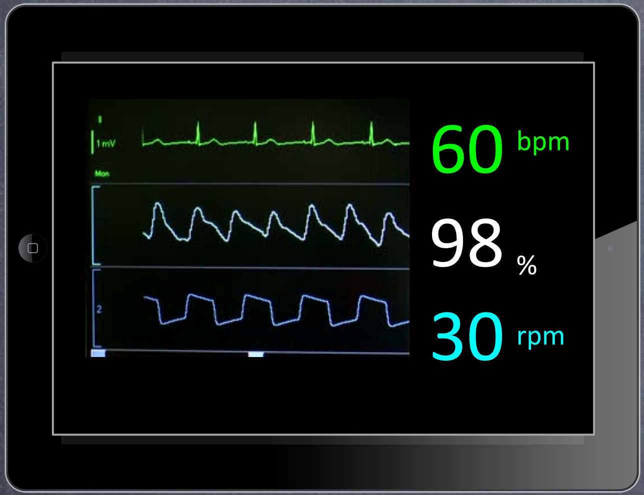
EE93 – Medical Mobile Devices and Apps



Lecture: Instrumentation

Introduction

- The Heart
- Electrocardiography
- 12-Lead ECG
- 3-Lead ECG
- Instrumentation Amplifier
- Digital Signal Processing

The Heart

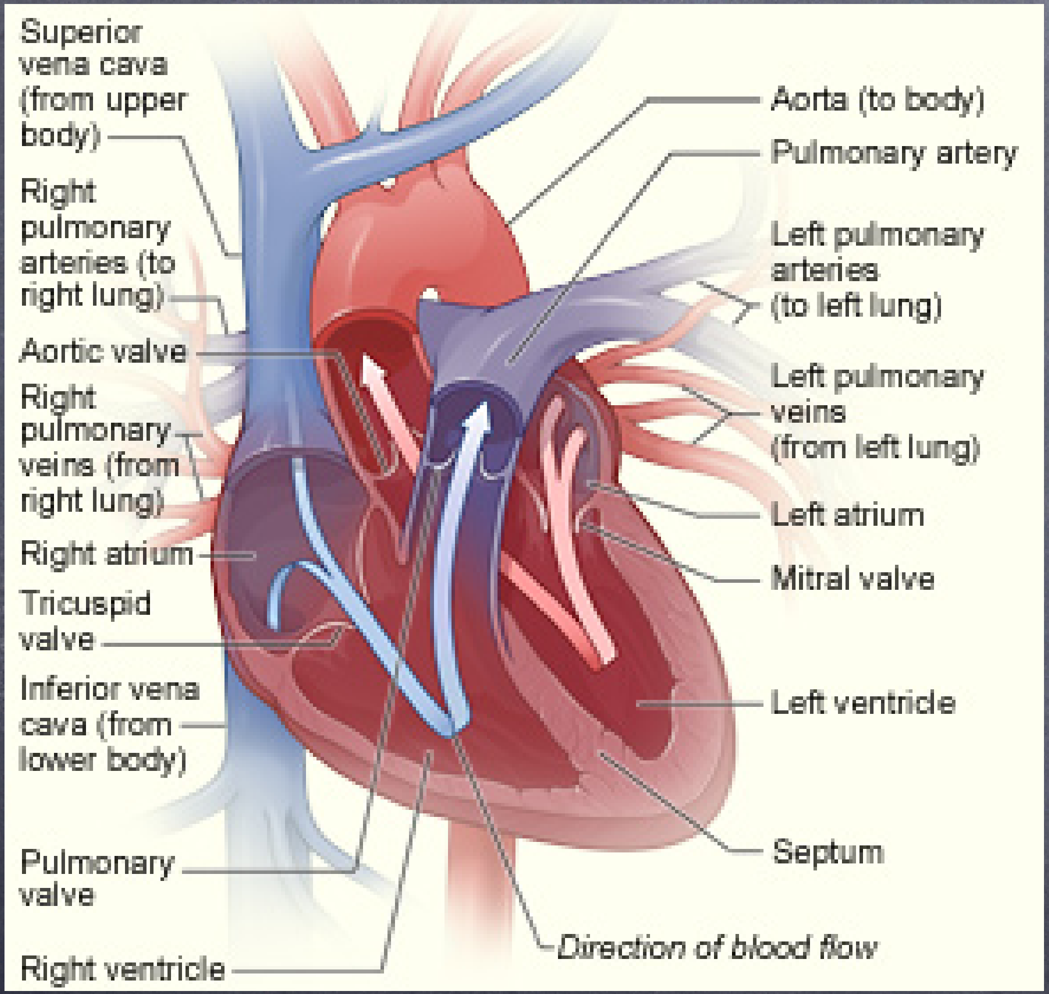
- Hollow muscular organ that pumps blood throughout the body by repeated, rhythmic contractions

- Cardiac from the Greek καρδιά, kardia, for "heart".

The Heart

- Located in the pericardium – a double-walled protective sac, center of human chest inside rib cage
- Three layers:
  - Epicardium – outer layer connective & protective tissue
  - Myocardium – the striated muscle of the heart, performs contraction
  - Endocardium – responsible for contraction
- Four chambers:
  - Two upper chambers: left atrium and right atrium (atria)
  - Two lower chambers: right and the left ventricle
  - Septum – dividing wall of muscle, separating right side from left side
    - Ventricular septum thicker atria septum.

The Heart



Source: www.nhlbi.nih.gov

- Blue arrow direction of oxygen-poor blood flow from rest of body to heart to lungs.
- Red arrow direction of oxygen-rich blood flows from lungs to heart and to rest of body

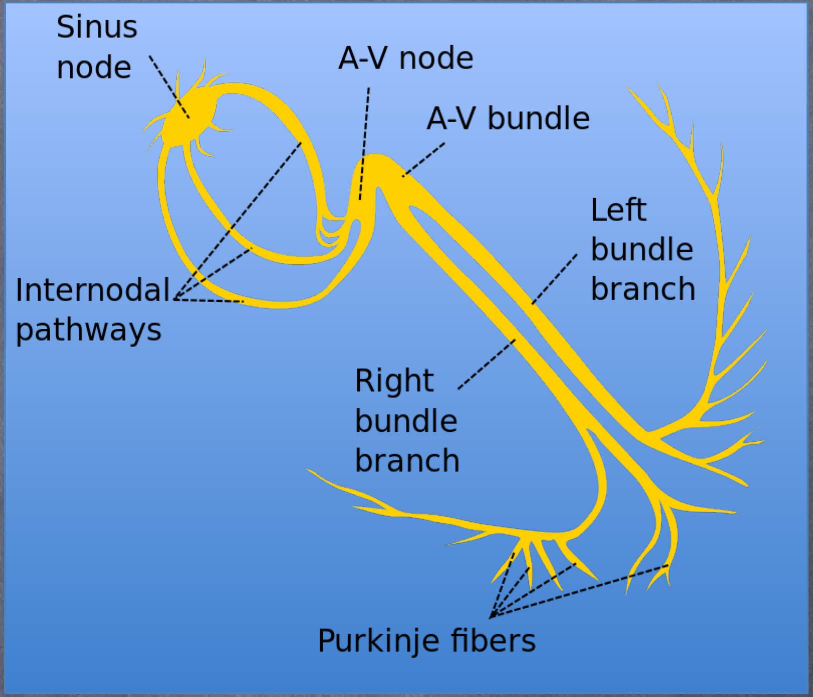
How the Heart Functions

- Right atrium collects de-oxygenated blood from the body
- Right atrium contracts pumping blood through tricuspid valve
- Tricuspid valve to right ventricle to the lungs
- Lung function – exchanged carbon dioxide for oxygen
- Oxygenated blood returns from lungs
- Left atrium collects oxygenated blood from the lung
- Left atrium pumps blood to left ventricle via bicuspid valve (mitral valve)
- Mitral valve pumps it out to the body (via the aorta)
- Blood returns to right atrium repeating the process

Note: ventricles are thicker, bigger than atria as they pump the blood into the circulatory system throughout the body

Electric Overview of the Heart

- Electrical conduction
  - Electrical potential begins at sinus node (right atrium)
  - Propagates across atria
  - Purkinje fibers conduct charge across ventricles and transmit signal to myocardium



Source: wiki

Electrocardiography (ECG)

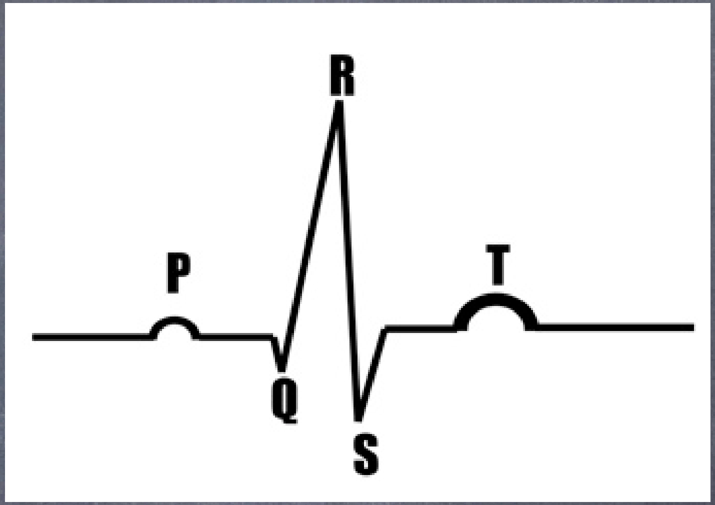
- Records the electrical activity and conduction system of the heart over time
- Measures electrical impulses of the polarization and depolarization of cardiac tissue capturing an electrical signal
- Calculates and translates electrical signal into a waveform

Why ECG? The Medical Approach

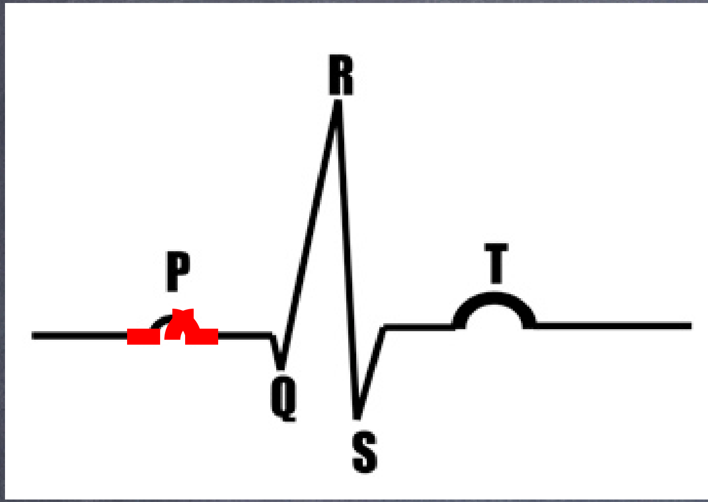
- General population screening for coronary heart disease
- Myocardial infarction (heart attack)
- Pulmonary embolism (blockage of the main artery of the lung
- Other disease history contributions
  - Hypertension
  - Arterial
  - Diabetes
  - Stroke

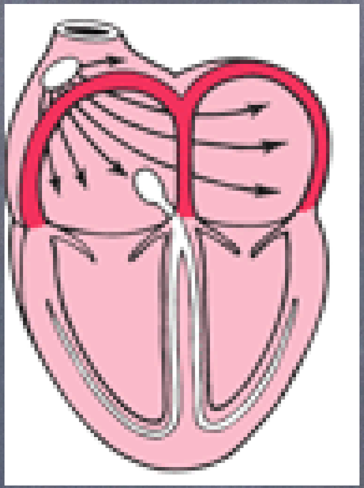
ECG – PQRST Wave

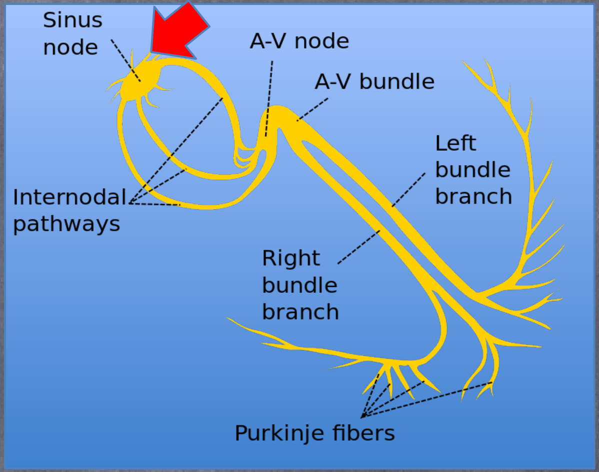
- ECG has five deflections
- Name is arbitrary
- QRS wave (complex) occurs in rapids succession
- Q is any downward deflection after the P wave
- R wave is upward deflection
- S is downward
- T wave follows S
- And sometimes a upward U wave (very small and not often seen; repolarization)



PQRST Wave

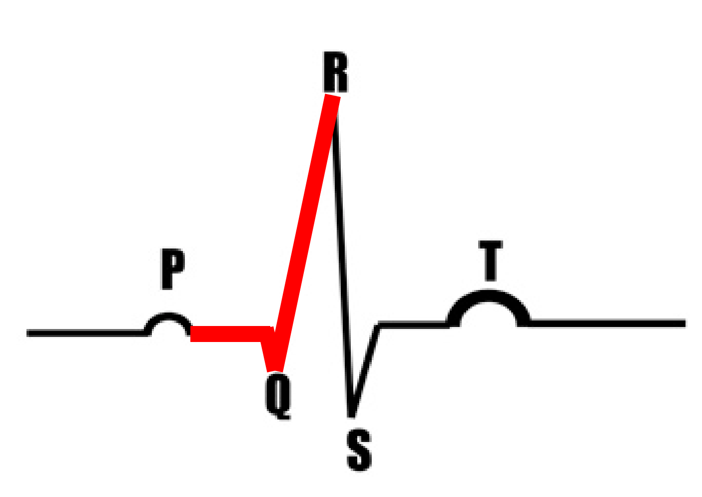


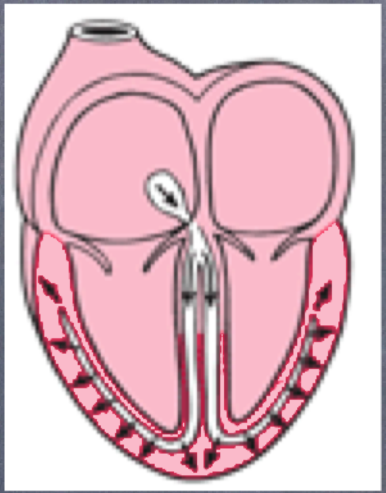


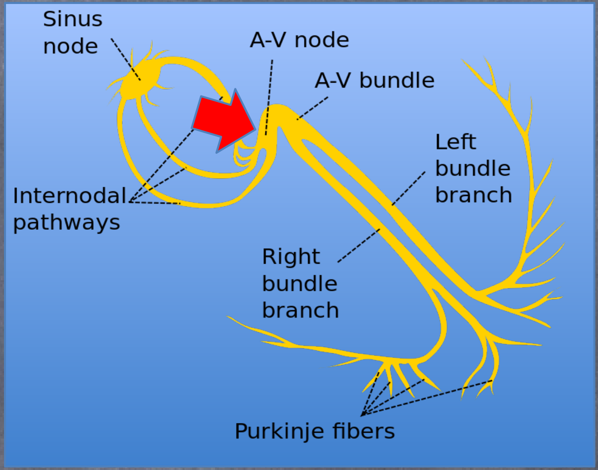


- Electrical impulse generated by is spontaneously generated by the sinoatrial node, nature’s pacemaker
- Impulse propagates via right atrium to Bachmann's bundle (fibers on outside of left atrium)
- Myocardium contracts
- Seen on the ECG as the P wave

PR Interval

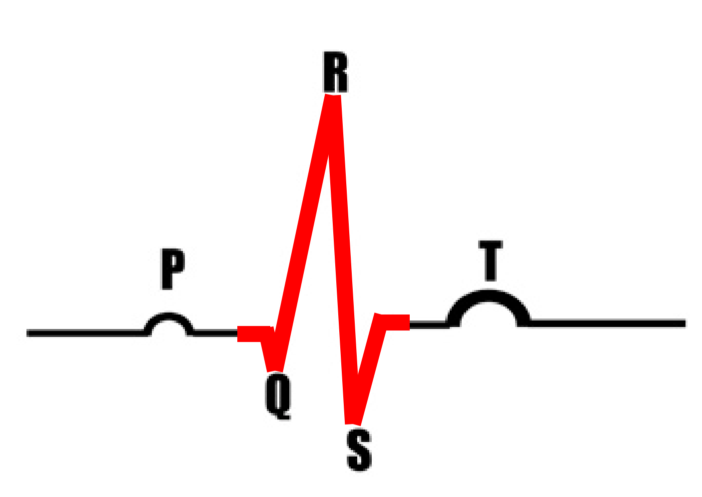


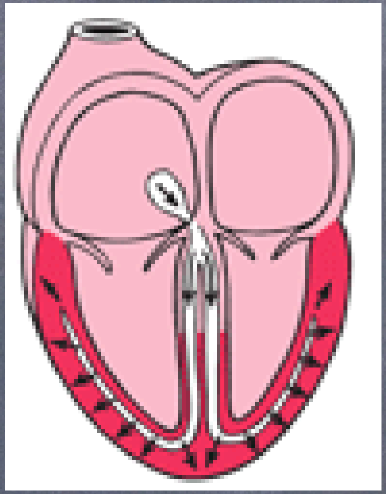


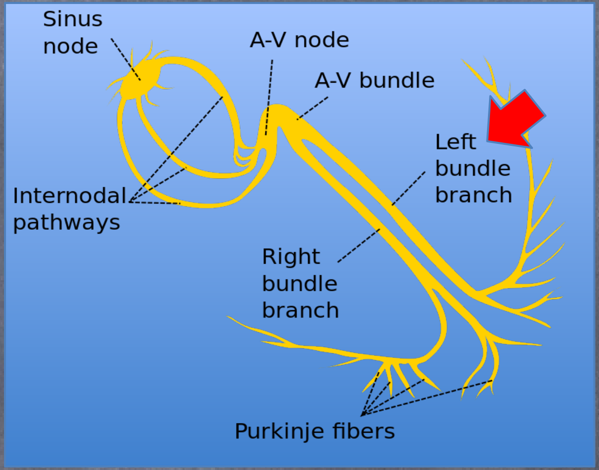


- PR Interval displays atrioventricular no**de's** critical delay in conduct of the impulse
- Delay prevents atria and ventricles from contracting at the same time (blood flow would cease to flow)
- PR Interval is made up of AV node delay and atrial repolarization

PQRST Wave

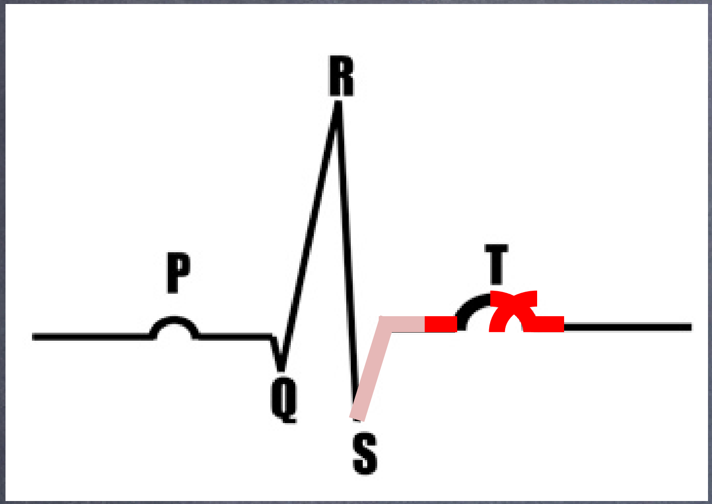


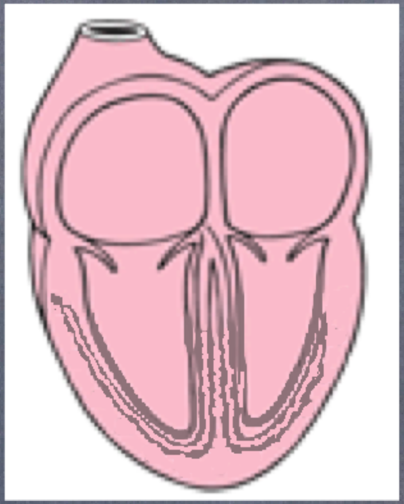
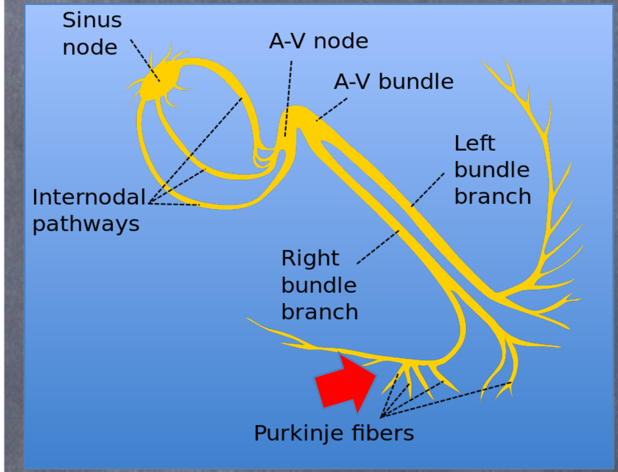




- Spread of electrical impulse across the ventricular myocardium
- Purkinje fibers:
  - Located in inner ventricular walls
  - Creates synchronized contractions of ventricles
  - Critical for maintenance of a consistent heart rhythm
- QRS complex – very rapid occurrence
- Begins (normal) with a downward deflection
  - Q: a larger upwards deflection
  - R: high peak
  - S: a downwards wave
- Action represents a complex ventricular depolarization and contraction.

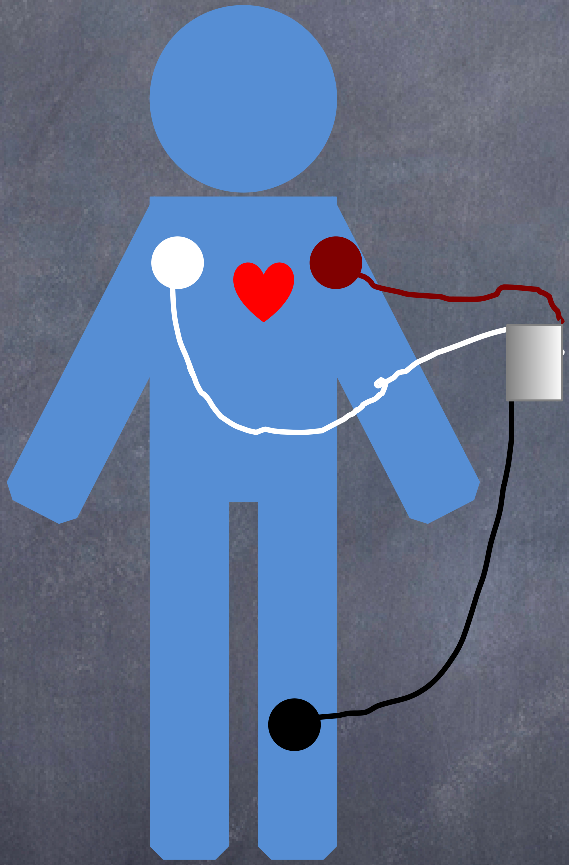
ST Interval & PQRST Wave

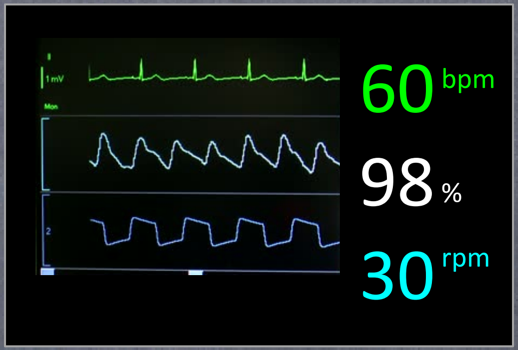


- Ventricular repolarization
- Recovery and resting state
- T wave – moderate upward wave indicating
- Includes ST Interval, T Wave, & U Wave

Measuring ECG





Source for ECG slides: Computing the Electrical Activity in the Heart: 1 (Monographs in Computational Science and Engineering) by Joakim Sundnes, Glenn Terje Lines, Xing Cai and Bjørn Frederik Nielsen (2007)

Measuring The Heart

- Use the Electrocardiogram (ECG)
- ECG:
  - Generates a waveform representing the electrical activity of the heart
  - Waveform patterns provide signs, symptoms, and damage of heart muscle
- ECG cannot:
  - Determine blood flow rate or pumping blood pressure
  - Masked conditions, e.g., cardiac arrest

ECG History

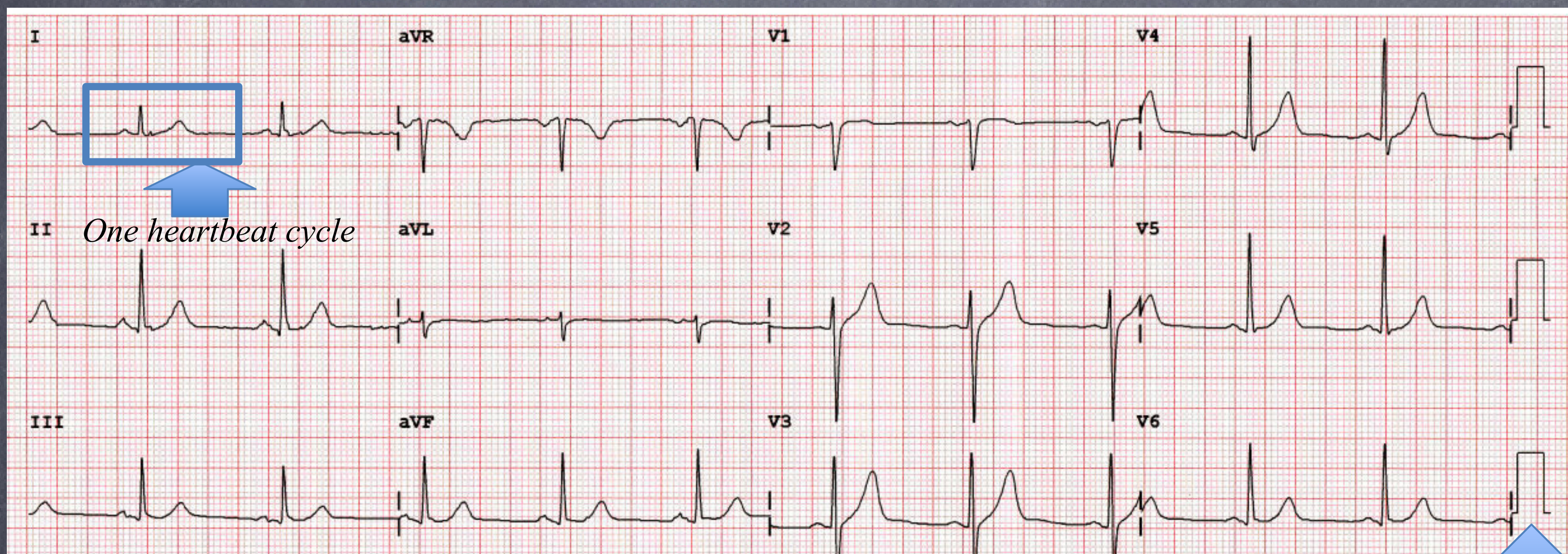
- *Augustus Désiré Waller, St Mary's Hospital, Edinburgh, shows cardiograph to students of the medical school, during lecture in 1888*
- *Wilhelm Einthoven, The Netherlands, demonstrates string galvanometer – with the limb leads labeled I, II, and III and the waveform labeled P, QRS, and T; receives Nobel prize in 1924 for discovering mechanism of the electrocardiogram*
- *Einthoven actually credits Waller with this discovery in 1895 paper; "Über die Form des menschlichen Elektrokardiogramms"*
- *Dutch spelling with a "K" oftens has ECG referred to as EKG*
- *Frank Wilson showed ECG unipolar potentials could be defined using a central terminal as reference by connecting 5 kΩ resistor from each terminal of the limb leads to the central terminal*

ECG: How & Why

- Amplifies depolarization and repolarization of the heart muscles through changes in the skin
- Heart cells at rest have negative polarity
  - Outside +, inside -, - 90 mV potential difference
- Movement toward neutral (0 volts) is called depolarization
  - Stimulated by Ca+ and Na+ flow into heart cells
  - Cell outside -, inside +
  - Current spreads along cells in a particular direction
- Repolarization: outside returns to +, inside -, returns to rest

ECG Waveform on Strip Chart

12-lead – showing in 4 columns by 3 rows



5 mm by 5 mm reference square 0,200 s duration by 0.5 mV amplitude

1 mm by 1 mm reference square 0,040 s duration by 0.1 mV amplitude

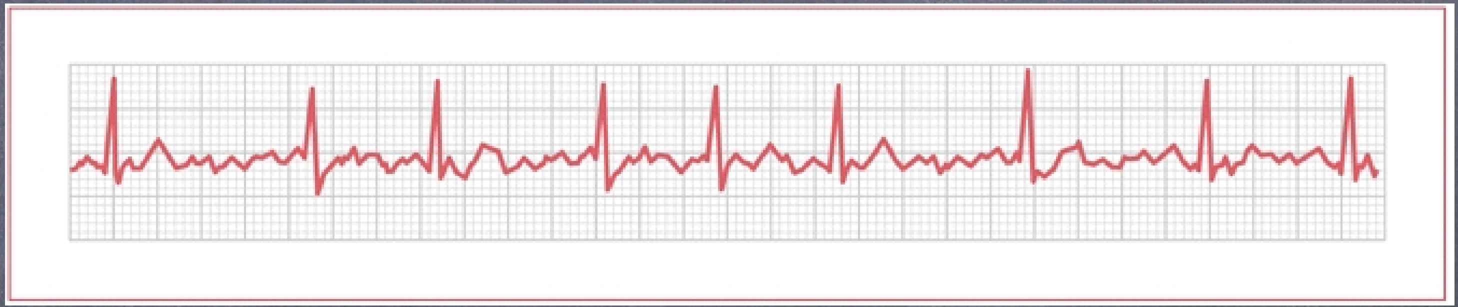
1 mV, 10 mm high reference pulse

Length: 0.200 s

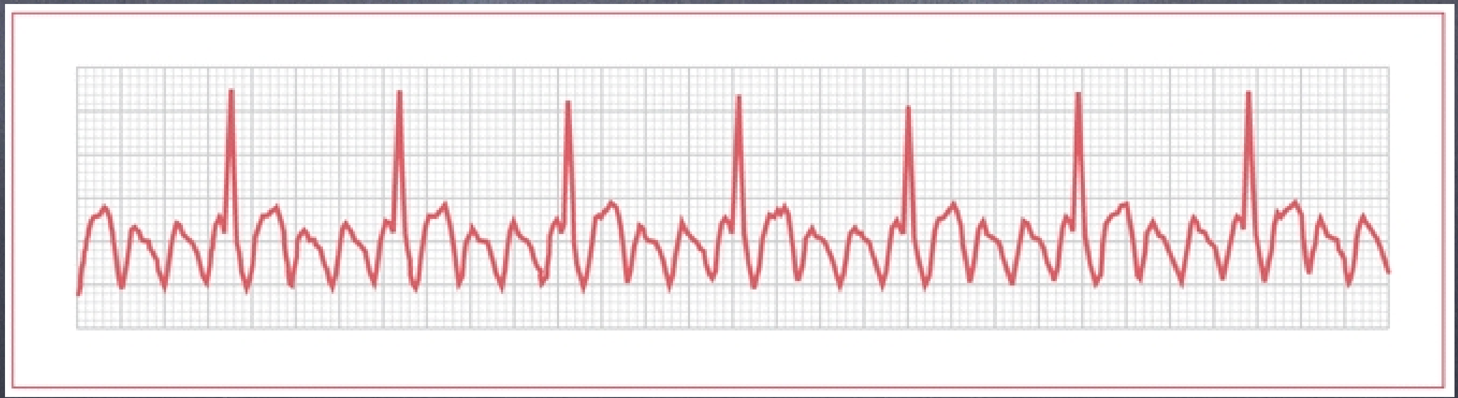
Measuring ECG

- ECG showing lack of sinus heart rhythm

ECG: Artrial Fibrillation (loss of T wave)



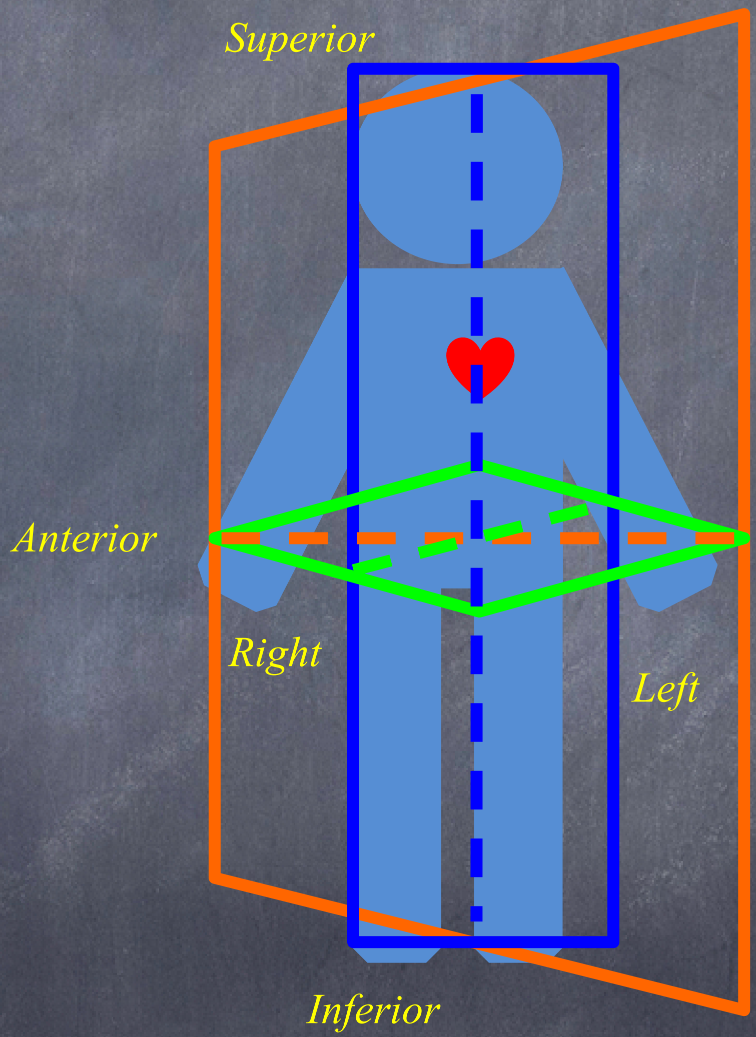
ECG: Artrial Flutter (sawtooth)



Source: http://www.ncbi.nlm.nih.gov/books/NBK2214/

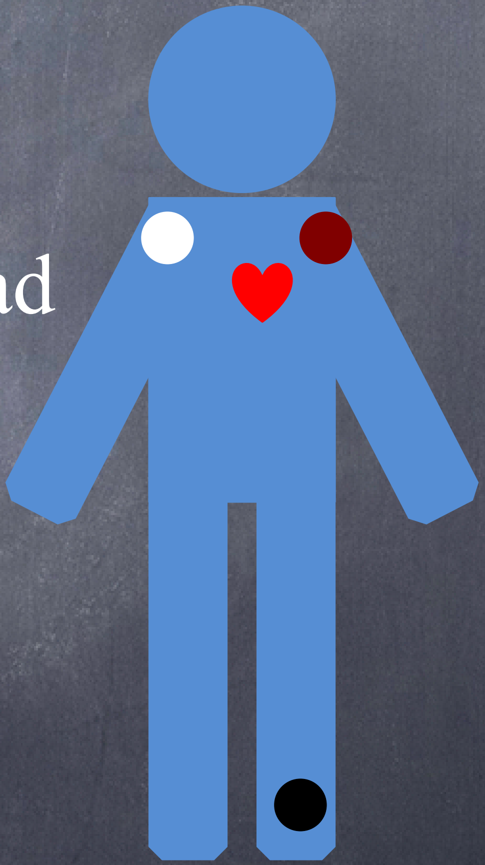
Lead Orientation (12-lead)

- ECG provides spatial information of electrical activity of heart
- Three orthogonal directions (approximate)
  - Right	Left
  - Superior Inferior
  - Anterior Posterior



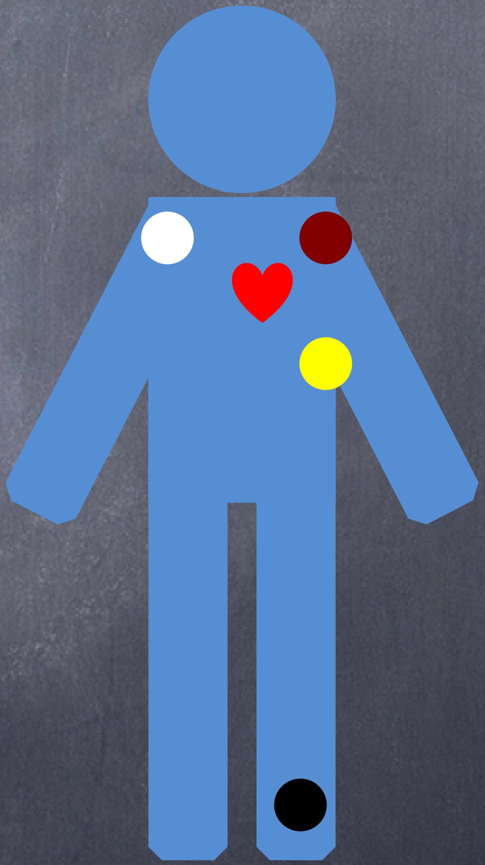
Lead Placement (12-lead)

- Electrodes positioned on body in pairs
  - LA+RA (left arm + right arm)
  - LA+LL (left arm + left leg)
  - RA+LL(right arm + left leg)
- Output from each pair is called a lead
- Leads
  - Bipolar (frontal plane)
  - Augmented (frontal plane)
  - Unipolar (horizontal plane)



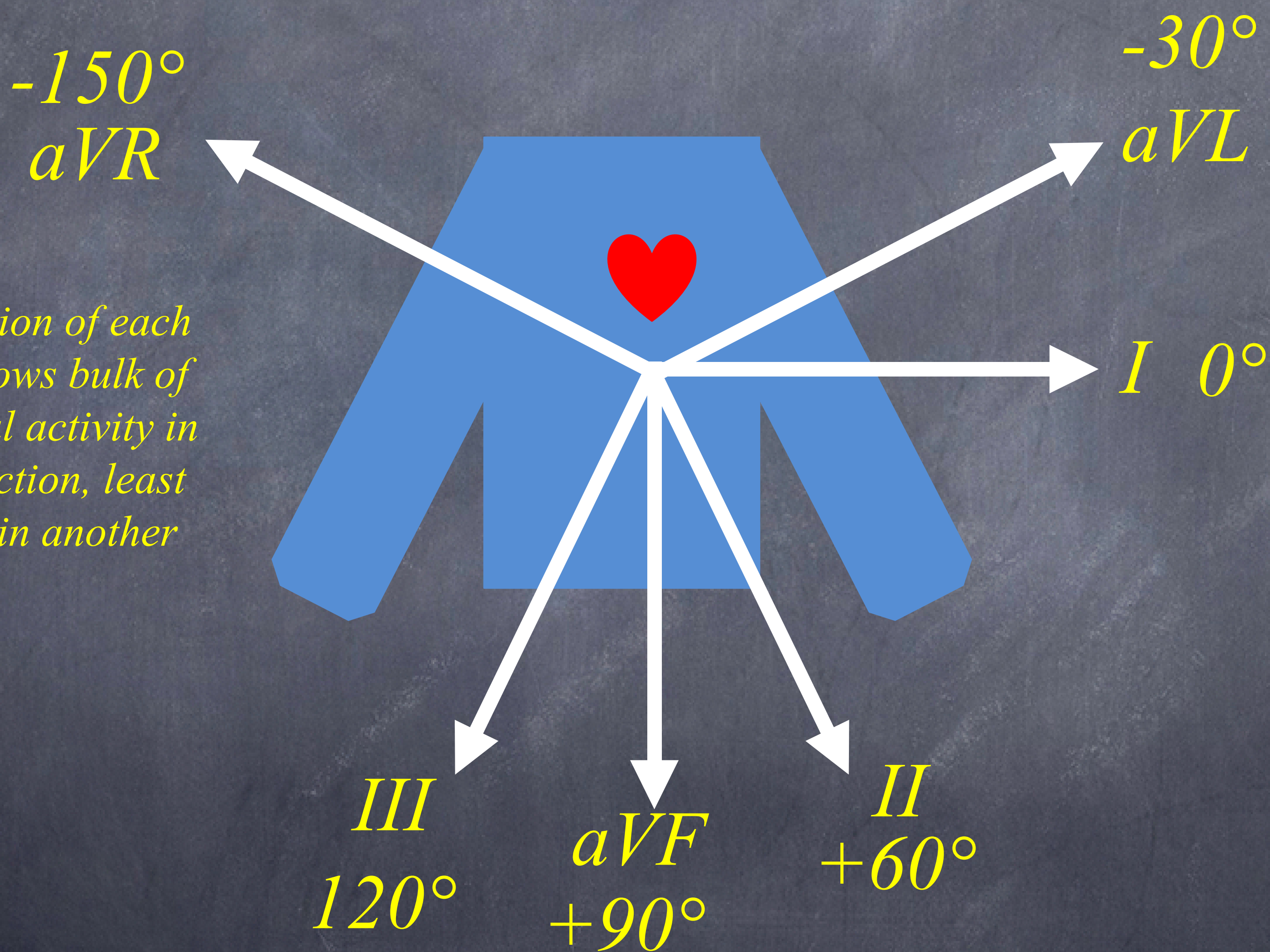
Lead Names

- Bipolar
  - Lead I (RA- to LA+), right, left
  - Lead II (RA- to LL+), superior, inferior
  - Lead III (LA- to LL+), superior, inferior
- Augmented
  - Lead aVR (RA+ to LA&LL-), right
  - Lead aVL (LA+ to RA&LL+), left
  - Lead aVF (LL+ to RA&LA-), inferior
- Unipolar (or precordial)
  - Leads V1, V2, V3, posterior, anterior
  - Leads V4, V5, V6, right, left



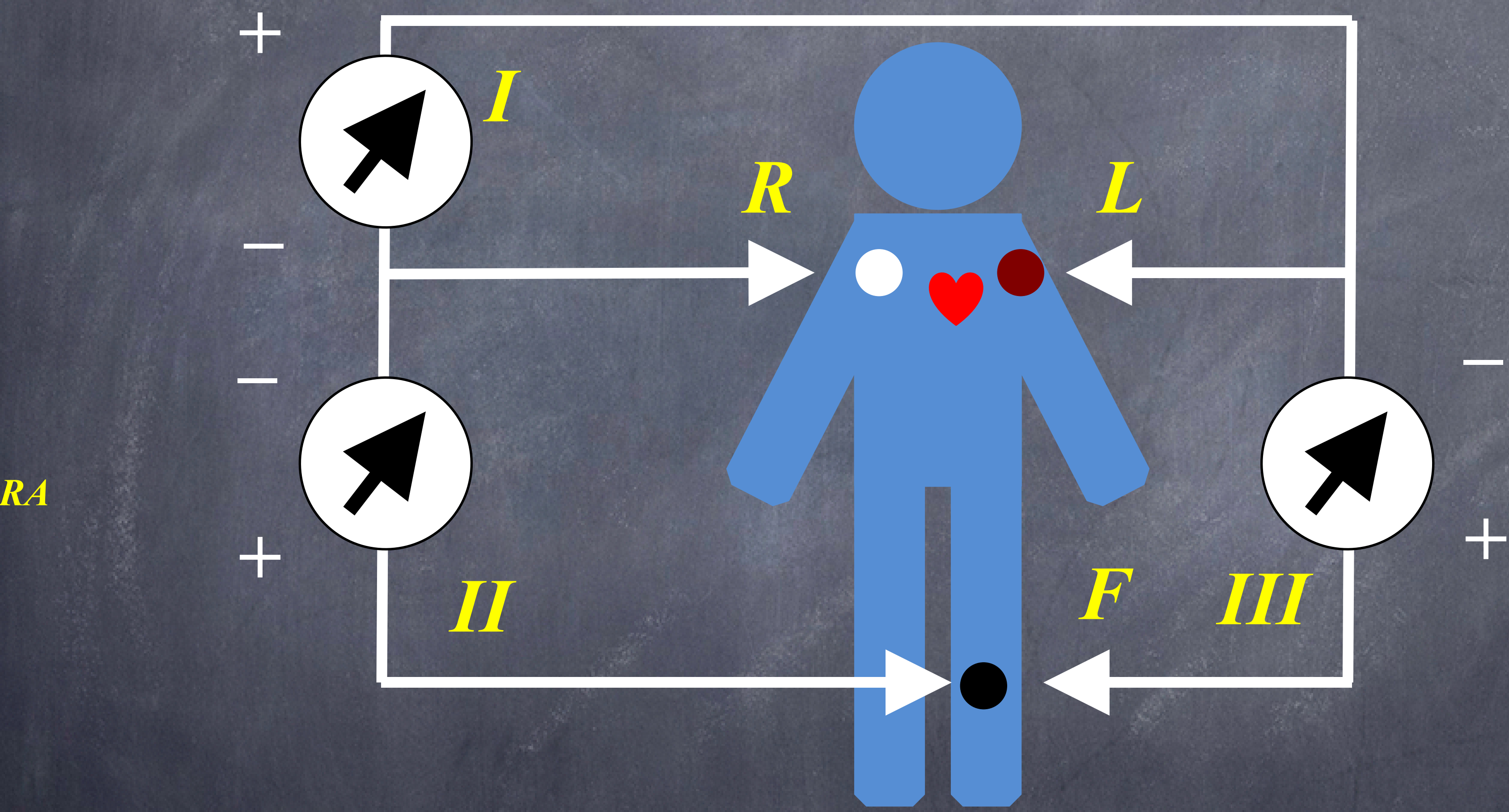
RA *LA* *LL* *Vn*

Hexaxial Reference System



Orientation of each lead: shows bulk of electrical activity in one direction, least actively in another

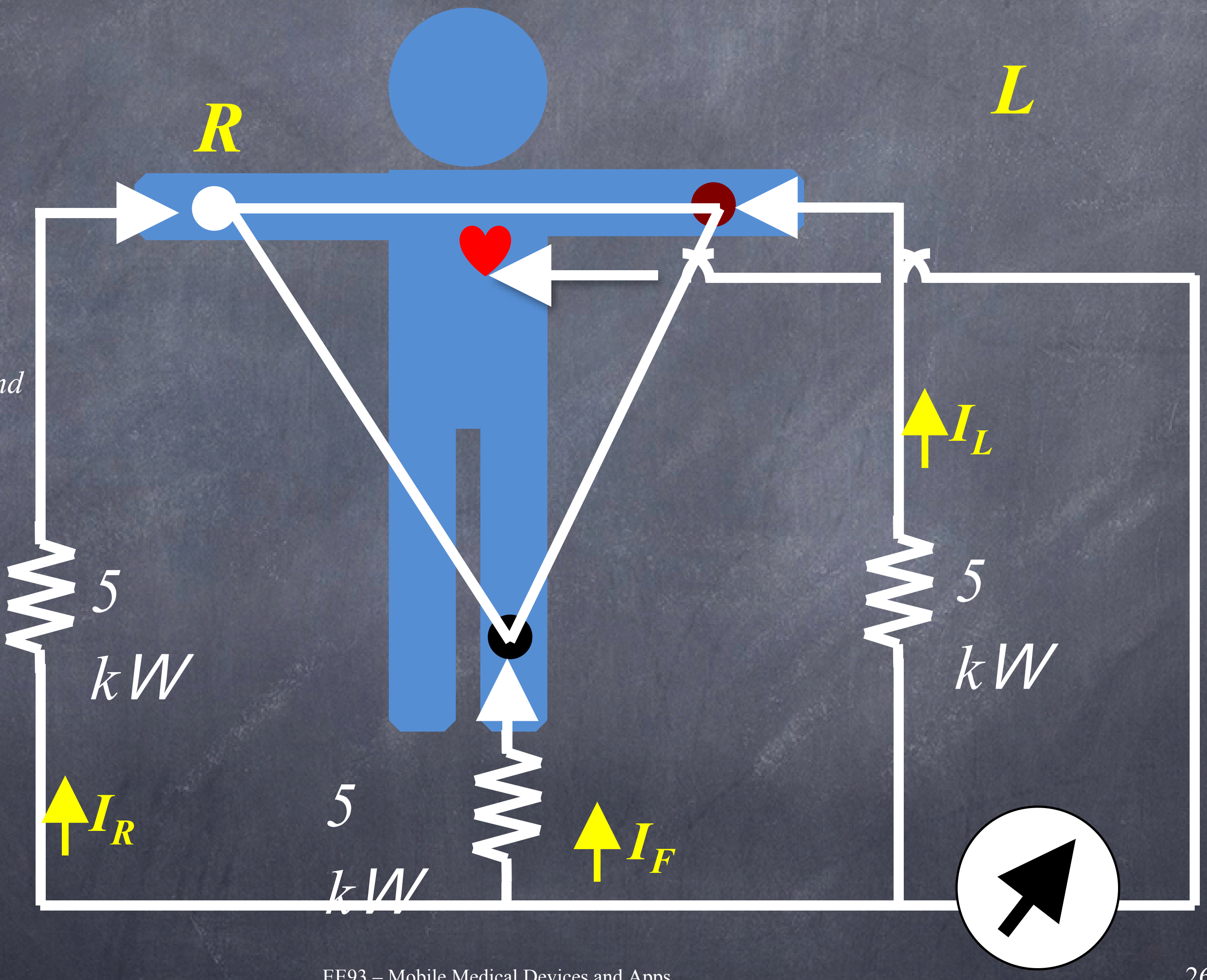
The Einthoven Leads I, II, III



$I = \varphi_{LA} - \varphi_{RA}$ $II = \varphi_{LL} - \varphi_{RA}$ $III = \varphi_{LL} - \varphi_{LA}$

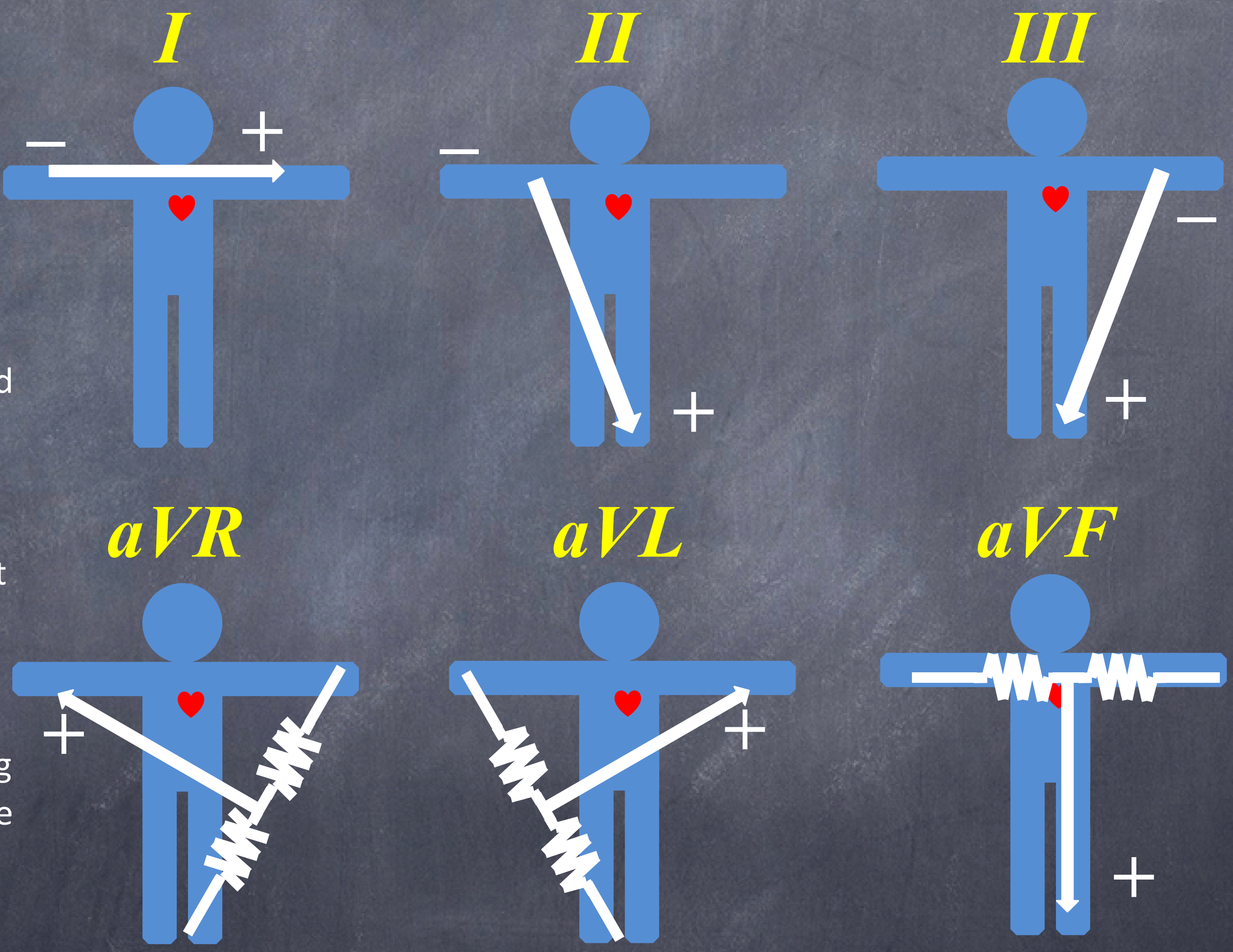
Wilson Central Terminal

Wilson suggested 5 kΩ resistances; while widely used today, high-input impedance bio amplifiers provide significantly higher impedances which increases CMRR and attenuates artifacts caused by electrode and skin impedance



Einthoven Leads & Triangle

- Twelve electrodes
- Leads placed between two limb (arm or leg) electrodes
- Einthoven: designated limbs leads as standard lead I, II and III
- Created triangle to show relationship of electrodes where heart at center is electrically null
- Einthoven's triangle is used when determining the electrical axis of the heart (heart angle)



Mathematical Relationship of Leads

- 12-lead
  - I, II, & III are bipolar
  - aVR, aVL, aVF, and V_1, V_2, V_3, V_4, V_5, V_6 are unipolar

Limb Leads

$$I = LA - RA$$
$$II = LL - RA$$
$$III = LL - LA$$

Augmented Limb Leads

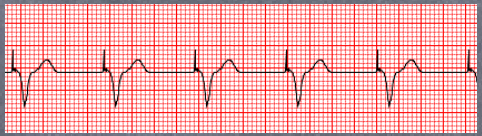
$$aVR = -\frac{I + II}{2}$$
$$aVL = I - \frac{II}{2}$$
$$aVF = II - \frac{I}{2}$$

Einthoven's Law

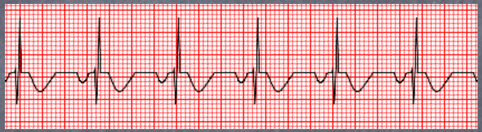
$$I + (-II) = III$$

ECG Artifacts

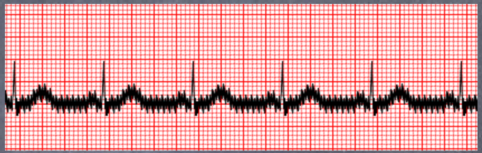
- Pacing spikes
  - Due to implanted artificial pacemaker – impacts QRS complex



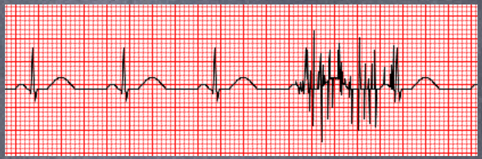
- Reversed or misplaced leads
  - Causes upside down waveforms



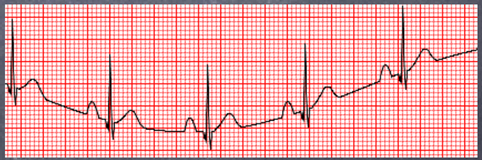
- AC interference
  - Due to 60 Hz (in USA) or 50 Hz (in EUR) noise coupled from power source



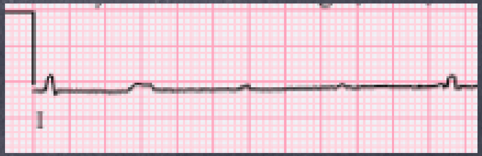
- Muscle tremor
  - Skeletal tremors from muscle contracture



- Wandering baseline
  - Patient moving, dirty leads, loose electrodes, DC power source ripple

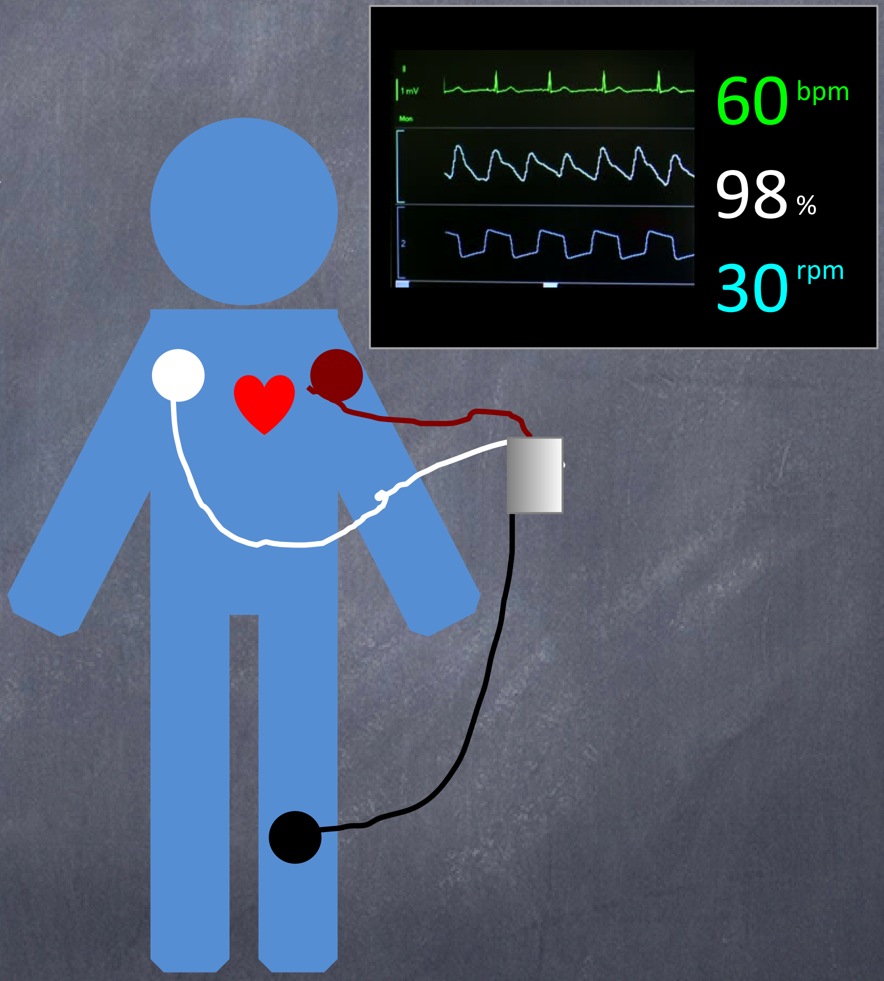


- Heart block
  - Impluse does not travel from SA node to atrium



Measuring ECG (3-Lead)

- 3-lead ECG uses right arm (or chest), left arm (or chest) and left foot
- Able to obtain PQRST wave
- Unable to obtain other leads and heart angle



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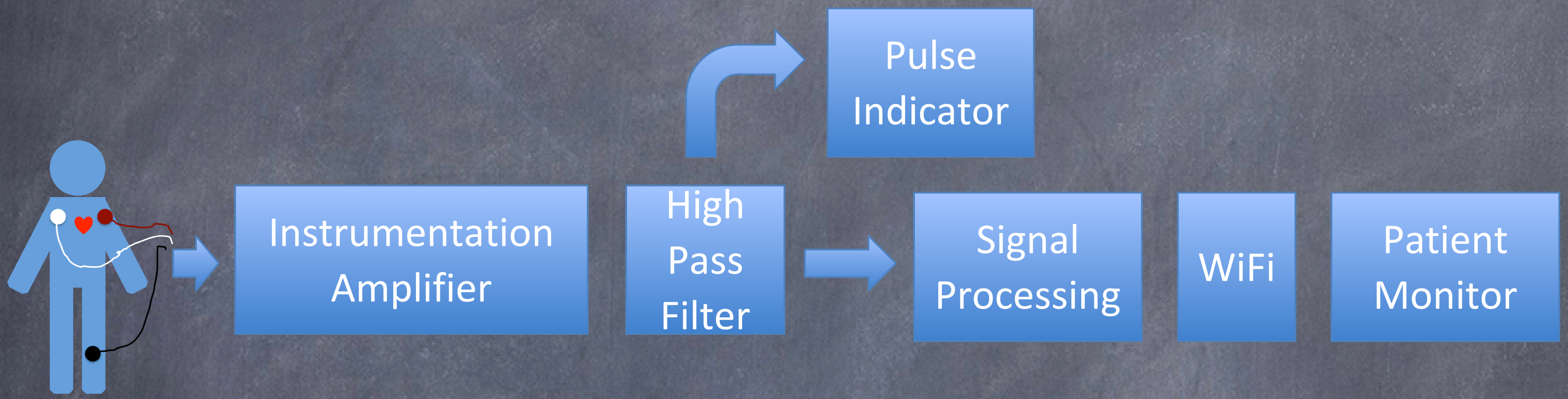
Designing & Building ECG (3-Lead)



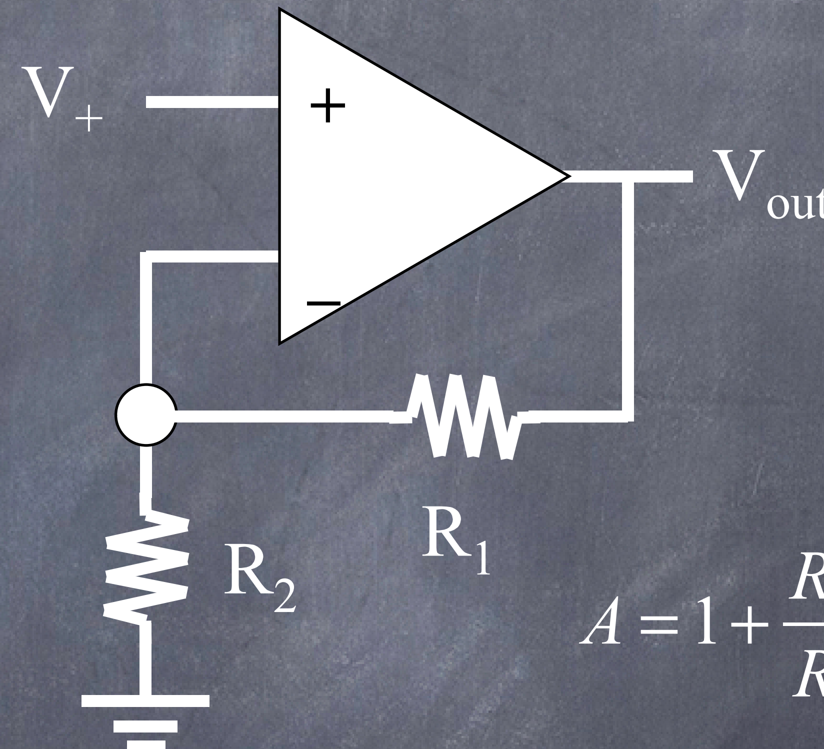
- Uses one-channel
- Collects Einthoven I
- Sufficiently easy, sufficiently difficult

Bio Amplifier

- Used to measure biological electrical signals from human beings (and animals)
- ECG signals:
  - Electrical range: 0.3 mV < V_{QRS} < 2 mVfor
  - Frequency range: 10 Hz to $F_{sampled}$ = 1kHz
- Bio amplifier spec (typical): [1]
  - Internal noise: < 2 mV
  - Input Impedance 10 MV
  - Operational bandwidth: 0.16 to 250 Hz
  - Bandwidth cutoffs >18 dB/octave
  - 60 Hz Notch filter
  - CMRR > 100
  - CM input range: ± 200 MV)
  - Shock protection: >2000 V

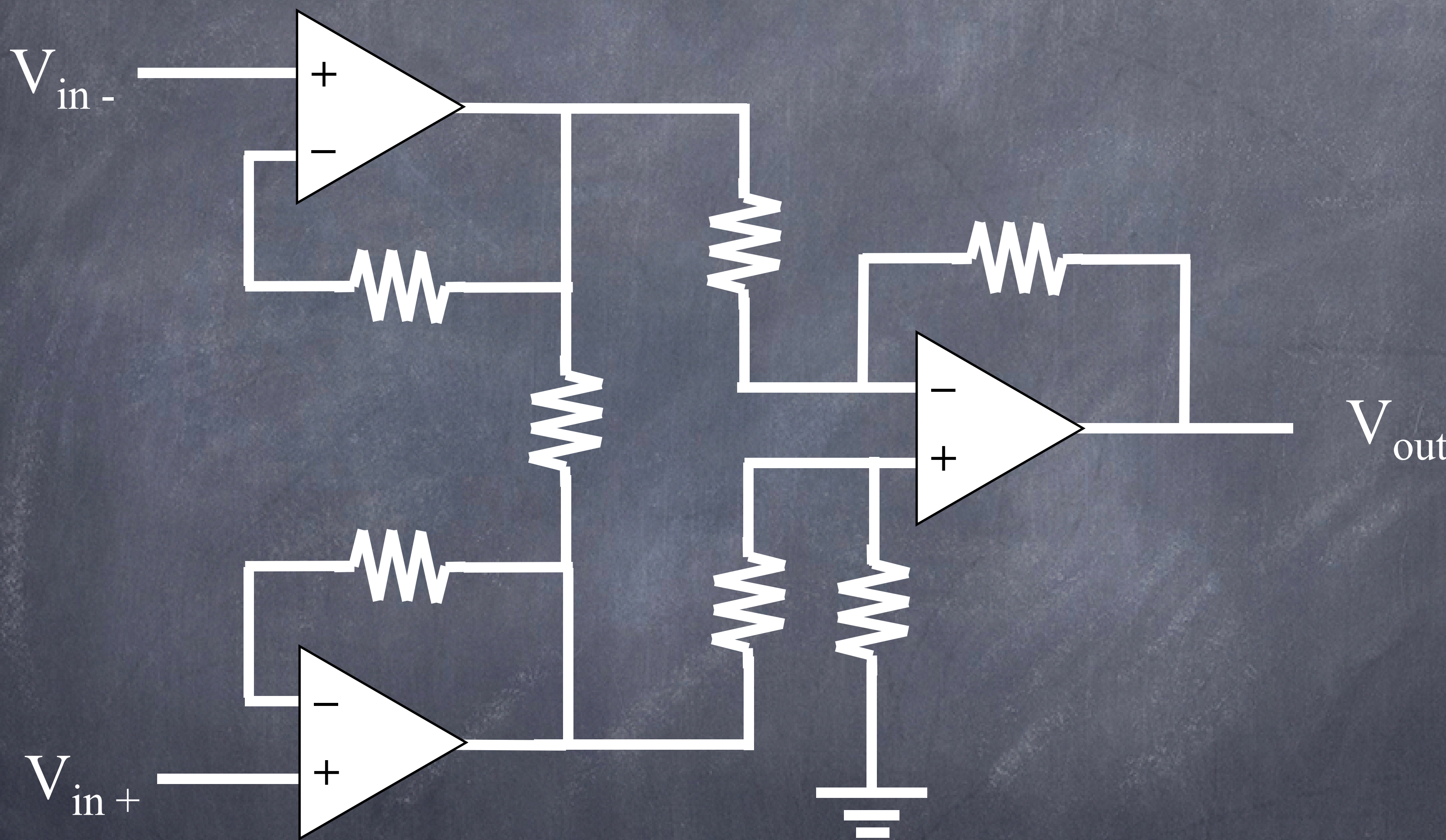
Bio Amplifier

- Use non-inverting op amp configuration
- Typical amplification gain: 100 < A < 500
- 100 kW / 1k W



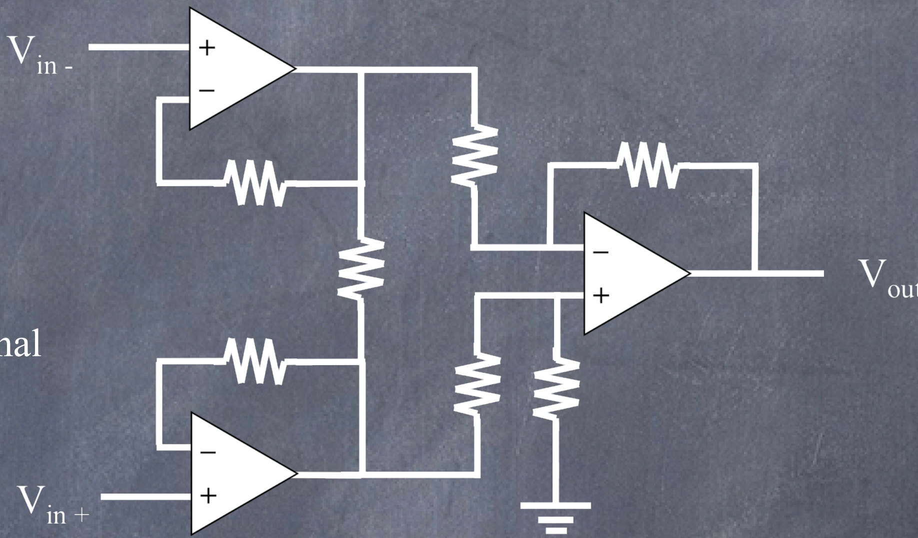
$$A = 1 + \frac{R_2}{R_1}$$

Instrumentation Amplifier



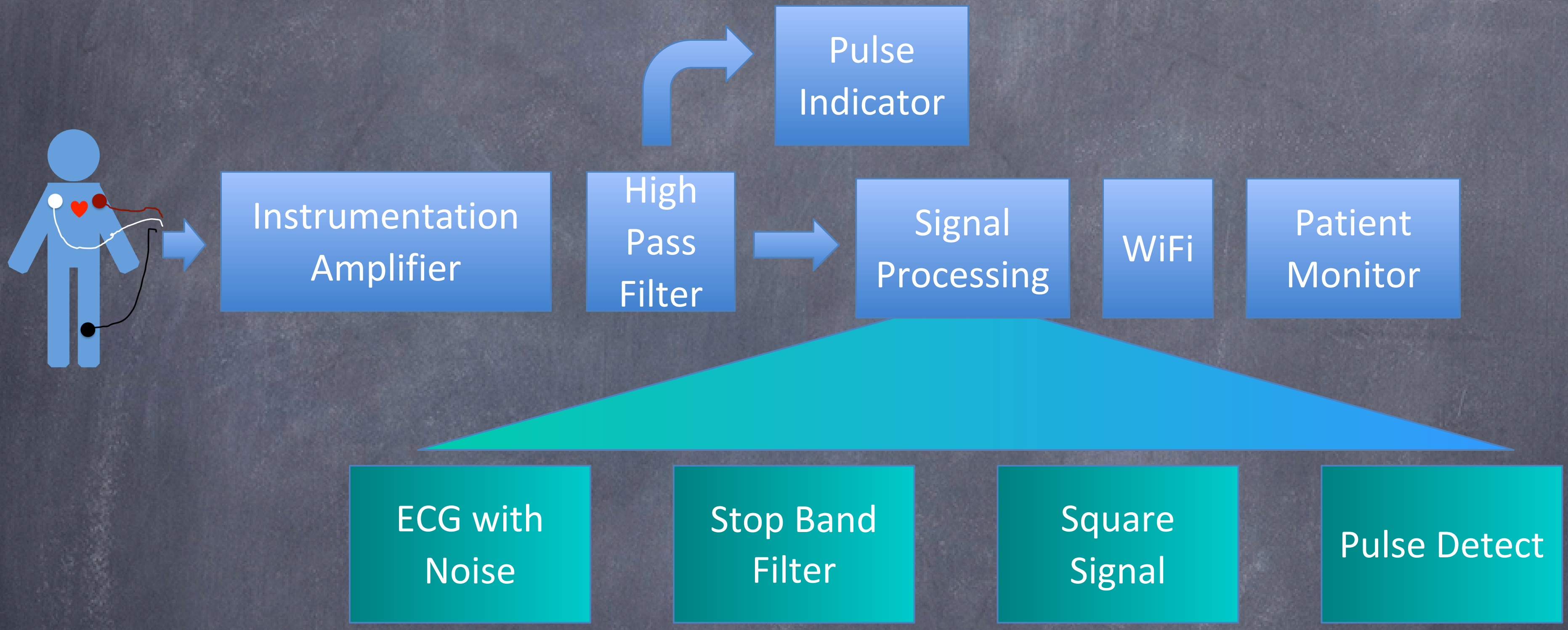
Instrumentation Amplifier

- Two different stages
  - Gain stage
  - Differential stage
- Purpose of each stage
  - Gain stage
    - Provides gain to entire signal
    - Does not remove common mode signal
  - Differential stage
    - Does not apply gain
    - Remove common mode signal

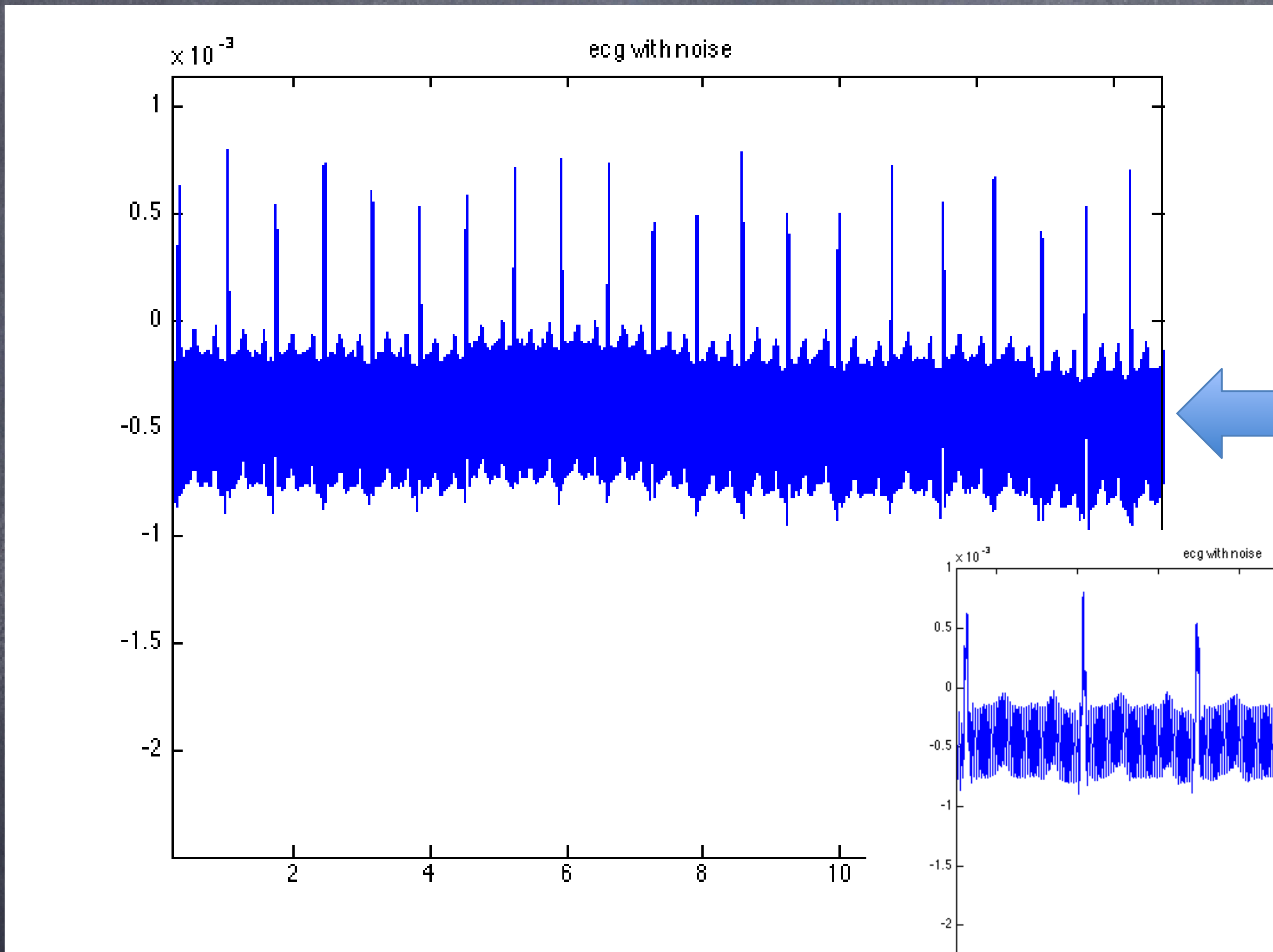


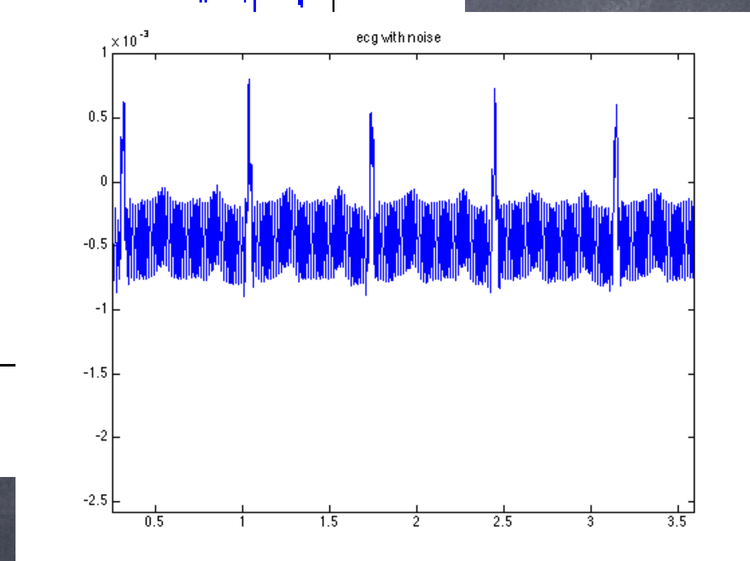
- Advantages
  - Amlifies signal, then in second stage remove noise and non-ideal or non-linear modalities to signal that has been gained
  - Symmetric front end provides great common mode rejection, common mode rejection vs frequency, and nice noise performance
- Disadvantage
  - Ability to have gain near voltage rails is limited

Signal Processing



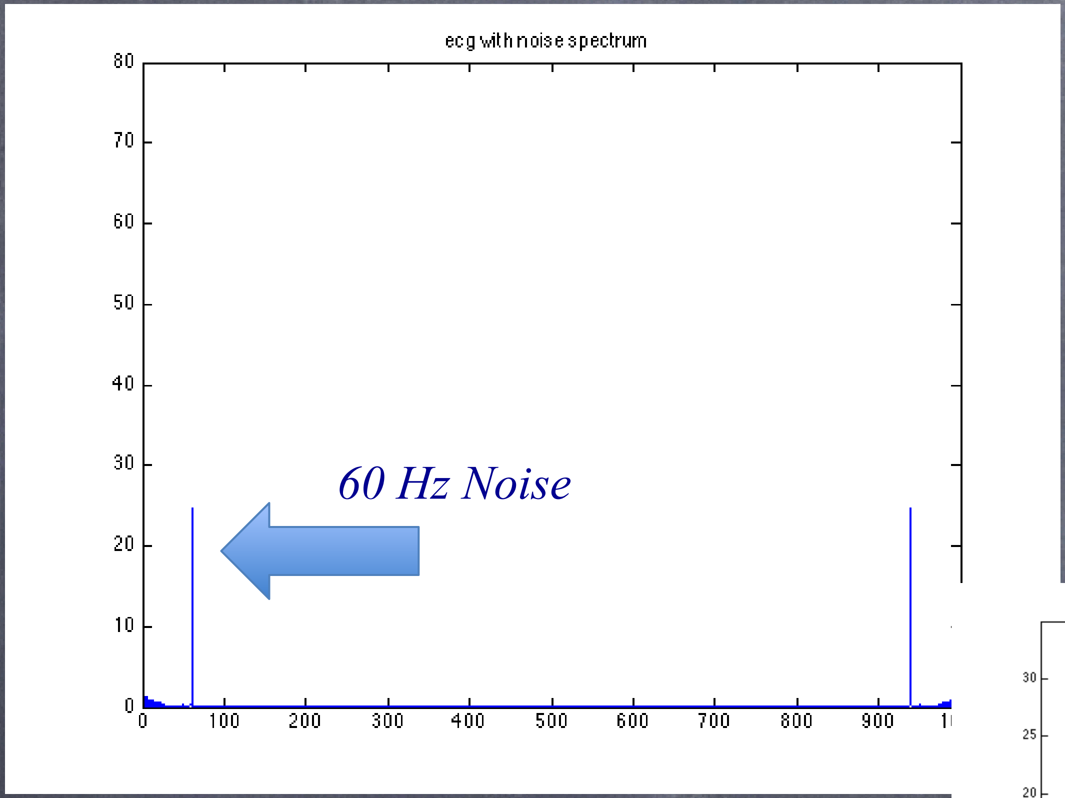
ECG with Noise



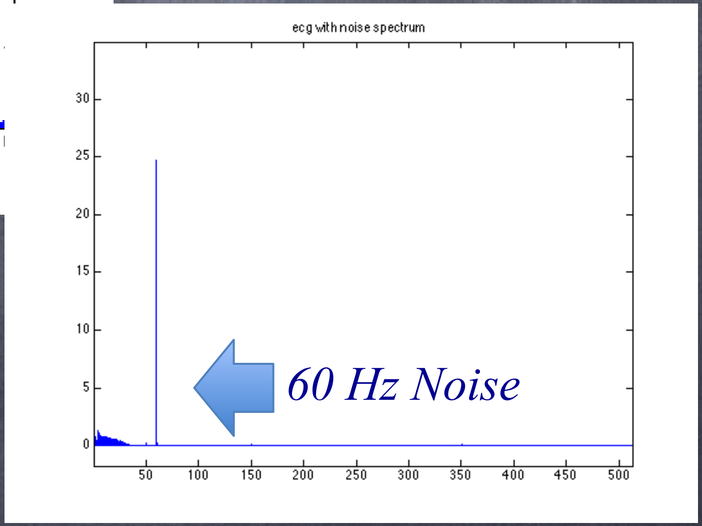


Note low signal to noise ratio for ECG signal (Gain 500, F_S = 1 kHz)

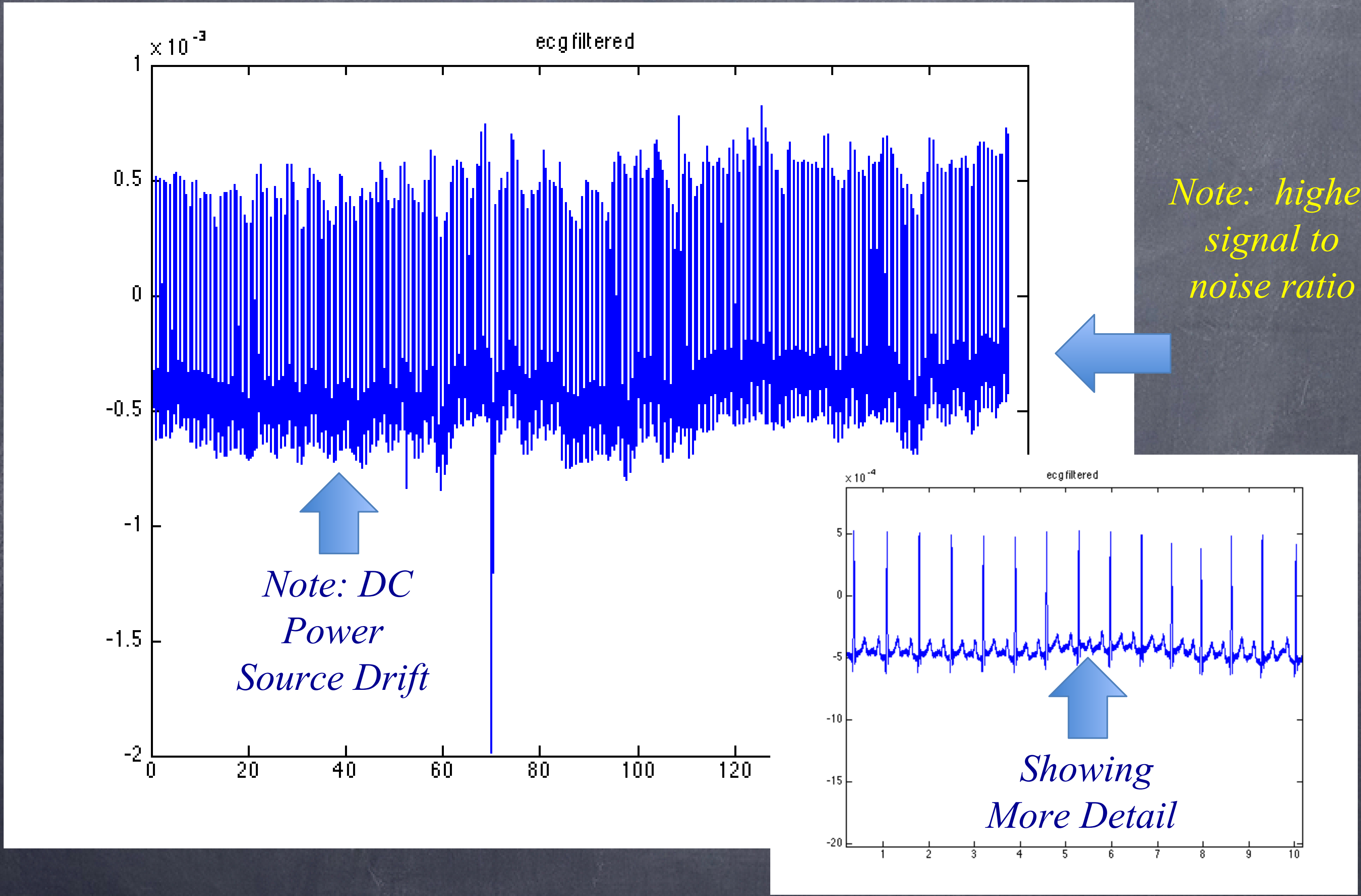
ECG with Noise Spectrum



Nyquist Spectrum = 500 Hz



ECG after High Pass Filter

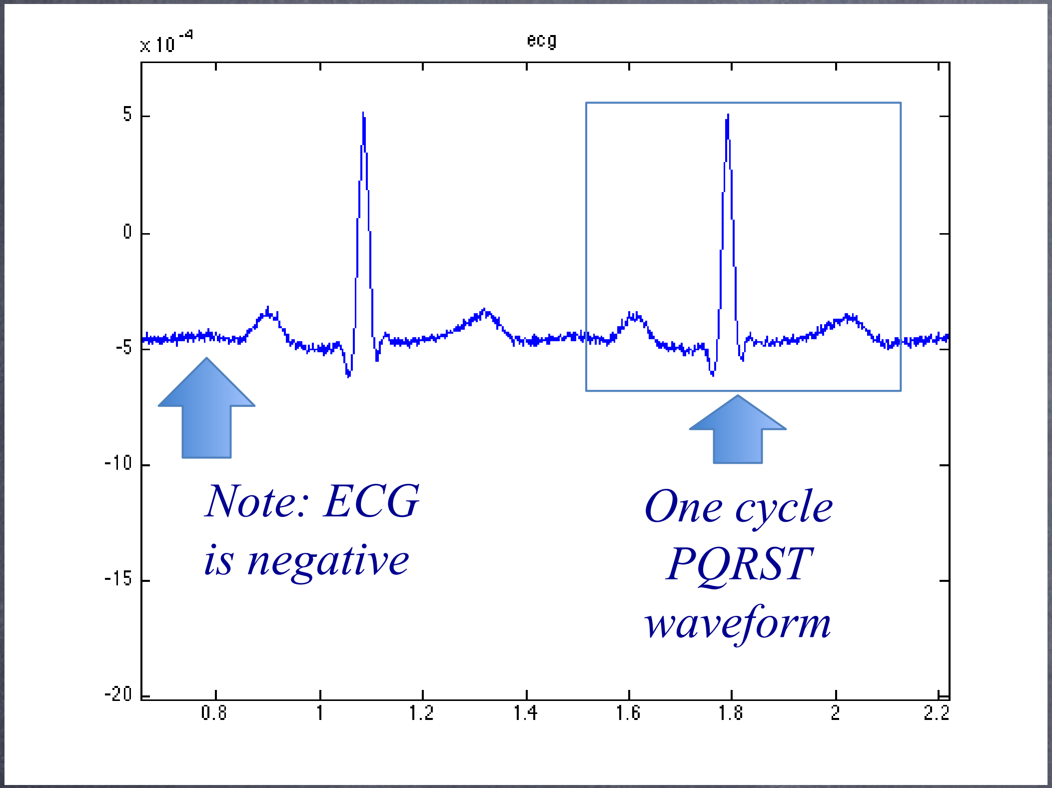


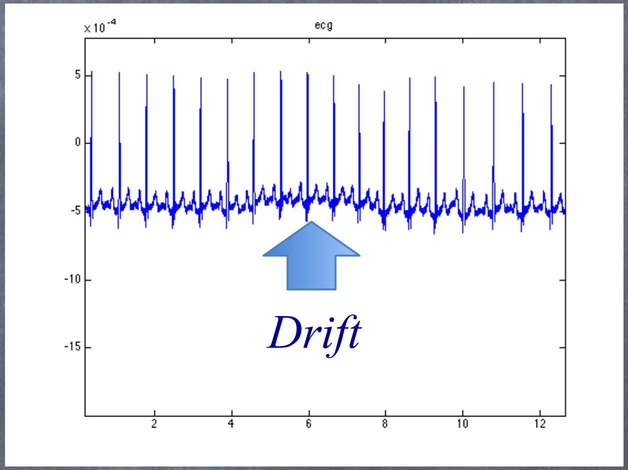
Note: DC Power Source Drift

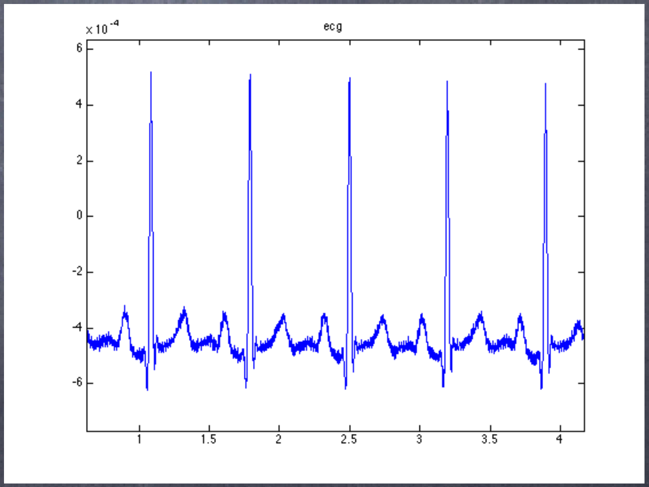
Note: higher signal to noise ratio

Showing More Detail

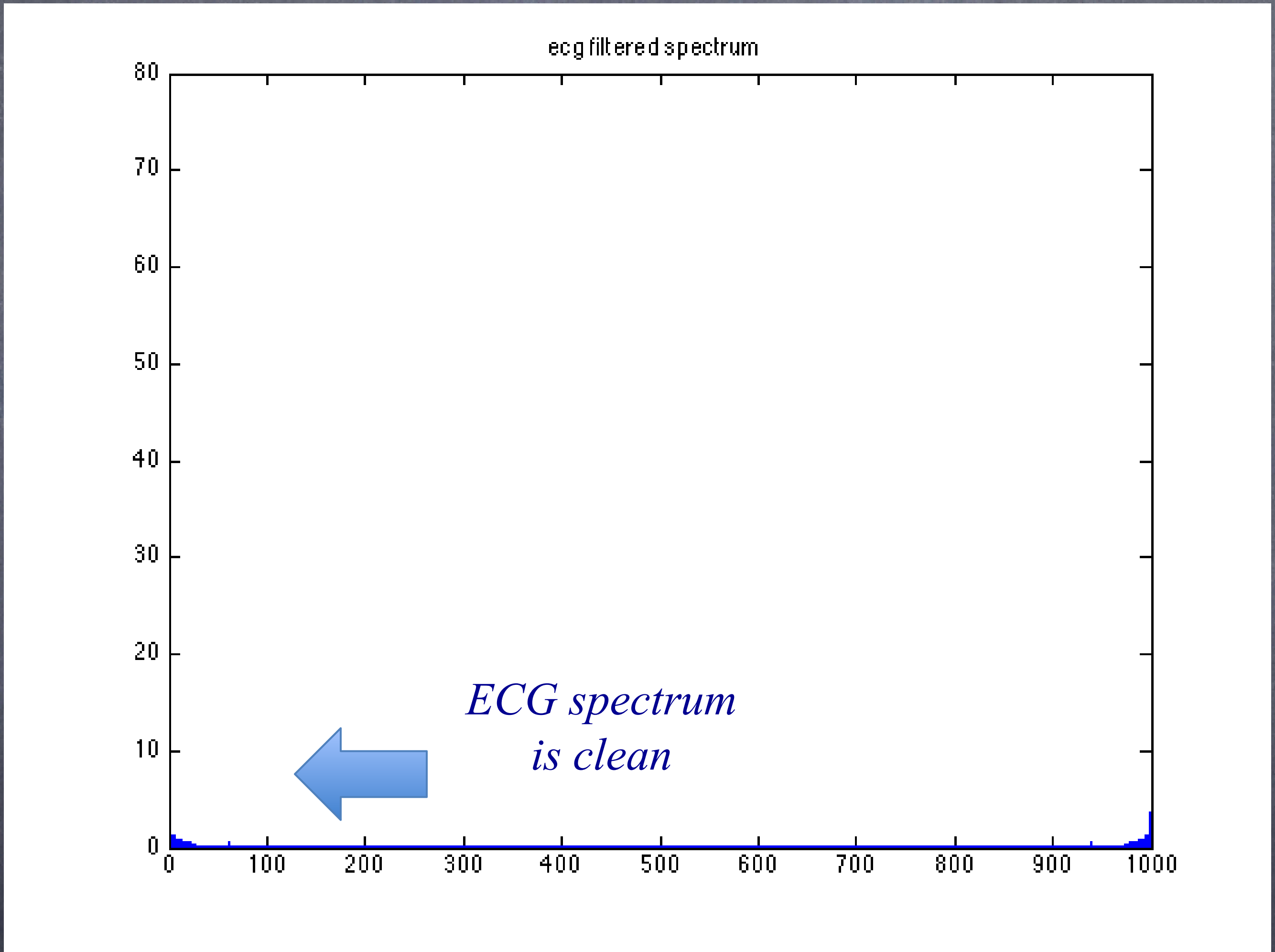
ECG after High Pass Filter -- Tight



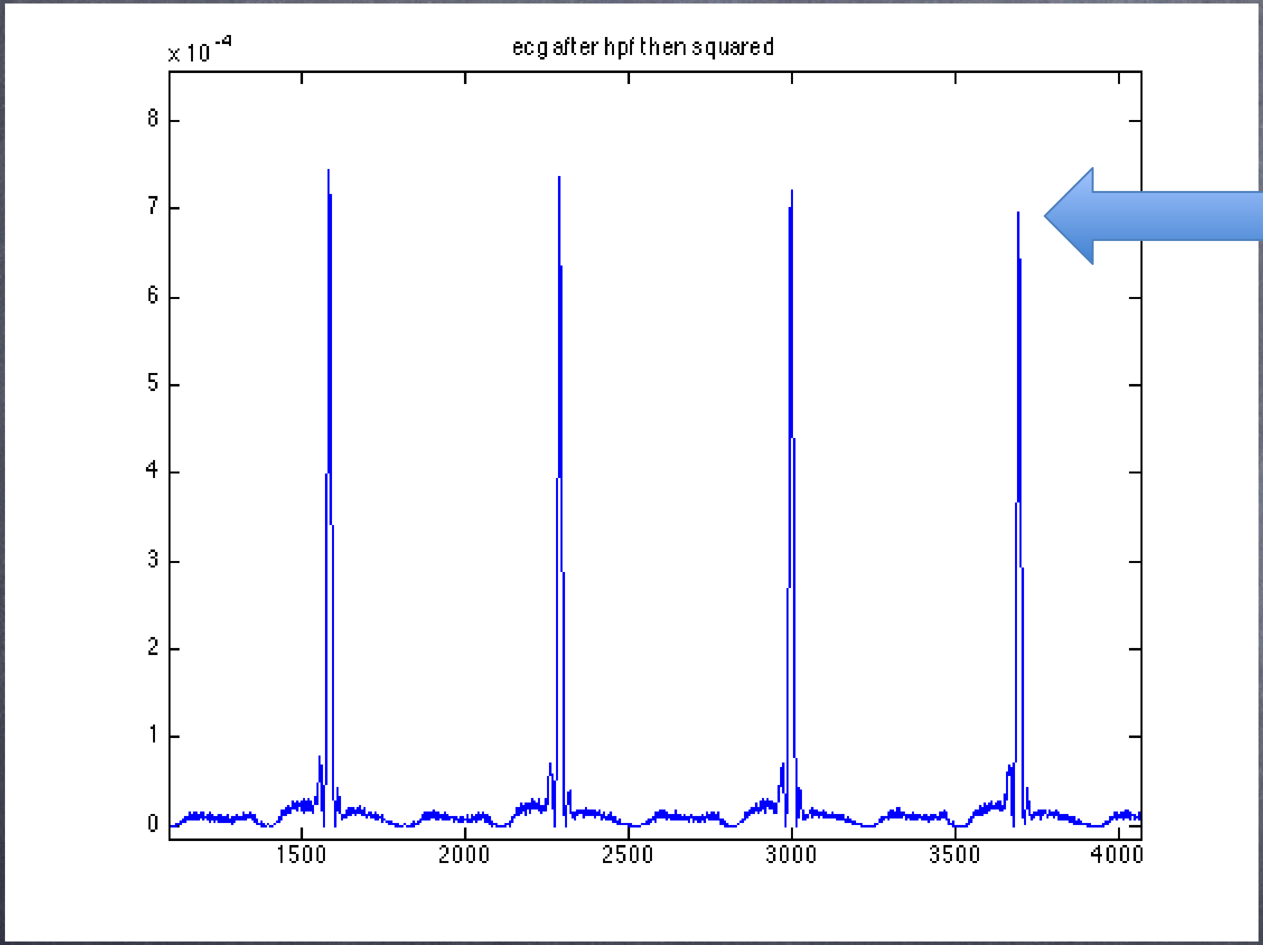




ECG after High Pass Filter Spectrum



ECG after HPF Squared

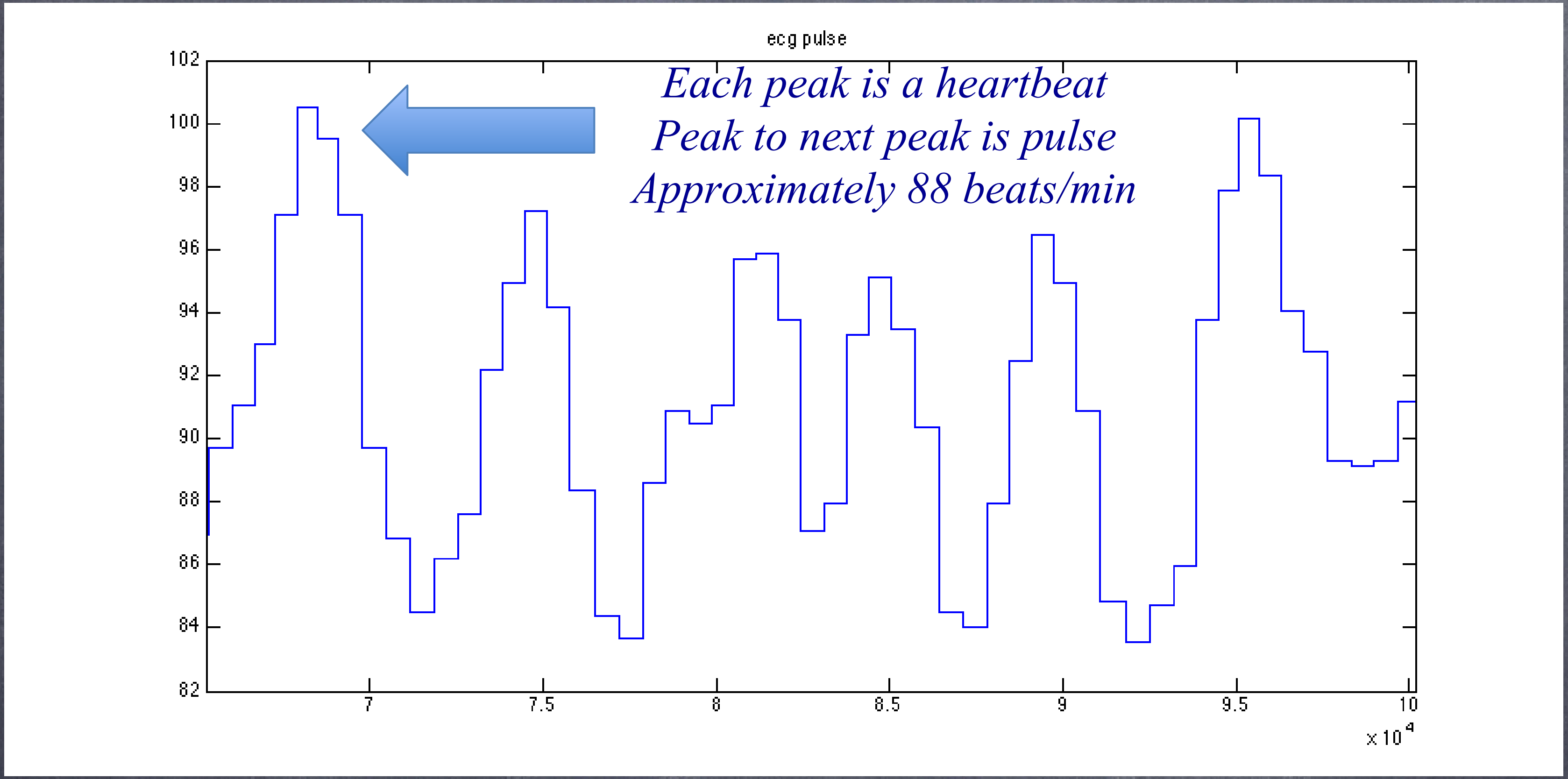


Able to count peaks
Threshold = 0.0005 mV

Note:

- *Very high signal to noise ratio*
- *No DC drift*
- *Positive*

ECG Pulse


ecg pulse
Each peak is a heartbeat
Peak to next peak is pulse
Approximately 88 beats/min
102
100
98
96
94
92
90
88
86
84
82
7
7.5
8
8.5
9
9.5
10
x 10^4