STANFORD
UNIVERSITY

EE122B
Introduction to Biomedical Electronics

Surface Biopotentials

Greg Kovacs, Laurent Giovangrandi

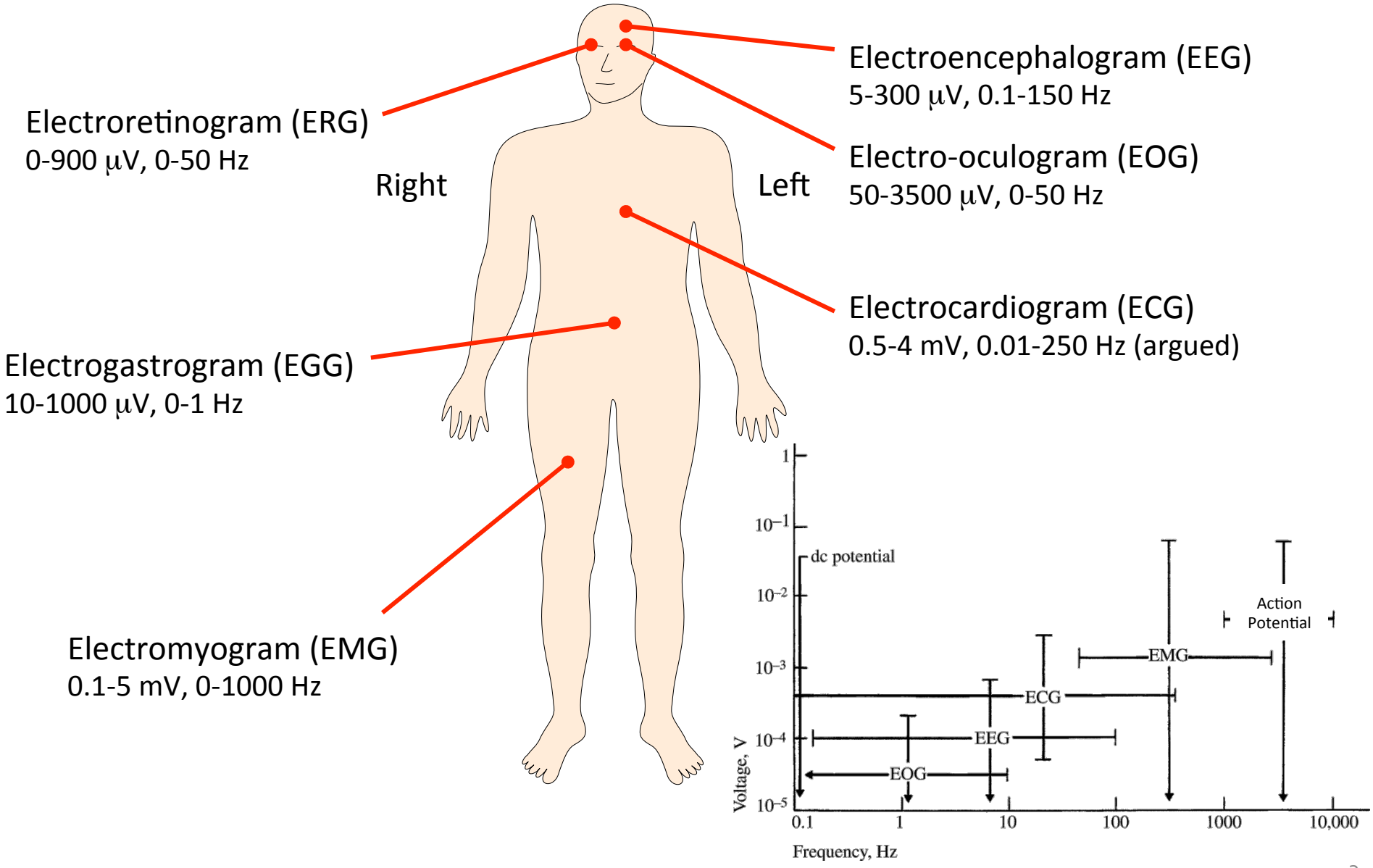
Department of Electrical Engineering
Stanford University

Content

The goal is to understand surface bioelectric potentials, their use in clinical settings, and the circuits and sensors required for their recording.

- Electrocardiogram (ECG)
  - From cell to heart to body
  - Electrodes
  - Circuits
  - Noise sources
  - Equipment
- Electroencephalogram (EEG)
- ExG – the other surface biopotentials
  - EMG
  - EOG
  - ERG

Overview of Surface Biopotentials

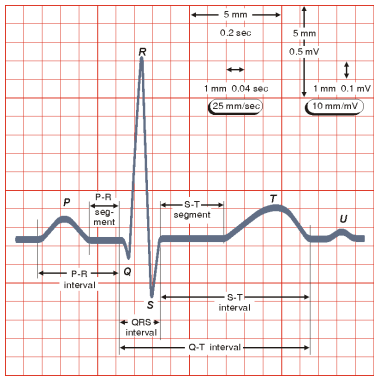


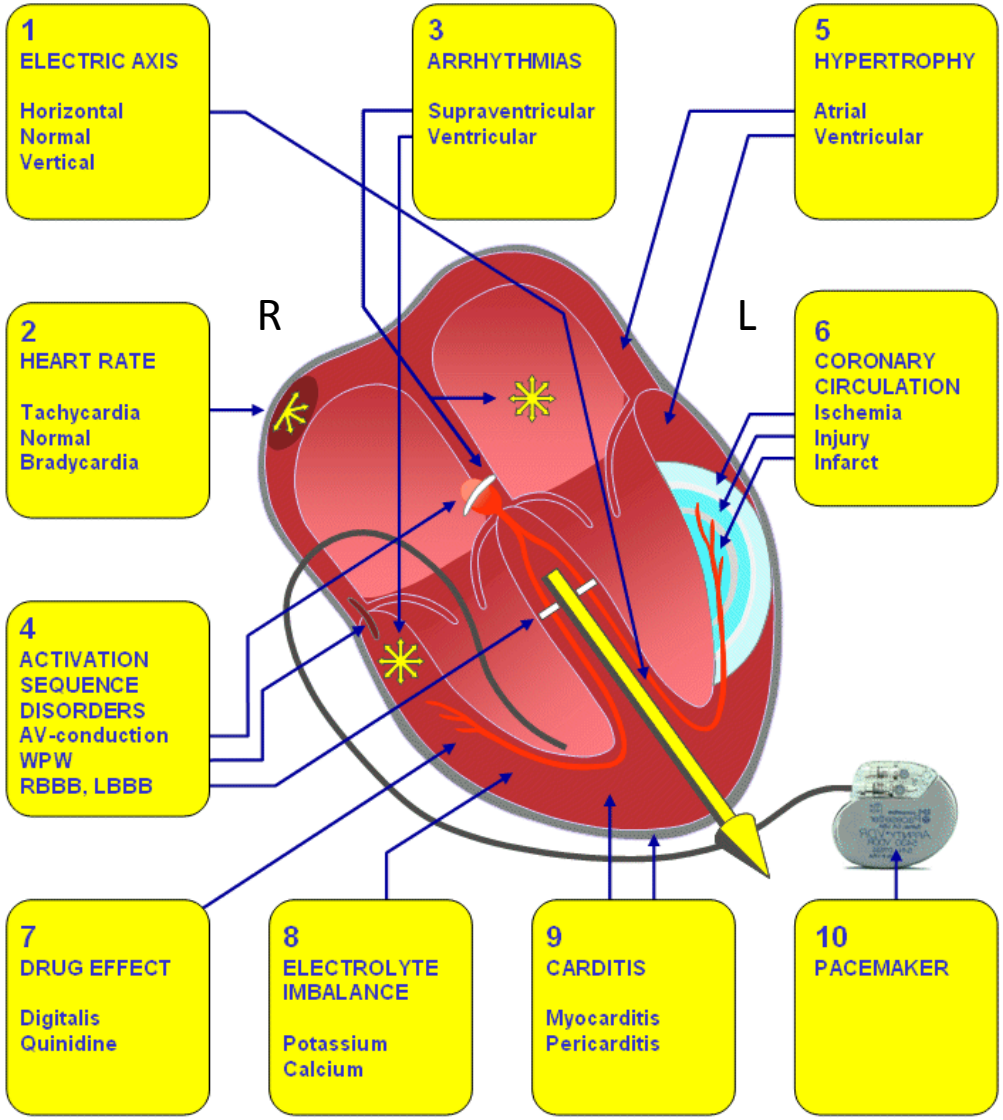
Fundamentals

Electrocardiogram

The Electrocardiogram

- The electrocardiogram (ECG) is the recording of the heart's electrical activity – the non-simultaneous signals from about 2 X 10^9 cardiomyocytes.
- It is very useful in the diagnosis of numerous heart conditions.
- Its establishment as a clinical tool earned its pioneer, Willem Einthoven, a Nobel Prize in 1924.





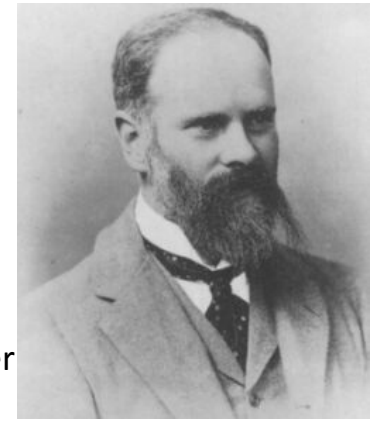
Source: Bioelectromagnetism, Malmivuo & Plonsey

How It Started…

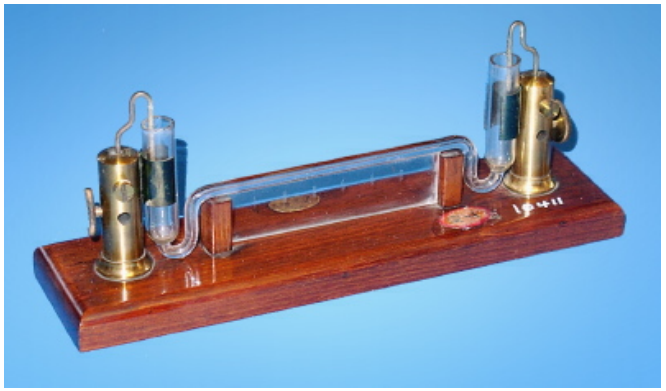
Many in the 18th century experimented with bioelectricity, often with therapeutic intent, without fully understanding the phenomena.

1838 First description of electrical activity linked to heart contraction by Carlo Matteucci.

1887 British physiologist **Auguste D. Waller** publishes the **first** human electrocardiogram, recorded with a capillary electrometer.

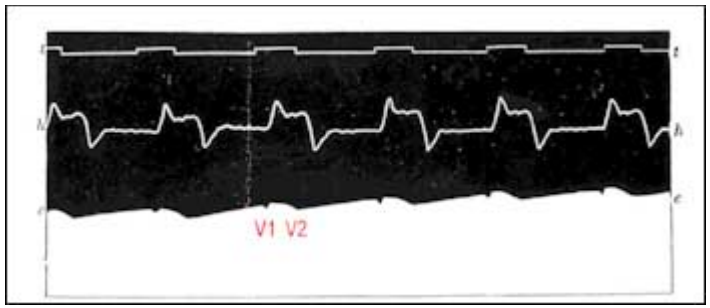


Auguste D. Waller



Lippman mercury galvanometer

First human ECG ever recorded, 1887, border between black and white is the ECG (middle is mechanical movement of apex).



Source: http://chem.ch.huji.ac.il/~eugeniik/ history/waller.html

How It Started…

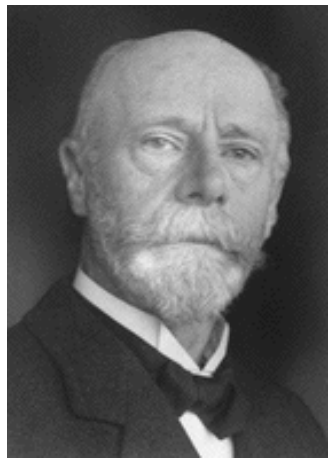
1895 Willem Einthoven, using an improved electrometer distinguishes five deflections which he names P, Q, R, S and T.

1901 Einthoven invents a new galvanometer (string galvanometer) for recording electrocardiograms. Weight: 600 pounds!

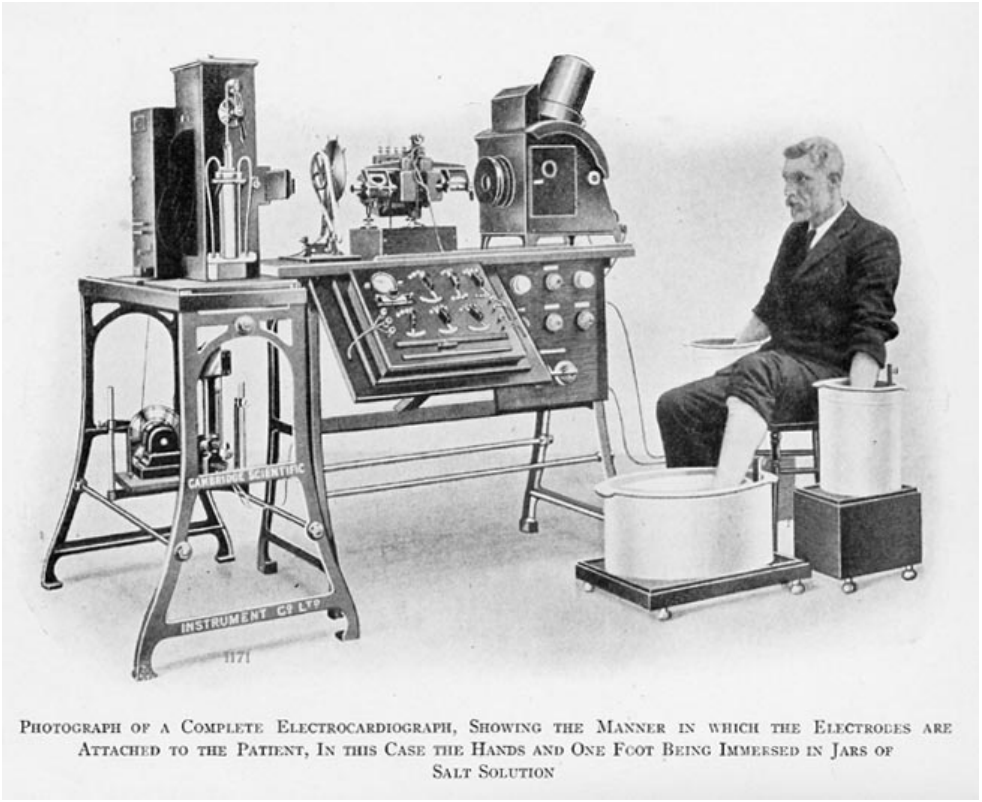
1905 First telemedicine application. Einthoven transmits ECG over 1.5 km via telephone cables.

1911 Einthoven describes his standard leads I, II and III.

1924 Willem Einthoven wins the Nobel prize for inventing the electrocardiograph.



Willem Einthoven



Photograph of a Complete Electrocardiograph, Showing the Manner in which the Electrodes are Attached to the Patient, In this Case the Hands and One Foot Being Immersed in Jars of Salt Solution

Original string galvanometer ECG

How It Started…

1928 First electronic ECG amplifier by Ernstine and Levine (vacuum tubes). First portable (50 pounds!) ECG by Sanborn (later bought by HP).

1934 Frank Wilson defines an 'indifferent electrode' later called the 'Wilson Central Terminal‘, by joining the wires from the right arm, left arm and left foot with 5000 Ohm resistors (basis for unipolar measurements).

1938 Definition of precordial leads V1-V6.

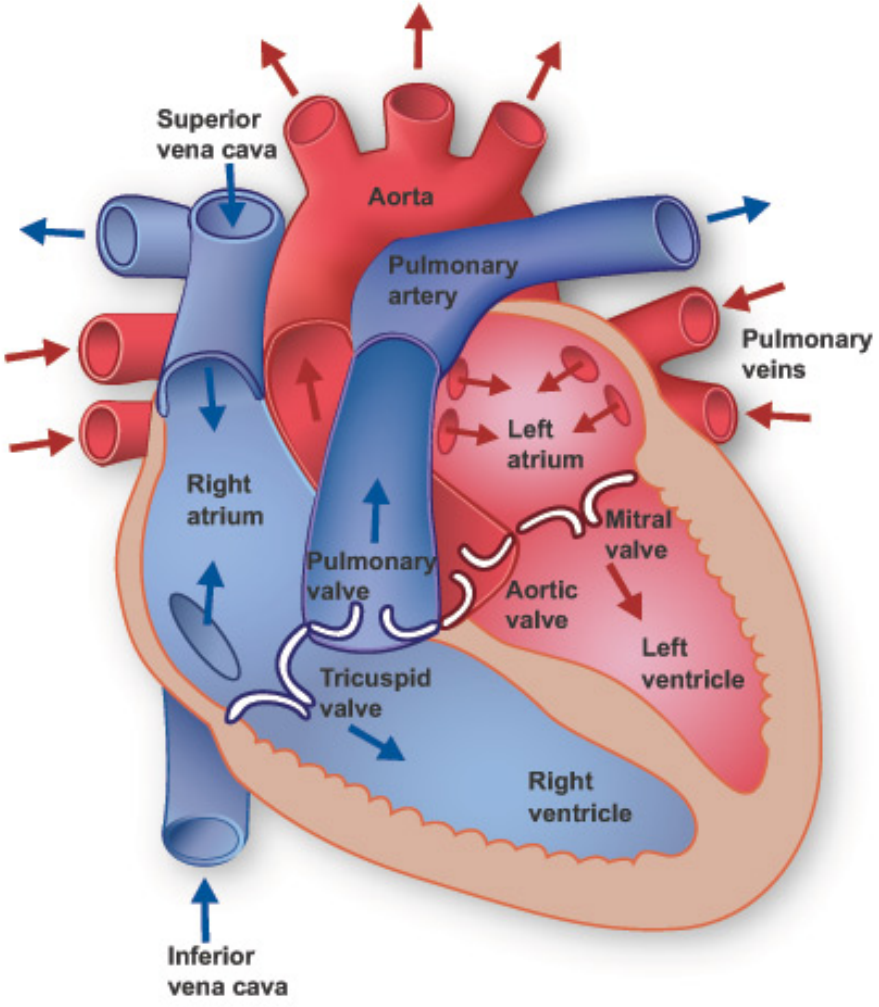
1942 Emanuel Goldberger improves Wilson’s terminal and defines ‘augmented leads’, which complete the 12-lead system in use today.

1949 First portable ECG recorder developed by Jeff Holter (75 pounds!), later known as Holter monitor.

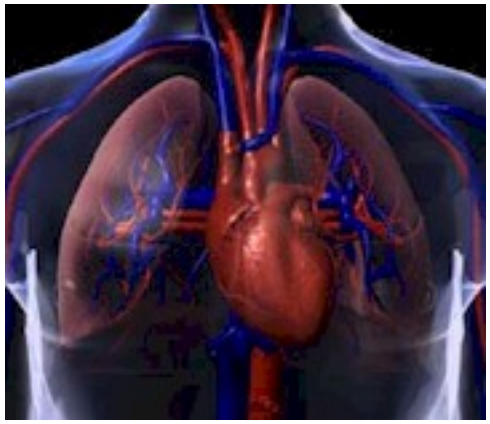
More detailed history at http://www.ecglibrary.com/ecghist.html and here: http://www.sahha.gov.mt/pages.aspx?page=665

Heart Anatomy

RIGHT



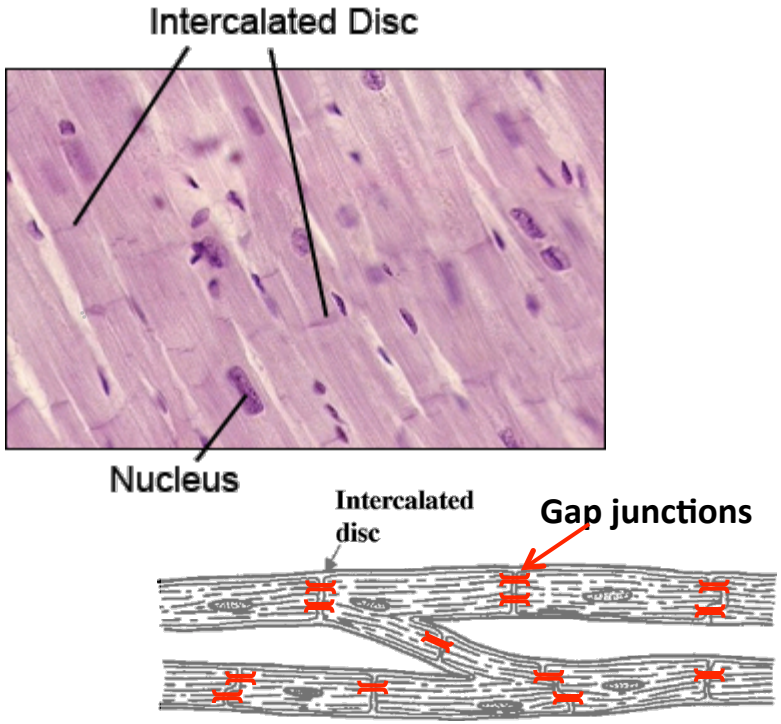
LEFT

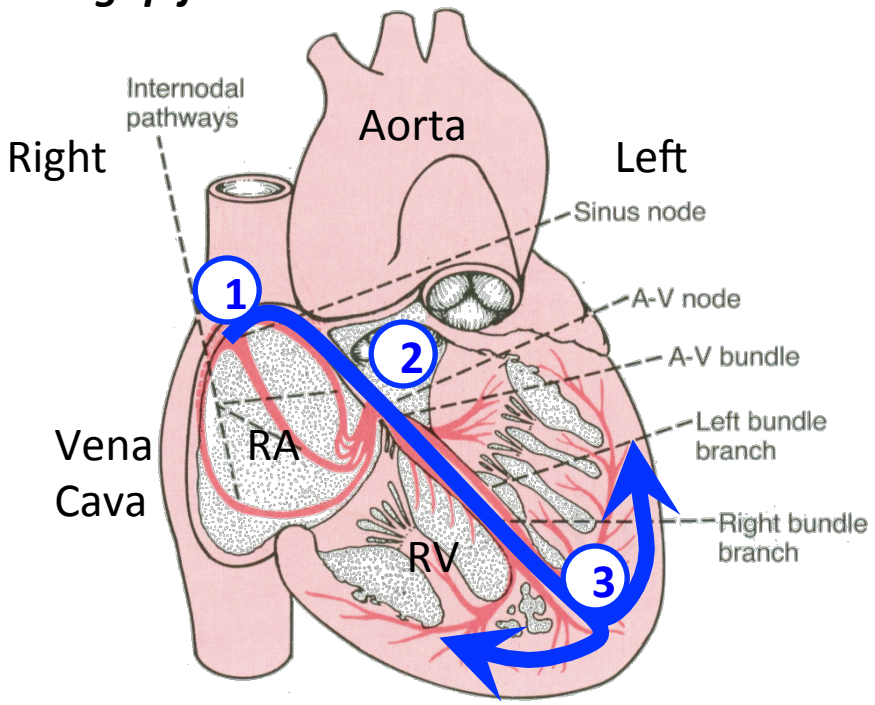


http://www.texasheartinstitute.org/HIC/Anatomy/images/fig1_crosslg.jpg

Electricity in the Heart

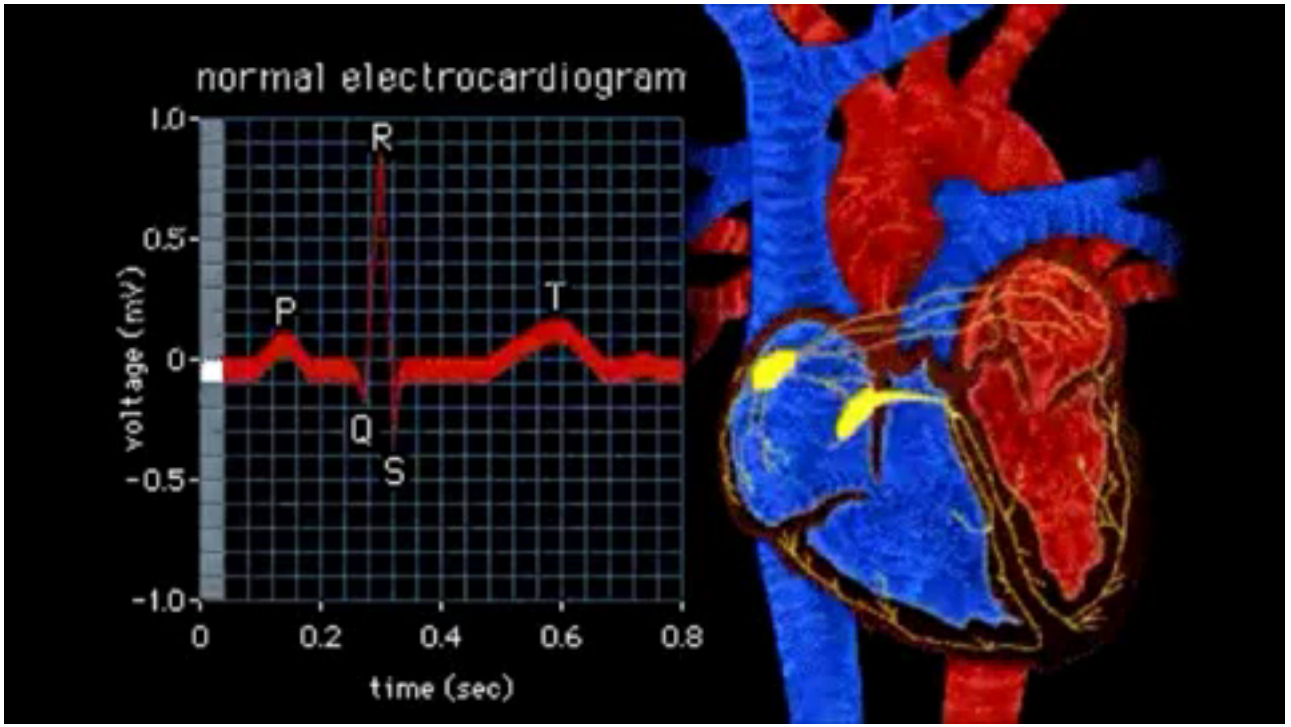
- From the previous lecture, we know how cellular potentials arise.
- Individual heart cells will all beat spontaneously if not stimulated (leaky K+ channels leading to rising potential and eventual depolarization).
- What happens at the organ level?
  - Depolarization initiates in cells at the top of the heart (***sinoatrial node***).
  - The depolarization propagates from one cell to the next, through a specialized conduction system and via resistive ***gap junctions***.





Source: http://medsci.indiana.edu/a215/virtualscope/docs/chap5_2.htm, Medical Instrumentation, J. Webster, 2009 & http://www.guidant.com

ECG Origins

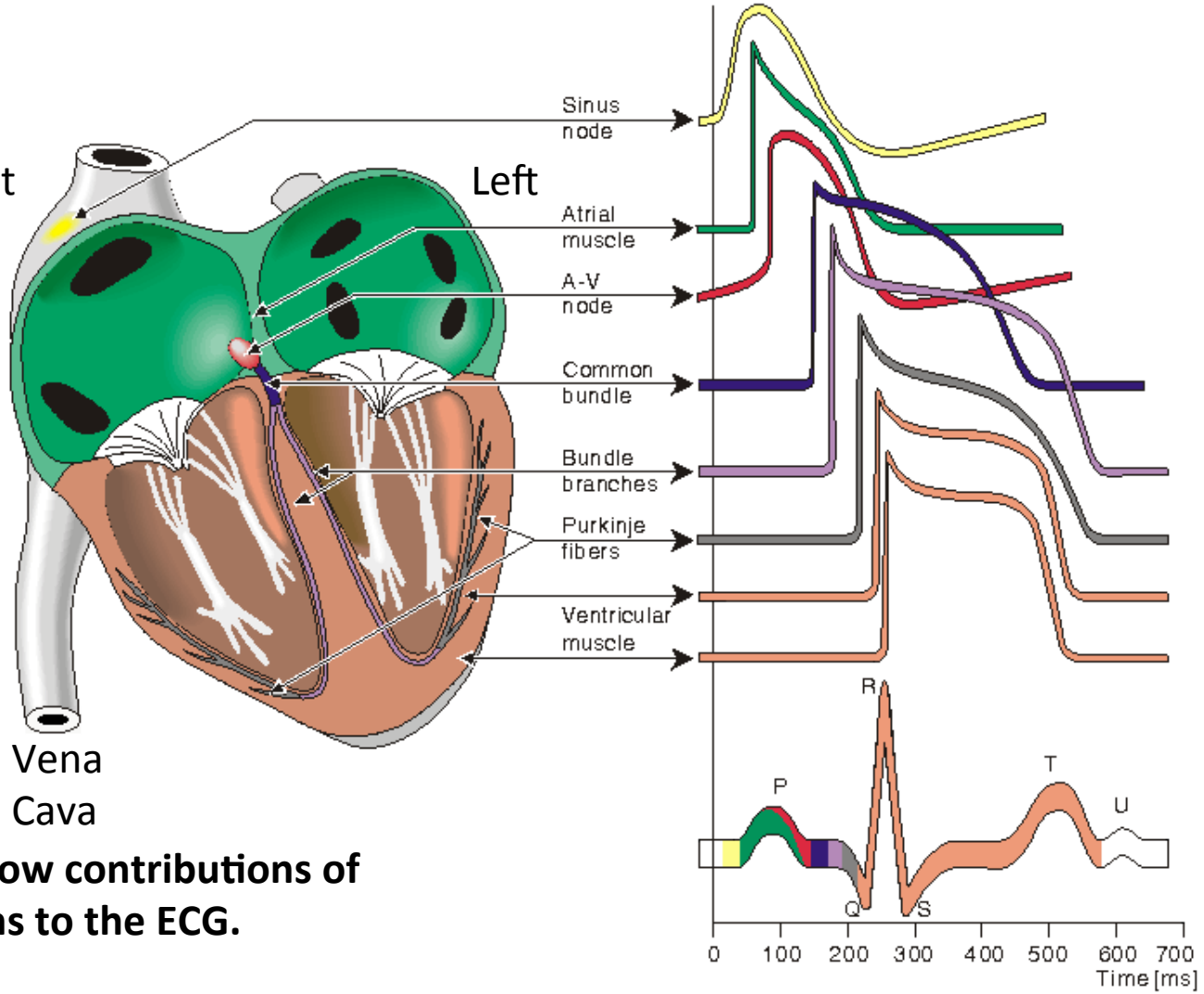


http://www.youtube.com/watch?v=lIQXzgesdDg

Action Potential Shape and Timings

Each region of the heart has a specific action potential shape, defined by the types of ion channels present in the cell membrane.

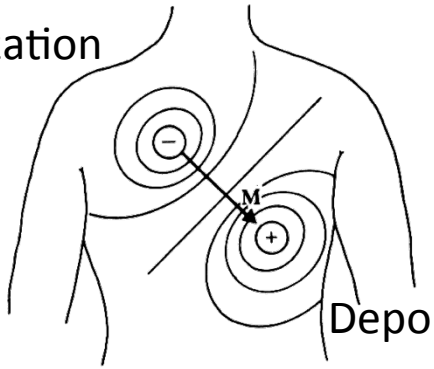
1 – SA node initiating depolarization (t=0)
1/2 – Atrial depolarization (~80ms)
2 – Delay of propagation at AV node (t=50-125ms)
2/3 – Fast propagation through Purkinje (~50ms)
3 – Depolarization of ventricle (~75ms starting at t=175ms)



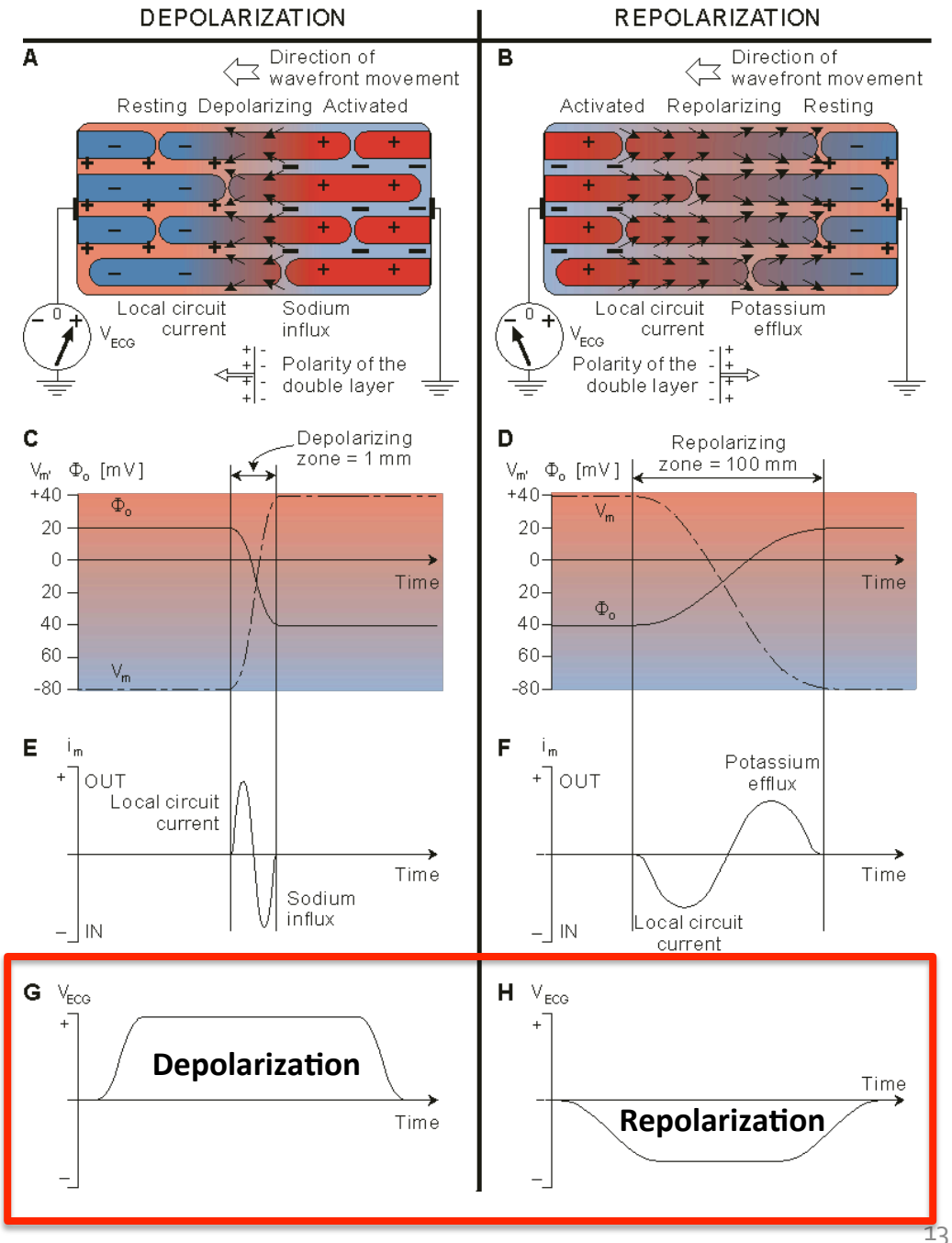
Important – colors show contributions of Different heart regions to the ECG.

From Cell to Heart: The Dipole Model

- The propagating action potentials generate a polarized wavefront through the cardiac tissue.
- In a simplified model, the organ can be assimilated to a *time-varying dipole* following the dominant axis of depolarization. The **cardiac vector M** represent the dipole moment.



Source: Bioelectromagnetism, Malmivuo & Plonsey, http://www.bem.fi

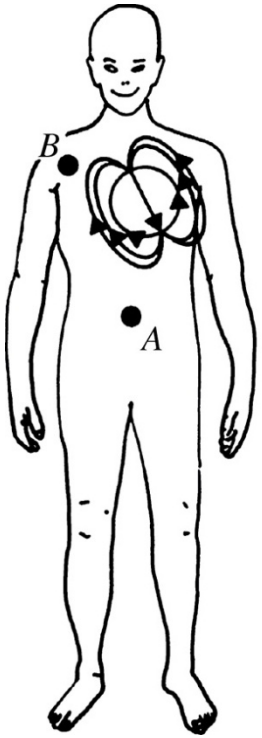


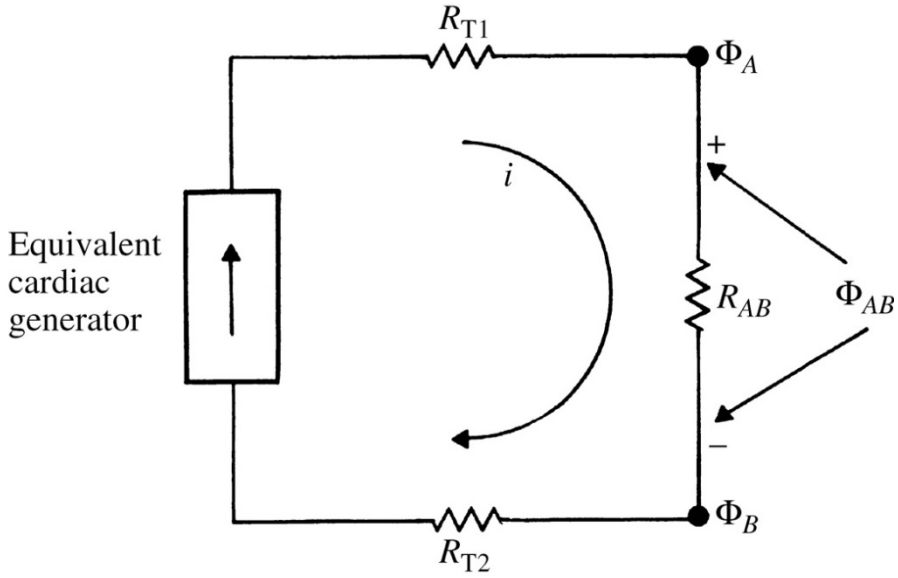
From Heart to Surface

Surface potentials can be described as potential differences within a (mostly resistive) volume conductor (distributed, three-dimensional conductor).

- Time-varying dipoles (magnitude, direction) produces time-varying waveforms between fixed points.
- Different measurement points (leads) produces different observations of the same dipole.
- For a single dipole, **three orthogonal measurement axes** completely characterize the dipole.

Key is to define standard electrode placement to allow inter-patient comparison.

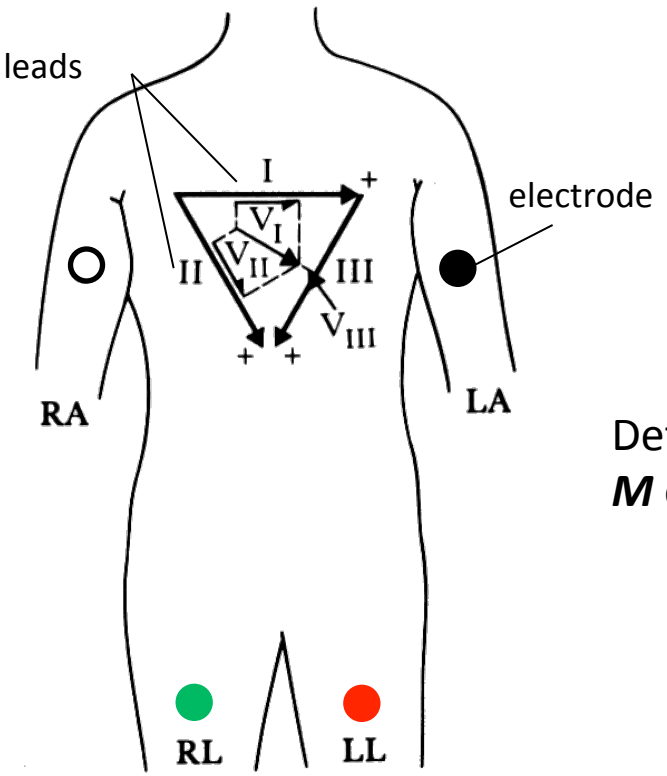




Source: Medical Instrumentation, J. Webster, Wiley, 2009

Einthoven Limb Leads

- Standard lead placement originally proposed by Einthoven.
- Three lead wires generate three leads (fourth, RL used as ground).
- Bipolar leads



AHA (USA) Color coding

$$\text{Lead I}: \quad V_I = LA - RA$$
$$\text{Lead II}: \quad V_{II} = LL - RA$$
$$\text{Lead III}: \quad V_{III} = LL - LA$$

Note that only two are independent!

According to Kirchhoff's law:

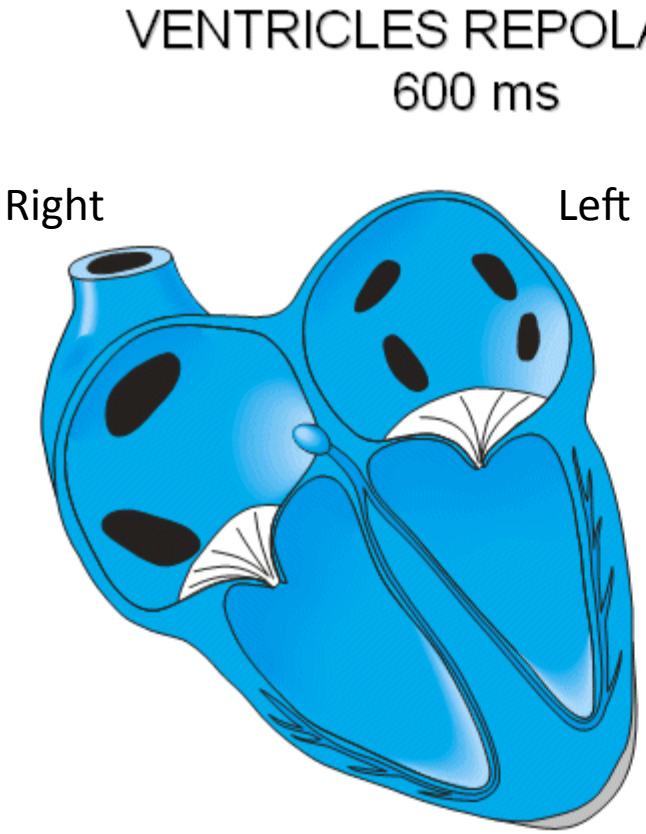
$$V_{\mathrm{I}} + V_{\mathrm{III}} = V_{\mathrm{II}}$$

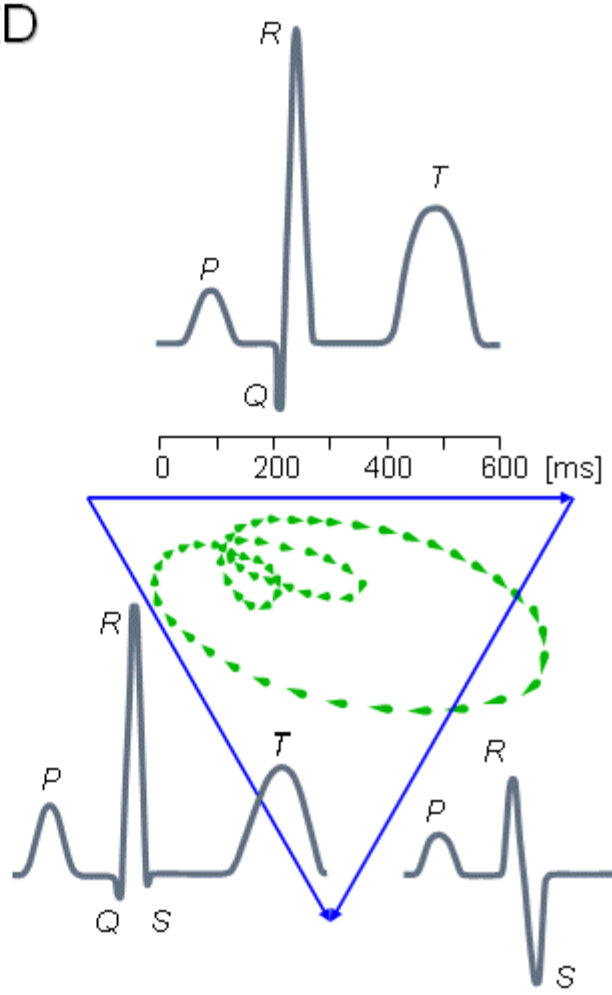
Detected voltages are the *projection* of the cardiac vector ***M*** onto the three vectors defined by the electrodes:

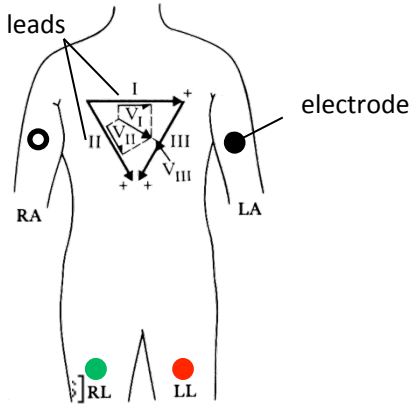
$$V_i = M \bullet a_i = |M||a_i|\cos\theta$$

M : cardiac vector
a_i : lead vector
θ : angle between cardiac and lead vectors

Projection on Limb Leads





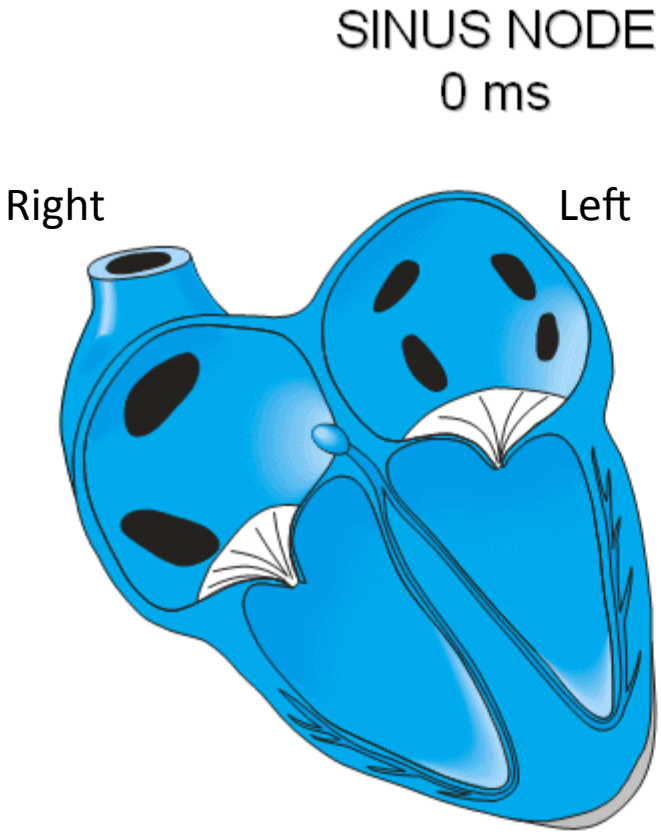


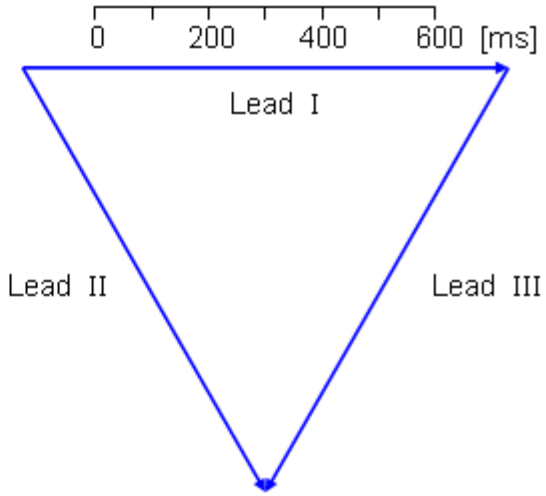
AHA (USA) Color coding

Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

Projection on Limb Leads

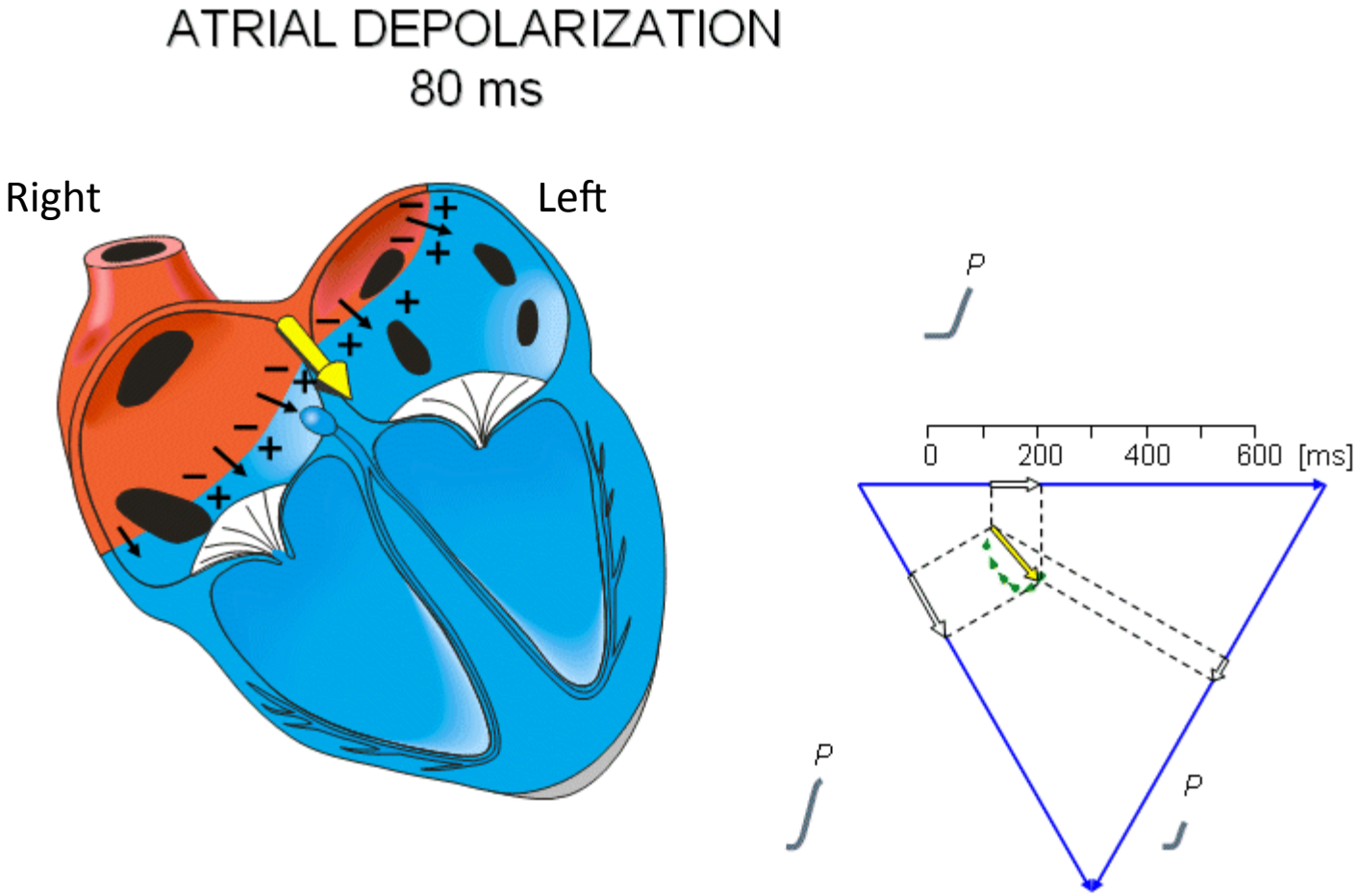




Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

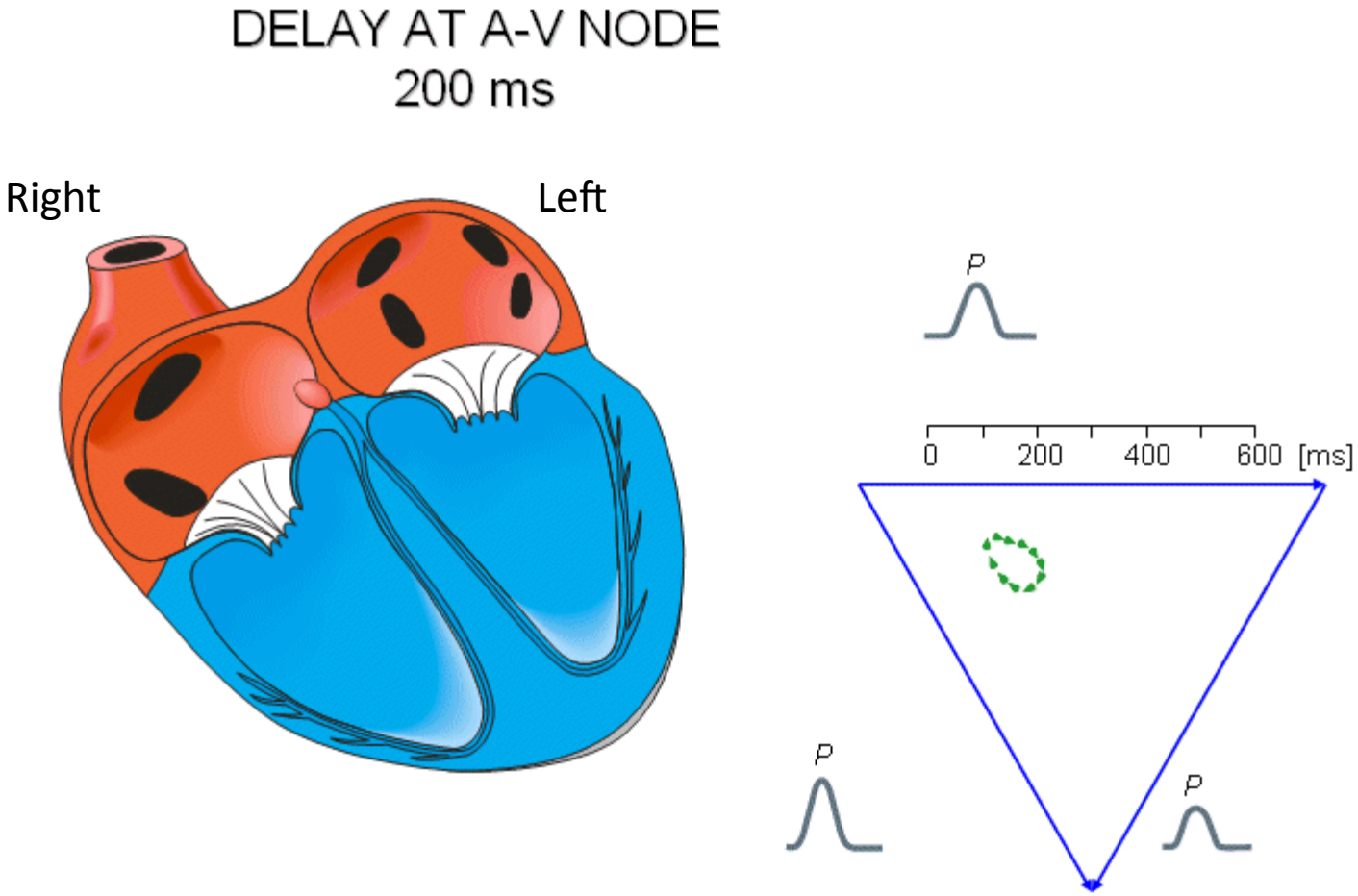
Projection on Limb Leads



Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

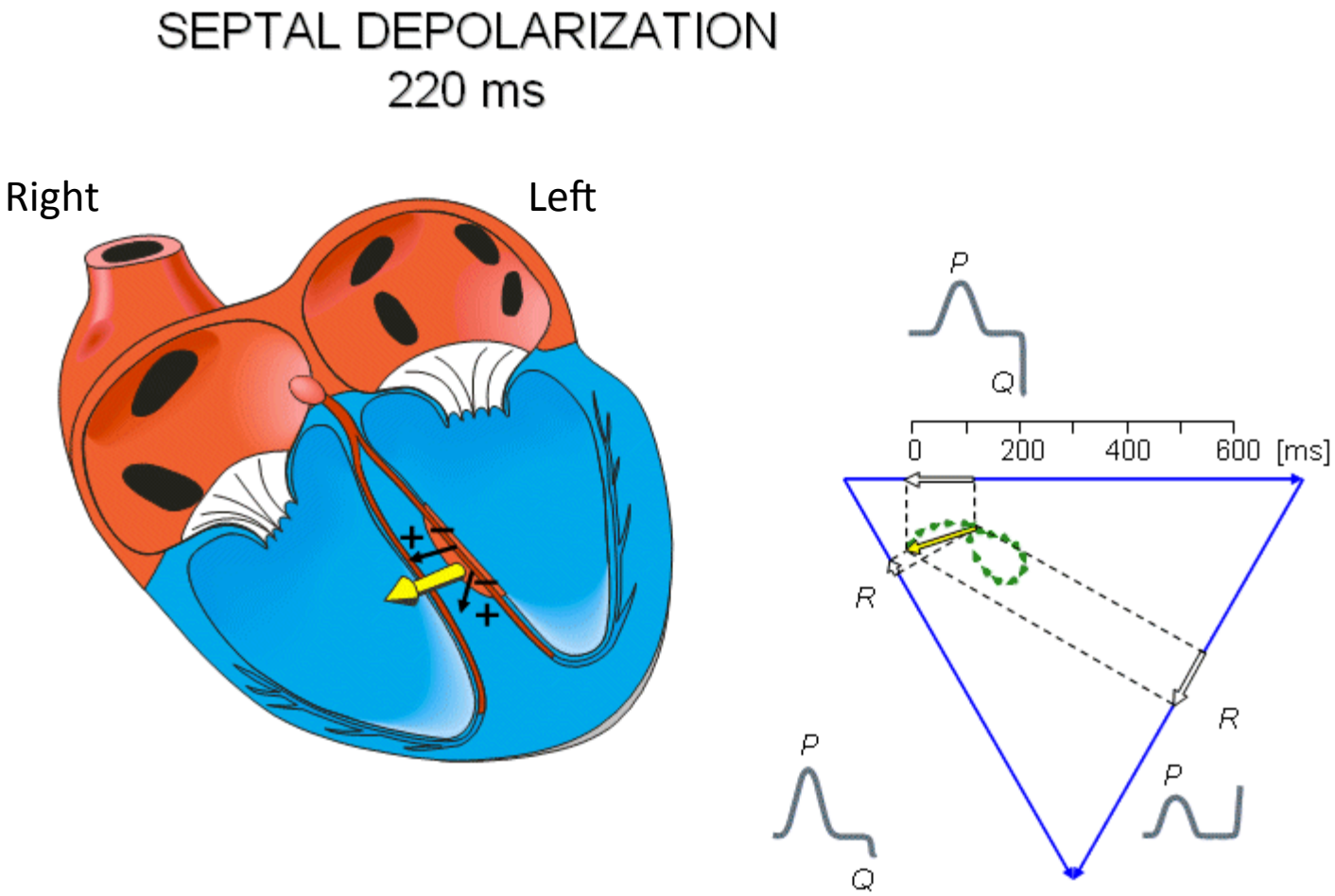
Projection on Limb Leads



Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

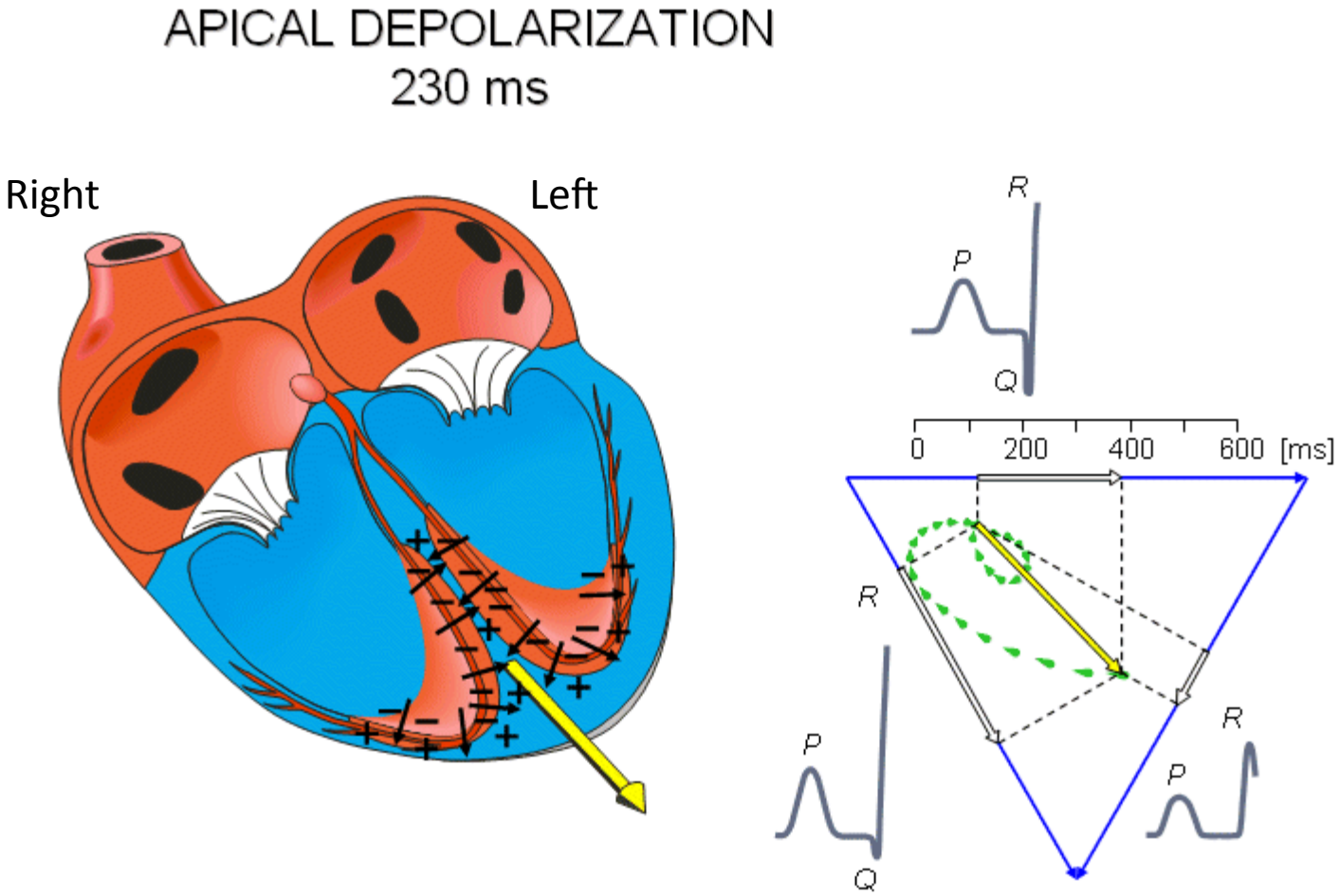
Projection on Limb Leads



Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

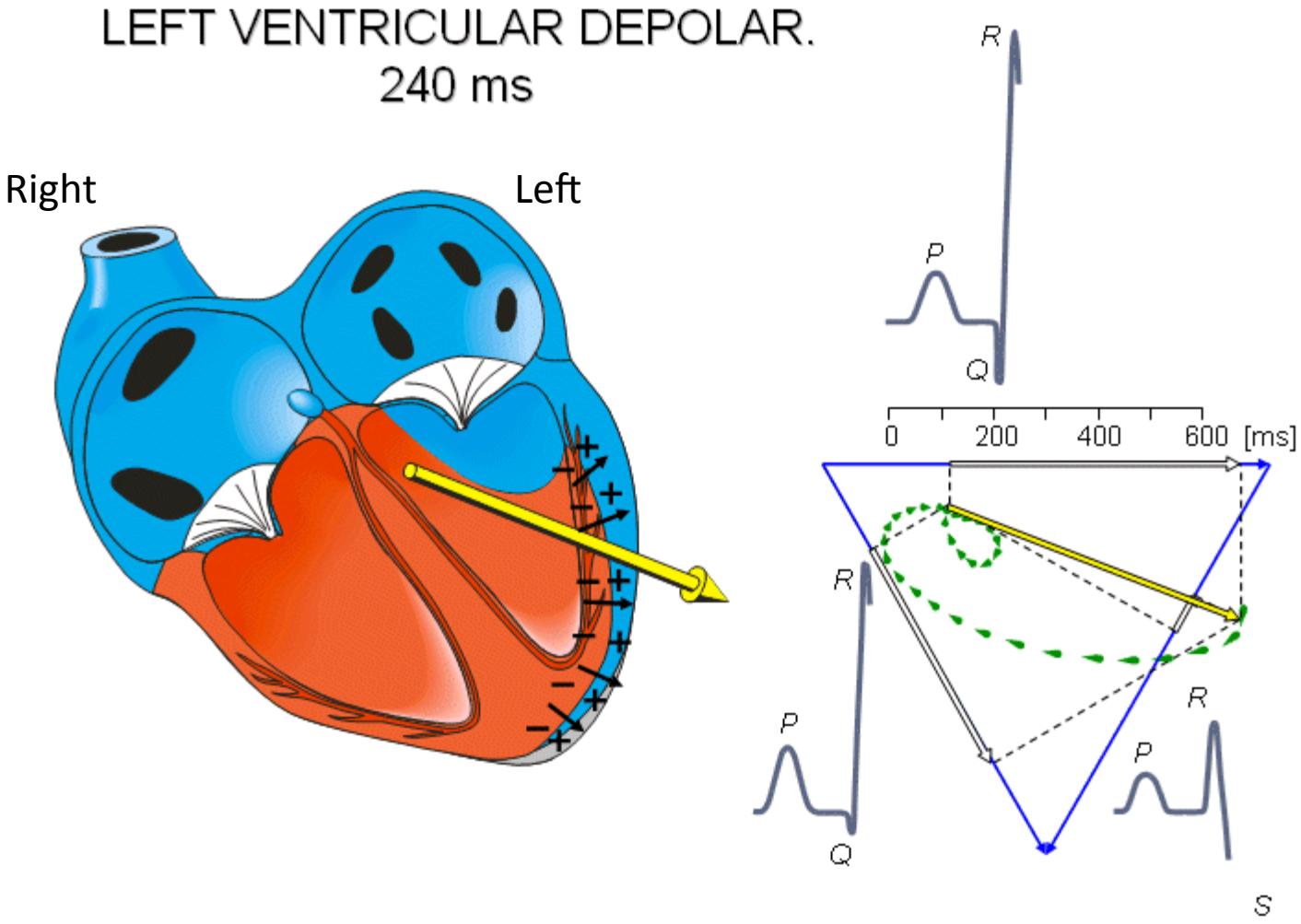
Projection on Limb Leads



Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

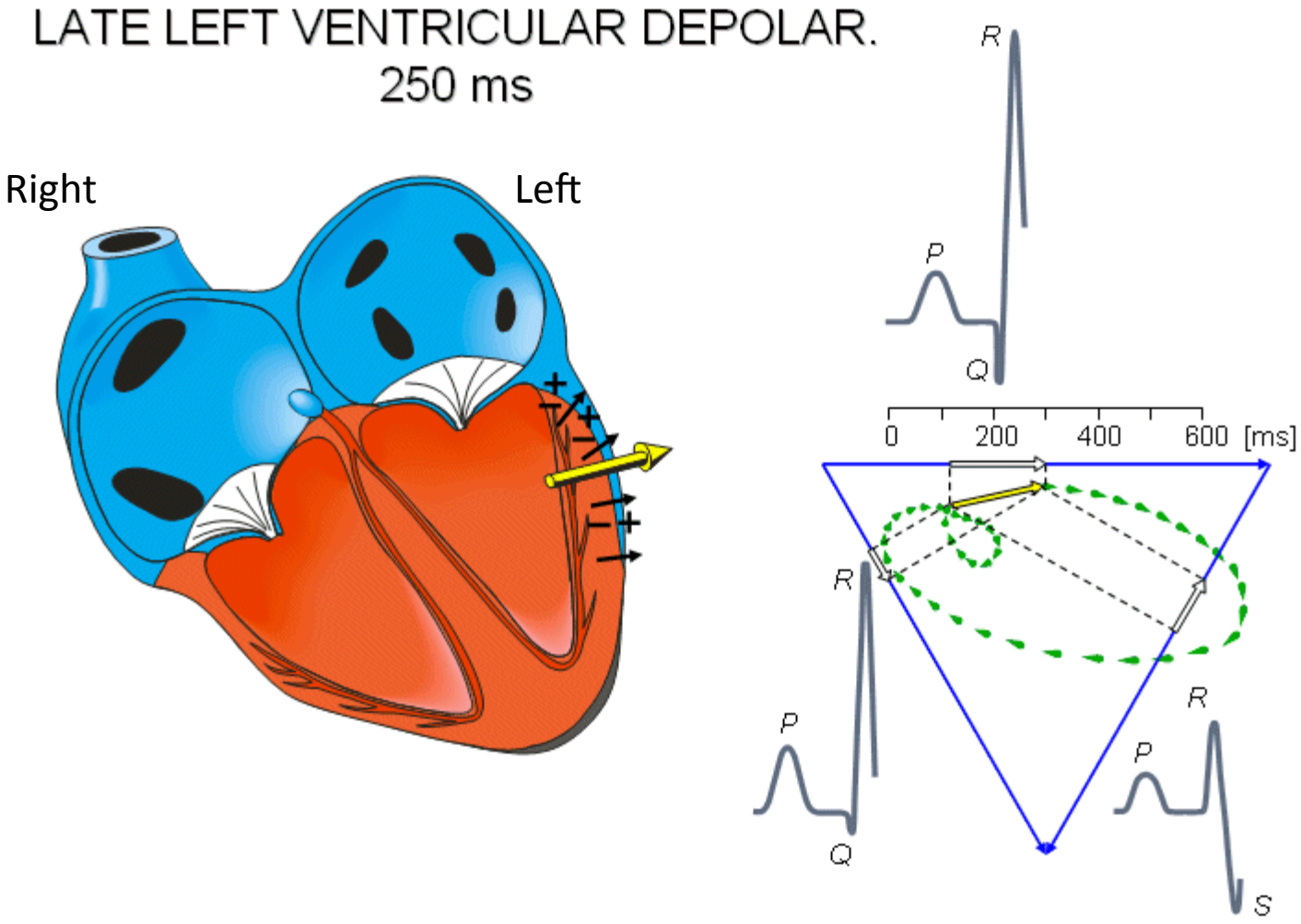
Projection on Limb Leads



Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

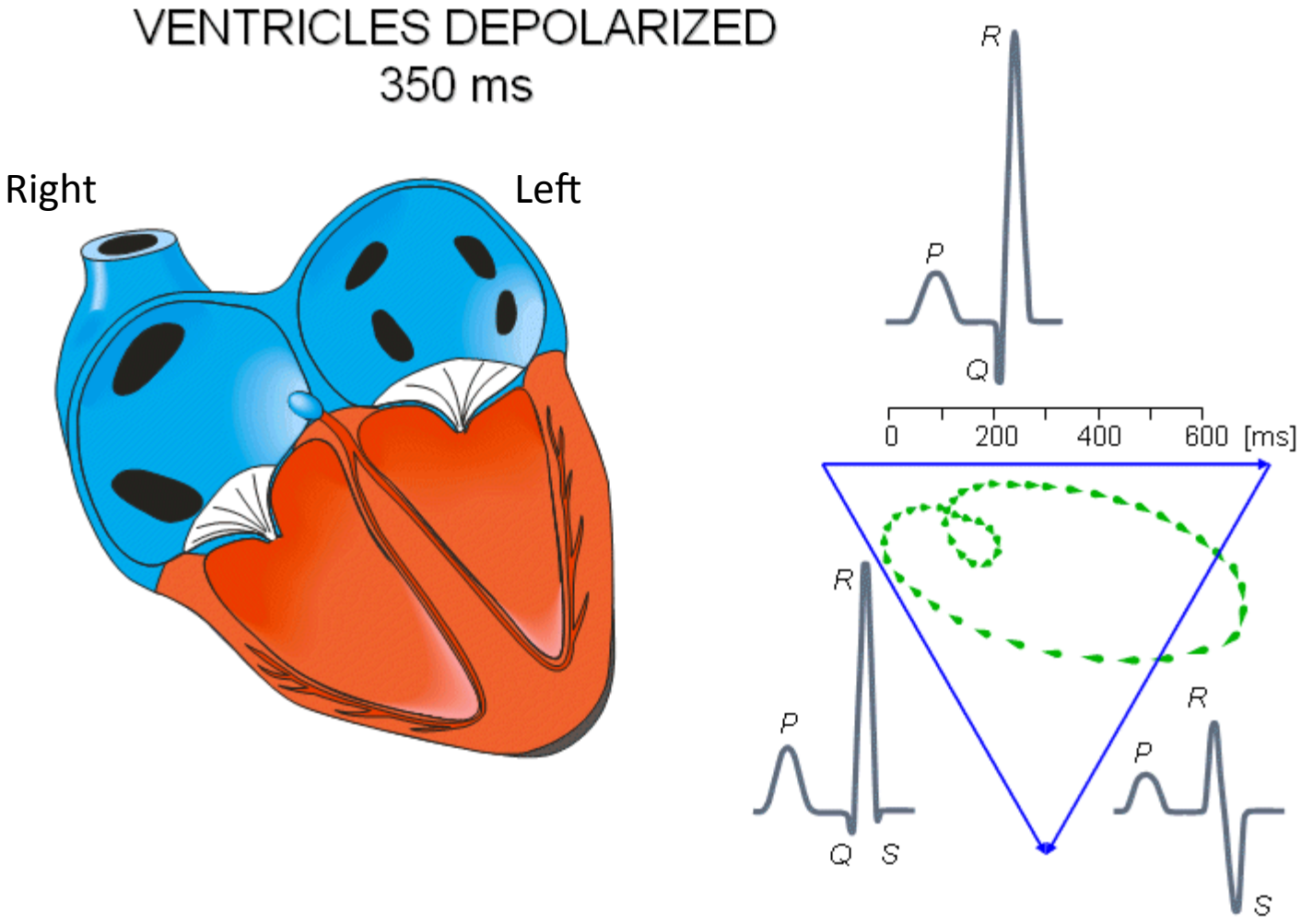
Projection on Limb Leads



Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

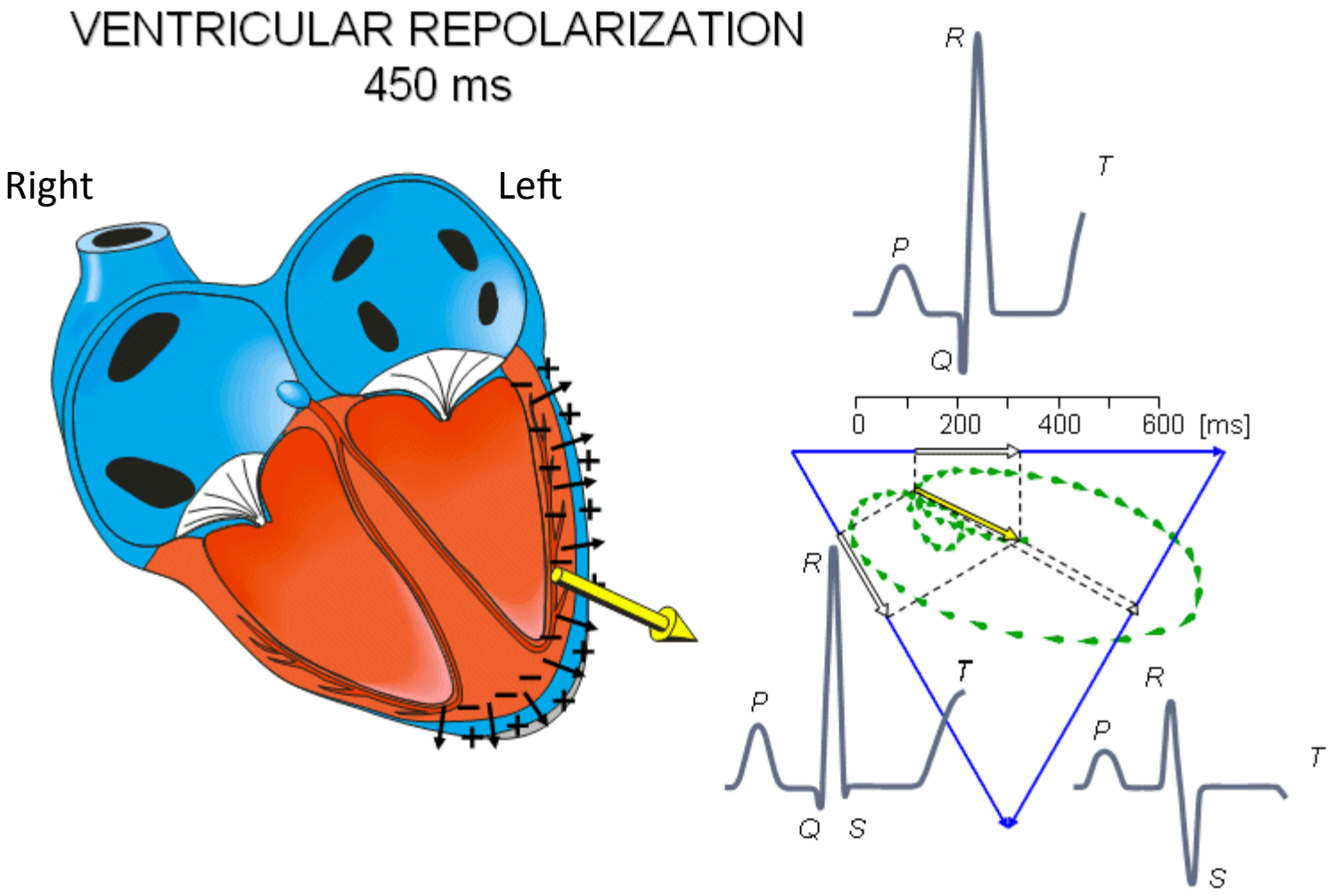
Projection on Limb Leads



Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

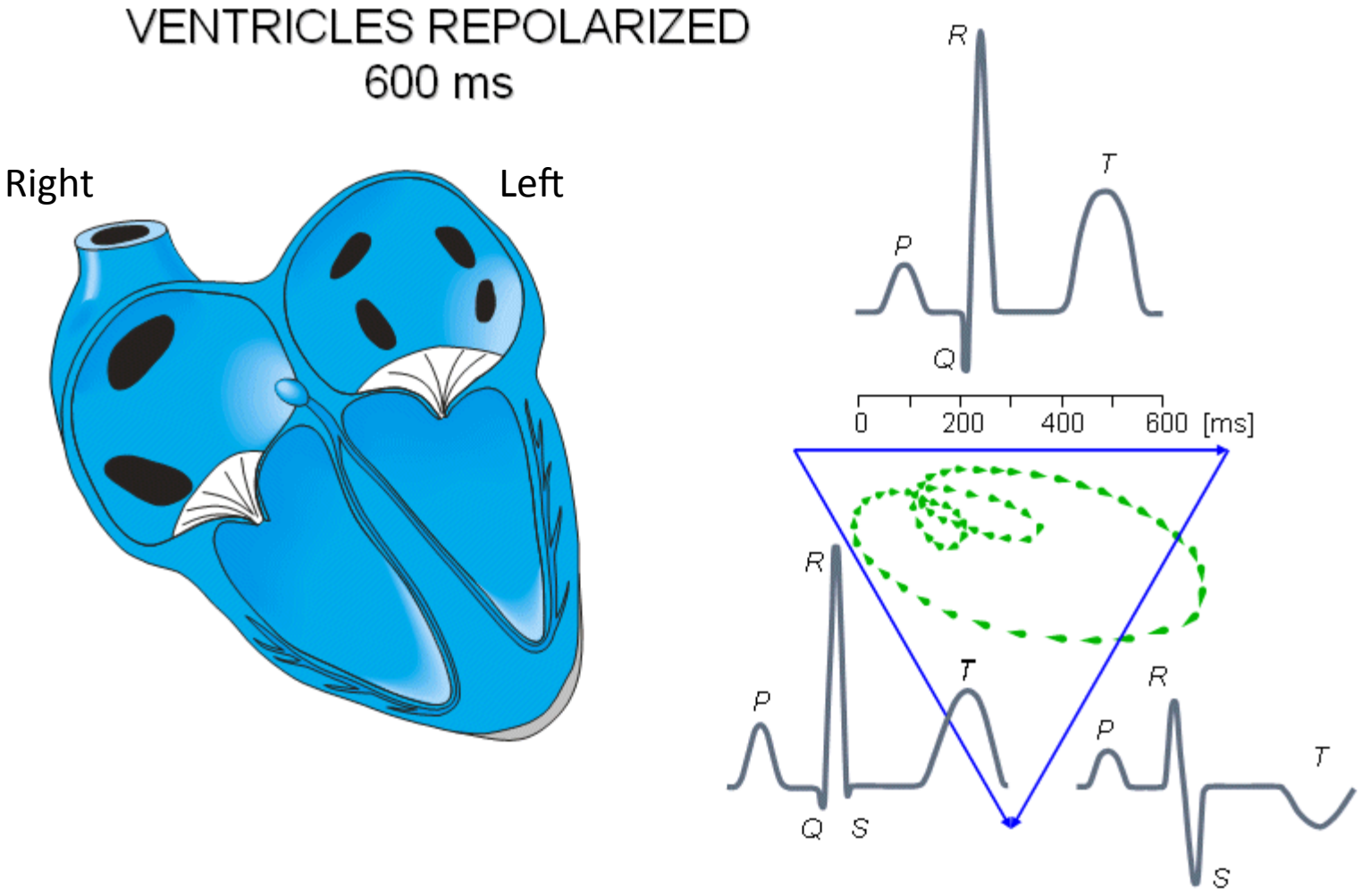
Projection on Limb Leads



Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

Projection on Limb Leads

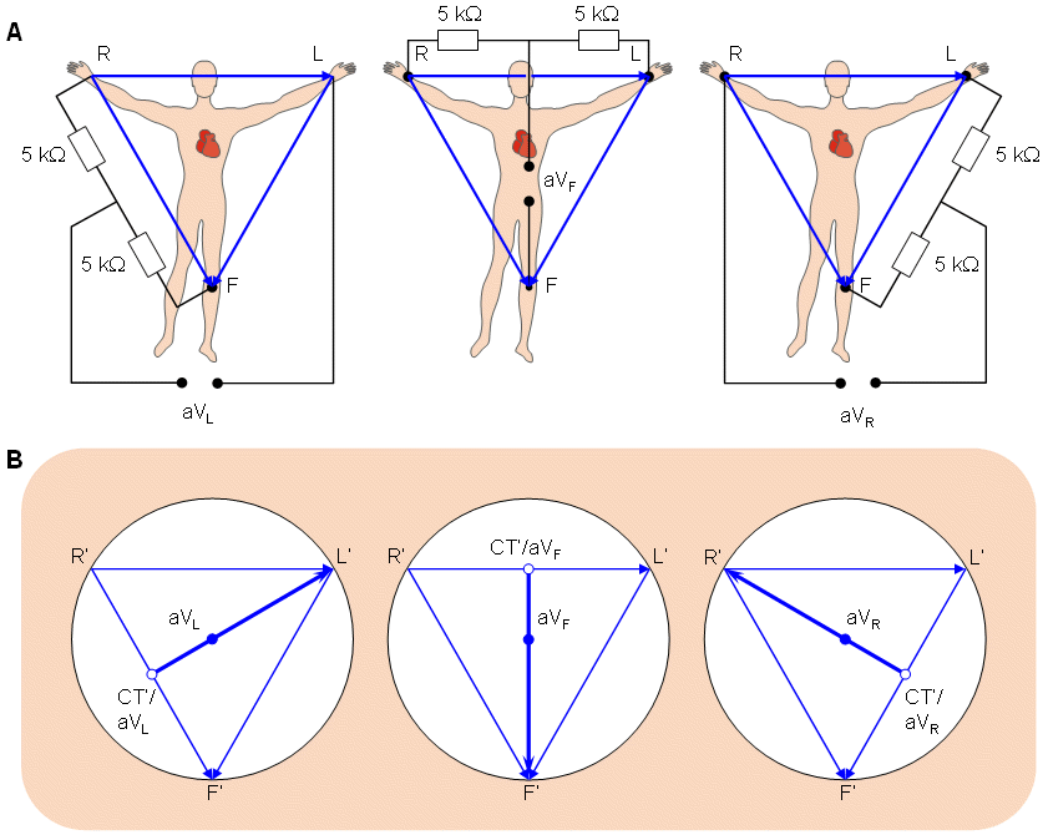


Another cool Flash animation can be found at:
http://library.med.utah.edu/kw/ecg/animations/ecg.html

Source: Bioelectromagnetism, Malmivuo & Plonsey

Augmented Leads

- Provide intermediate axes to Lead I, II & III.
- Useful to determine cardiac axis.

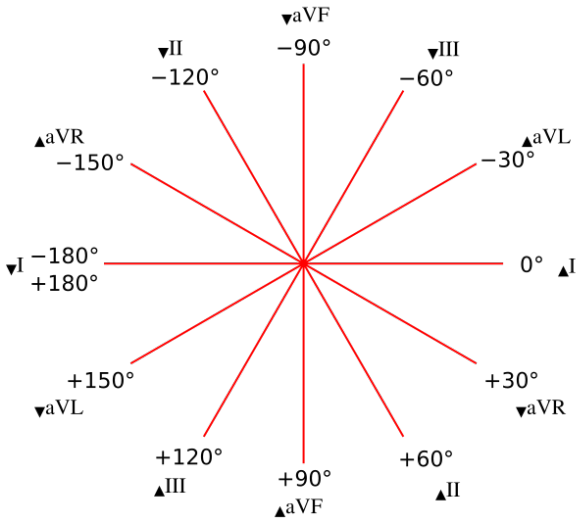


$$aVR = RA - \tfrac{1}{2}(LL + LA)$$

$$aVL = LA - \tfrac{1}{2}(LL + RA)$$

$$aVF = LL - \tfrac{1}{2}(RA + LA)$$

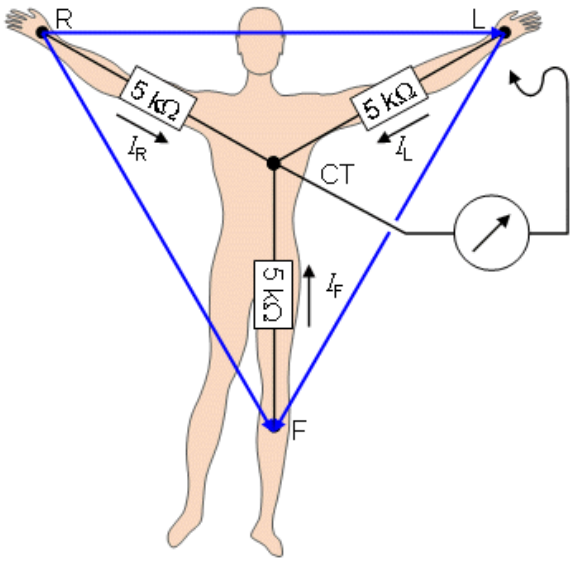
Hexaxial reference system:



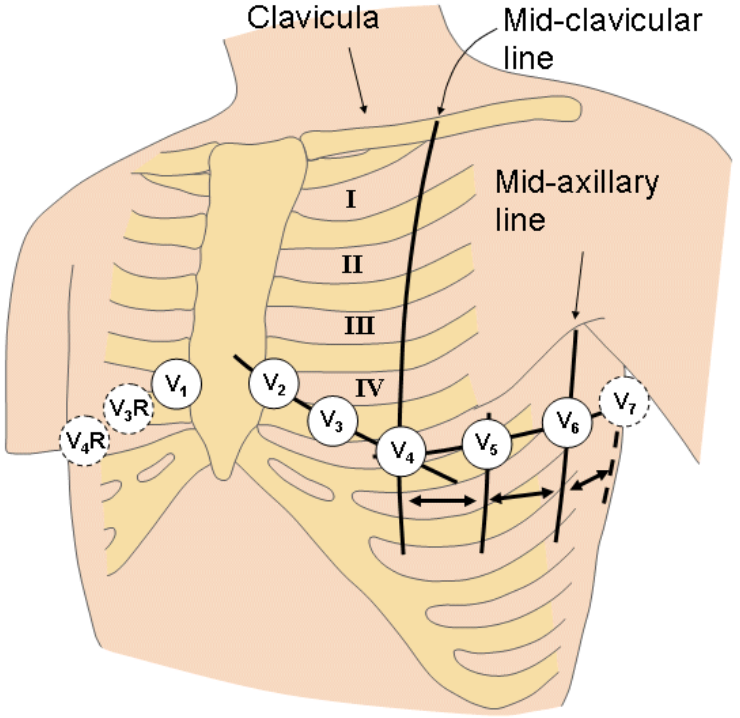
Source: Bioelectromagnetism, Malmivuo & Plonsey & Wikipedia

Precordial Leads

- $V_1, V_2, V_3, V_4, V_5, V_6$
- *Unipolar* leads (referenced to the Wilson Central Terminal – average of RA, LA and LL)
- Provide information in the transverse (horizontal) plane.



Wilson central terminal (virtual reference)



Source: Bioelectromagnetism, Malmivuo & Plonsey

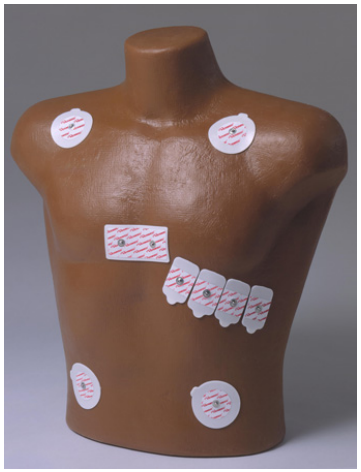
12-Lead System

- Diagnostic ECG usually uses the standard 12-lead system (derived from 10 physical leads):

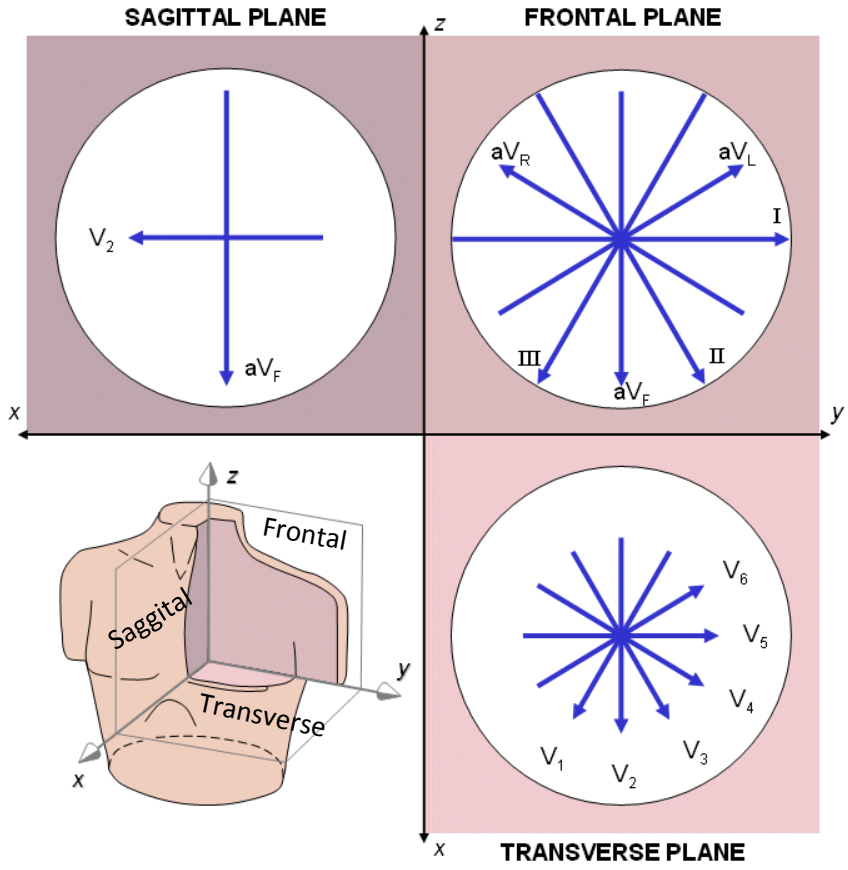
$$I, II, III$$

$$aVR, aVL, aVF$$

$$V_1, V_2, V_3, V_4, V_5, V_6$$

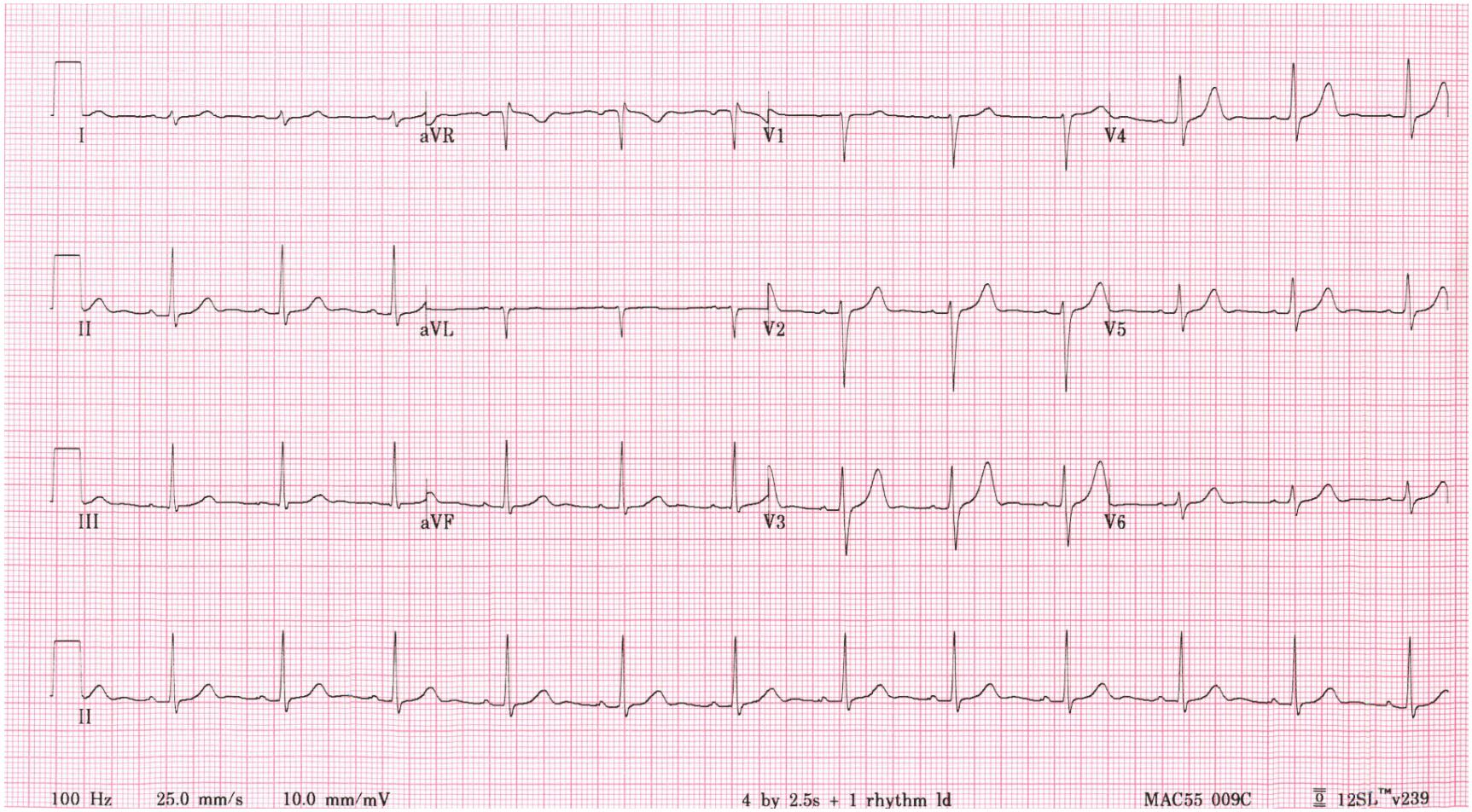


All electrodes on torso:
Mason & Likar configuration



Source: Bioelectromagnetism, Malmivuo & Plonsey

Example of 12-lead Recording

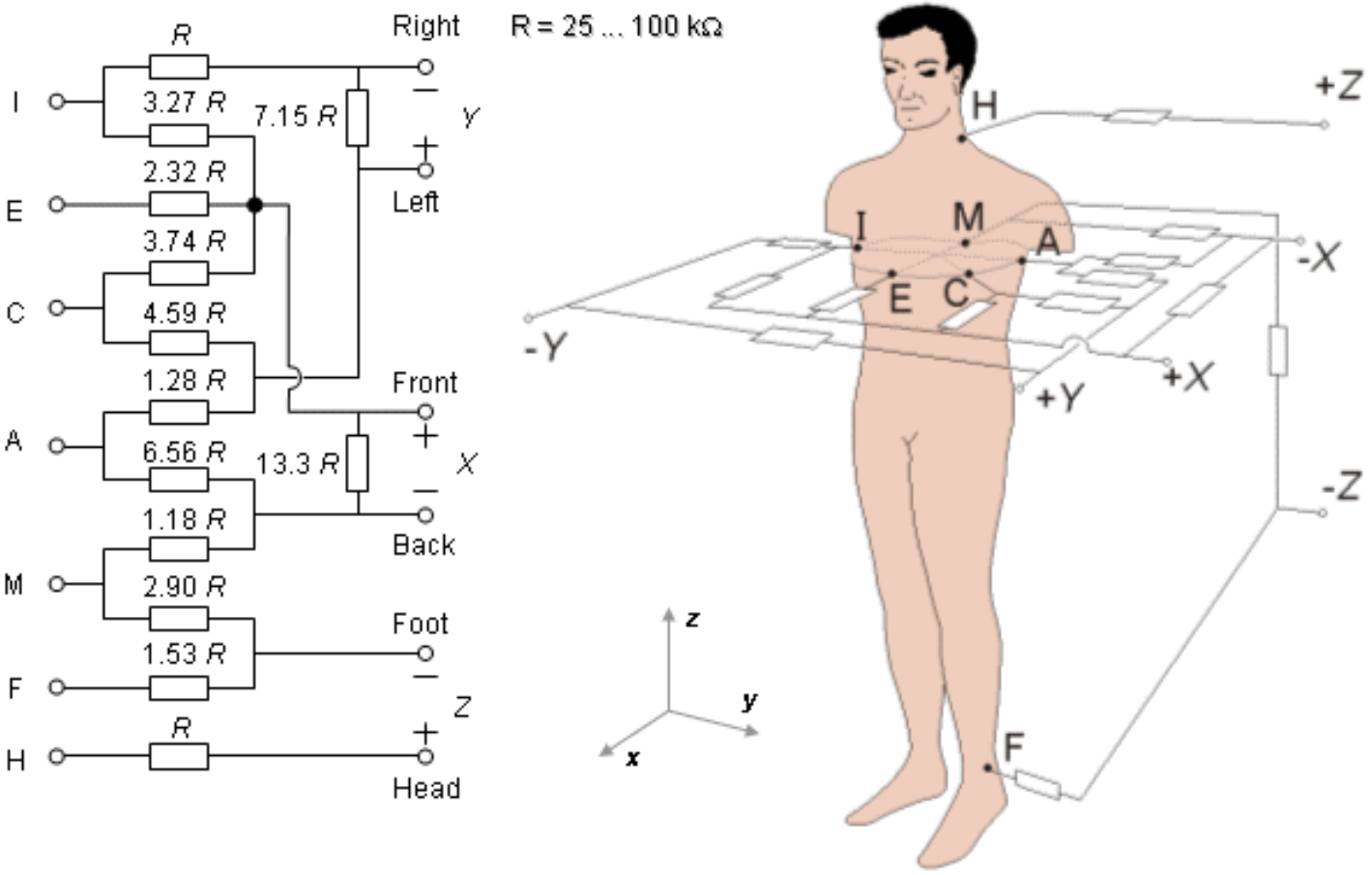


What is the cardiac axis?

More examples at http://www.ecglibrary.com/ecghome.html

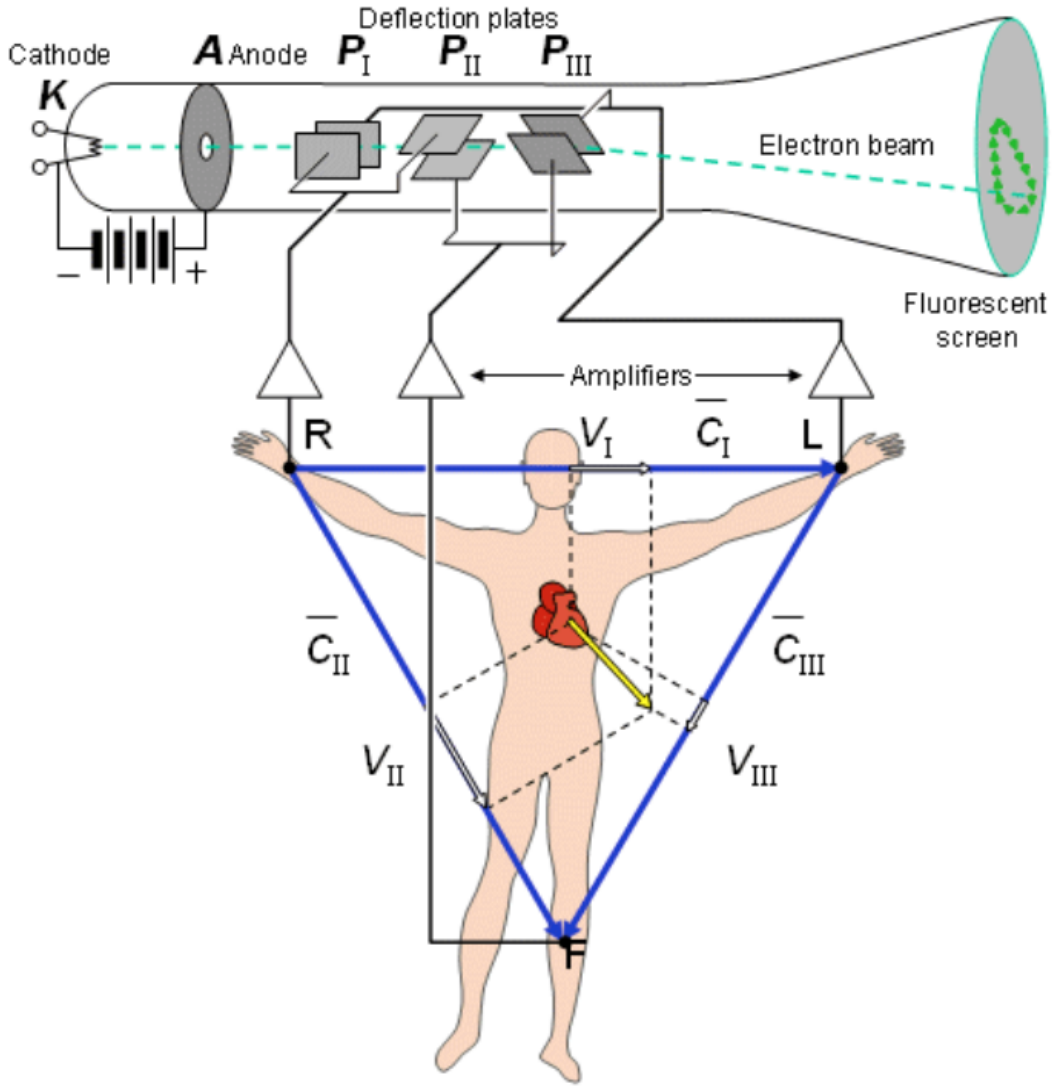
Frank Lead System

- Designed to provide three orthogonal leads X, Y and Z to fully characterize cardiac vector $\boldsymbol{M}$.



Source: Bioelectromagnetism, Malmivuo & Plonsey

Hollman Vector Display (1937)



Source: Bioelectromagnetism, Malmivuo & Plonsey

Lead Definition Summary

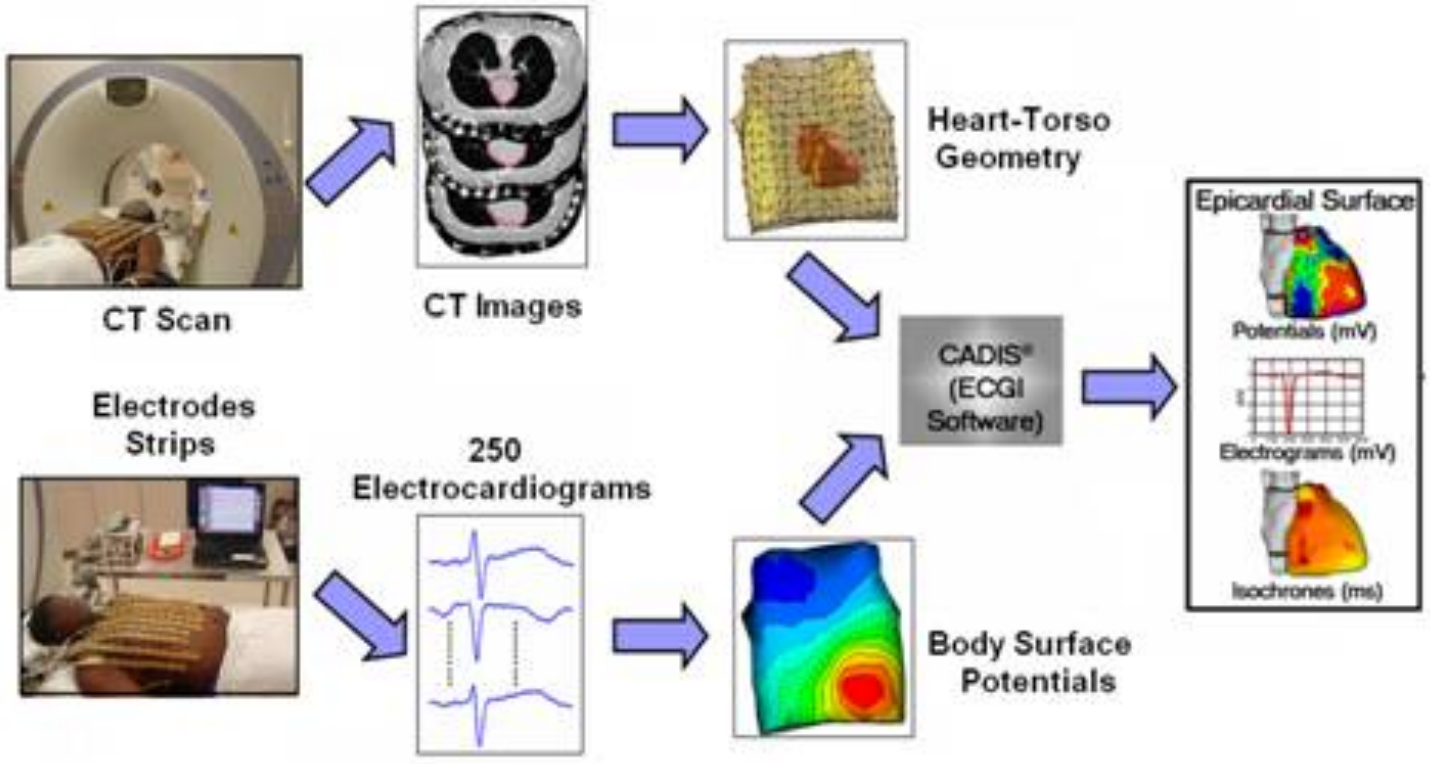
Lead Nomenclature	Definition	Name of lead
I II III	I = LA - RA II = LL - RA III = LL - LA	Bipolar limb leads (Einthoven)
aVR aVL aVF	aVR = RA - 0.5 (LA + LL) aVL = LA - 0.5 (LL + RA) aVF = LL - 0.5 (LA + RA)	Augmented leads (Goldberger)
V1 V2 V3 V4 V5 V6	V1 = *V1* - 0.333 (LA + RA + LL) V2 = *V2* - 0.333 (LA + RA + LL) V3 = *V3* - 0.333 (LA + RA + LL) V4 = *V4* - 0.333 (LA + RA + LL) V5 = *V5* - 0.333 (LA + RA + LL) V6 = *V6* - 0.333 (LA + RA + LL)	Unipolar chest leads (Wilson)
X Y Z	X = 0.610A + 0.171C - 0.781l Y = 0.655F + 0.345M - 1.000H -0.374E - 0.231C	Orthogonal vector leads (Frank)

Note *VX* = physical location, not cardinal ECG lead.

Source: AAMI EC11:1991

Cardiac Mapping (ECGi)

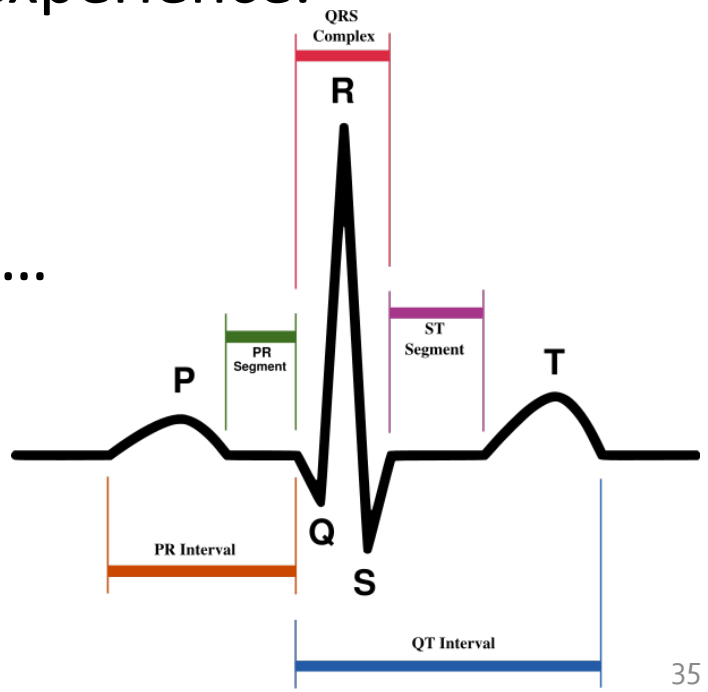
- Dipole model is practical, but simplistic.
- Solving the *inverse problem* requires more knowledge about the volume conductor (body), as well as about the surface electrical activity (higher spatial resolution).



Source: http://rudylab.wustl.edu/research/inverse/implementation.htm

Clinical Relevance – A Few Examples

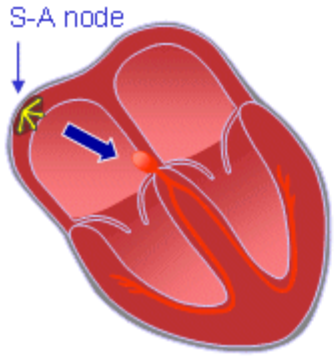
- ECG is hugely helpful in the diagnosis of many heart conditions.
- Despite the lack of unique solution to the inverse problem, many diagnoses can still be done based on existing knowledge (e.g., size of heart, conduction velocity,…), clinical evidence, and experience.
- Applicable to diagnoses of rhythm disturbances, ischemia/infarction, drug effects, pacemaker problems,…
- A few examples of interesting or abnormal ECG are given thereafter.

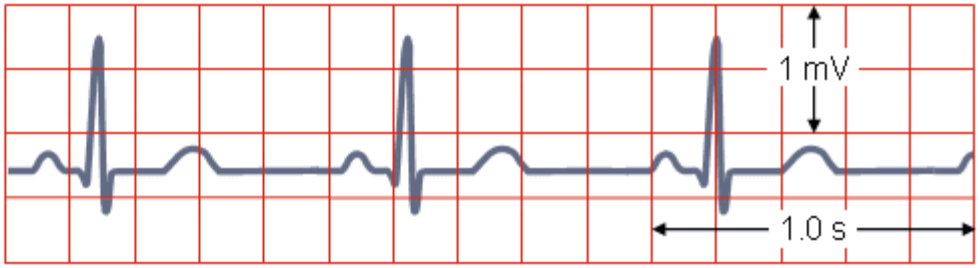


ECG Examples

NORMAL SINUS RHYTHM

Impulses originate at S-A node at normal rate

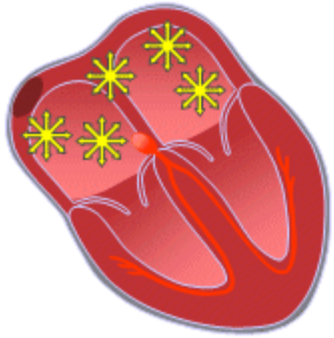


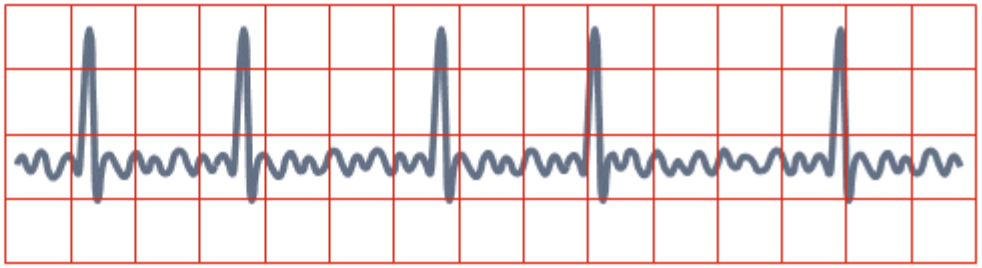


All complexes normal, evenly spaced. Rate 60 – 100/min.

ATRIAL FIBRILLATION

Impulses have chaotic, random pathways in atria





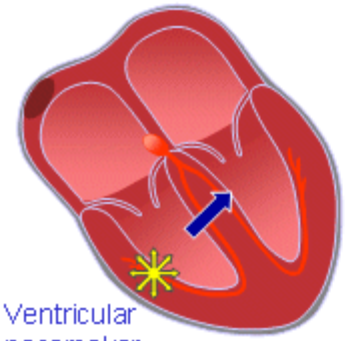
Baseline irregular, ventricular response irregular

Source: Bioelectromagnetism, Malmivuo & Plonsey

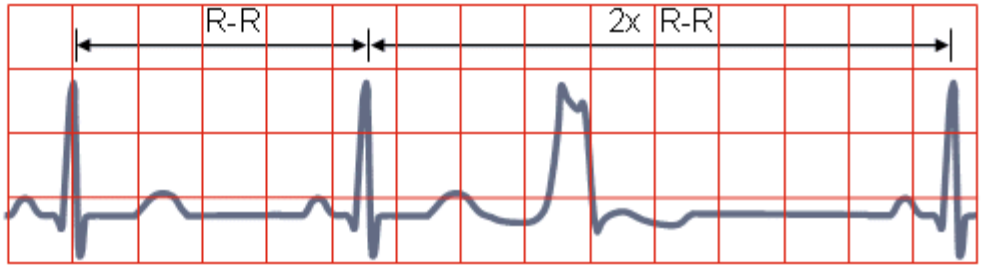
ECG Examples

PREMATURE VENTRICULAR CONTRACTION

A single impulse originates at right ventricle



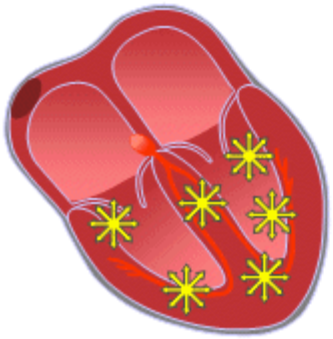
Ventricular pacemaker

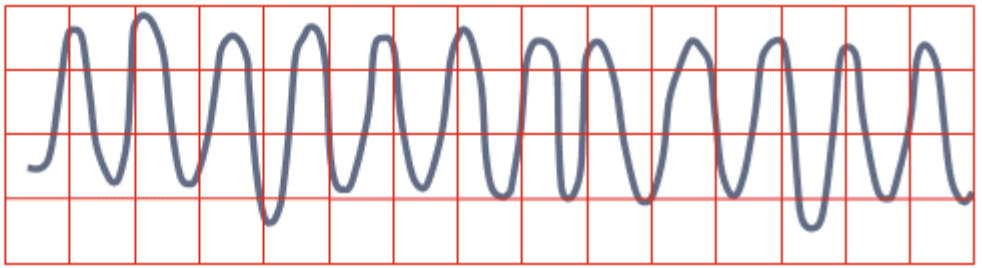


Time interval between normal R peaks is a multiple of R-R interval

VENTRICULAR FIBRILLATION

Chaotic ventricular depolarization



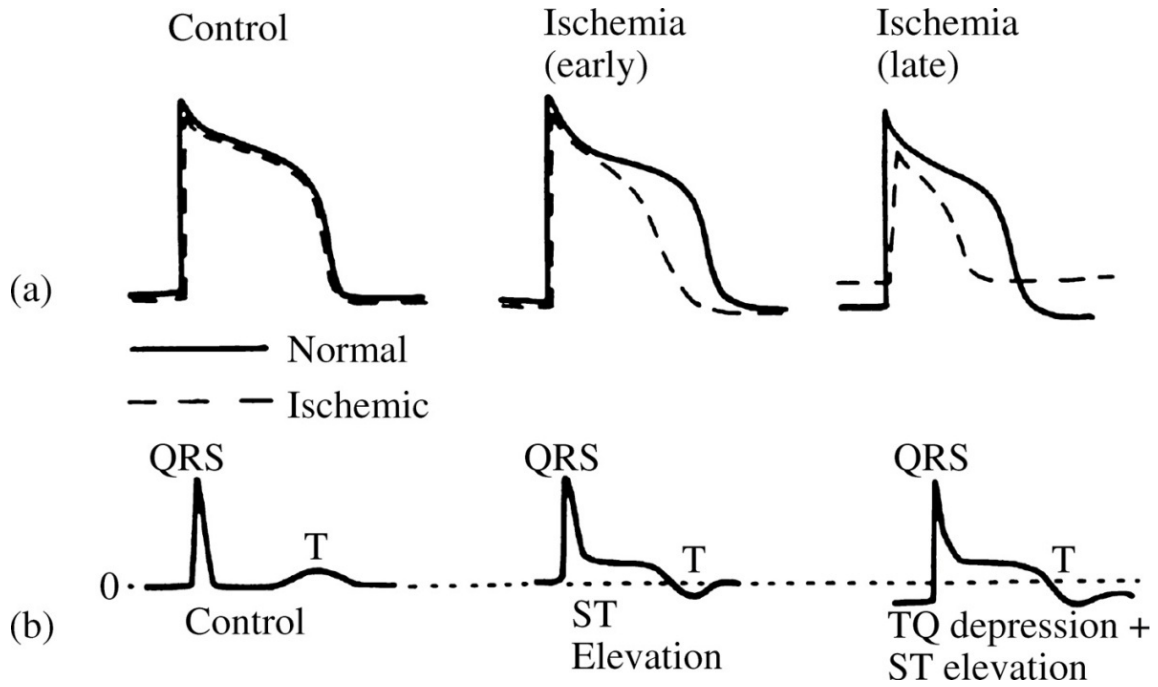


Rapid, wide irregular ventricular complexes

Source: Bioelectromagnetism, Malmivuo & Plonsey

ECG Examples

ISCHEMIA DETECTION



Slower conduction through ischemic region leads to slower AP upstroke, resting and ST segment level change due to loss of K^+ and uptake of Na+ within ischemic cells, as well as Ca^{++} accumulation.

Source: Medical Instrumentation, J. Webster, Wiley, 2009

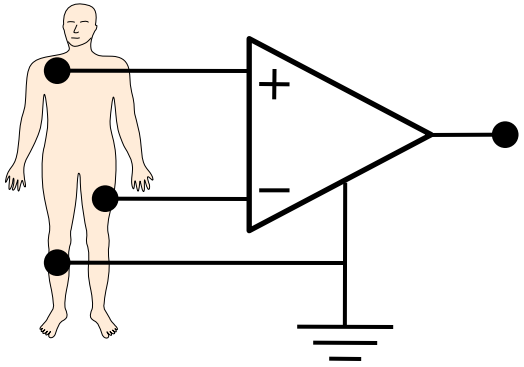
Measurements

Electrocardiograph

Basic ECG Amplifier

The basic ECG amplifier measures the potential difference between two points on the body.

Typical requirements:



- **High input impedance**

  Minimal attenuation of signal

- **High differential gain** over bandwidth of interest

  ECG signals are 0.5 - 4 mV

- **Low common mode gain** (high CMRR)

  Reject external noise (60 Hz power line, etc.)

- **Calibrated gain**

  Necessary for diagnostics

- **Standardized bandwidth**

  Diagnostic-quality ECG requires at least 0.05 -150Hz

Standard Requirements

In the USA, ANSI/AAMI (Association for the Advancement of Medical Instrumentation) set standards for ECG monitoring equipment:

- EC11:1991 – Diagnostic electrographic devices
- EC13-2002 – Cardiac monitors, heart rate meters, and alarms
- EC38:1998 – Ambulatory electrocardiographs

Extracts:

- *Frequency response*
  - Monitoring (EC38): 0.67-40 Hz
  - Diagnostic (EC11): 0.05-150 Hz (simplified)
- *System noise*
  - Monitoring (EC38): max. 100 μV p-p, input-referred
  - Diagnostic (EC11): max. 30 μV p-p, input-referred
- *Input impedance*
  - Min. 2.5 MΩ
- *Leakage currents*
  - Max. 0.1 μA on input leads
- *Overload protection*
  - Min. 5000V / 360J
- …

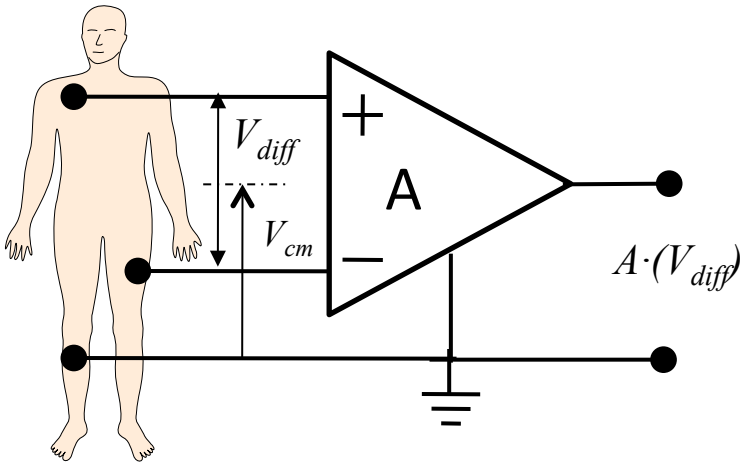
Source: ANSI/AAMI EC11:1991, EC38:1998, EC13:2002

Refresher: Differential Amplifiers

Differential amplifiers are used to amplify small differential signals with common-mode signals.

Typical properties:

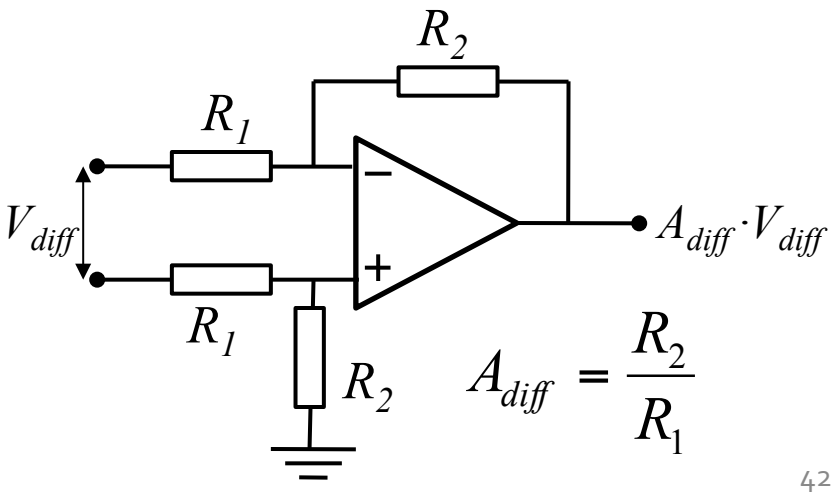
- Differential inputs
- Single-ended output
- Large differential gain
- Small common-mode gain



An **Instrumentation Amplifier** (IA) has, in addition:

- A high input impedance
- A higher ratio of differential over common-mode gain (CMRR).

Typical difference amplifier:

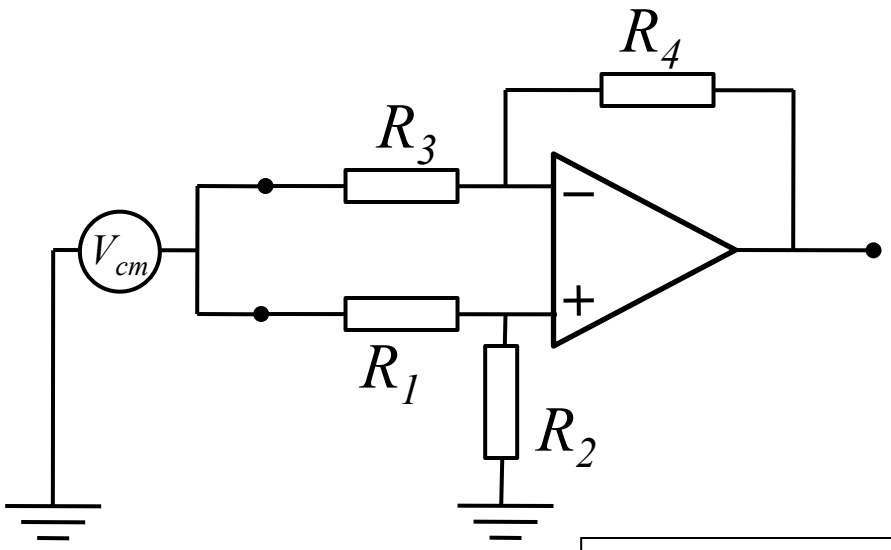


Common-Mode Rejection Ratio

- CMRR is the ability of the amplifier to reject common mode voltage in favor of differential mode voltages:

$$CMRR = 20\log\left(\frac{A_{diff}}{A_{cm}}\right)$$

- CMRR is mostly due to resistor mismatch.
  For instance, in a standard difference amplifier:



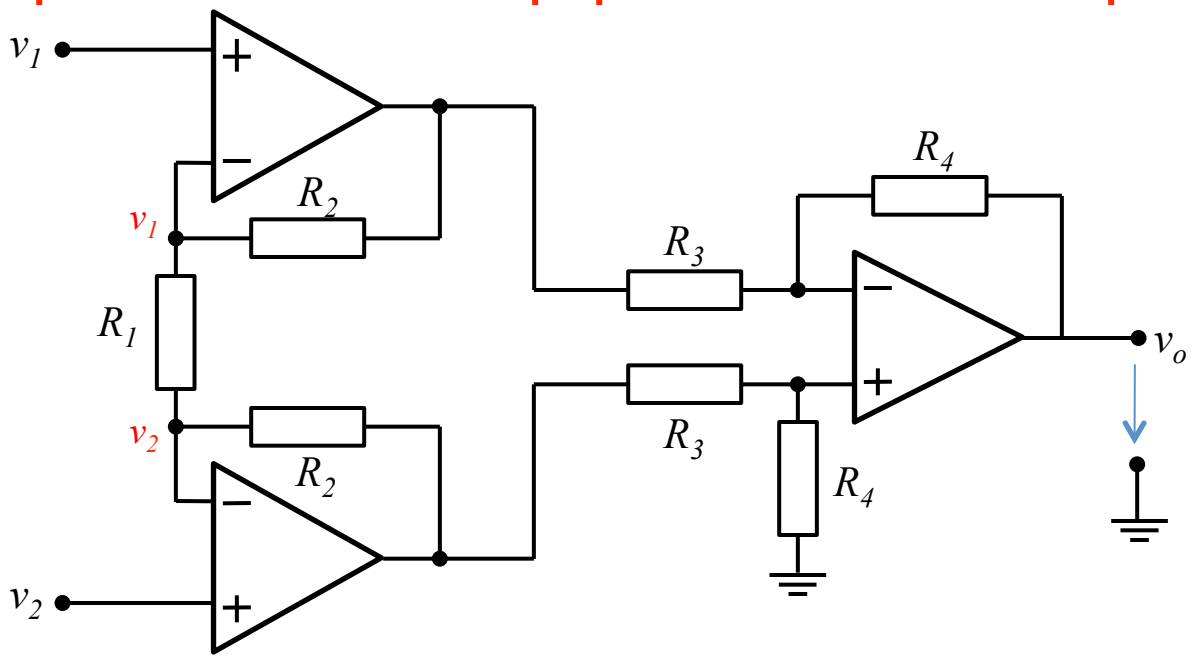
$$A_{cm} = \frac{R_2(R_3 + R_4) - R_4(R_1 + R_2)}{R_3(R_1 + R_2)}$$

Only when $\frac{R_2}{R_1} = \frac{R_4}{R_3}$ that $A_{cm} \rightarrow 0$

Monolithic diff-amps can achieve CMRR in excess of 100 dB

Three-Op-Amp Instrumentation Amplifier

$$A_{diff} = 1 + \frac{2R_2}{R_1}, \quad A_{CM} = 1 \qquad A_{diff} = -\frac{R_4}{R_3}, \quad A_{CM} = 0^*$$



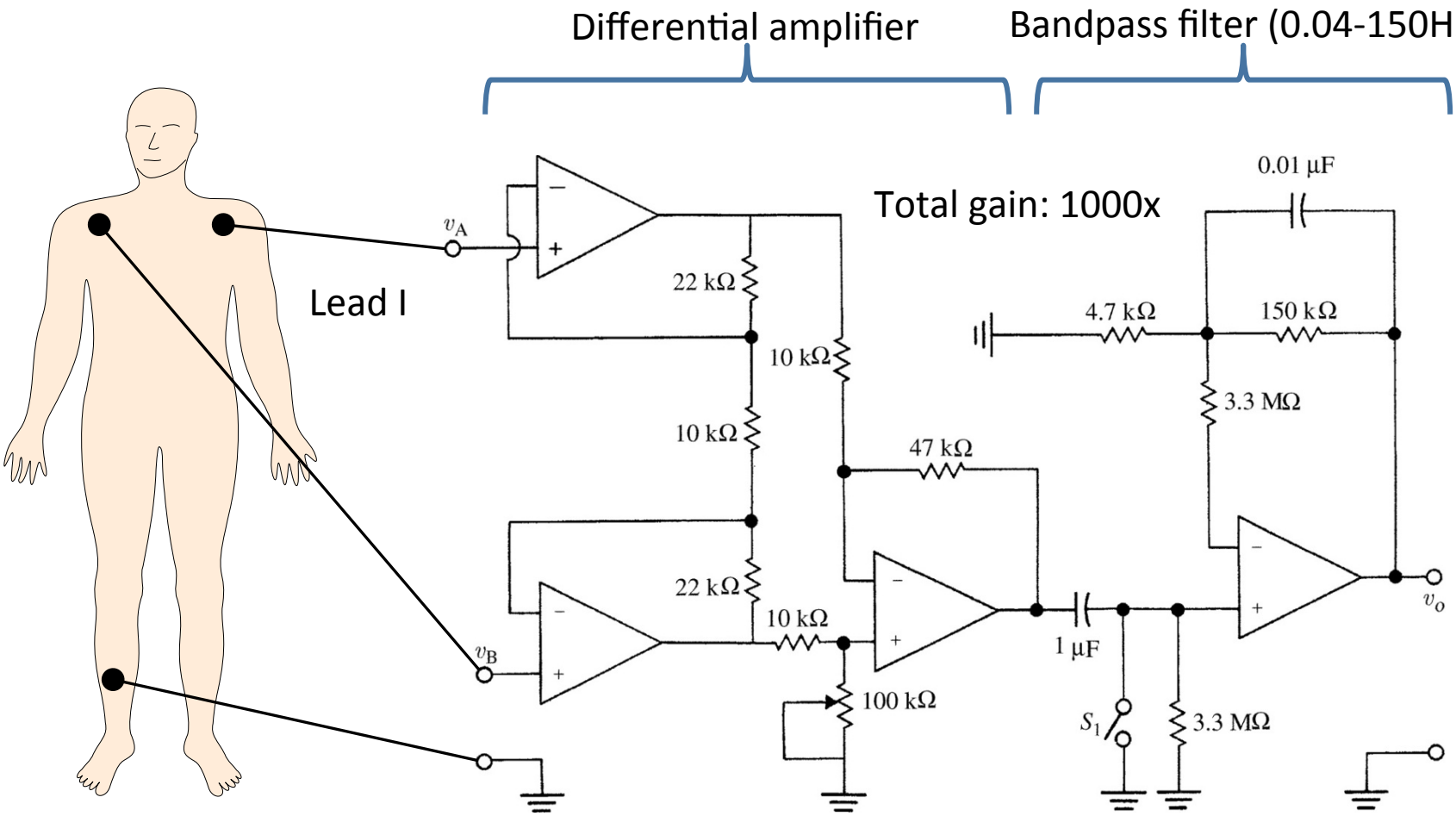
- Very high input impedance
- Gain can be set with only one resistor.
- Optimized CMRR

* Theoretical A_{CM}, only if R3 and R4 are perfectly matched. In reality, there is always a small residual A_{CM} on the differential stage (see previous slide).

$$A_{diff} = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)$$

For one-resistor gain adjust, set $R_4 = R_3$ and fix R_2.

Basic ECG Amplifier (Bipolar Leads)

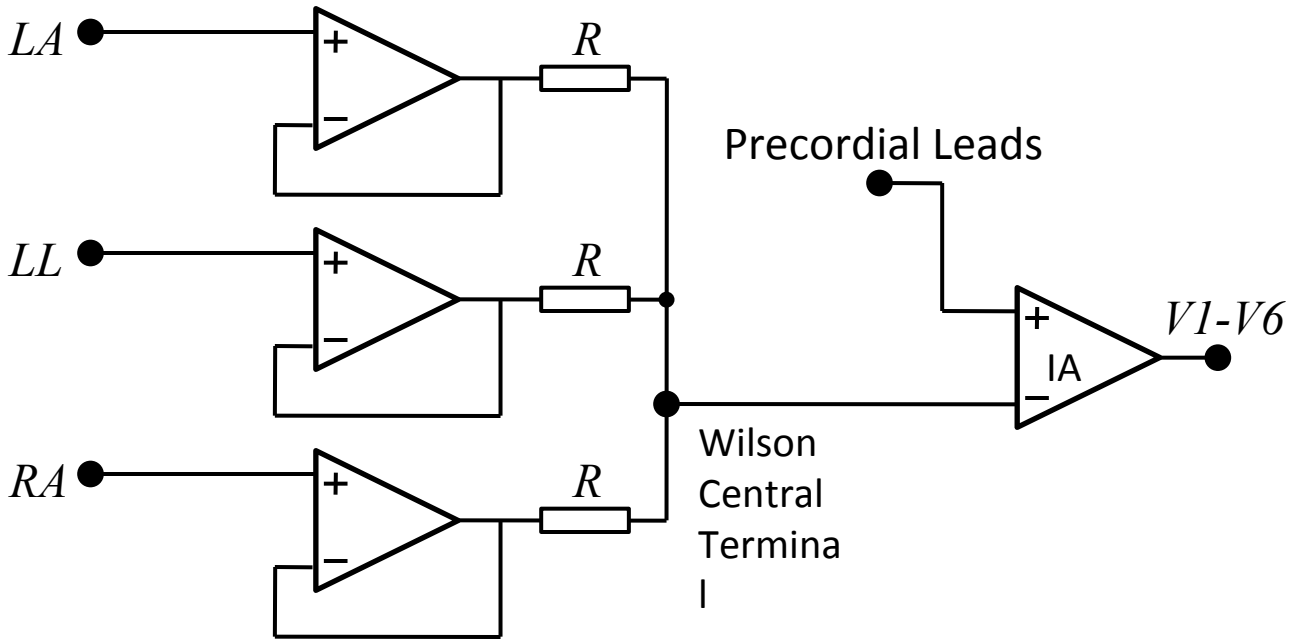


Note: input protection not shown

Source: Medical Instrumentation, J. Webster, Wiley, 2009

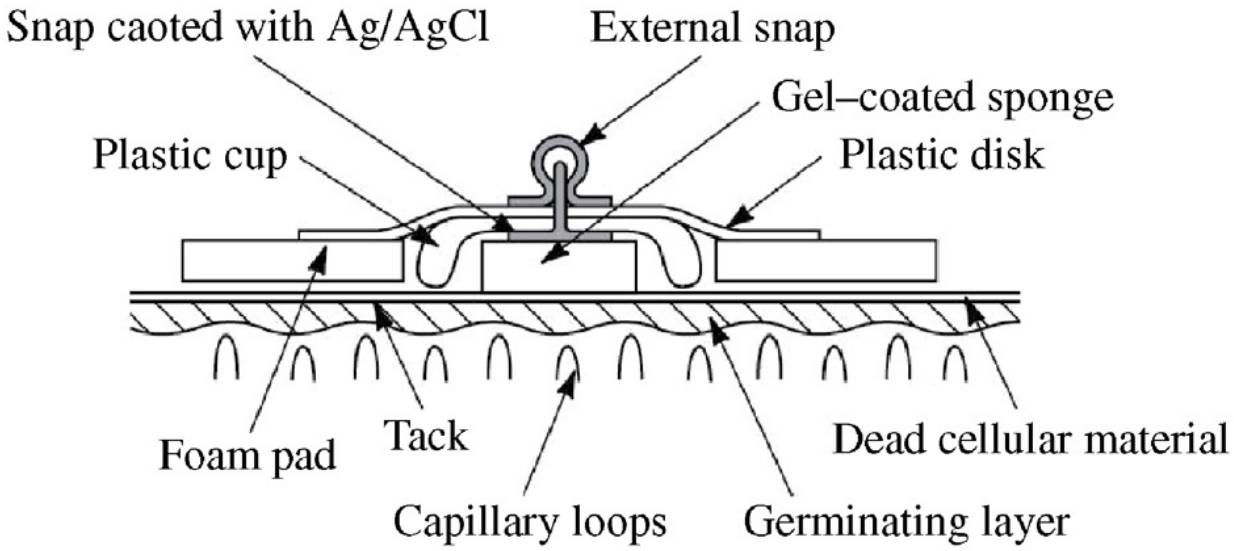
Augmented and Precordial Leads

- For augmented and precordial leads (unipolar), a voltage reference must first be created by summing appropriate leads (e.g. LL+LA+RA for WCT, LL+LA for aVR,…).
- Summation can be either done by resistor network before (as shown earlier) or after buffering (shown below for precordial leads).



ECG Electrodes

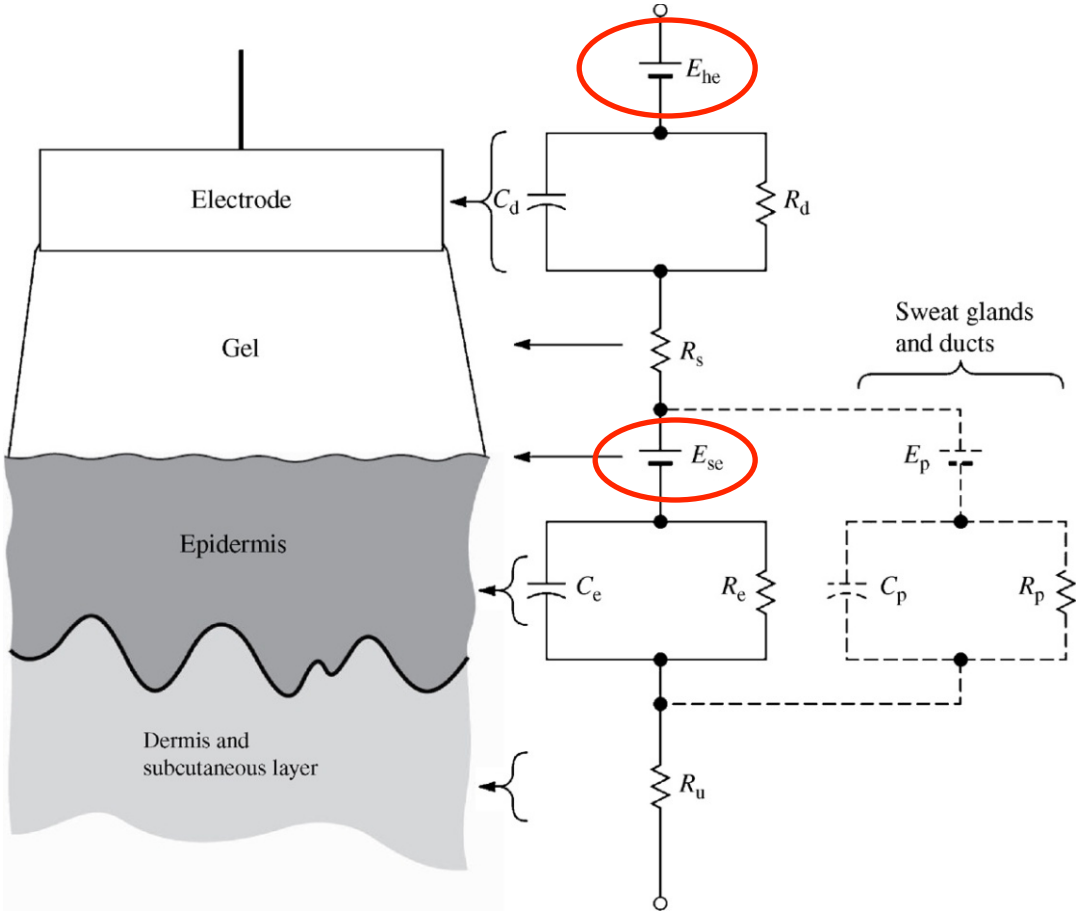
- Typical ECG electrodes are Ag/AgCl gel-based, adhesive electrodes:
  - An Ag/AgCl electrode contacts the skin through a conductive gel, ensuring good contact and low impedance (typically 50-150kΩ @ DC-10Hz)
  - Can be used for both acute or long-term monitoring (limited by skin irritation).



3M™ Red Dot™

Source: Medical Instrumentation, J. Webster, Wiley, 2009

Electrode-Skin Interface Model



For a typical Ag/AgCl gel electrode:

Electrode-gel impedance:

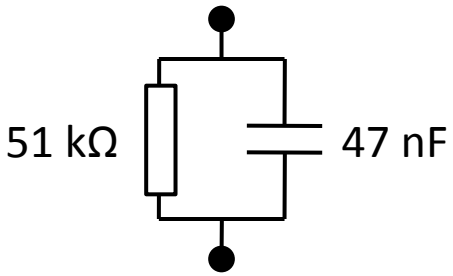
R_d < 1 kΩ @ 10Hz

Gel-skin impedance:

R_e ≈ 50-100 kΩ @ 10Hz

Varies from 200kΩ/cm^2 at 1Hz to 200Ω/cm^2 at 1MHz

Standardized Electrode-Skin model (ANSI/AAMI):



Half-cell potentials contributing to large DC offsets (→300mV!) on input of differential amplifier, thus requiring AC coupling.

Dry Electrodes

Dry electrodes do not use gel or other conductive layer between the metal electrode and the skin.

- Much higher impedance, typically.
- Can be passive or active (contains pre-amplification in the electrode).

A few examples:

Advanced Bioelectrics AccuHeart™
Capacitive electrodes, active

NuMetrex
Cloth electrodes, passive

Orbital Research Electrodes
Dry electrodes, passive

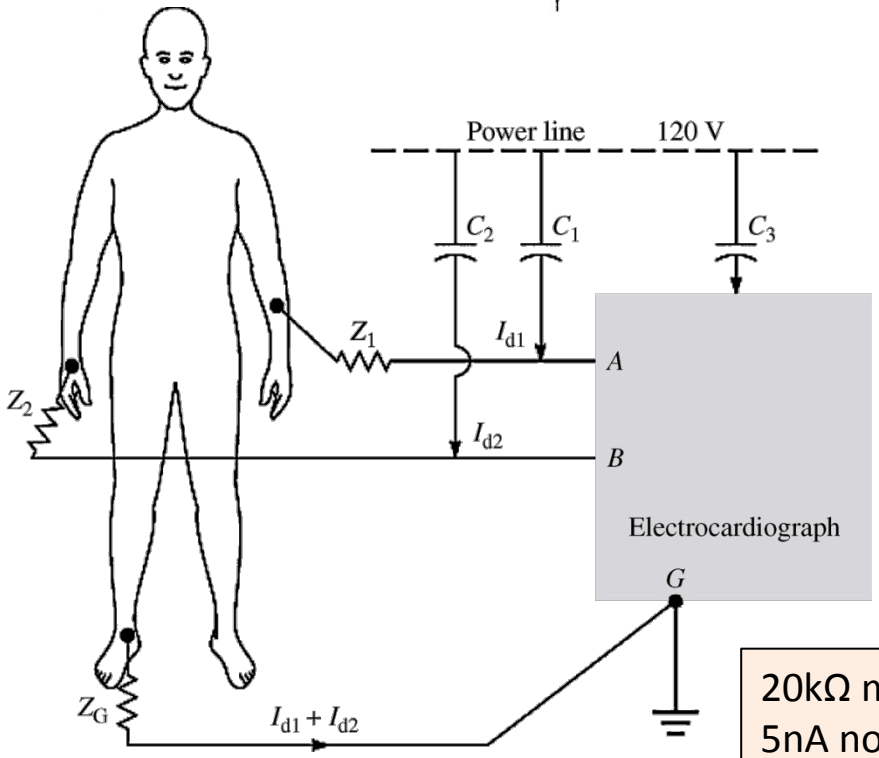
Noise Issues in ECG

- Various types of noise can alter the quality of the recording:
  - Extrinsic
    - Power line interference (cable coupling, body coupling, inductive coupling)
    - Electromagnetic interference (EMI)
    - Motion artifacts
    - Overvoltage transients (defibrillation)
    - Amplifier noise
    - Ground loops
  - Intrinsic:
    - 'Muscle noise' (EMG)
    - Motion artifacts

Power Line Interference

Major issue, since the cables and body acts as large antennas!

Typical 50/60 Hz noise super-imposed on ECG



20kΩ mismatch & 5nA noise → 100μV noise!

1) **Capacitive coupling through cables**

$$V_A - V_B = I_{d1}Z_1 - I_{d2}Z_2 \approx I_d\left(Z_1 - Z_2\right)$$

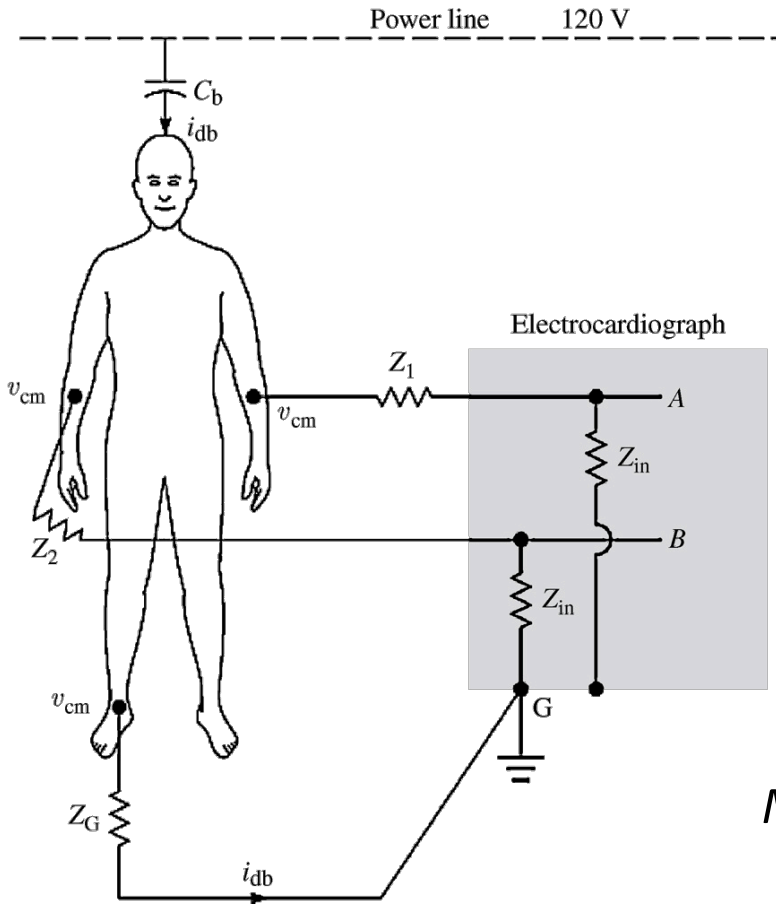
Differential signal proportional to electrode impedance mismatch.

Mitigation strategies:

- Low impedance electrodes
- Shielded cables

Power Line Interference

2) **Capacitive coupling through body**



➡ Common-mode noise voltage:

$$V_{CM} = I_{db} Z_G$$

50 kΩ electrode & 1 μA current→ 50 mV common mode voltage (V_{CM})

➡ Differential noise voltage due to electrode impedance mismatch:

$$V_A - V_B \approx V_{CM}\left(\frac{Z_2 - Z_1}{Z_{in}}\right)$$

50 mV V_{CM}, 20kΩ mismatch & 10 MΩ input impedance→ 100μV noise

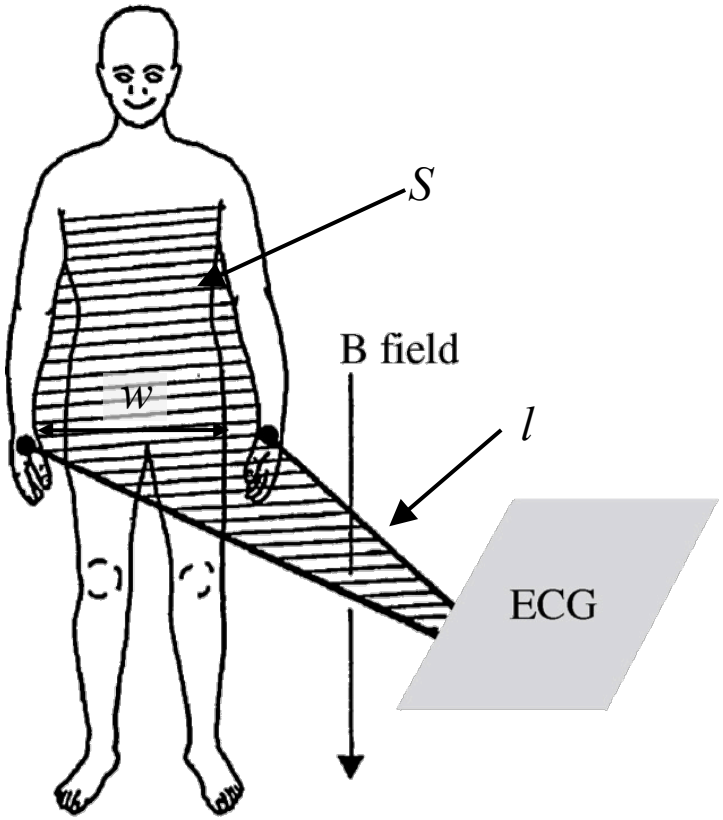
Mitigation strategies:

- Low impedance electrodes
- High CMRR and input impedance amplifier

Power Line Interference

3) **Inductive coupling:** Induced current proportional to area of single loop and field strength.

$$(V_A - V_B) = -S \cdot B \sin(\omega t)$$



Or, alternatively, for someone moving his arms

$$(V_A - V_B) = -B \cdot l \cdot \frac{dw}{dt}$$

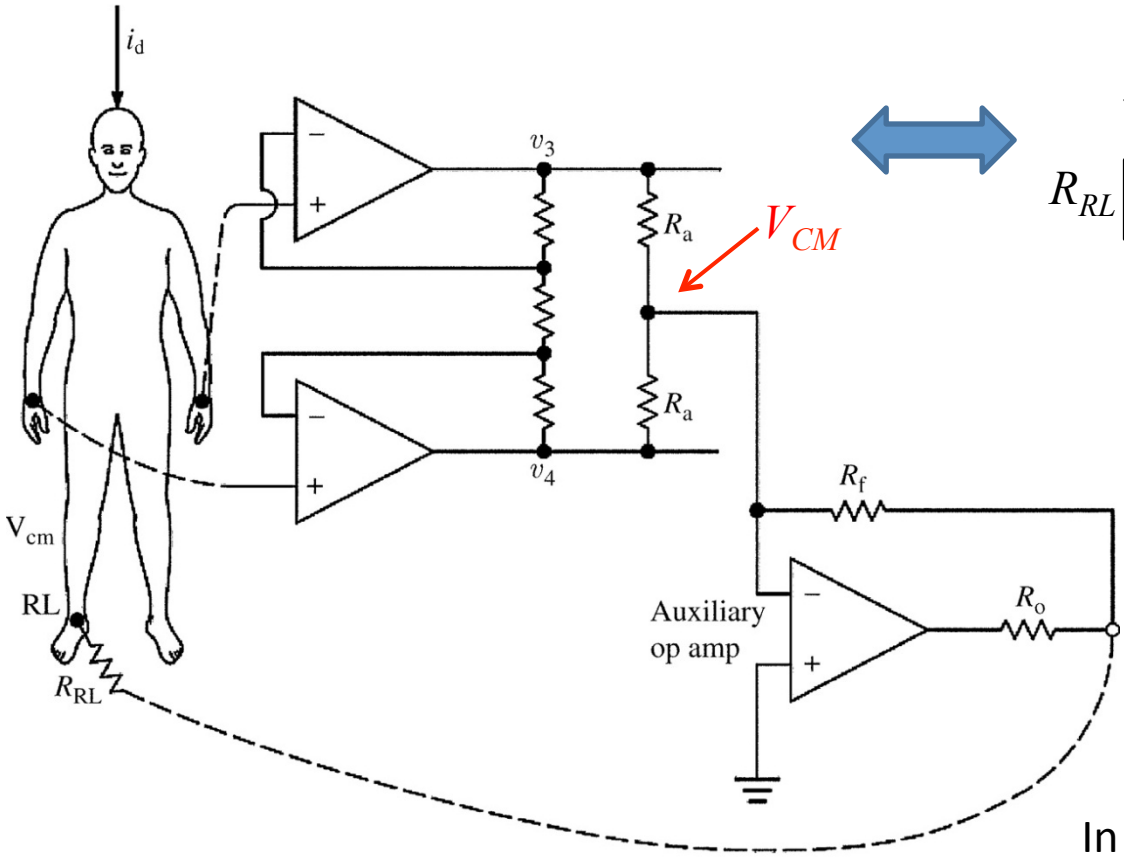
Unlikely scenario: someone clapping hands at 1 Hz, in the earth magnetic field (50 μT) → 50 μV noise

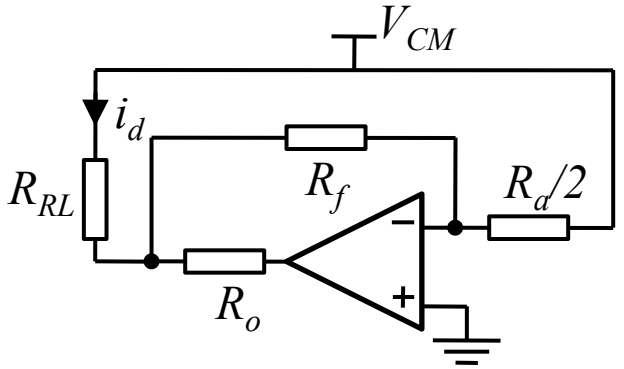
Mitigation strategies:

- Twisting cables
- Low impedance electrodes

Driven Right-Leg (DRL)

Common-mode voltages can be reduced using a right-leg (RL) drive. Instead of grounding RL, it is driven to cancel V_{CM} by negative feedback, based on its measurement in the first stage of the instrumentation amplifier.





$$V_{CM} = \frac{R_{RL} i_d}{1 + 2R_f / R_a}$$

For a displacement current I_d =0.2μA, R_{RL} = 100kΩ, R_f=1MΩ and R_a=25kΩ, V_{CM} = 0.6mV, instead of 50mV

In practice, V_{CM} is buffered, and R_f and R_o are chosen above 1 MΩ to limit the injected current.

Source: Medical Instrumentation, J. Webster, Wiley, 2009

Driven-Right-Leg - Application

Common-mode voltage is typically sampled across the gain resistor.

Example shown for a nerve/EMG amplifier, but similar to an ECG application except for the output filters.

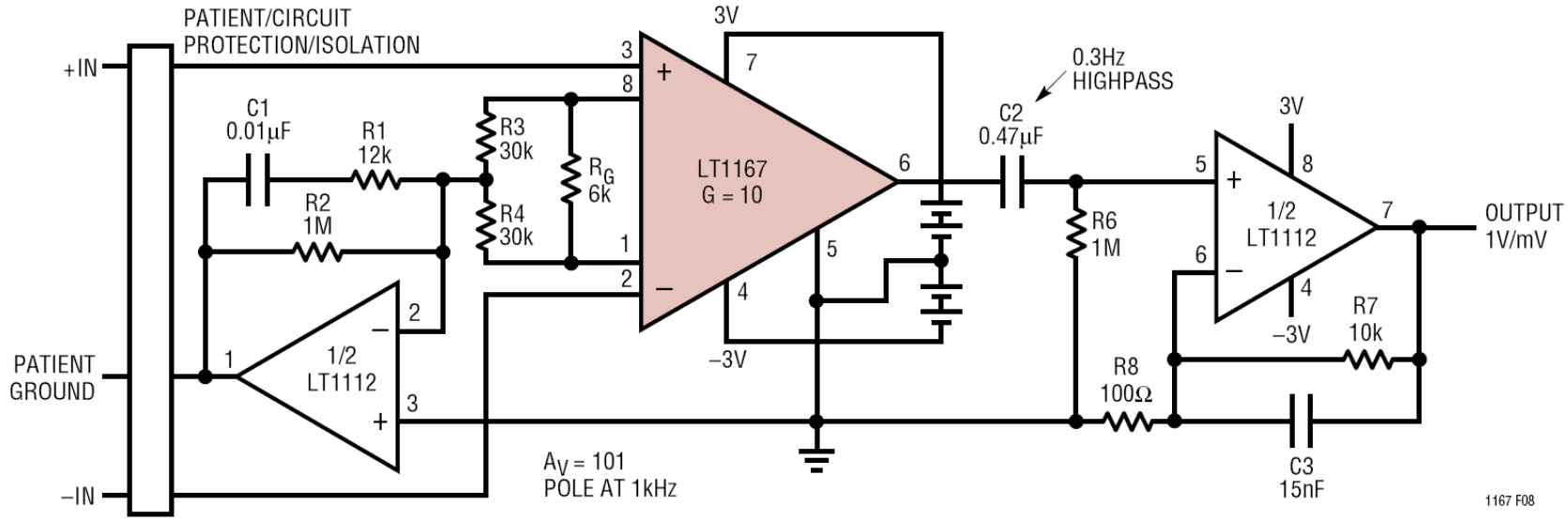


Figure 8. Nerve Impulse Amplifier

Note: no resistor is shown at the output of the right-leg driver, because a separate patient isolation is assumed (white box).

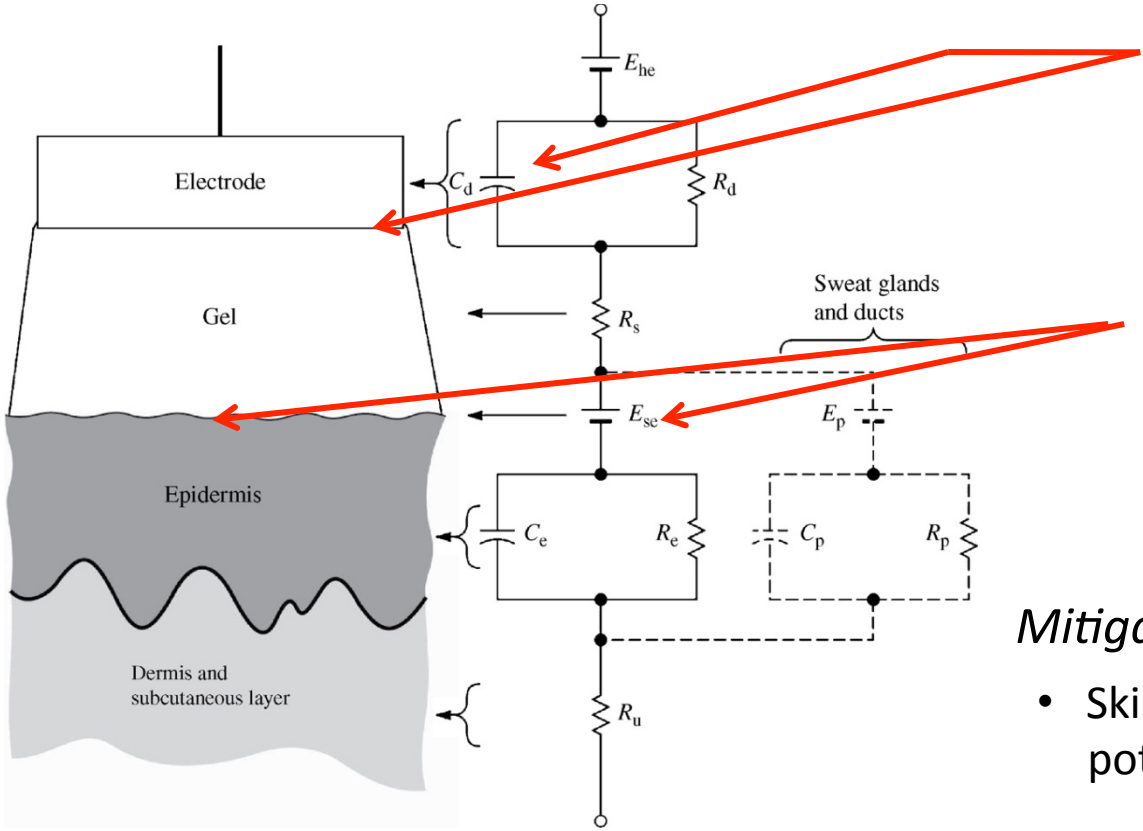
Source: LT1167 datasheet, Linear Technologies

Motion Artifacts

Motion artifacts are primarily generated by the movement of charges at the electrode, and to a lower extent to cable movements (see inductive coupling).

Analysis of a gel electrode:

Lowest susceptibility to motion artifact among non-invasive electrodes



Movement of the **electrode/ electrolyte interface** disturbs the charges, introducing noise.

Movement of **gel electrolyte/ skin interface** disturbs the gel-skin potential, introducing noise.

Mitigation strategies:

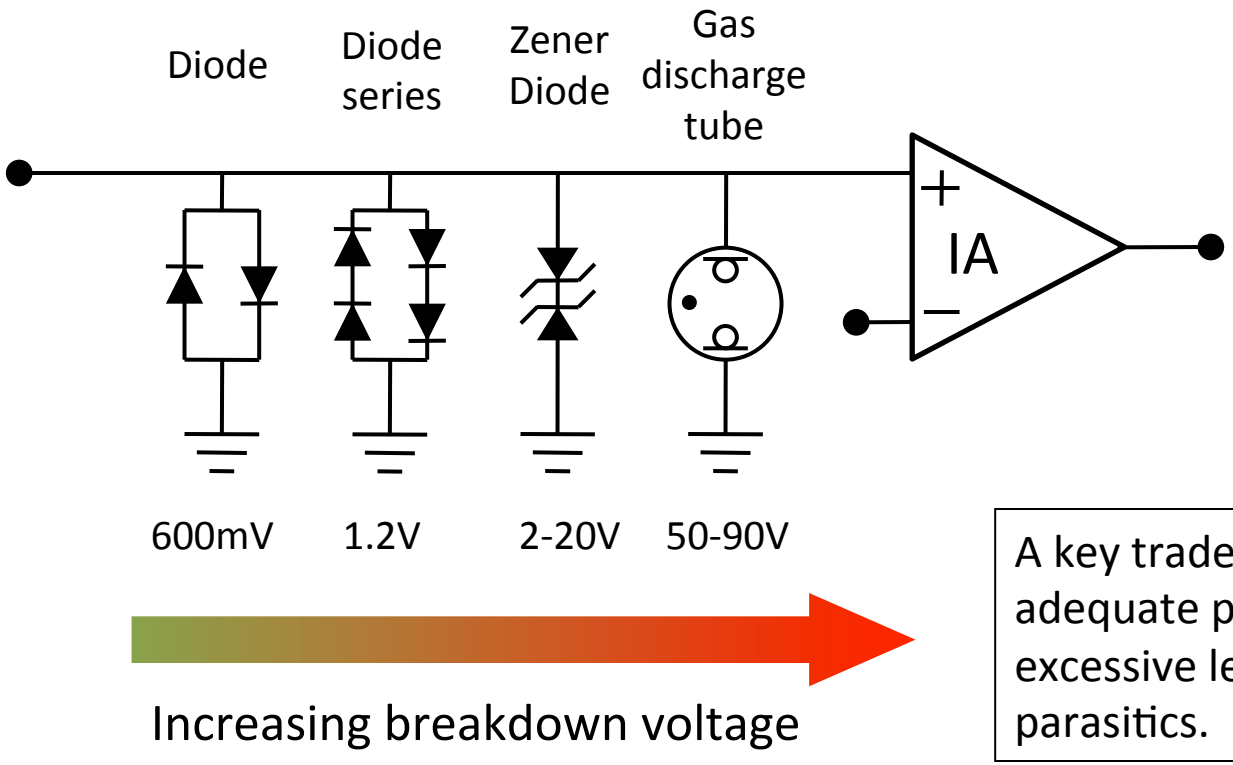
- Skin preparation (reduce gel/skin potential and skin impedance)

Source: Medical Instrumentation, J. Webster, Wiley, 2009

Overvoltage Protection

Large external voltages such as defibrillator shocks and static discharge are extreme noise sources that require protection to avoid circuit damage.

This is achieved by various means of input protections:



A key tradeoff is obtaining adequate protection without excessive leakage currents and parasitics.

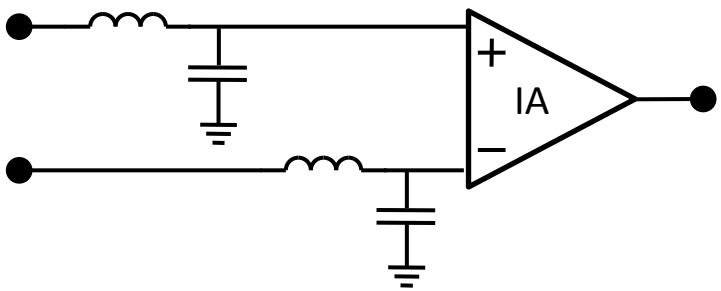
Other Noise Sources

- Electromagnetic Interferences (EMI)

  Due to ambient EM waves (cell phones, microwaves, CRT,…)

  Mitigation:

  - Shielding (must use high permeability material, such as steel or MuMetal)
  - Input decoupling (small capacitor to ground at the input)
  - Chokes (small inductance in series with inputs)



- Ground Loops

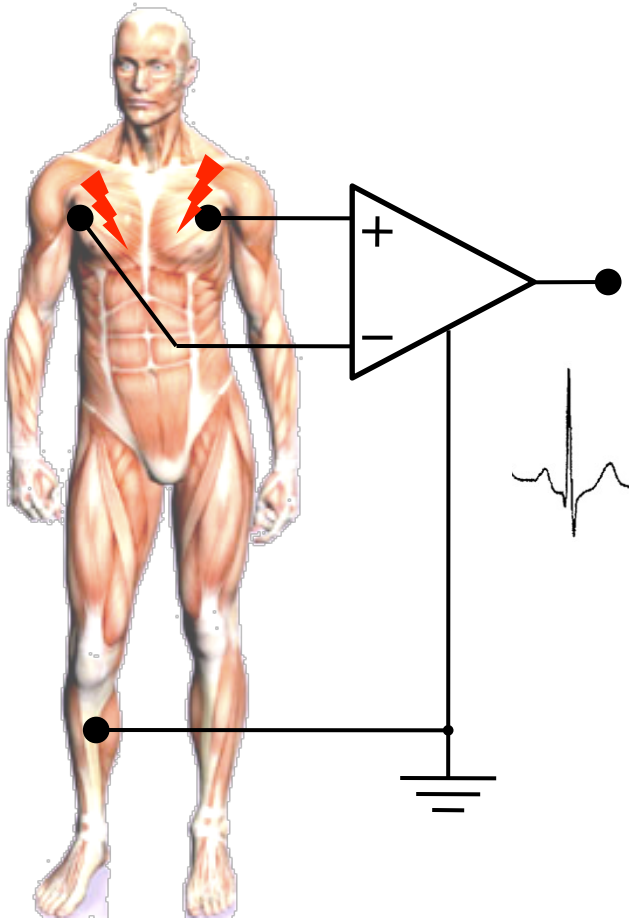
  Due to multiple, grounded instruments connected to the patient (DANGER!!)

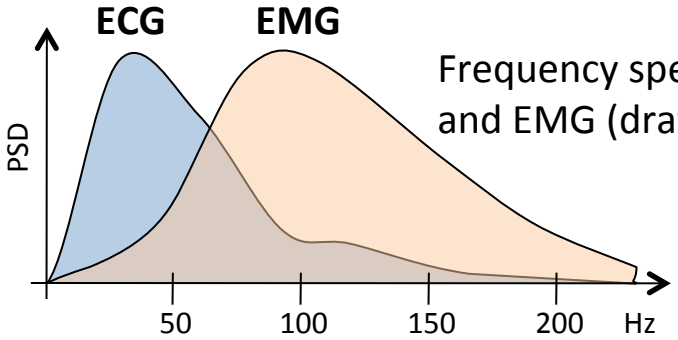
  Mitigation:

  - Isolated instrument/leads

Muscle Noise (EMG)

Muscle noise is produced by the firing of muscle fibers during contraction, and is the basis of the electromyogram (EMG). EMG has an **overlapping frequency spectrum**, which makes it difficult to remove completely.





Frequency spectra for ECG and EMG (drawing)

Typical EMG noise

Mitigation strategies:

- Electrode placement
- Narrow band-pass filtering

Instruments

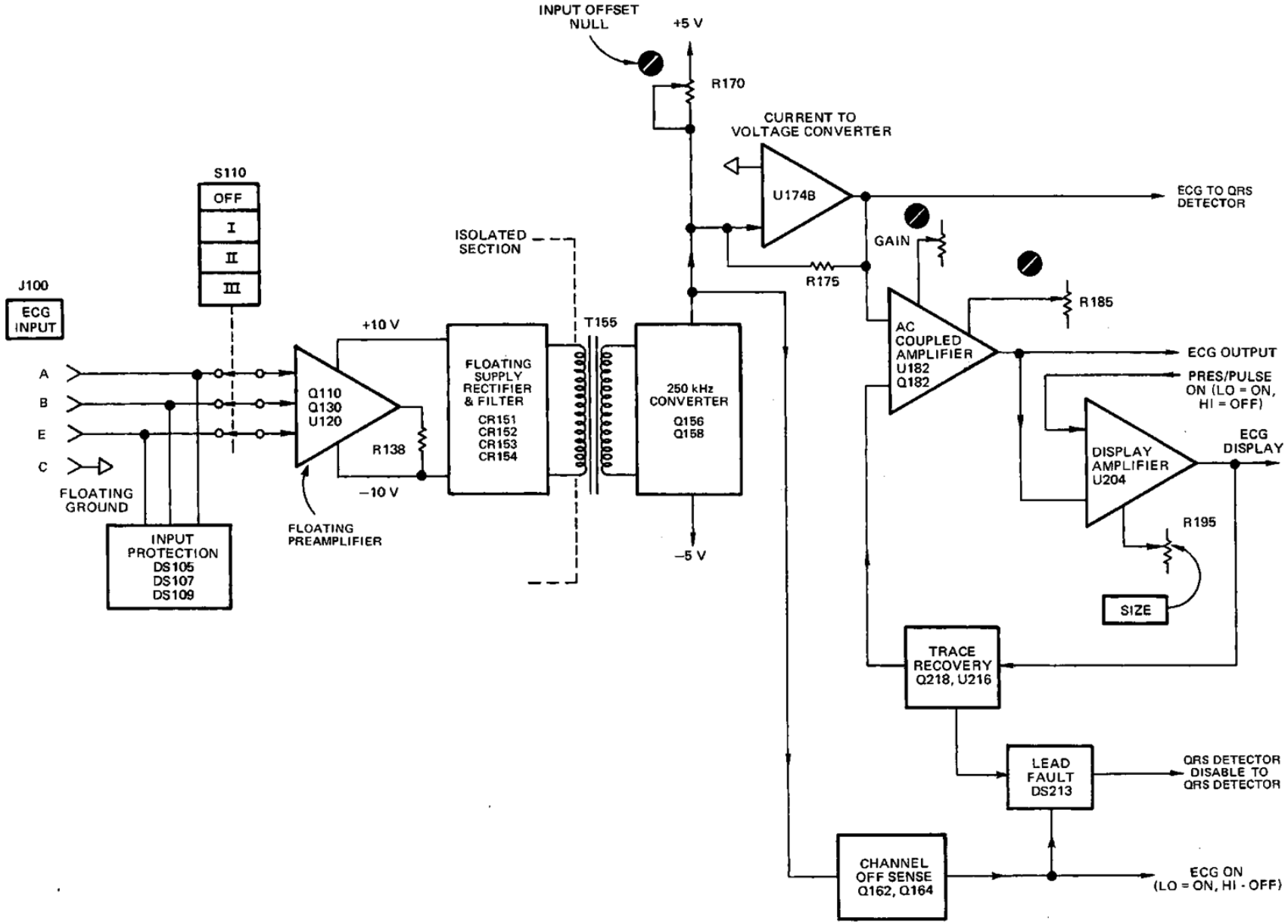
Electrocardiograph

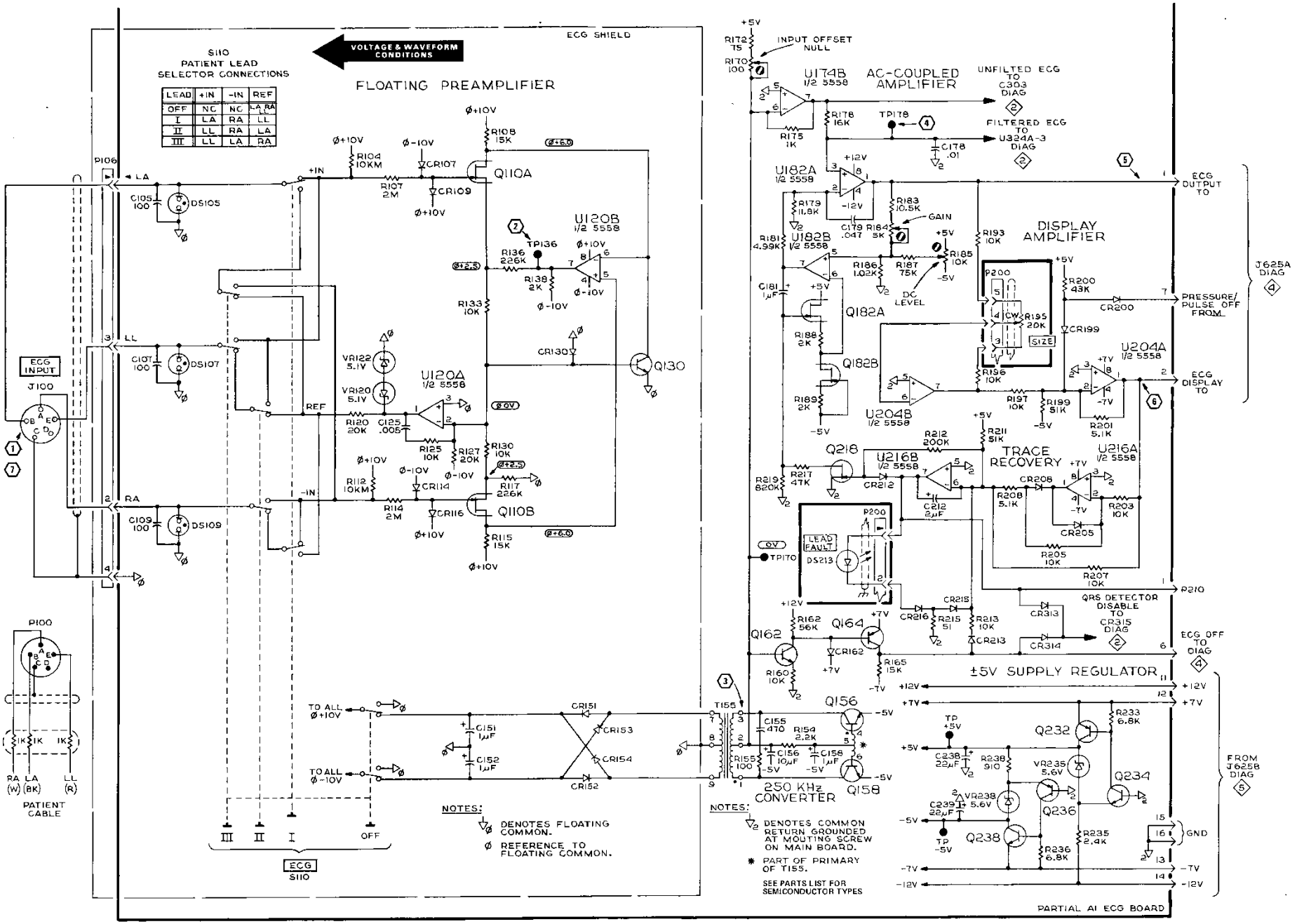
First, A Classic – Tektronix 414

- Commercial, CRT-based ECG instrument, 1980's vintage.
- Excellent illustrative example, since schematics are NOT given for most modern instruments.
- All of the basic functions for the limb leads (I, II, and III) are shown, with filtering, isolation and so on.

Source: eBay

Block Diagram – Tektronix 414

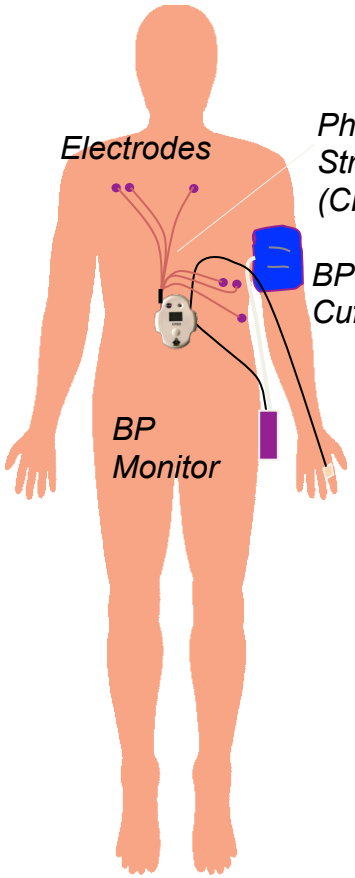


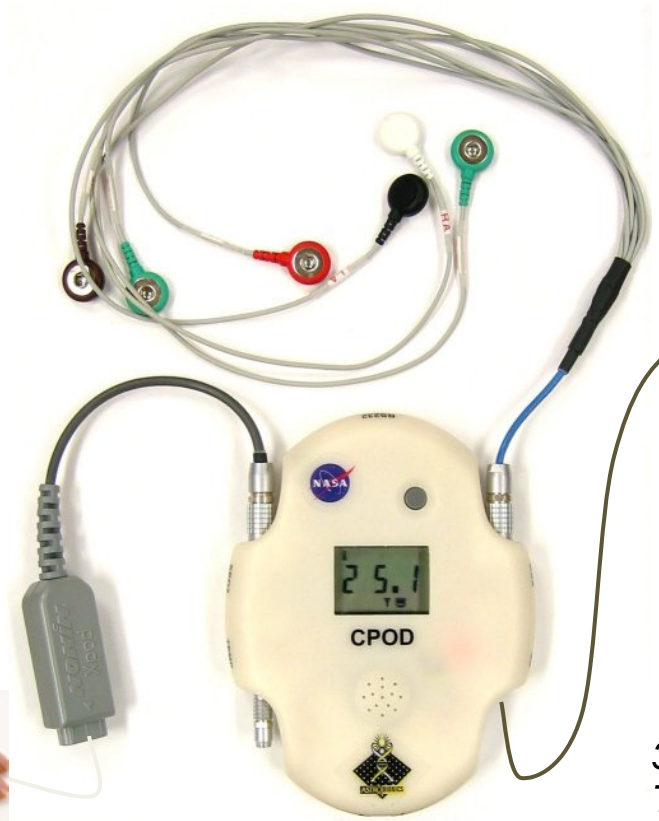


Source: Tektronix 414 Manual

REV A, AUG 1978
2042-81

LifeGuard CPOD Wearable Monitor





ECG (lead II & V5)
Respiration

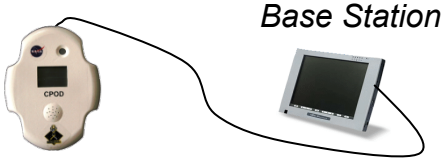
Blood Pressure Monitor (Accutracker II)

Pulse Oximeter (Nonin SpO_2)

3-axis accelerometer
Temperature

CPOD Data Logger

Real-time wired or wireless transmission



Base Station

or

Base Station

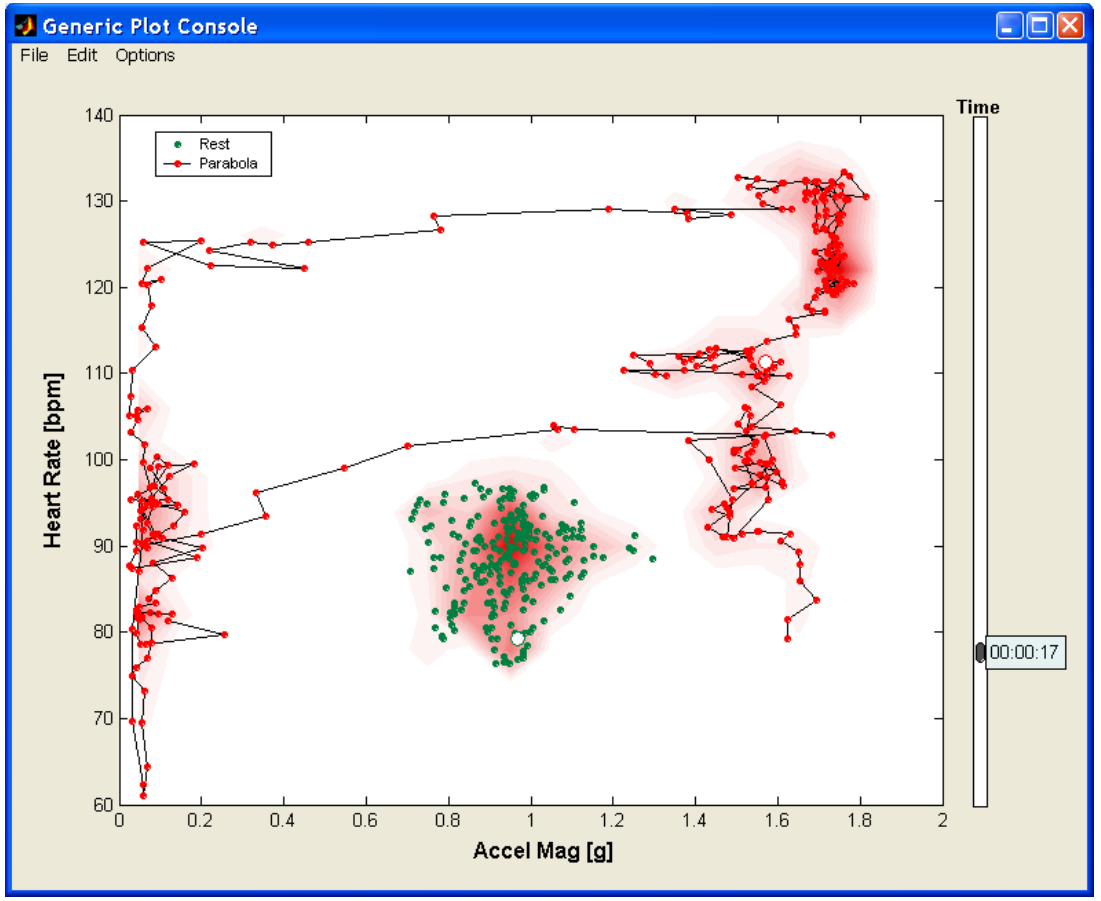
Courtesy of K. Mundt/K. Montgomery

LifeGuard CPOD Wearable Monitor

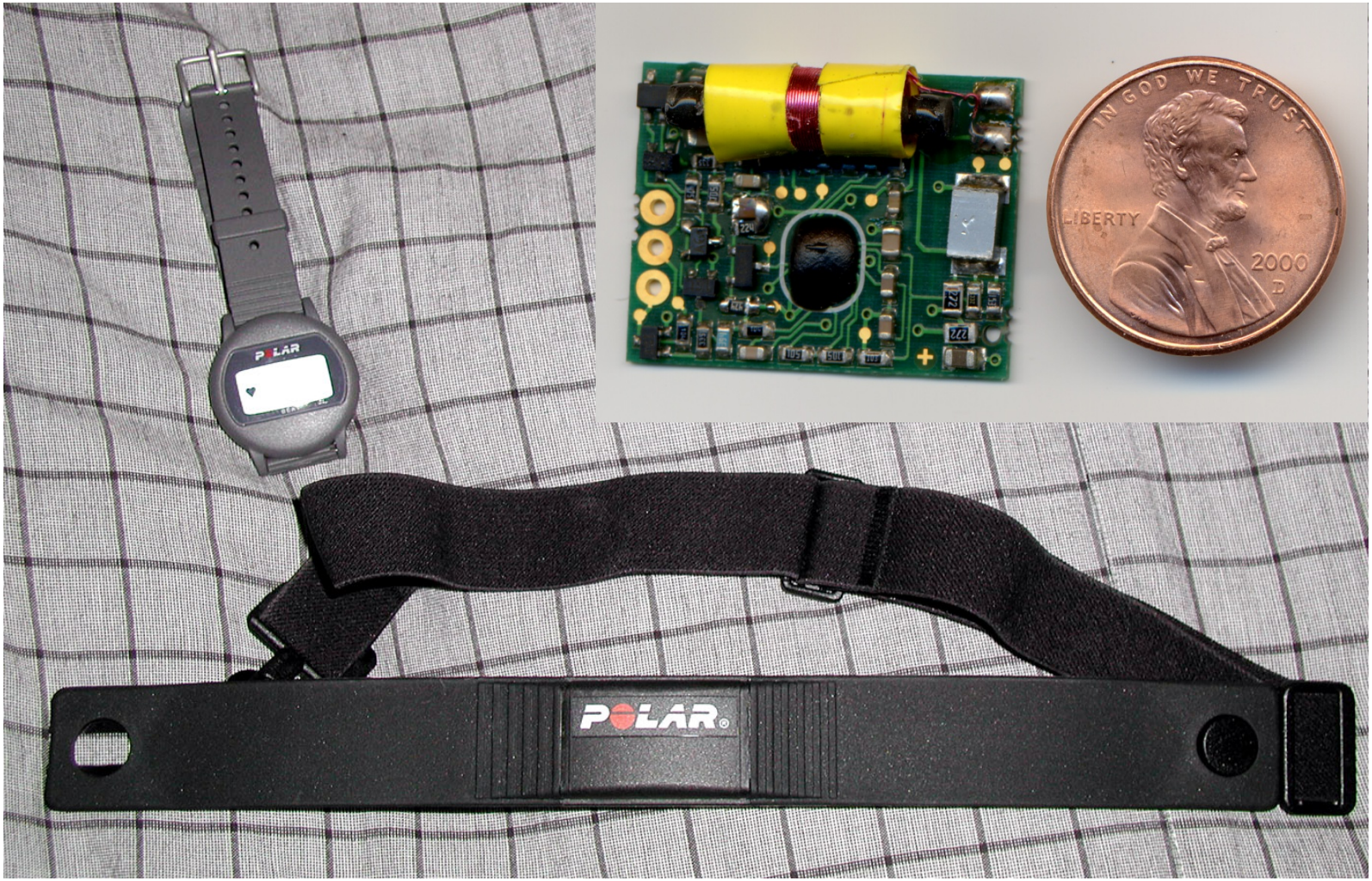
KC-135 'Vomit Comet'

Correlation of physiologic status with situational data:

Heart rate excursion during a microgravity parabola!



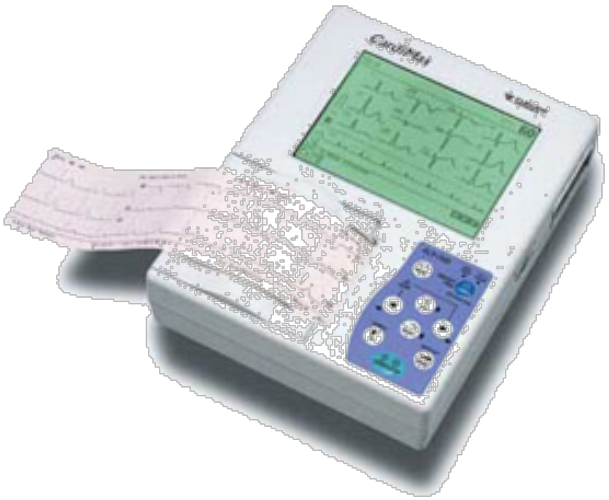
Polar™ Heart Rate Monitor



Polar™ heart-rate transmitter - provides magnetically-coupled bursts of ≈ 5 kHz energy that mark the start of each heartbeat (i.e., you don't get the actual waveform).

Current Commercial Systems

- Diagnostic 12/15-lead ECG
- Ambulatory monitors (Holters)
- Telemetry systems
- Patient Monitors



Fukuda Denshi CardiMax 12-lead electrocardiograph

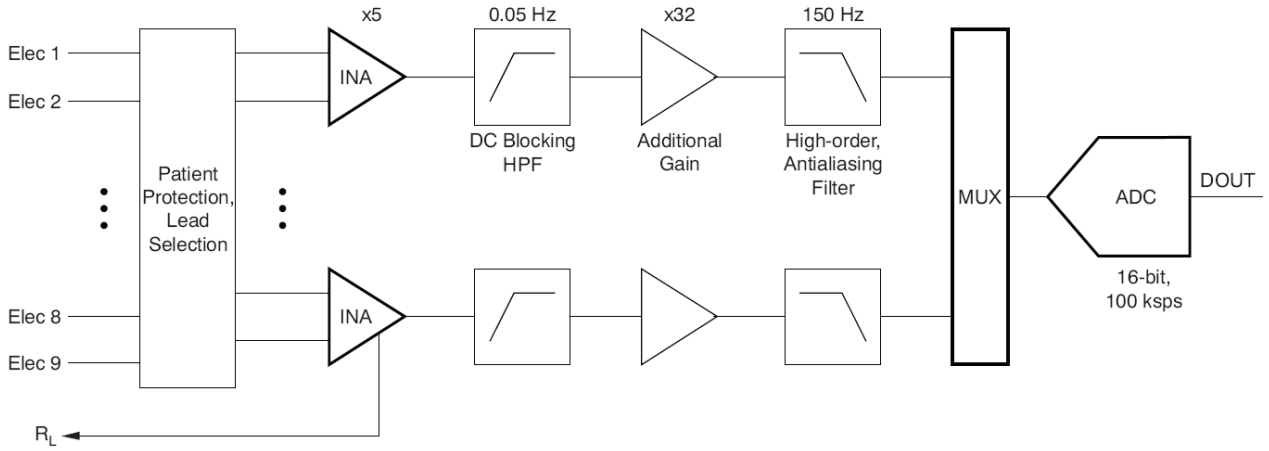
WelchAllyn Propaq® patient monitor

WelchAllyn Micropaq® ECG telemetry systems

Mortara H3+ Holter monitor

Trends in ECG Circuit Topologies

As everywhere, digital is gaining ground. New topologies aim at converting as soon as possible to the signal into digital, and then apply processing.



Conventional topology *analog signal conditioning, SAR ADC.*

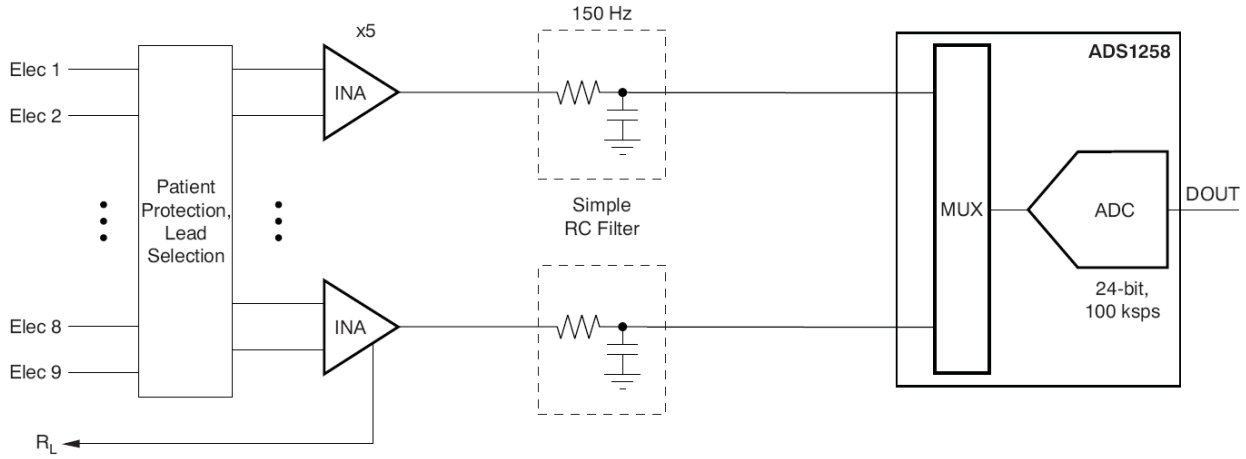
Issues to consider:

- **Part counts**
- **Cost**
- **Size**

New topology: *minimal analog signal conditioning, Delta-Sigma ADC, digital filtering.*

Issue to consider:

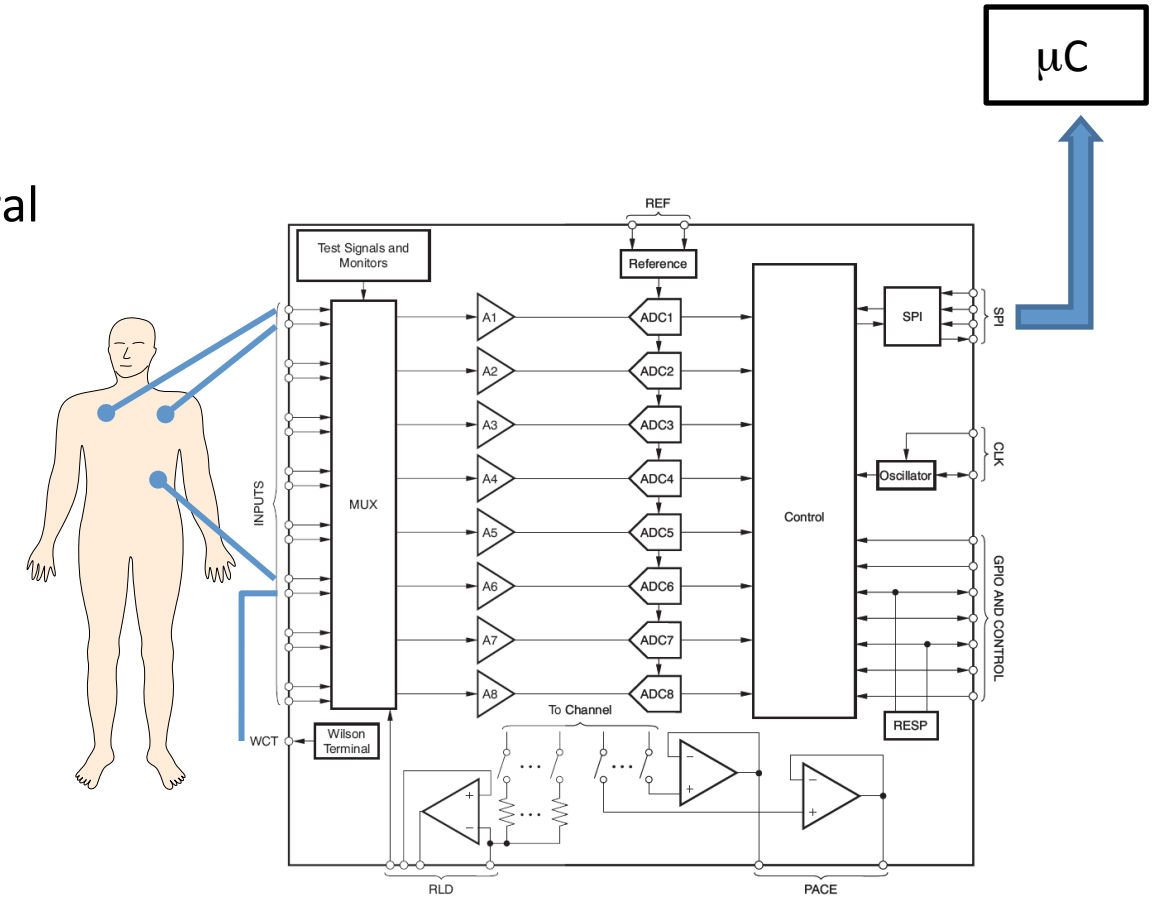
- **Power**



Source: Texas Instruments, Application Report, SBAA160, 2009

Integrated Front-End

- Texas Instruments ADS1294/6/8
  - Up to eight bipolar inputs
  - 24-bit ADC, 32ksps
  - 0.75mW per channel
  - Integrated Wilson Central Terminal
  - Right-leg drive circuit
  - Lead-off detection
  - Pacing pulse detection
  - 8x8mm, 64-pin BGA



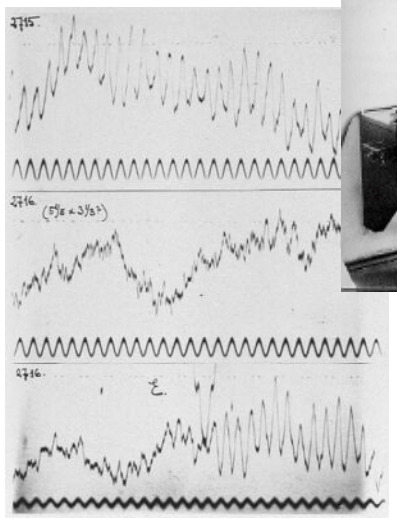
Source: Texas Instruments, Datasheet ADS1298

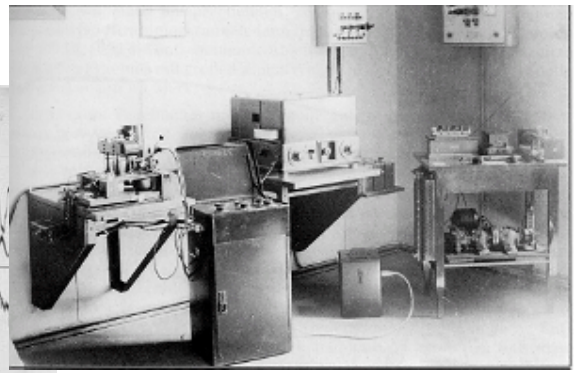
Electroencephalogram

Electroencephalogram - History

- Published in 1929 by Hans Berger.
  - "Über das Elektrenkephalogramm des Menschen" (On the Electroencephalogram in man)
- Disbelieved at the time.
  - Was not reproduced until 1934.
- Acquired signals from his 15 year old son, Klaus.
- First encountered 8 - 12 Hz waves.
- Now known as alpha waves.

First recorded signals by Berger





Source: http://chem.ch.huji.ac.il/~eugeniik/history/berger.html

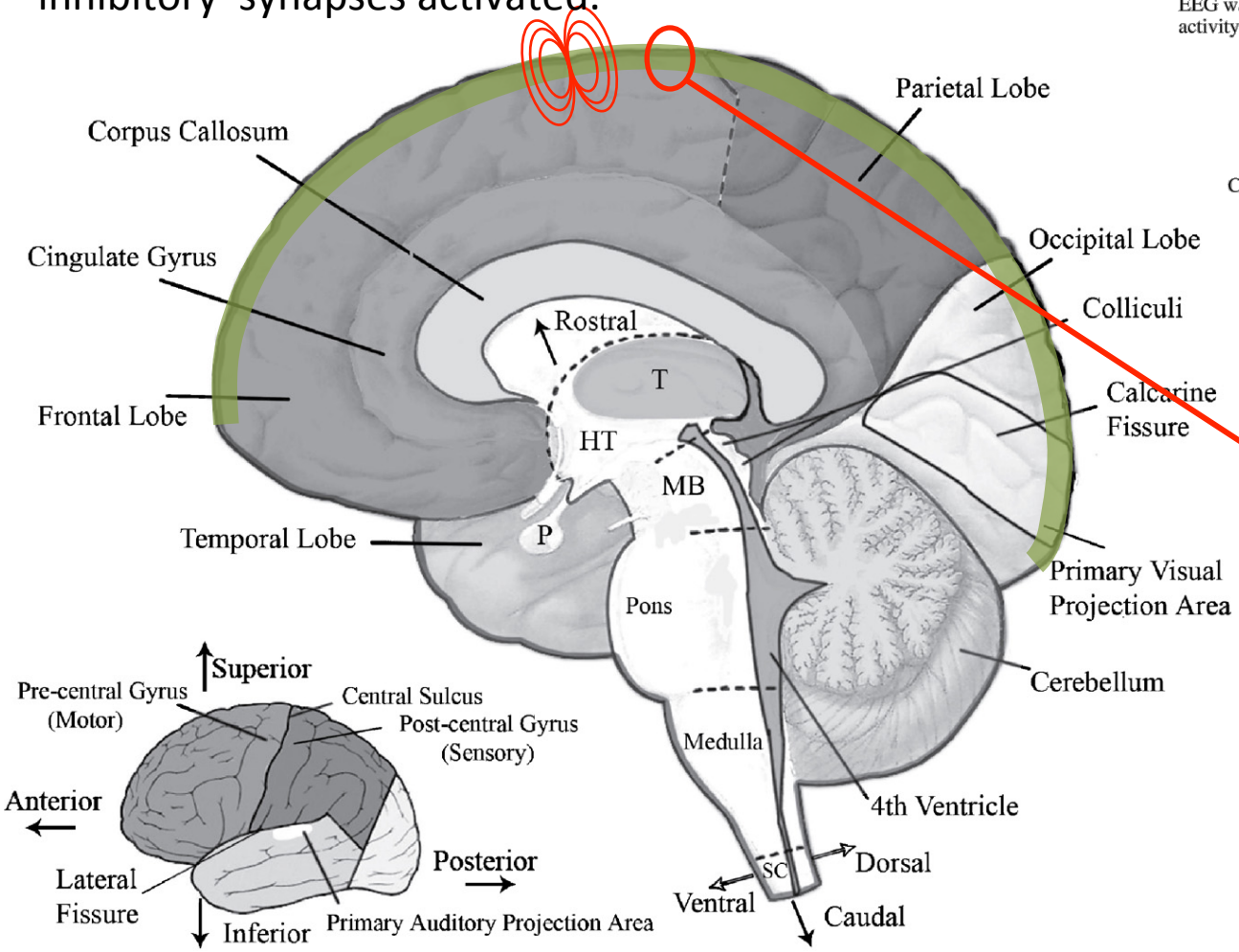
Electroencephalogram (EEG)

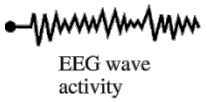
- The electroencephalogram is the recording of minute electrical potentials, random or evoked, at the surface of the head.
- Recorded potentials are mainly the activity of pyramidal cells in the outer layer of the cerebral cortex, perpendicular to the surface.
- In evoked potentials, measured potentials are the results of simultaneous firings of action potentials in the cortex.
- Non-evoked potentials are related to fluctuation of postsynaptic potentials (PSPs).

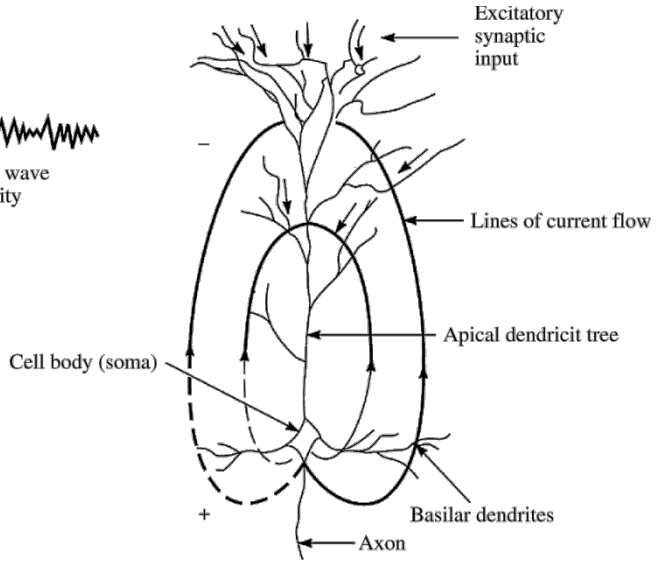
Fun fact: There are about 86 billion neurons in a human brain.

Origin of Brain Potentials

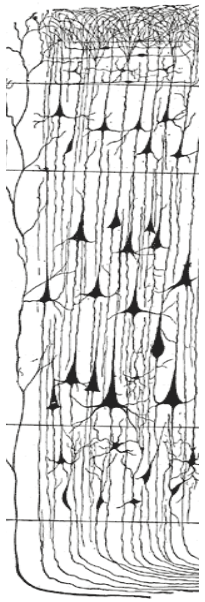
Organized pyramidal cells generate shifting current dipoles depending on proportion of excitatory or inhibitory synapses activated.







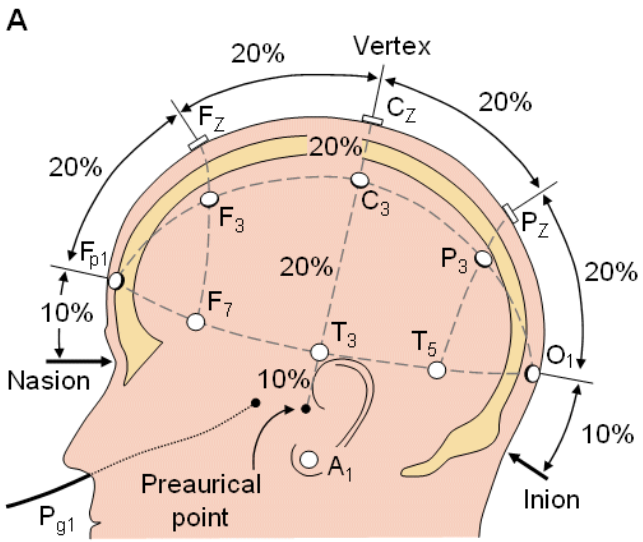
Sink-Source Model

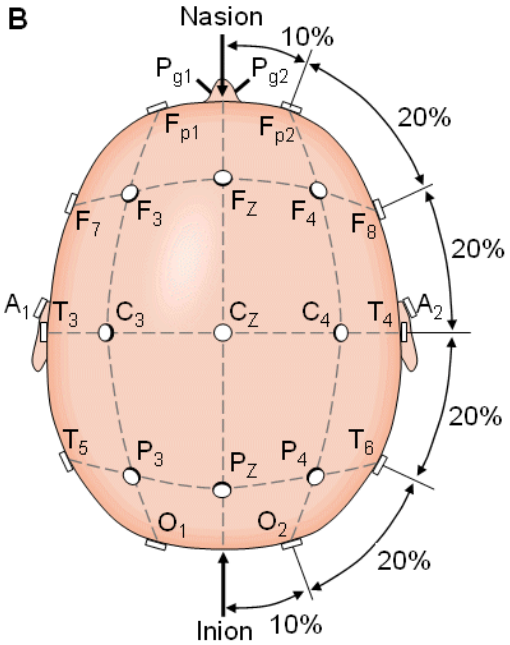


Source: Bioelectromagnetism, Malmivuo & Plonsey

EEG Measurements

- Biopotential amplifiers for EEG are similar to ECG amplifiers. Main differences lie in **bandwidth** (EEG: **0-150 Hz**, lower than ECG), **gain** (higher than ECG - EEG signals are typically **5 - 300 μV**), and **noise** (lower than ECG, higher CMRR).
- Electrodes can be both **unipolar** (with respect to a single electrode, typically the ear) or **bipolar** (adjacent electrodes).



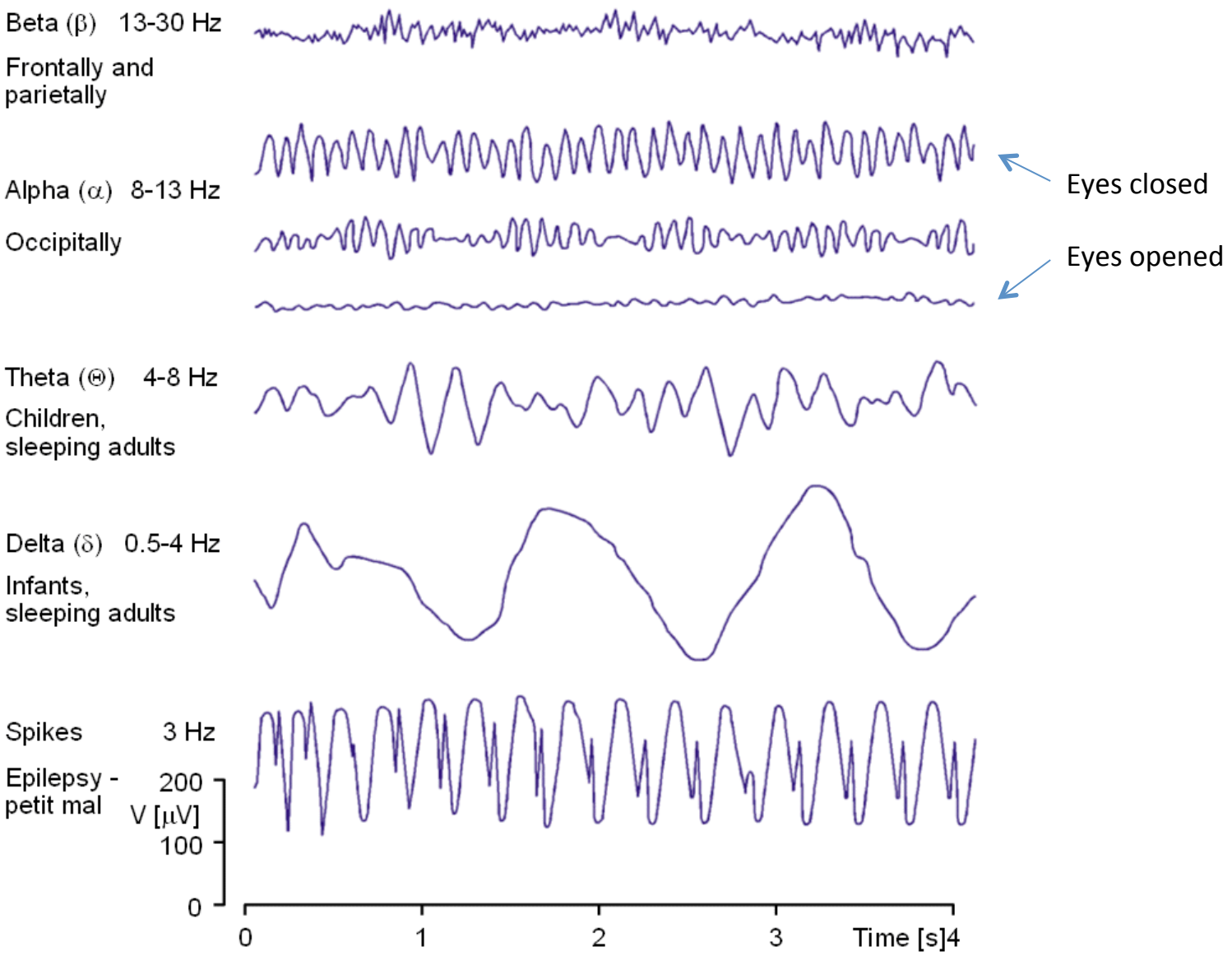


"10-20" standardized electrode system:
(21 electrodes)

- A = Ear lobe,
- C = central,
- P_g = nasopharyngeal,
- P = parietal,
- F = frontal,
- F_p = frontal polar,
- O = occipital,
- T = Temporal.

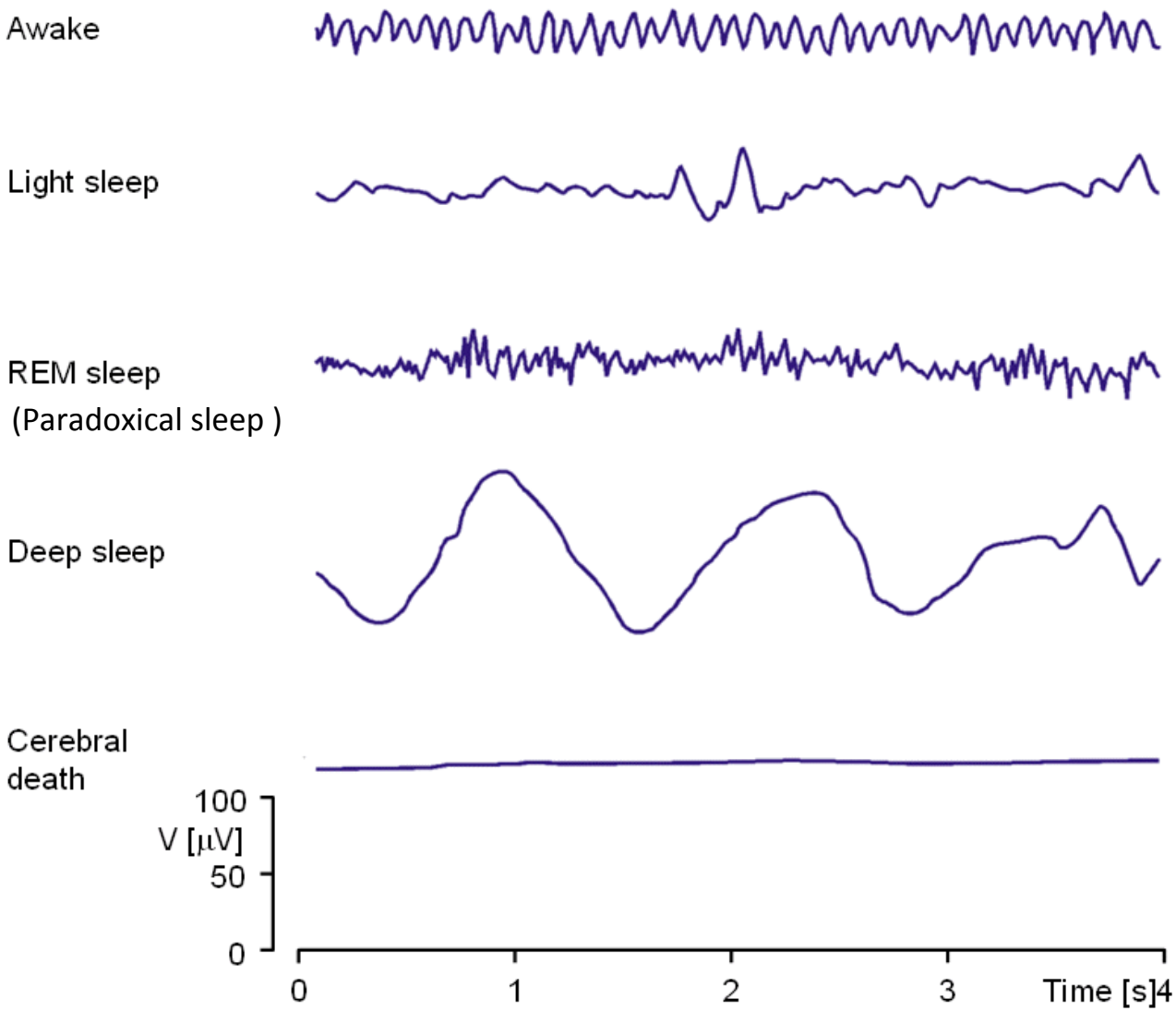
Source: Bioelectromagnetism, Malmivuo & Plonsey

Typical EEG Waves



Source: Bioelectromagnetism, Malmivuo & Plonsey

Sleep Patterns

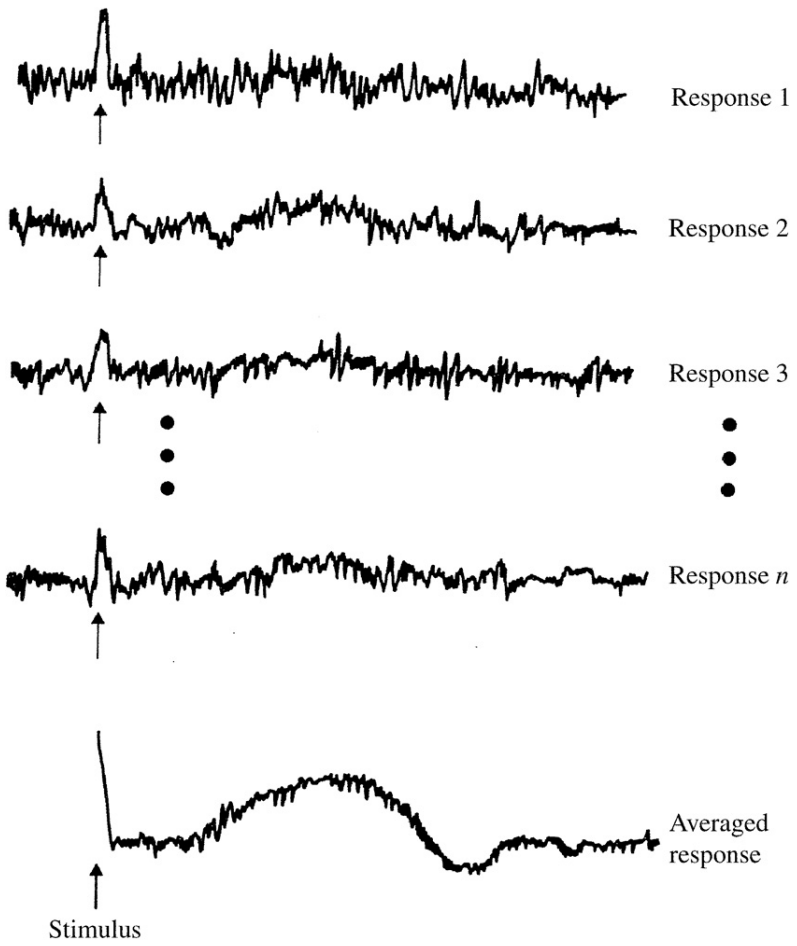


EEG is typically used in sleep studies to detect sleep stages.

Source: Bioelectromagnetism, Malmivuo & Plonsey

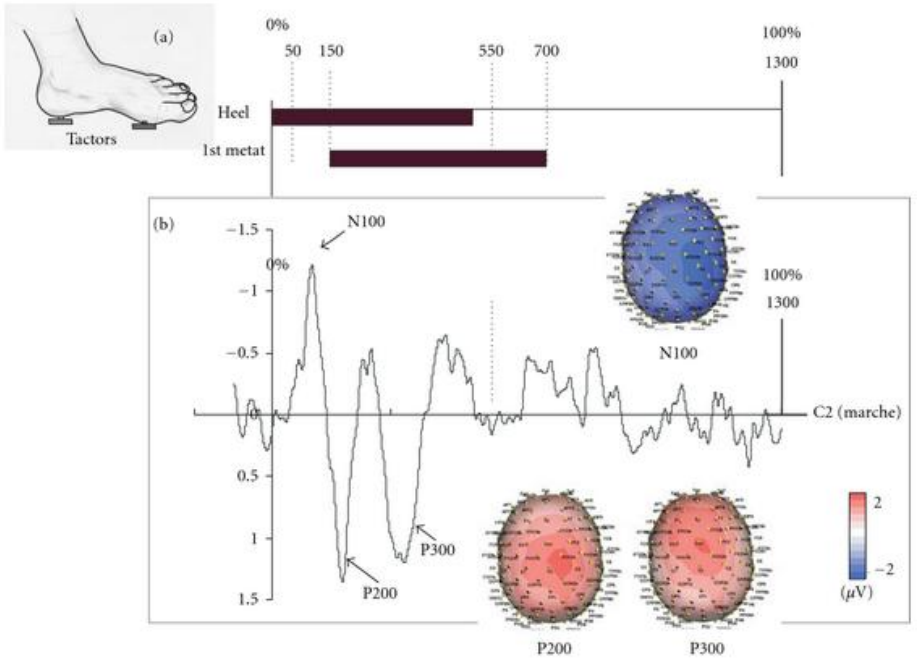
Evoked Potentials

- As opposed to ECG, EEG signals can be triggered by a stimulus (light, sound, electrical/magnetic impulse) to measure evoked potentials.
- These potentials are usually buried in the noise, but can be *ensemble averaged* based on the time of the stimulus.
- SNR improves as $\sqrt{n}$, where n is the number of responses averaged.



Source: Medical Instrumentation, J. Webster, Wiley, 2009

Evoked Potentials - Diagnostics



Foot vibration invoked potentials. Note Inversion of amplitude scale (common, unfortunately).

http://www.hindawi.com/journals/np/2012/375148/fig8/

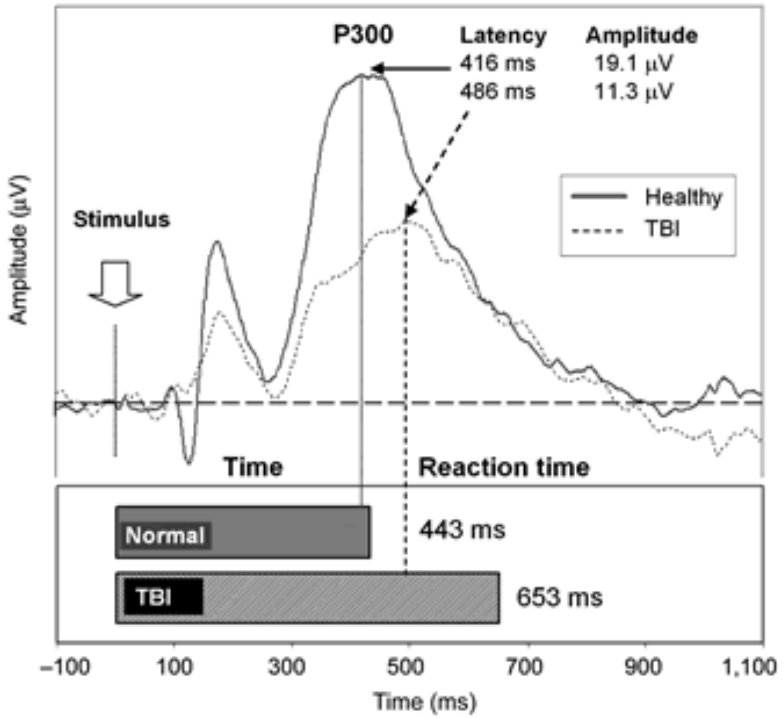


Figure.
Grand-average event-related potential (ERP) waveforms and reaction times. TBI = traumatic brain injury.

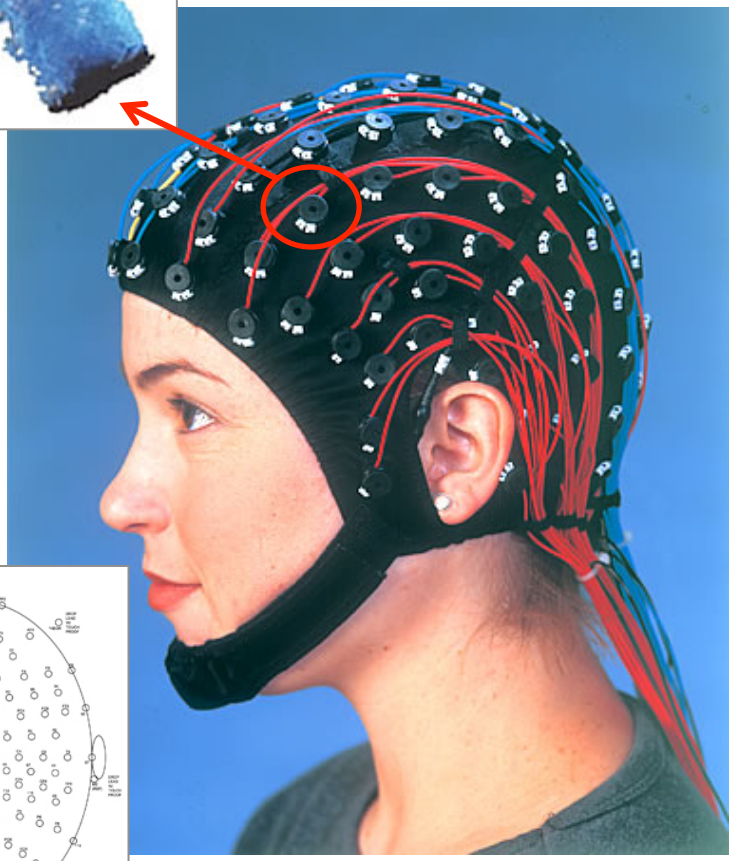
Responses to flashed images of human faces on a monitor.

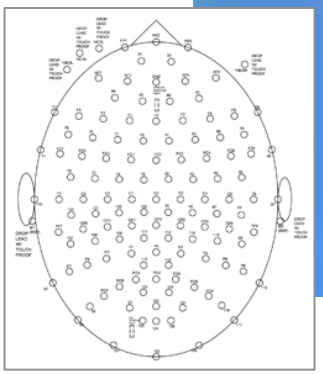
http://www.rehab.research.va.gov/jour/05/42/1/lew.html

EEG System Example

NeuroScan EEG System

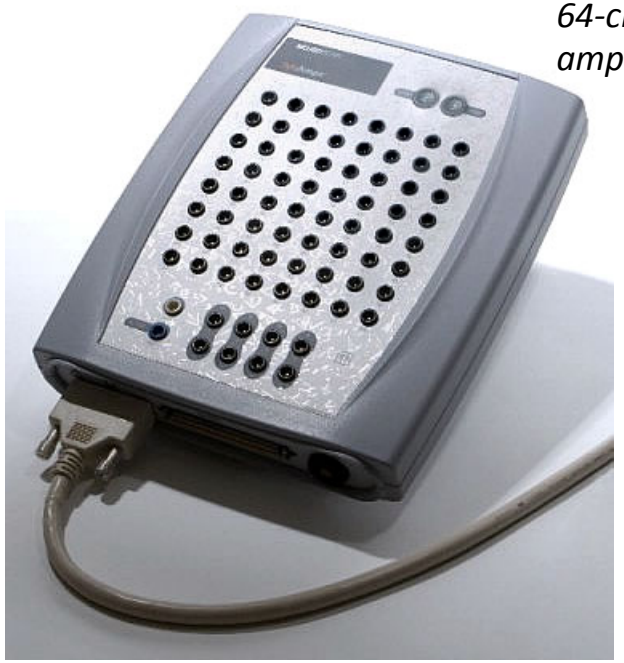
QuickCap Electrodes, SynAmps RT amplifier





128-electrode cap

64-channel amplifier

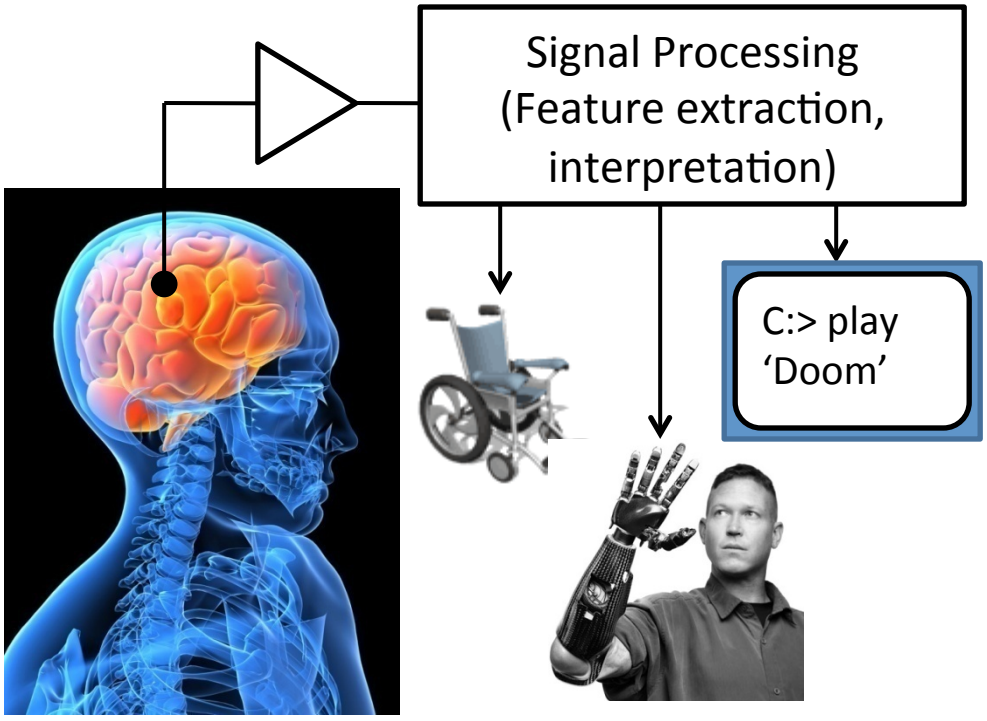


Channel Count	64
Sampling Rate	20,000 Hz / Channel (max), simultaneous sampling
A/D Resolution	24 Bit
Input Impedance	10 GOhms
CMRR	110 dB
Input Noise	<0.5 uV RMS DC to 200Hz, <1.5uV RMS full BW
Bandwidth	DC-3500 Hz
System Gain (AC Mode)	2010

Source: Compumedics NeuroScan

Application: Brain-Machine Interface

- Control of a computerized system through brain waves.
- Application in restoration of motor control (paraplegic, quadriplegic), communications (speech, writing on computer), games,…



After Wolpaw, Clin. Neurophys., 2002

OCZ Neural Impulse Actuator (NIA)

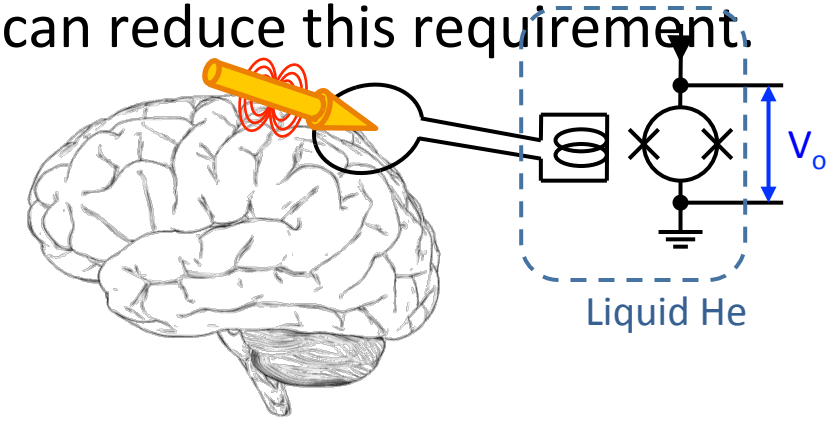
OCZ & grounding!

NeuroSky MindSet

Emotiv EPOC

Magnetoencephalography (MEG)

- Detect *magnetic fields* induced by currents flowing in neurons.
- MEG amplitude: 10 - 1000 fT (Earth's field: 50 - 60 μT, urban noise: 100 nT).
- Recorded with ultra-sensitive SQUID (Superconducting QUantum Interference Devices) sensors, with noise around 1 fT/ $Hz^{0.5}$.
- Non-invasive, non-contact method.
- Less sensitive to tissue non-uniformities.
- Higher spatial resolution then EEG (millimeters vs. centimeters).
- Usually requires a magnetically-shielded room, although differential sensors (gradiometer) can reduce this requirement.
- Can also be applied to heart (magnetocardiography, or MCG).

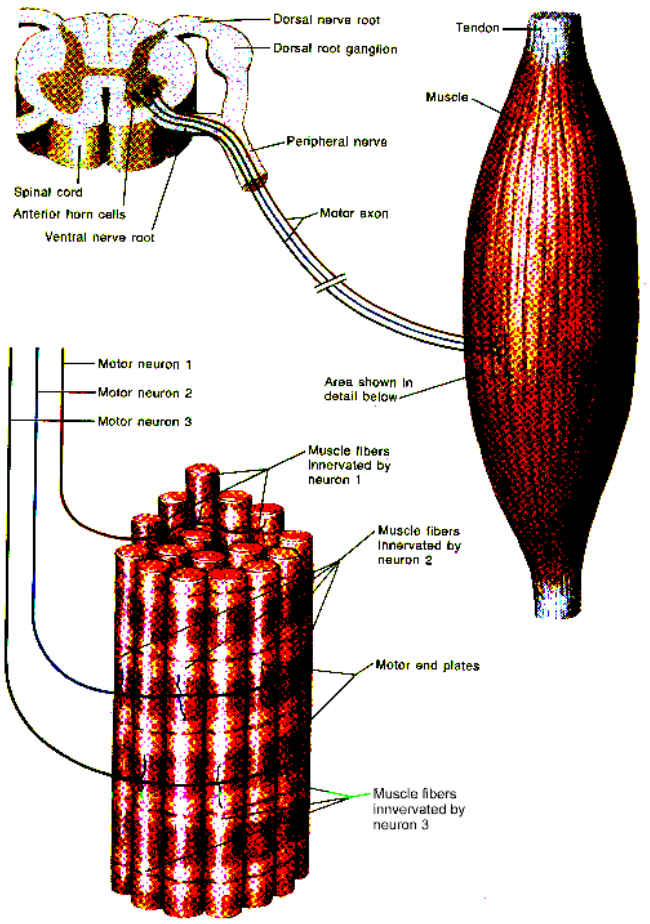


EMG, ERG, EOG

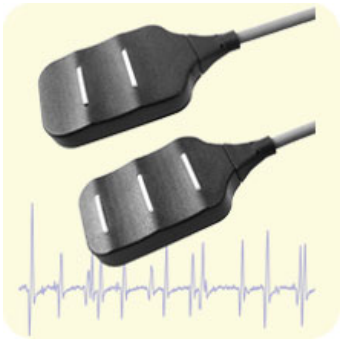
Other Surface Biopotentials

Electromyogram (EMG)

- Measurement of single motor unit (SMU) activity (one motor neuron + muscle fibers).
- Single SMU signals are triphasic, 3-15ms long, and 20-2000μV amplitude. Firing rate varies between 6 and 30 Hz.
- **Intramuscular EMG** uses needle electrodes. Best frequency (up to 10 kHz) and spatial resolution.
- **Surface EMG** (sEMG) uses bipolar electrodes on the skin. Lower bandwidth (*20-500Hz*) than intramuscular. Amplitude is within *0.01-5mV*.
- sEMG electrodes are either of gel-type (similar to ECG), or active (e.g., Delsys).



Source: http://nmrc.bu.edu/tutorials/motor_units/motor_units_pic.html

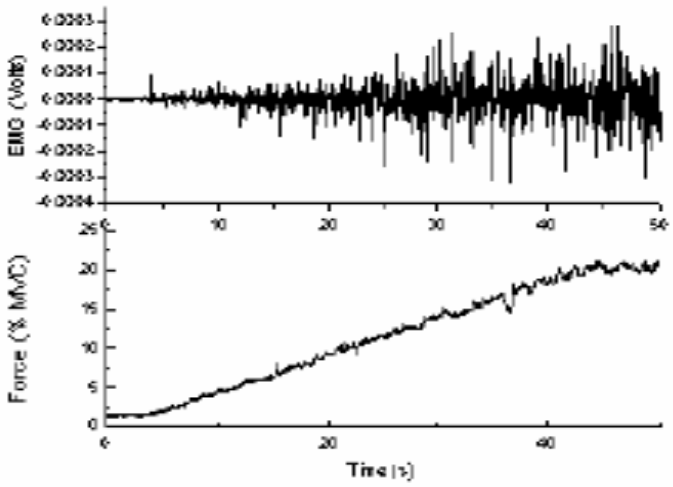


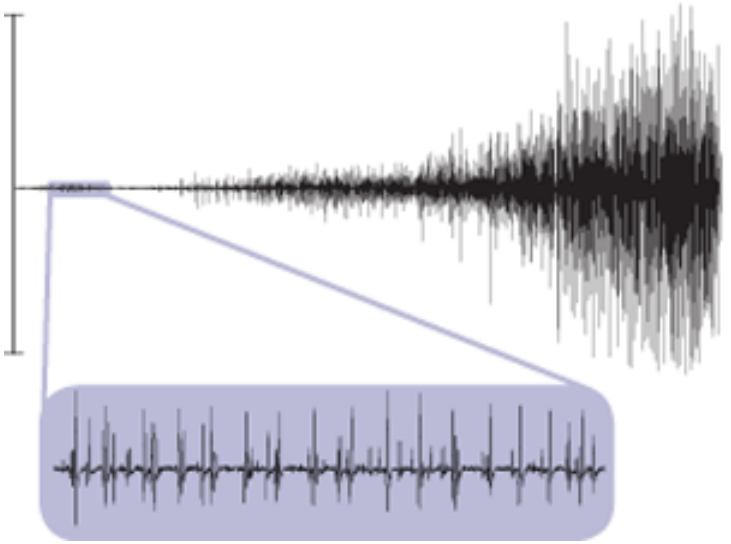
Source: http://www.delsys.com/Products/EMGSensors.html

Surface Electromyogram (sEMG)

- "Recommended for kinesiologic analysis of movement disorders; for differentiating types of tremors, myoclonus, and dystonia; for evaluating gait and posture disturbances; and for evaluating psychophysical measures of reaction and movement time." (American Academy of Neurology, 2000)

Example of sEMG during graded efforts:

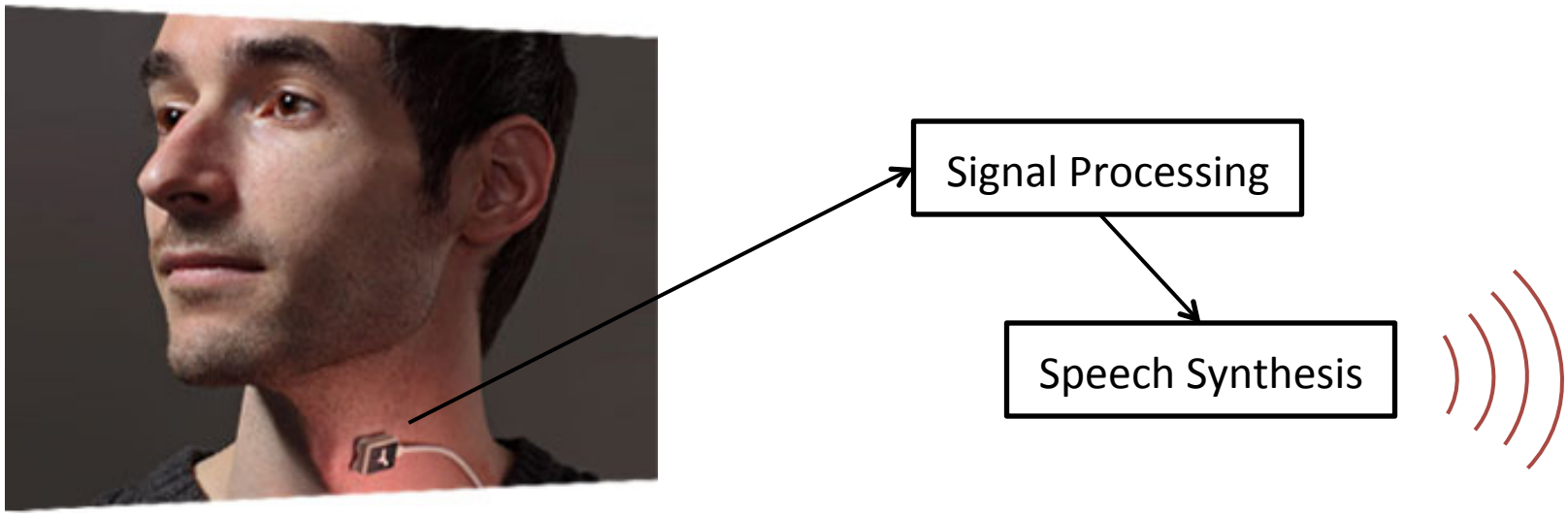




Source: http://www.delsys.com. Copyright protected, Carlo J. De Luca

sEMG BCI Application

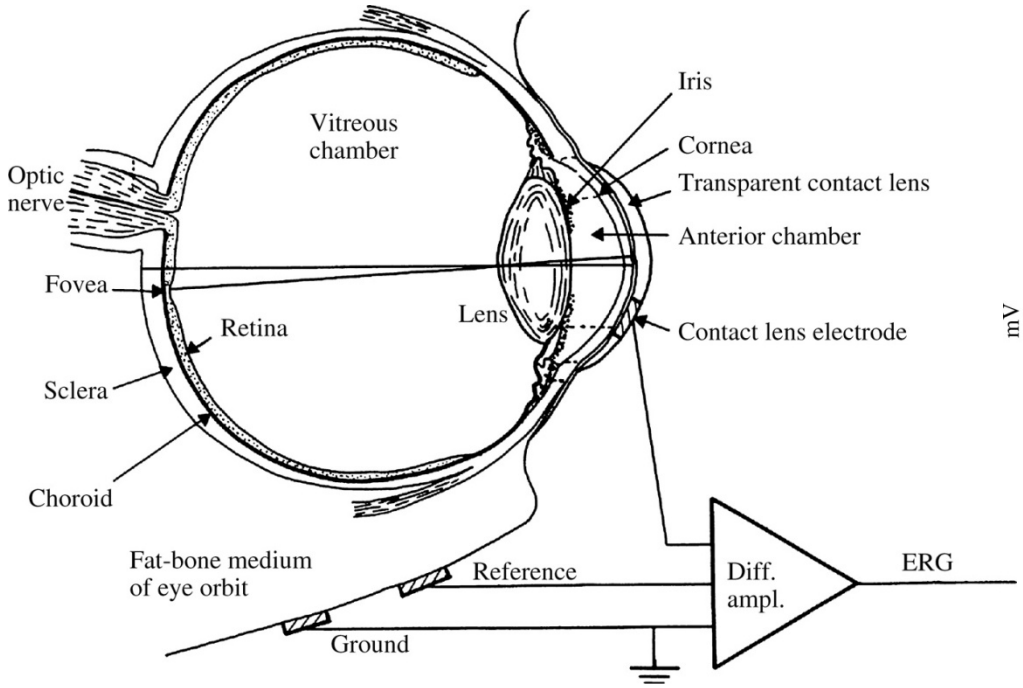
- sEMG are also applicable in brain-computer interfaces, by sensing muscle nerves activation.
- Example: Ambient Audeo's BCI to restore speech by sensing larynx muscles.

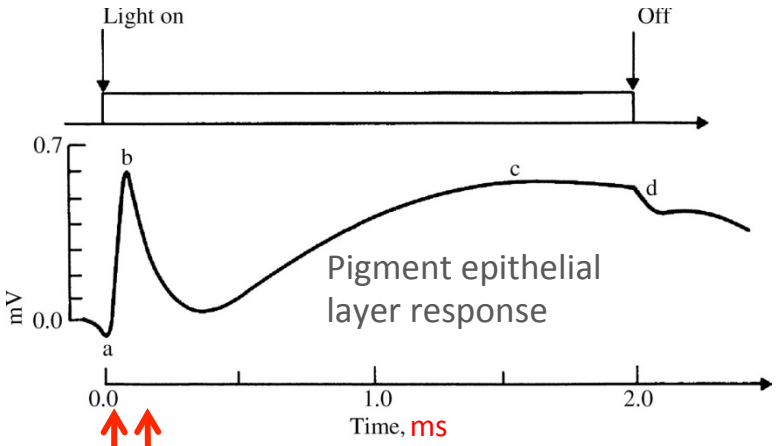


Source: http://www.theaudeo.com

Electroretinogram (ERG)

- Measurement of electrical response of retinal cells (photo-receptors, bipolar, amacrine, ganglion cells) to light stimuli .
- Used for diagnosis of various retinal diseases (e.g., retinitis pigmentosa).
- Small signals (0-900 μV), limited bandwidth (0-50 Hz).





Late-receptor potential (LRP)

Photoreceptors output, bipolar & ganglion cells

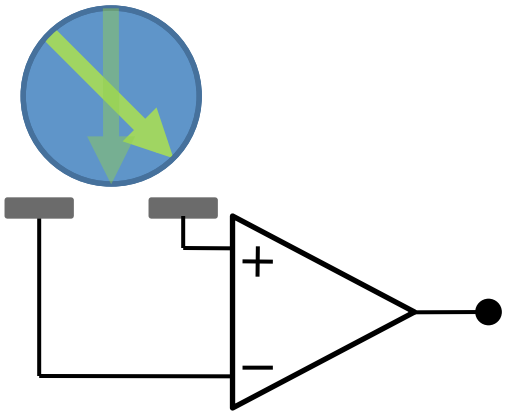
Early-receptor potential (ERP)

Photopigments

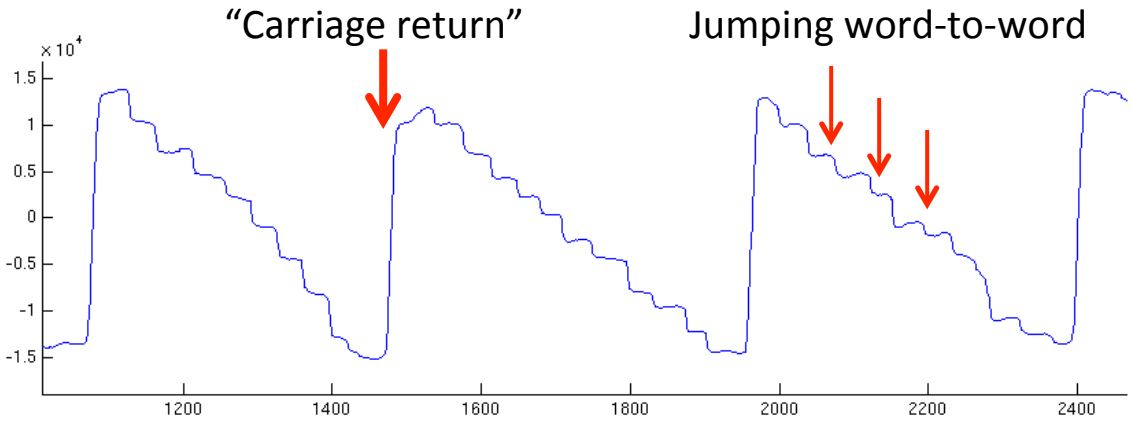
Source: Medical Instrumentation, J. Webster, Wiley, 2009

Electro-Oculogram (EOG)

- Corneo-retinal potential (CRP) forms a steady dipole that can be sensed with two electrodes on each side of the eye.
- Linear between ±30°, with an accuracy of 1°.
- Requires a DC amplifier for angle recovery. Signals in the 50 – 3,500 μV range, up to 50 Hz.
- Useful in assessment of pigment epithelium (light/dark contrast), and for human interface.



Recording of the EOG while reading:



Source: A. Bulling, et al., Robust Recognition of Reading Activity in Transit Using Wearable Electrooculography, Pervasive 2008

Lab this week

Electrocardiography - Record your heart!

Movie from Gettyimages. Copyright protected.