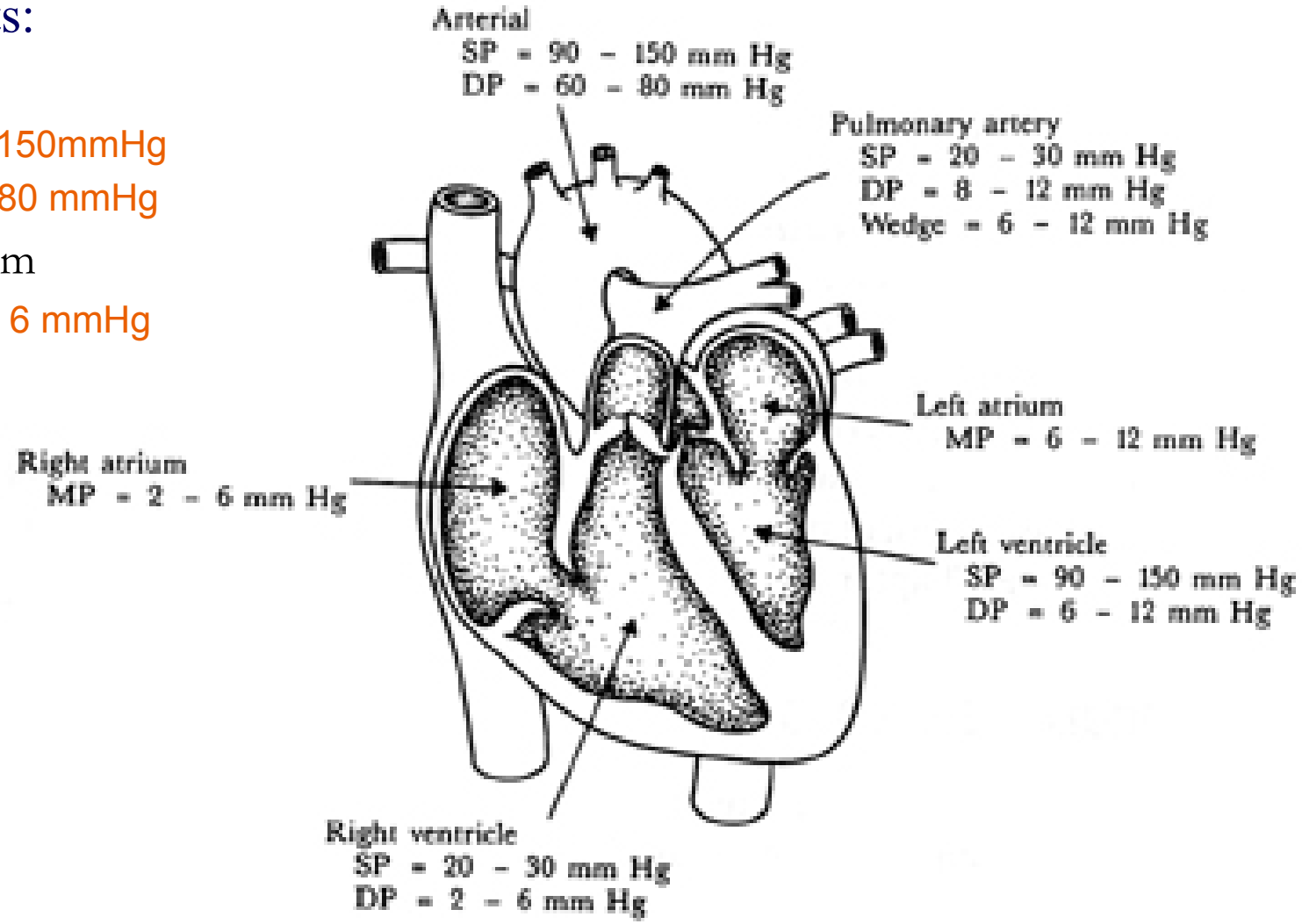


The Blood Pressure

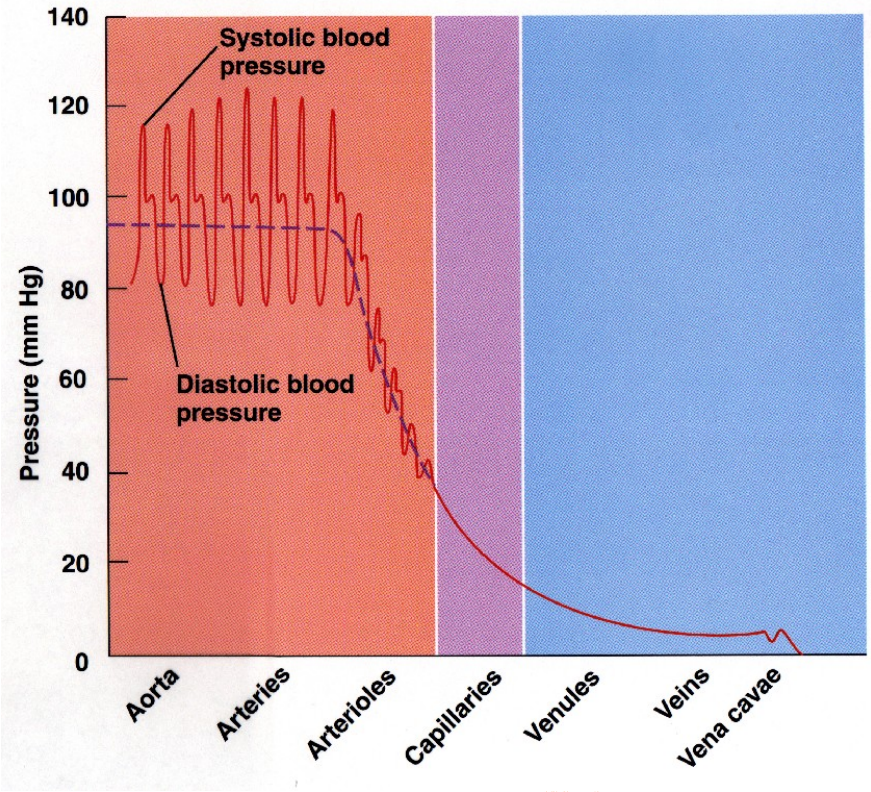
- What does the actual blood pressure signal looks like…?
  - First need to understand the pressure gradient and how blood moves around
- Blood transports O_2 and nutrients to tissues, and carry metabolic waste away from the cells
  - The transportation is made possible by a "pressurized vessel" system, the arteries, veins, arterioles, venuoles and capillaries, 100,000 km in all…
  - The pressure is provided by a mechanical pump, the heart.
  - Measuring this pressure at various locations of this transportation network carries significant clinical information. These measurements can be made directly or indirectly
  - The blood always travels down its ***pressure gradient***

The Blood Pressure

- Highest points:
  - Aorta
    - SP: 90-150mmHg
    - DP: 60-80 mmHg
  - Right atrium
    - MP: 2 – 6 mmHg



The Blood Pressure



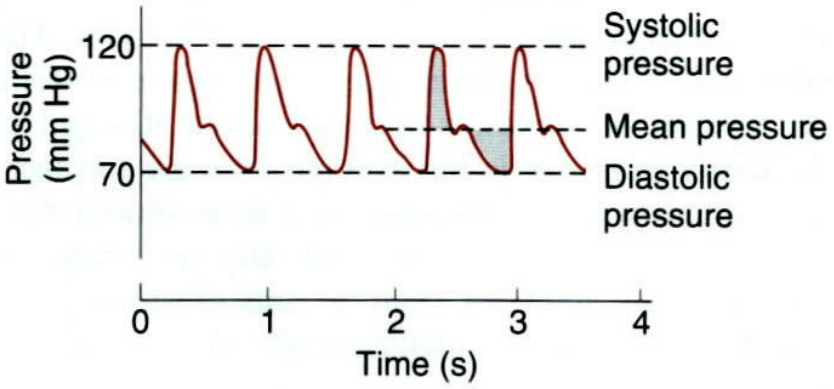
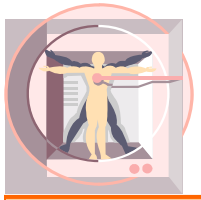
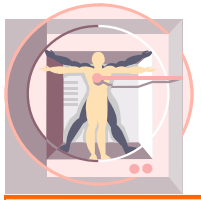


Figure 30–16. Brachial artery pressure curve of a normal young human, showing the relation of systolic and diastolic pressure to mean pressure. The shaded area above the mean pressure line is equal to the shaded area below it.



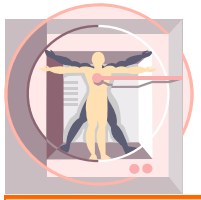
Properties of Biological Signals

- Biological signals, in general are extremely difficult to process:
  - First, they are difficult to acquire
  - The signal amplitudes are very small, which require large amplification, which in turn increases the amount of noise
  - They are very prone to noise
    - In part due to large amplification
    - In part due their small original amplitude (and hence masked by external, stronger signals)
    - In part due to the presence of so many other biological signals in the near vicinity, e.g. one often sees EMG noise on ECH, EOG noise on EEG, etc.
  - They are non-stationary: their frequency content changes with time → Fourier based techniques are often not adequate
  - The noise spectrum often coincides with that of the signal spectrum, and hence standard filtering approaches fail → need more advances adaptive filtering techniques.



Characterization of Biological Signals

Measurement	Range	Frequency, Hz	Method
Blood flow	1 to 300 mL/s	0 to 20	Electromagnetic or ultrasonic
Blood pressure	0 to 400 mmHg	0 to 50	Cuff or strain gage
Cardiac output	4 to 25 L/min	0 to 20	Fick, dye dilution
Electrocardiography	0.5 to 4 mV	0.05 to 150	Skin electrodes
Electroencephalography	5 to 300 μ V	0.5 to 150	Scalp electrodes
Electromyography	0.1 to 5 mV	0 to 10000	Needle electrodes
Electroretinography	0 to 900 μ V	0 to 50	Contact lens electrodes
pH	3 to 13 pH units	0 to 1	pH electrode
pCO_2	40 to 100 mmHg	0 to 2	pCO_2 electrode
pO_2	30 to 100 mmHg	0 to 2	pO_2 electrode
Pneumotachography	0 to 600 L/min	0 to 40	Pneumotachometer
Respiratory rate	2 to 50 breaths/min	0.1 to 10	Impedance
Temperature	32 to 40 °C	0 to 0.1	Thermistor



Looking Ahead

- Please do read about action potentials before you come to Dr. Tahamont's class next week.
- Read the introductory chapter from Sornmo text (posted on the class web page)
- Find one recent article from any technical journal or magazine regarding biomedical signal processing – read it prepare a one-two paragraph short essay to read in class.
  - IEEE Transactions on Biomedical Engineering
  - IEEE Engineering in Medicine and Biology Society Magazine
  - others…
- The week after: DSP review – It will be a lot less painful if you review your DSP notes before coming to class – Obviously, we assume that you already know that material – we will cover entire DSP in one week – at breathtaking speeds, needless to say!