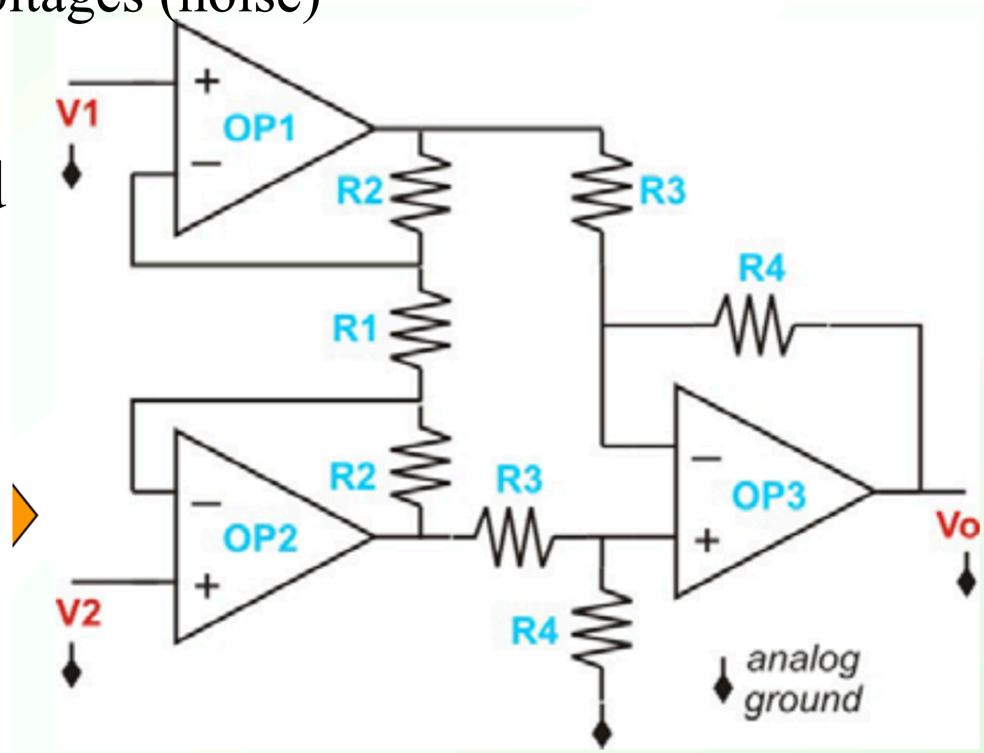
ESE 3400: Medical Devices Lab

Lec 4: September 27, 2023

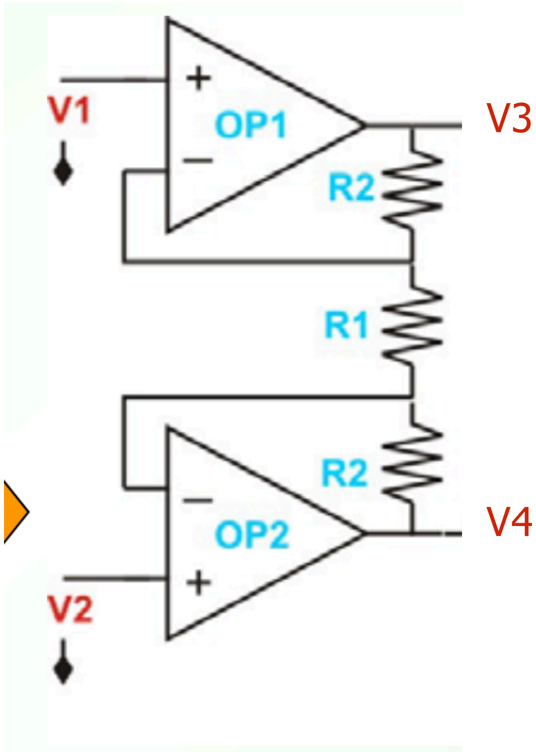
Electrical Safety and Isolation, Electrocardiogram and Heart Rate

Instrumentation Amplifier

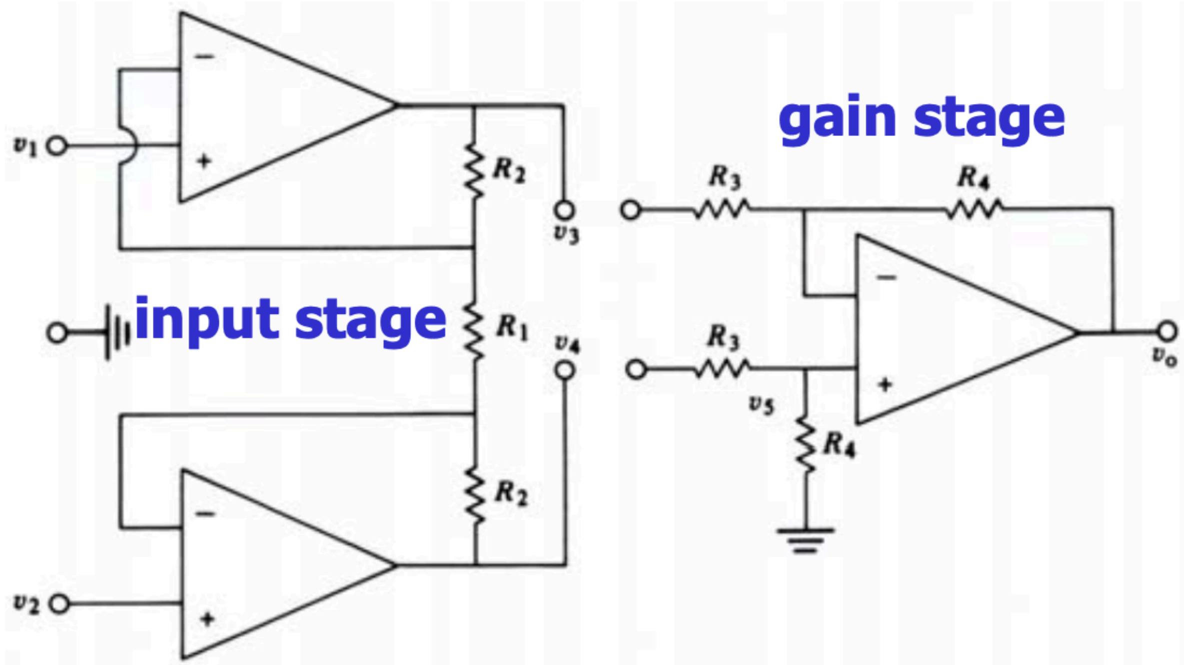
- This 3-op-amp circuit is called an **instrumentation amplifier**
- Input stage characteristics
  - low common-mode gain
    - -rejects common mode voltages (noise)
  - high input impedance
  - Input stage gain adjusted



Instrumentation Amplifier



Instrumentation Amplifier

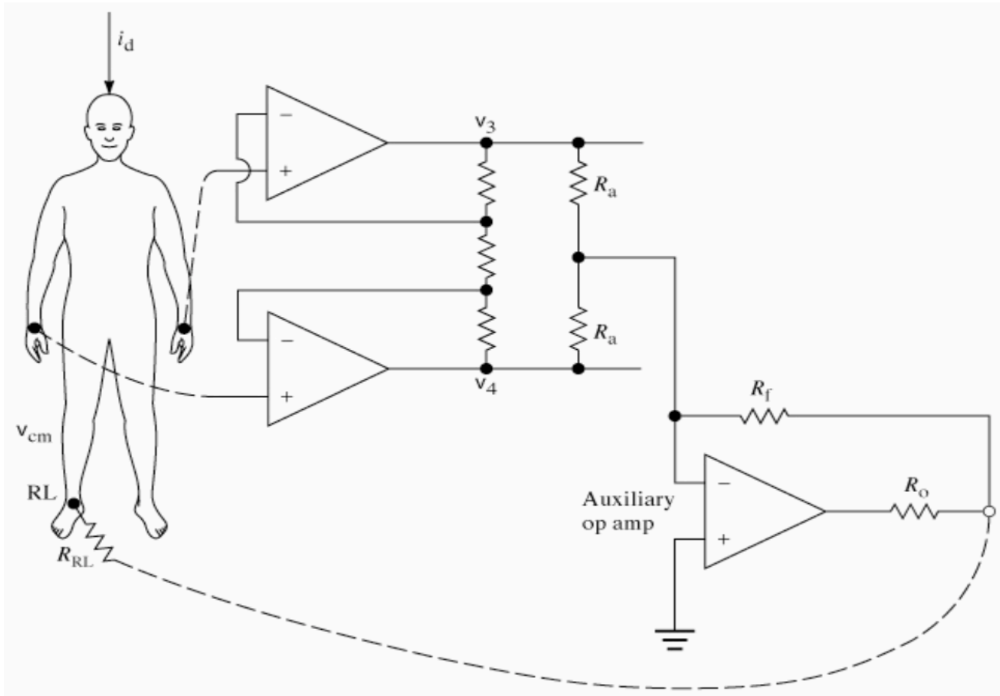


$$\frac{v_0}{v_i} = \left(\frac{2R_2 + R_1}{R_1}\right)\frac{R_4}{R_3}$$

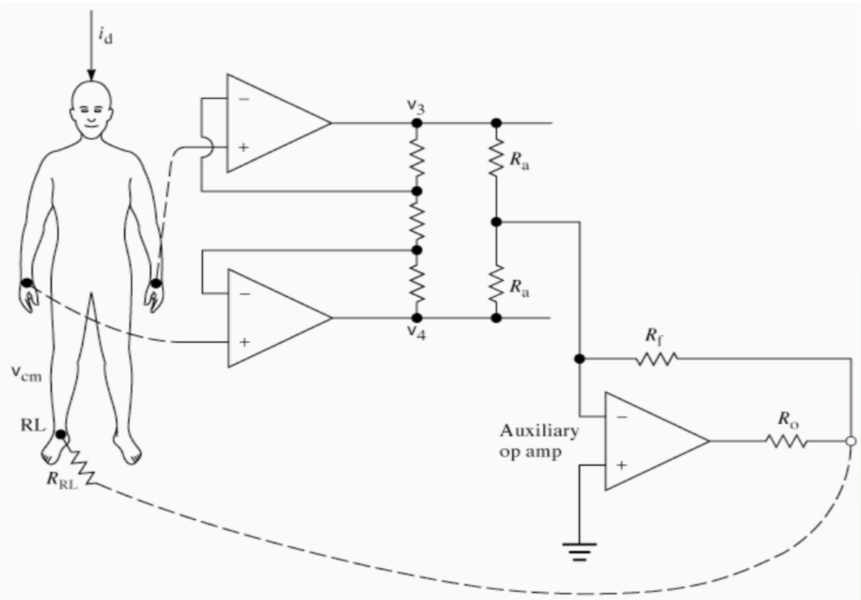
- Overall amplifier
  - Amplifies only the differential component
    - High common mode rejection ratio
  - High input impedance suitable for biopotential electrodes

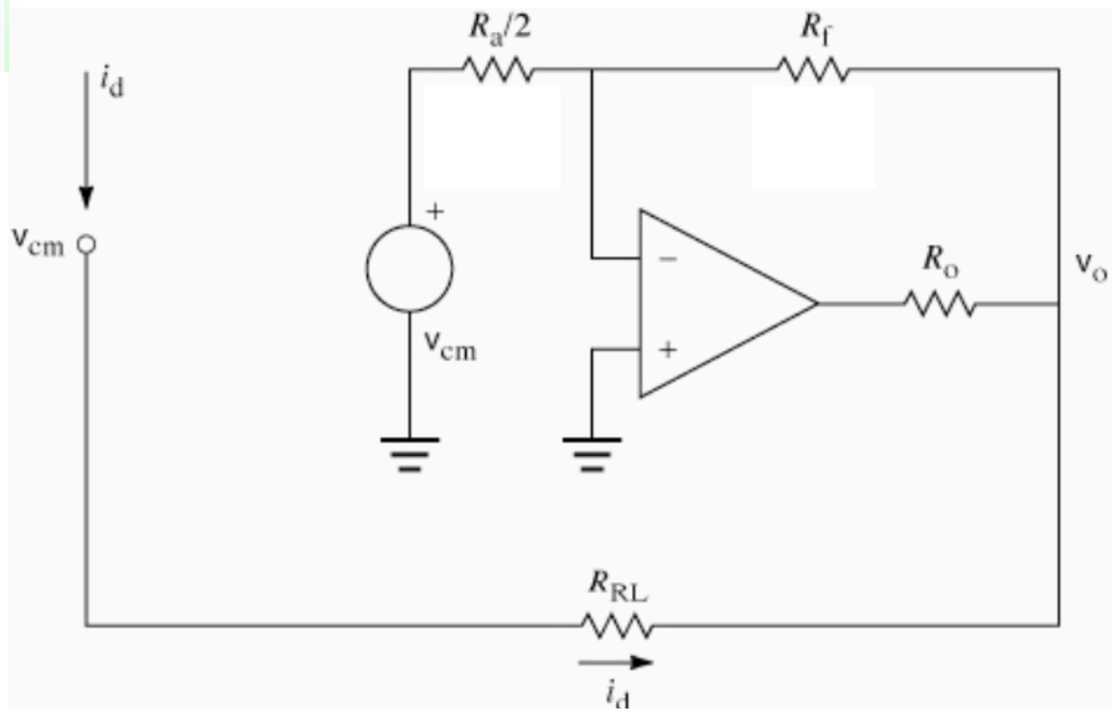
Driven Right Leg System

- Motivation
  - Reduce interference in amplifier
  - Improve patient safety
- Approach
  - Patient right leg tied to output of an auxiliary amp rather than ground
  - Common mode voltage on body sensed by averaging resistors, Ra's & fed back to right leg
  - Provides negative feedback to reduce common mode voltage
  - If high voltage appears between patient and ground, auxiliary amp effectively un-grounds the patient to stop current flow



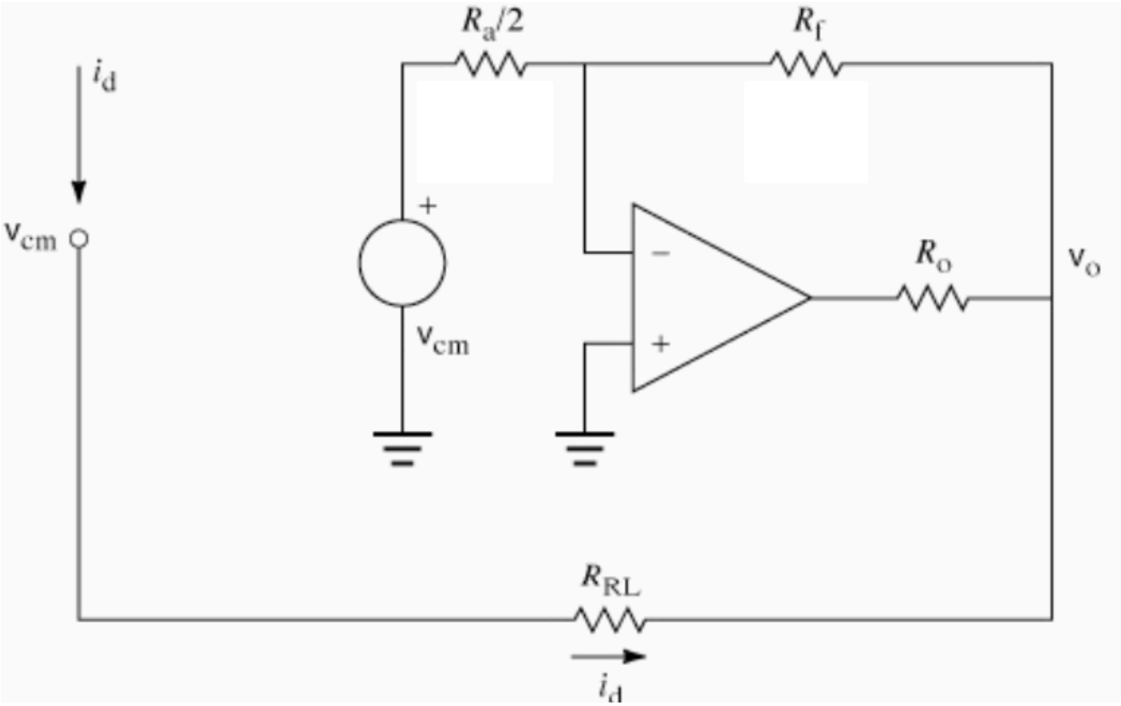
Driven Right Leg System Example



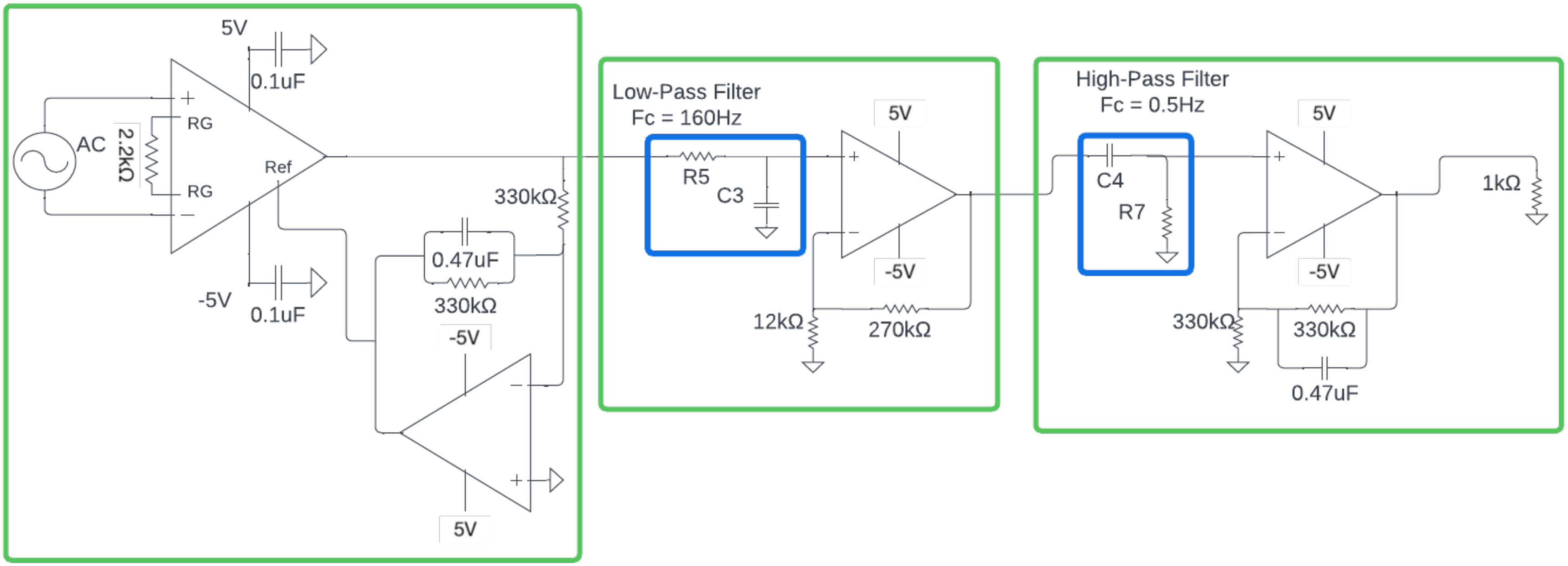


Driven Right Leg System Example

- **Problem**: Determine the common-mode voltage v_{cm} on the patient in the driven-right-leg circuit when a displacement current i_d flows to the patient from the power lines. Choose appropriate values for the resistances in the circuit so that the common-mode voltage is minimal. With a worst-case electrode resistance of 100kΩ, what is the v_{cm} when i_d = 0.2uA?

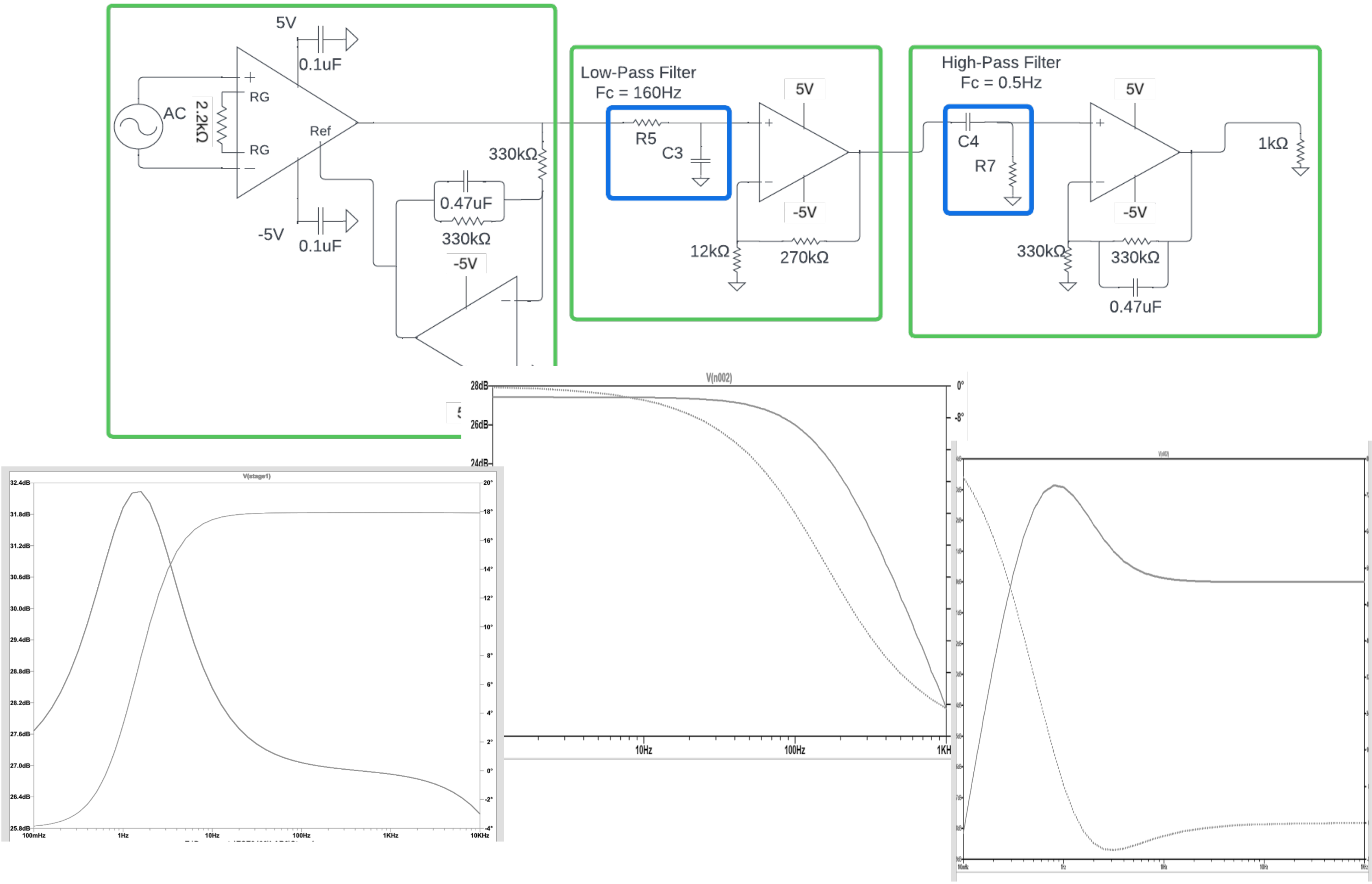


Lab 3



5V
0.1uF
AC
2.2kΩ
RG
RG
Ref
-5V
0.1uF
330kΩ
0.47uF
330kΩ
-5V
5V
Low-Pass Filter
Fc = 160Hz
5V
R5
C3
-5V
12kΩ
270kΩ
High-Pass Filter
Fc = 0.5Hz
5V
C4
R7
-5V
330kΩ
330kΩ
0.47uF
1kΩ

Lab 3


5V
0.1uF
AC
2.2kΩ
RG
RG
Ref
-5V
0.1uF
330kΩ
0.47uF
330kΩ
-5V
Low-Pass Filter
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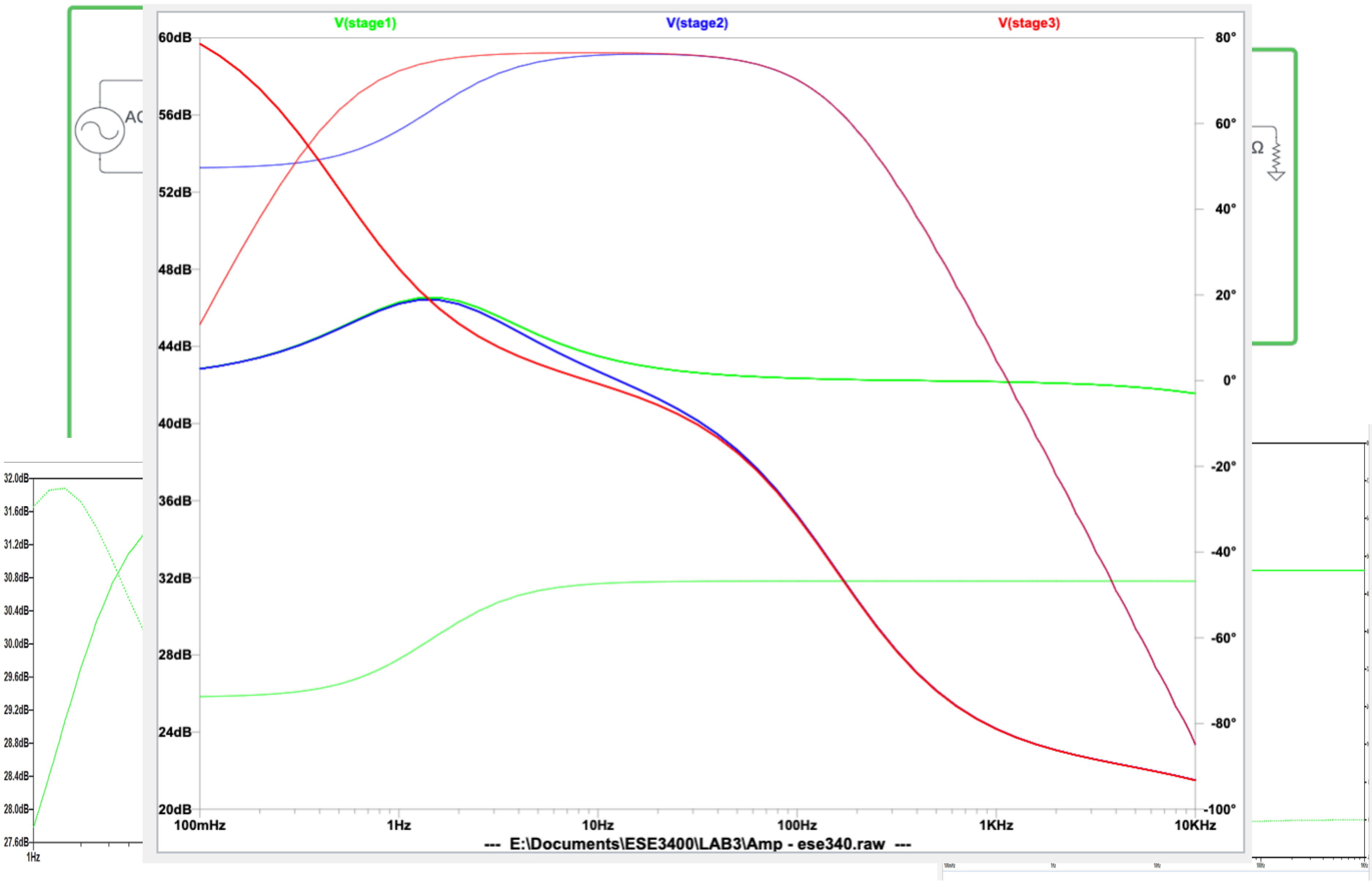
R5
C3
5V
-5V
12kΩ
270kΩ
High-Pass Filter
Fc = 0.5Hz
C4
R7
5V
-5V
330kΩ
330kΩ
0.47uF
1kΩ
V(n002)
28dB
26dB
24dB
0°
-8°
10Hz
100Hz
V(stage1)
32.4dB
31.8dB
31.2dB
30.6dB
30.0dB
29.4dB
28.8dB
28.2dB
27.6dB
27.0dB
26.4dB
25.8dB
20°
18°
16°
14°
12°
10°
8°
6°
4°
2°
0°
-2°
-4°
100mHz
1Hz
10Hz
100Hz
1KHz
10KHz

Lab 3



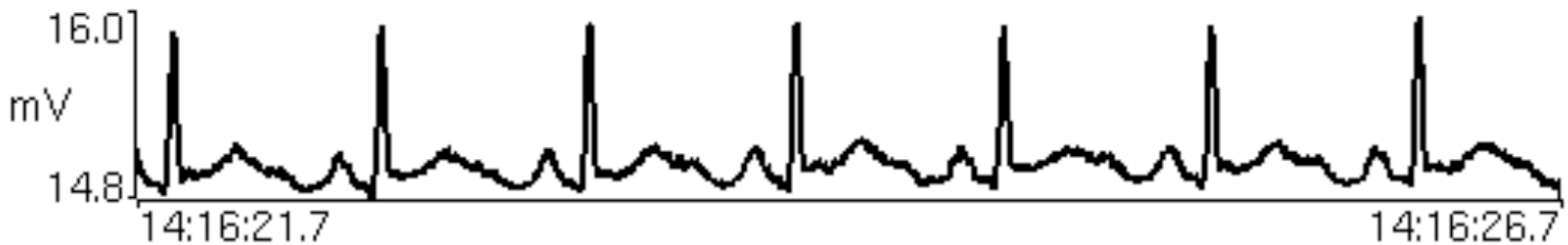
V(stage1)
V(stage2)
V(stage3)
60dB
56dB
52dB
48dB
44dB
40dB
36dB
32dB
28dB
24dB
20dB
80°
60°
40°
20°
0°
-20°
-40°
-60°
-80°
-100°
100mHz
1Hz
10Hz
100Hz
1KHz
10KHz
--- E:\Documents\ESE3400\LAB3\Amp - ese340.raw ---

Lecture Outline

- ECG signal
  - PQRST, Heart Rate
- Electrode placement
  - Einthoven's Triangle
  - 10-Electrode (12-Lead) ECG
- Electrical Safety
  - Perception thresholds
  - Macroschocks and microshocks
  - Sources of Leakage
  - Solutions
    - Ground loops and Electrical isolation

The Electrocardiogram

- If two surface electrodes are attached to the upper body (thorax), the following electrical signal will be observed:



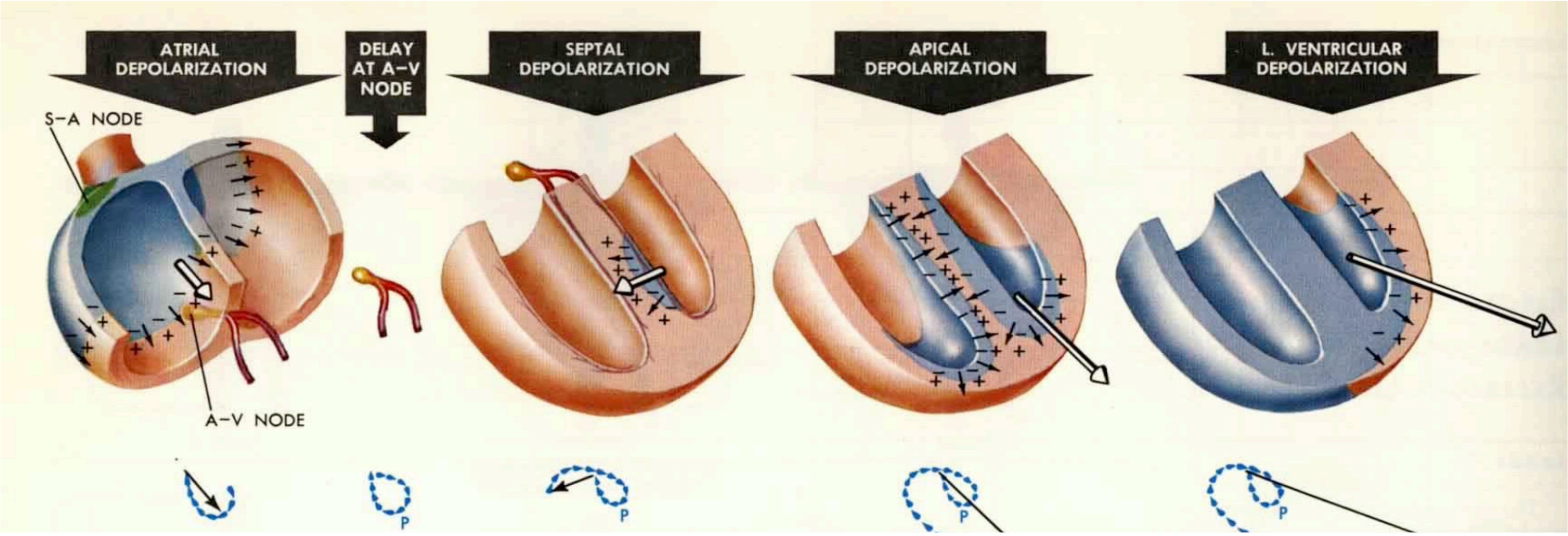
- This is the ECG

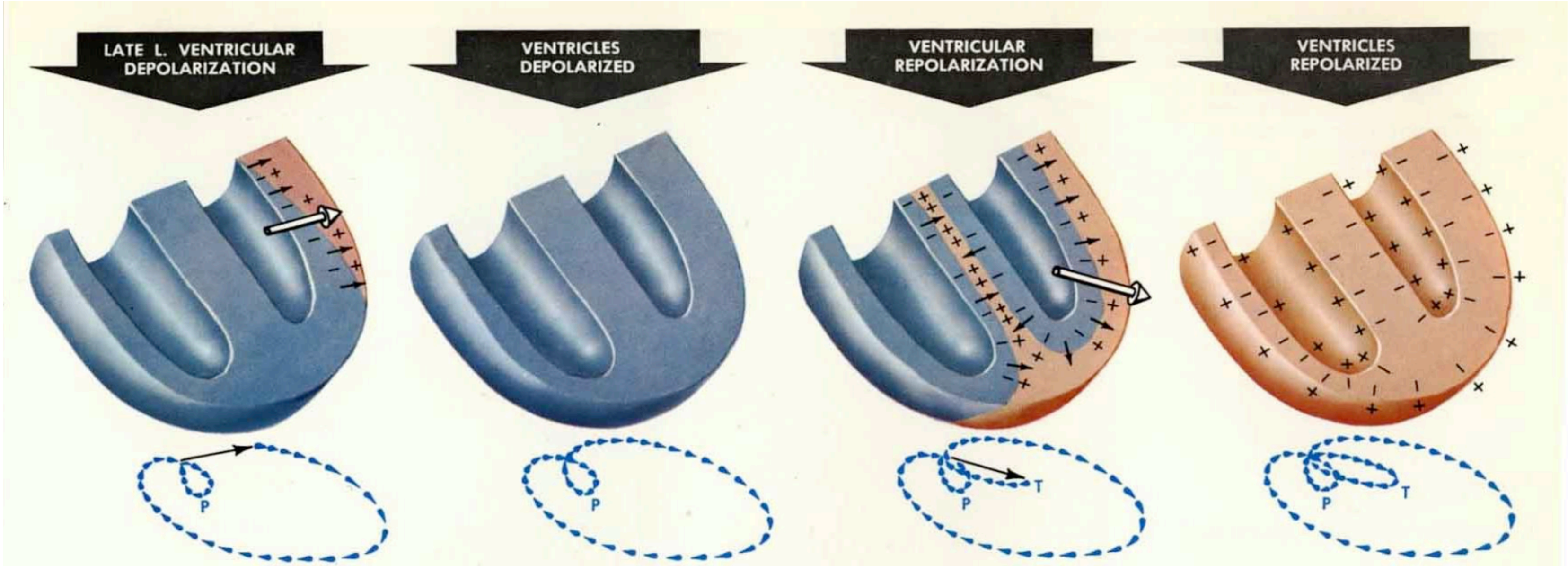
- Usually use more than just two electrodes…

The Origin of the ECG

- Atrial and ventricular contractions are the result of carefully timed depolarizations of the cardiac muscle cells
- The timing of the heart cycle depends on:
  - Stimulus from the pacemaker cells
  - Propagation between muscle cells
  - Non-excitable cells
  - Specialized conducting cells (Atrio-Ventricular Node)

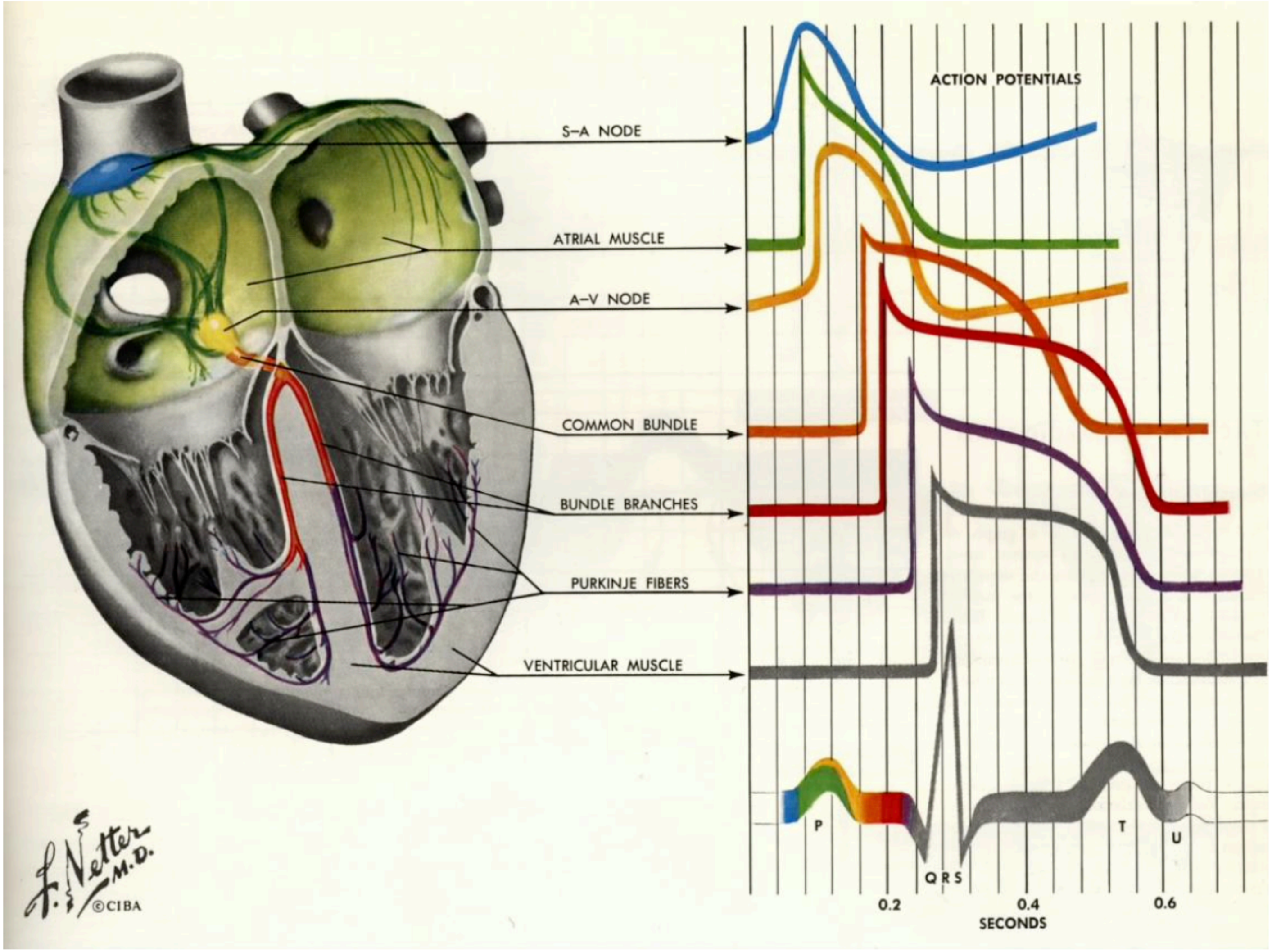
Excitation of the Heart



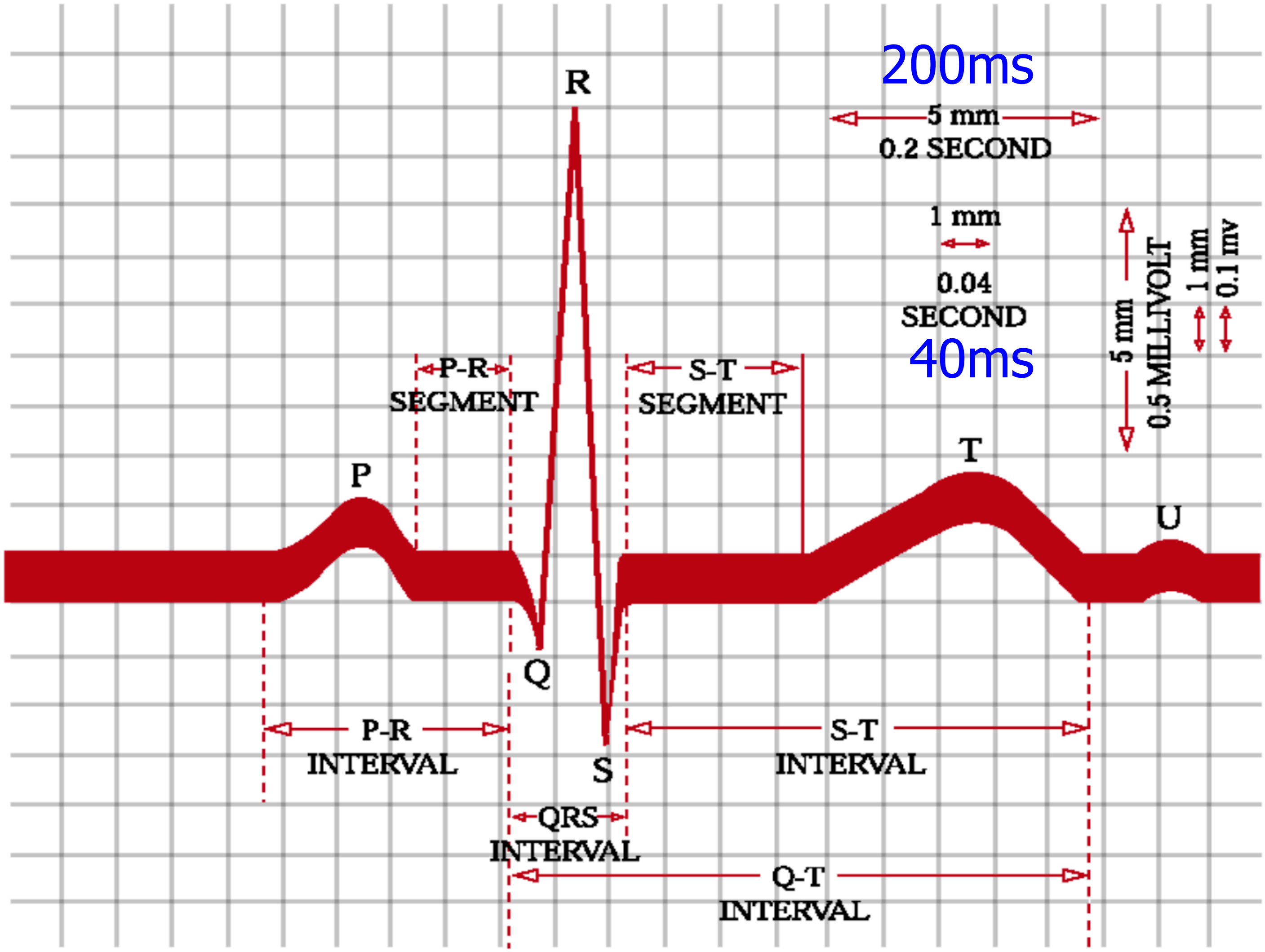


Cardiac Electrical Activity

- Putting it all together:



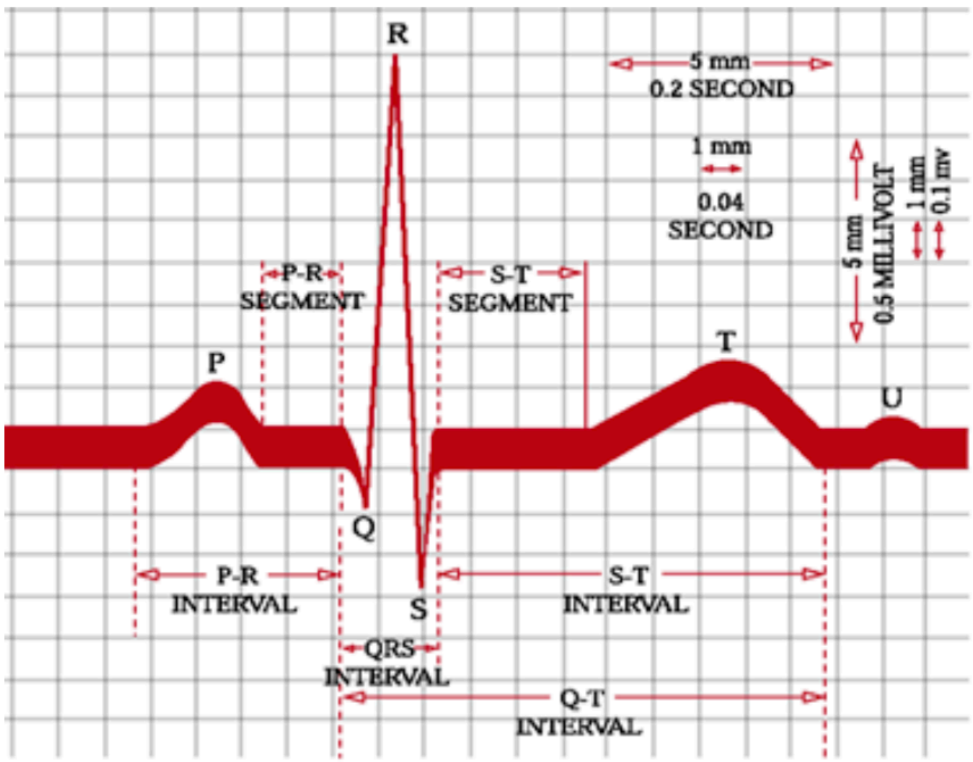
Typical ECG Signal



Recording Conventions, Waveform Nomenclature, and Normal Values for the Electrocardiogram.

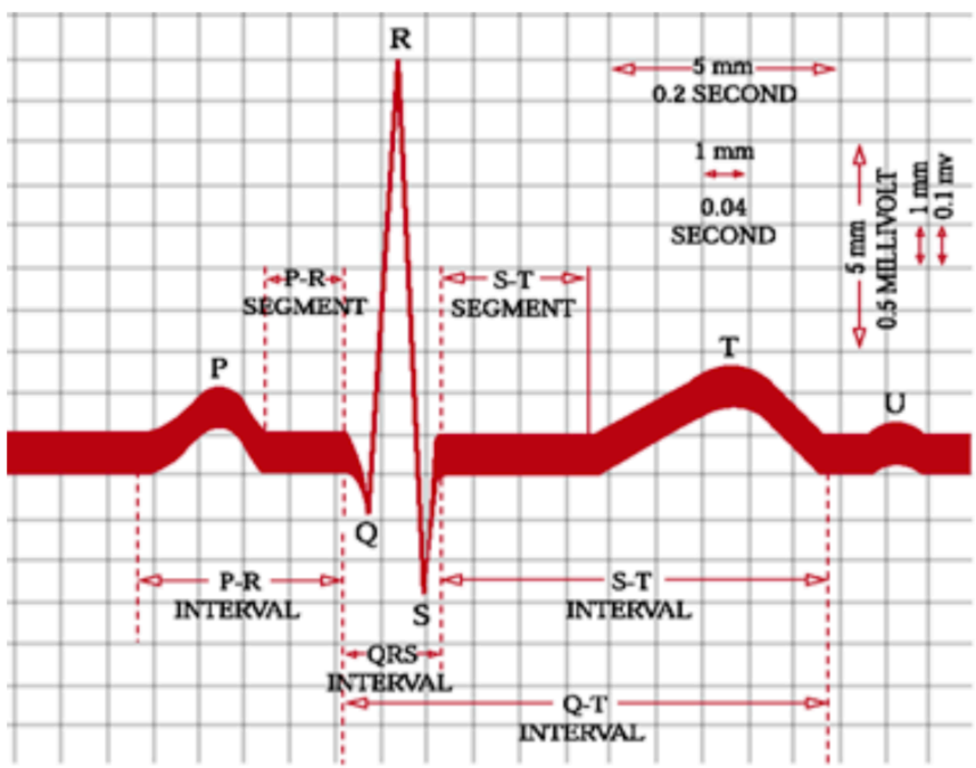
Components of ECG Signal

- P-wave: a small low-voltage deflection caused by the depolarization of the atria prior to atrial contraction
- QRS complex: the largest-amplitude portion of the ECG, caused by currents generated when the ventricles depolarize prior to their contraction



Components of ECG Signal

- T-wave: ventricular repolarization
- P-Q interval: time interval between the beginning of the P wave and the beginning of the QRS complex
- Q-T interval: characterizes ventricular repolarization



Heart Rate

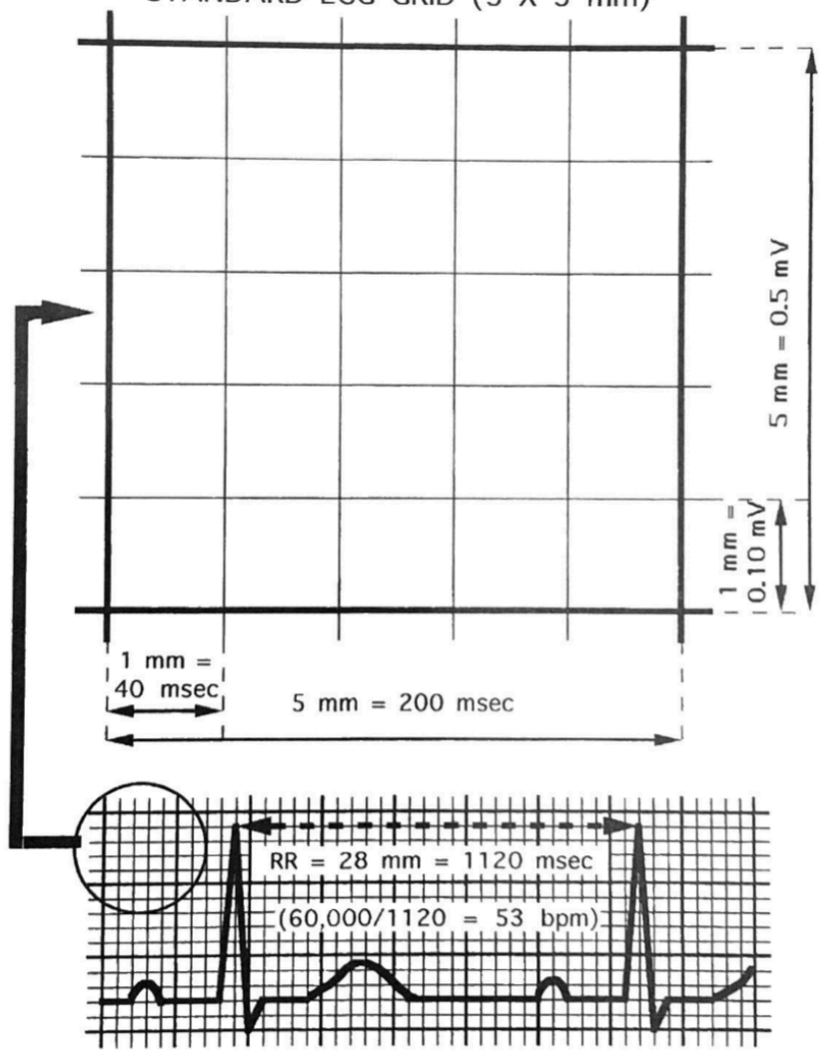
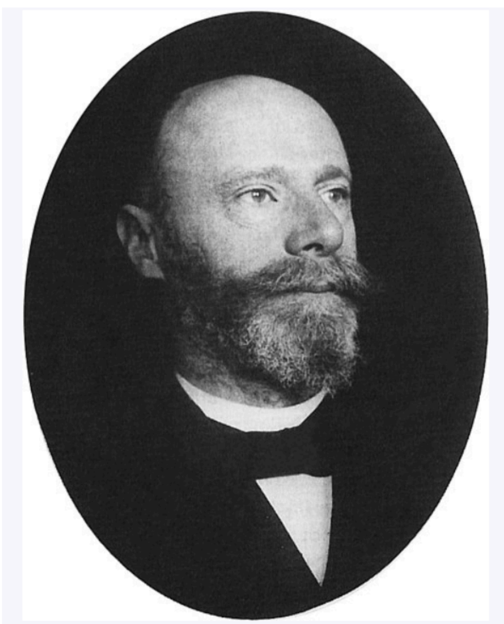


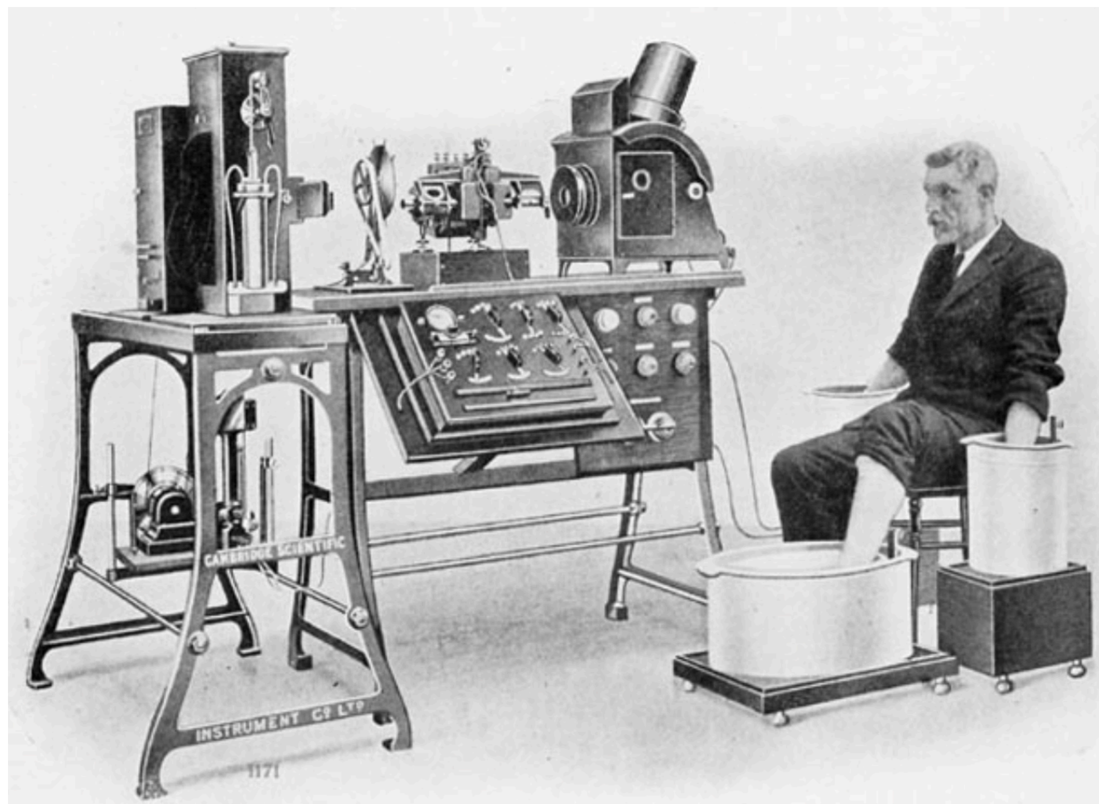
FIGURE 2.8

Heart rate determination.

ECG Measurement

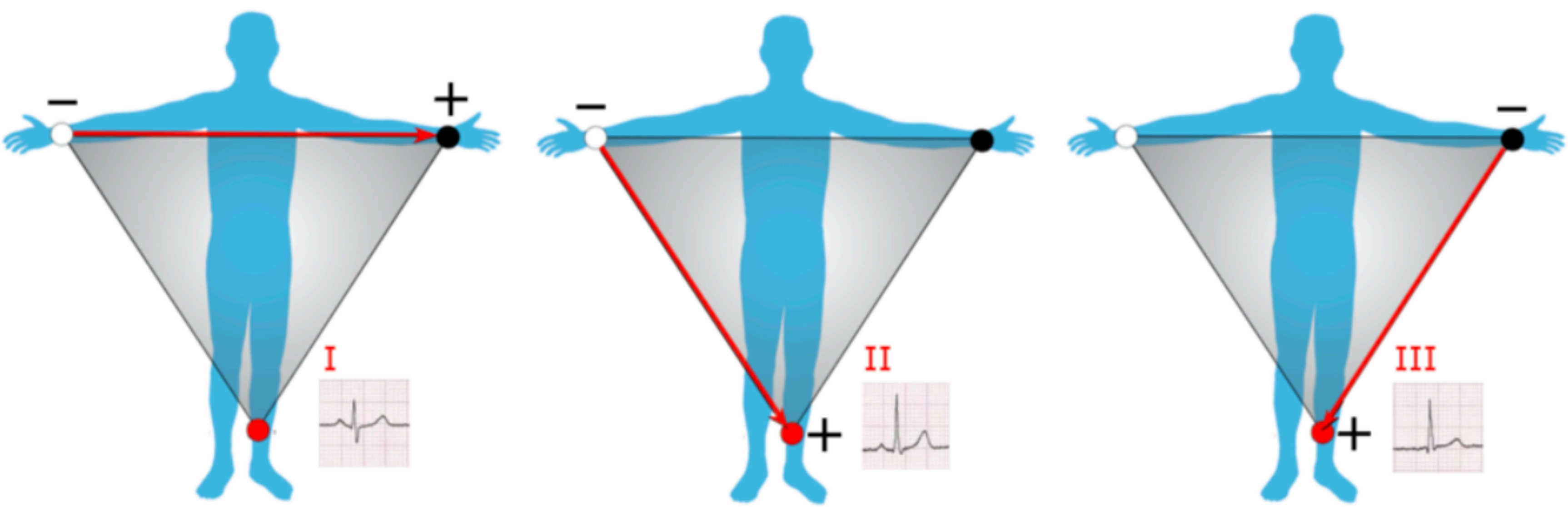
- Willem Einthoven
  - Invented string galvanometer
  - His assignment of the letters P, Q, R, S and T to the various deflections are still used





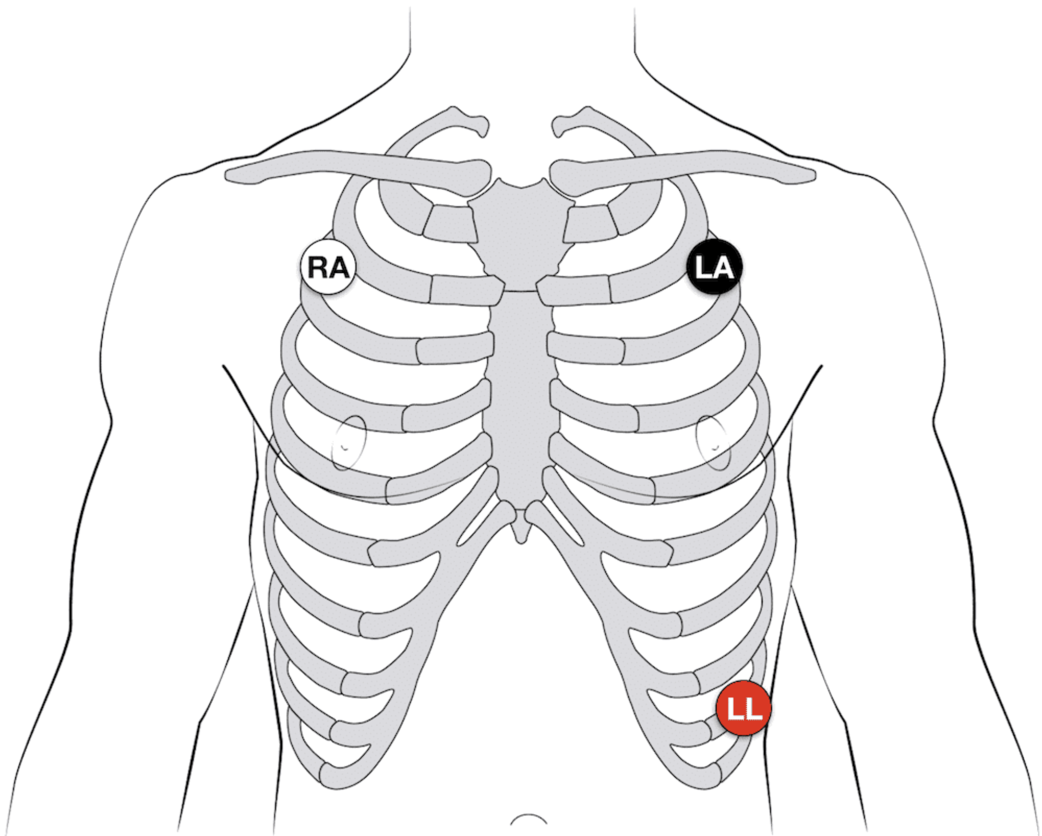
Einthoven's Triangle

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



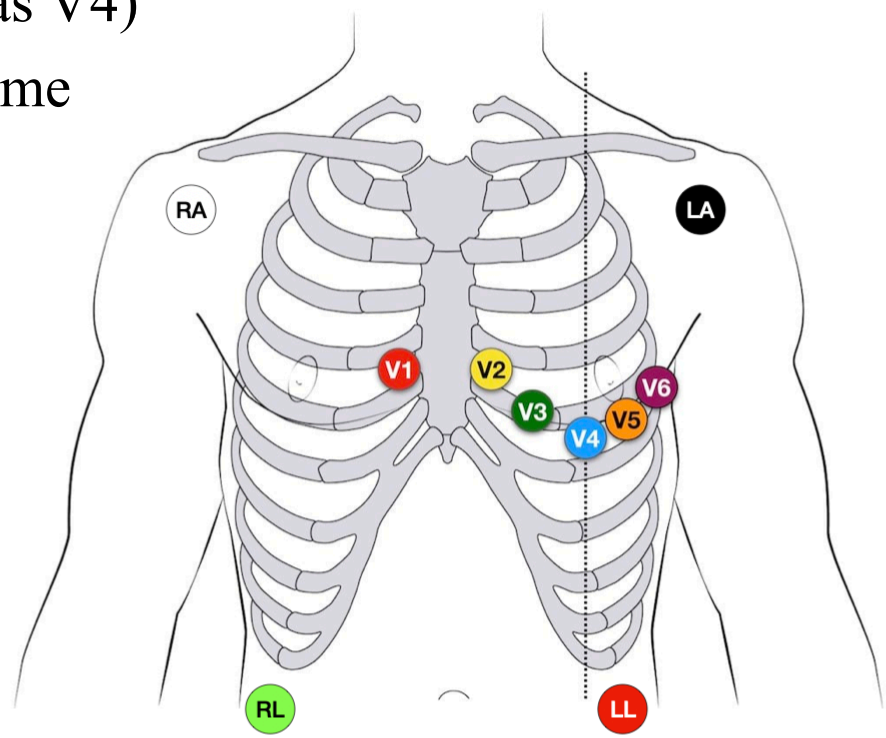
3-Electrode System

- Uses **3** electrodes (RA, LA and LL)
- Monitor displays the bipolar leads (I, II and III)
- To get best results – Place electrodes on the chest wall equidistant from the heart (rather than the specific limbs)

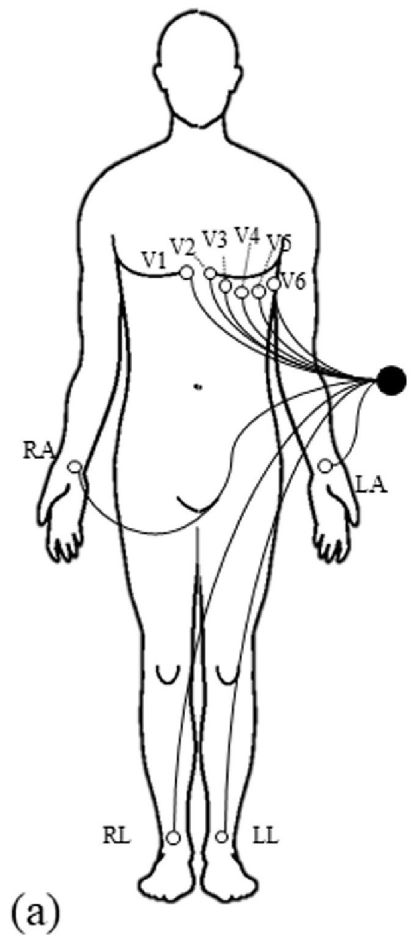


10-Electrode System (12-Lead ECG)

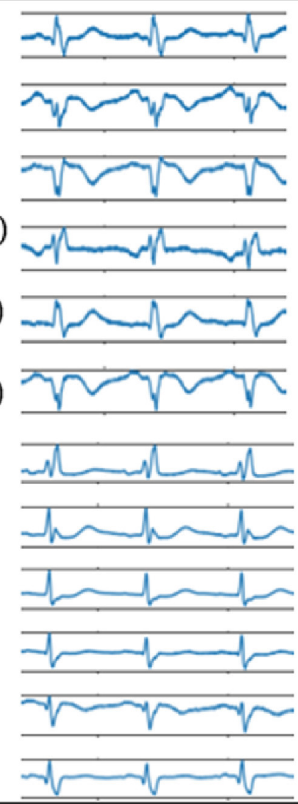
- V1: at the 4th intercostal space (ICS), on the right sternal border
- V2: 4th ICS, along the left sternal border
- V4: 5th ICS, at the mid-clavicular line
- V6: 5th ICS, mid-axillary line (same level as V4)
- V5: 5th ICS, at the anterior axillary line (same level as V4)
- V3: midway between V2 and V4



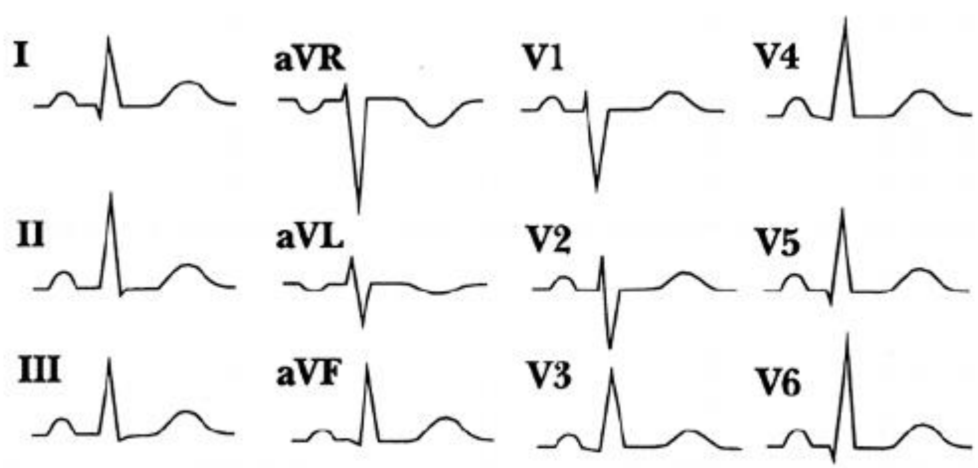
10-Electrode System (12-Lead ECG)

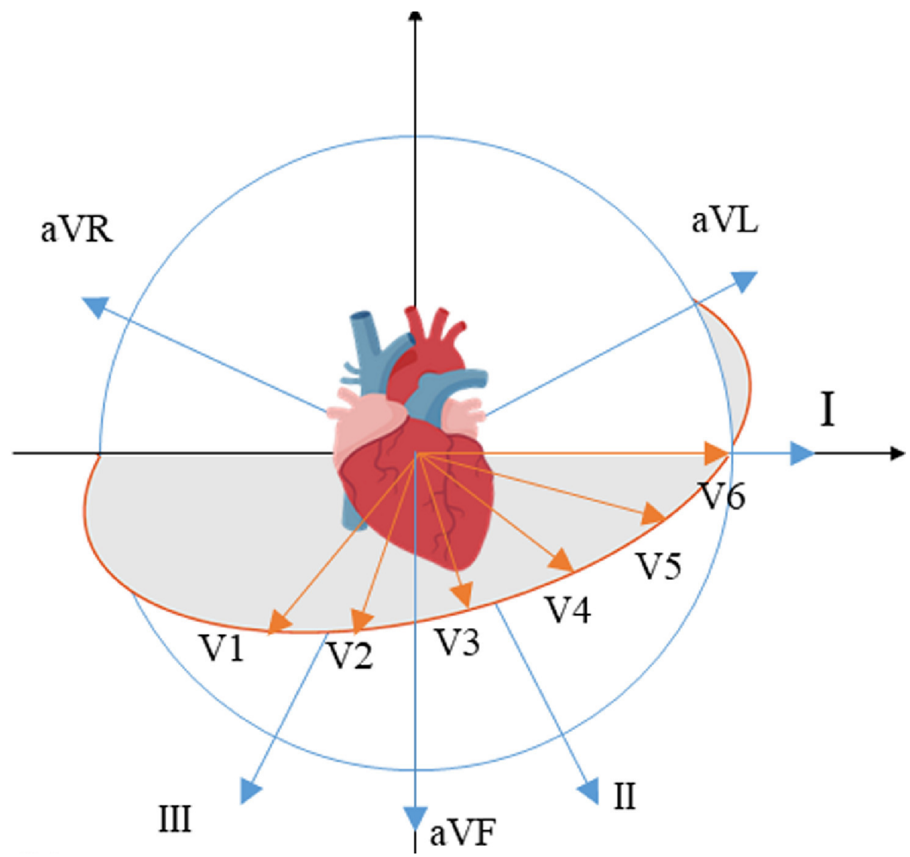


V_w	$\frac{1}{3}(RA + LA + LL)$
I	$LA - RA$
II	$LL - RA$
III	$LL - LA$
aVR	$\frac{3}{2}(RA - V_w)$
aVL	$\frac{3}{2}(LA - V_w)$
aVF	$\frac{3}{2}(LL - V_w)$
V1	$V1 - V_w$
V2	$V2 - V_w$
V3	$V3 - V_w$
V4	$V4 - V_w$
V5	$V5 - V_w$
V6	$V6 - V_w$

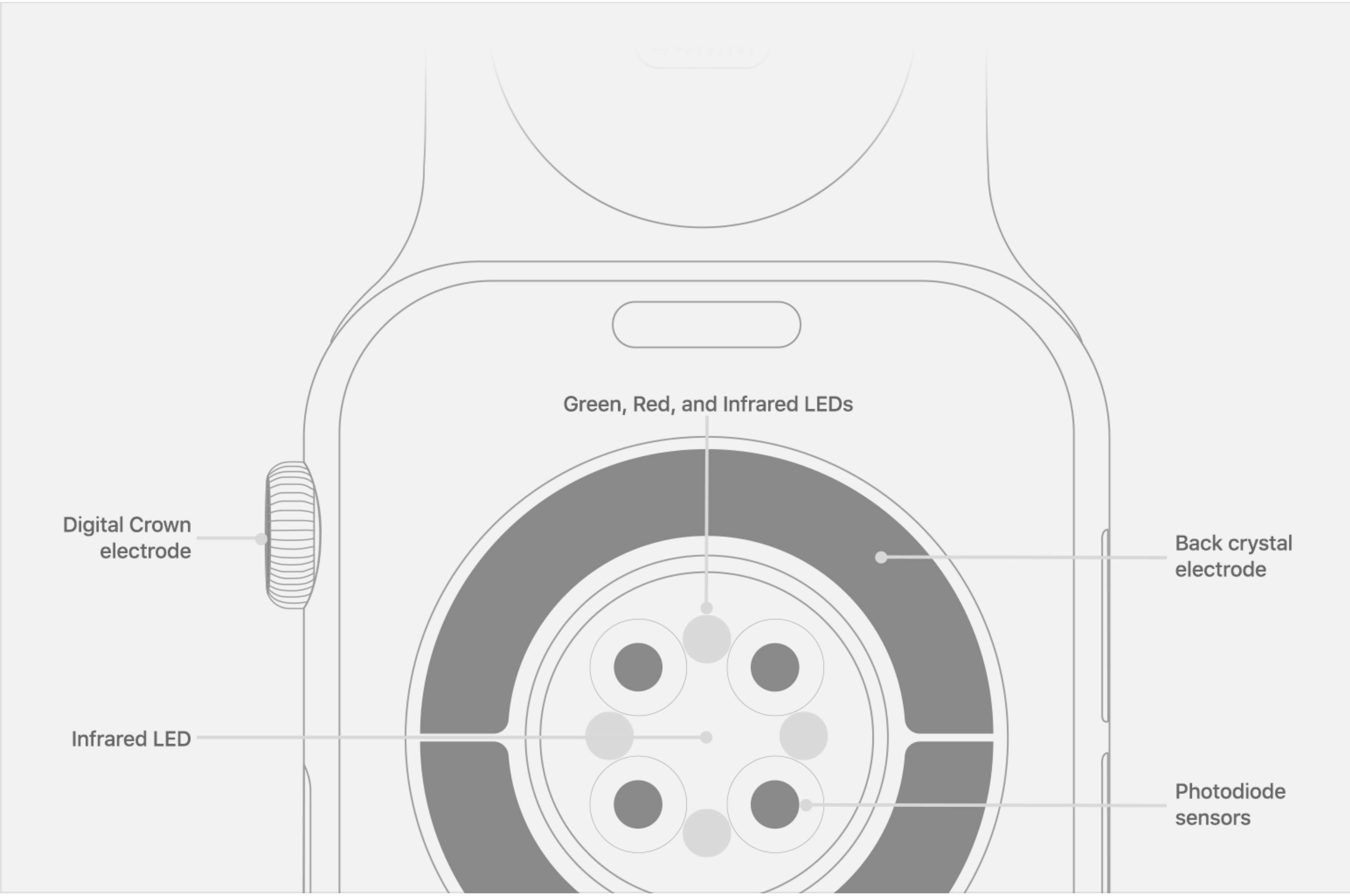


10-Electrode System (12-Lead ECG)





Apple Watch

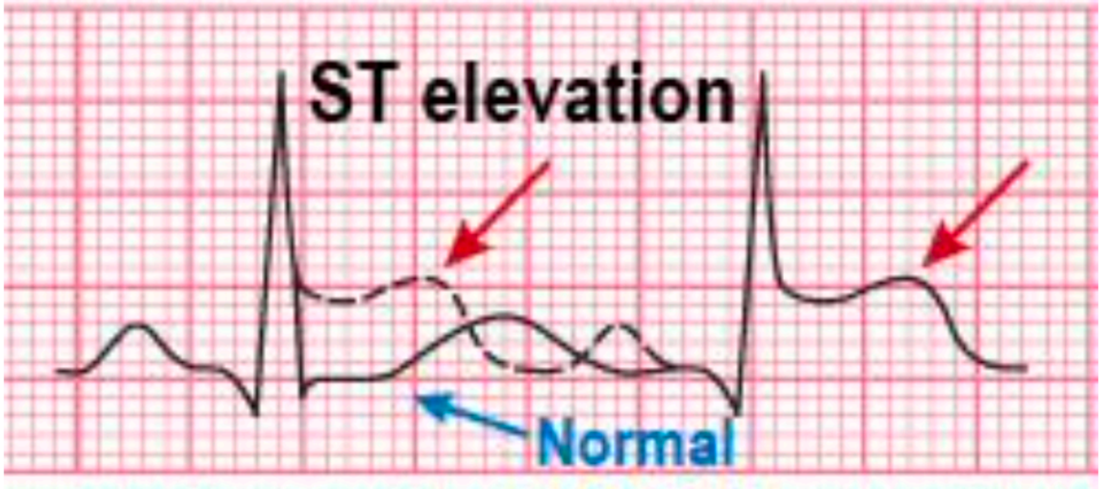

Green, Red, and Infrared LEDs
Digital Crown
electrode
Back crystal
electrode
Infrared LED
Photodiode
sensors

Diagnostic Uses of ECG

- Fetal monitoring (both before birth & during)
- Patient monitoring in Ambulance, Intensive Care Unit or Coronary Care Unit
  - S-T segment elevation to diagnose heart attacks
  - Evidence of cardiac muscle damage (infarct)
- Detection of precursors to heart attacks:
  - Abnormal heart beats (e.g. many ectopic beats, TWA)
  - Abnormal heart rhythms

Use of ECG in CCU

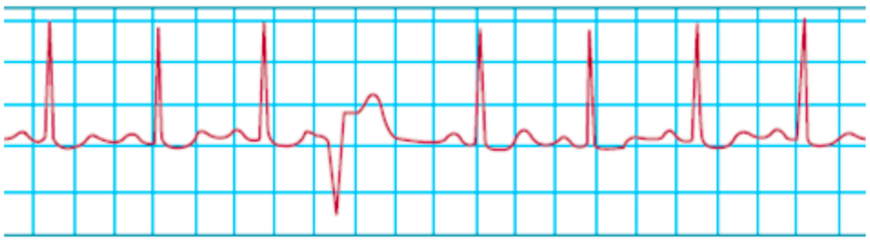
- The ECG is highly informative in the diagnosis of a heart attack (Myocardial Infarct)
  - Insufficient blood supply to the cardiac cells due to a blockage in the coronary arteries (ischaemic heart condition) causes S-T segment elevation



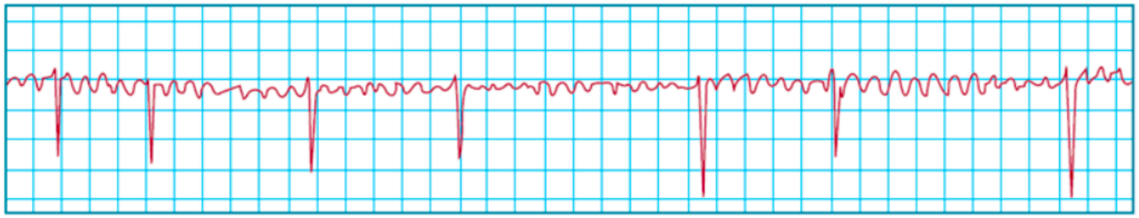
  - After the heart attack, cardiac muscle damage (infarct) generally leads to a loss of amplitude in the ECG

ECG Abnormalities

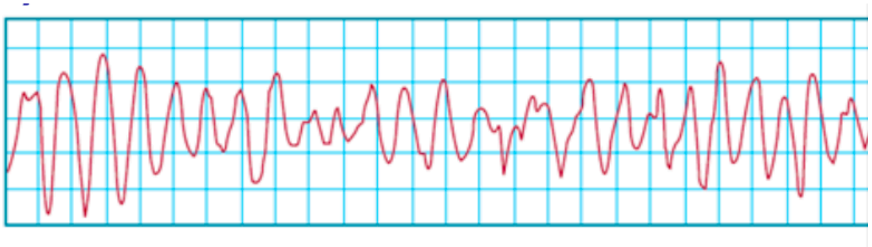
- Analysis of the ECG can provide early warning of potential problems
- Ectopic beats originate somewhere other than the Sino-Atrial (SA) node and often have different shapes (morphologies)



- Abnormal heart rates (arrhythmias) can be treated



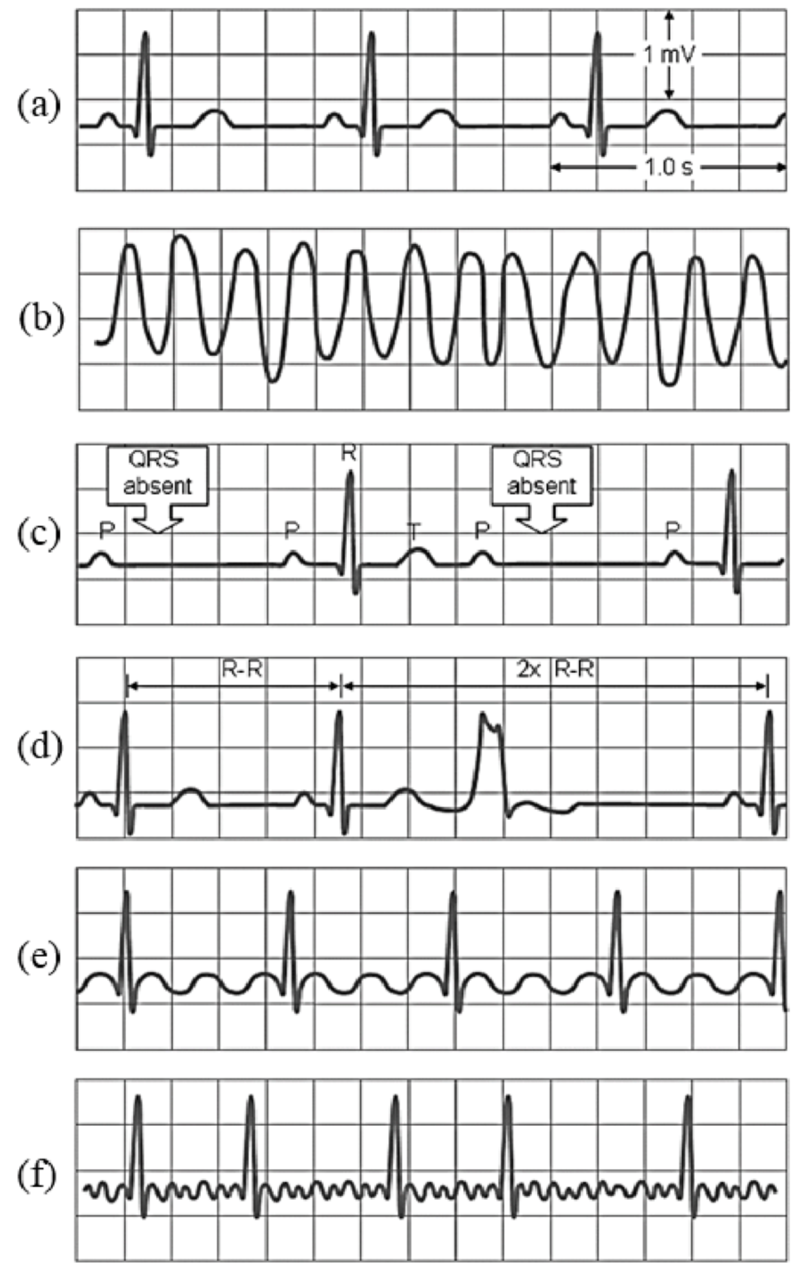
Atrial fibrilation



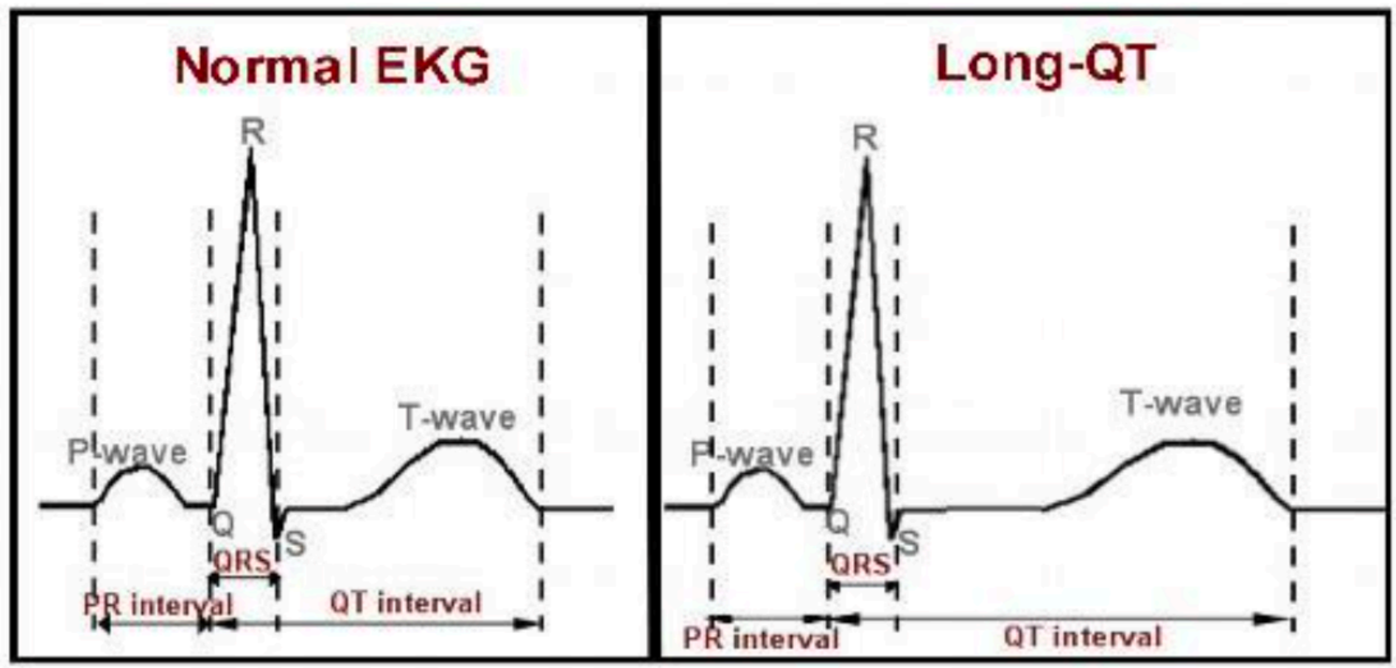
Ventricular fibrilation

Abnormal ECGs

- (a) Normal Sinus Rhythm
- (b) Ventricular Fibrillation
- (c) Atrioventricular Block
- (d) Premature Ventricular Contraction
- (e) Atrial Flutter
- (f) Atrial Fibrillation



Other Intervals in ECG Analysis



- The most important interval in the ECG is the QT interval
- A longer than normal QT interval is a good indicator of long QT syndrome (LQTS)

QT Interval Measurement

- LQTS is a potentially fatal condition that renders sufferers vulnerable to an arrhythmia known as torsade de pointes
- When this rhythm occurs, the heart is unable to beat effectively and the blood flow to the brain falls dramatically
- The result is a sudden loss of consciousness and possible cardiac death

Detecting ECG Abnormalities

- Two methods are in common use:
  - Ambulatory monitoring
  - Exercise stress ECGs

Ambulatory ECG Monitoring

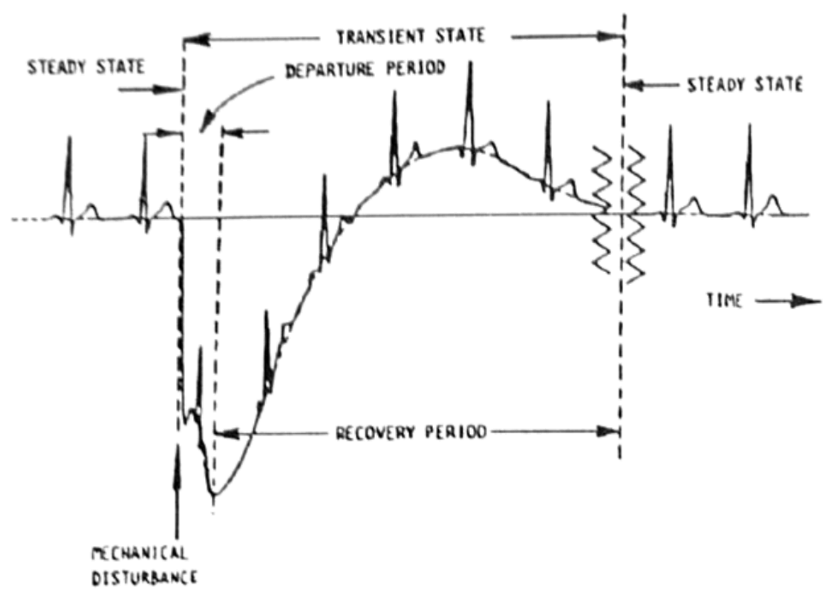
- ECG monitored for 24 hours.
- Results printed out:
  - 24-hour summary detailing the heart rate and S-T segment changes over the period of the test
  - Detailed information on ECG recorded at the time of a significant event (e.g. arrhythmia)

Analysis of ECG waveform

- Diagnostic information can be obtained by analysis of the amplitude and relative timing of the various segments
- The simplest interval to measure is the R-R interval (from which the heart rate is derived)
- Two types of heart rate meters:
  - Averaging heart rate meter
  - Beat-to-beat heart rate meter

QRS Detection

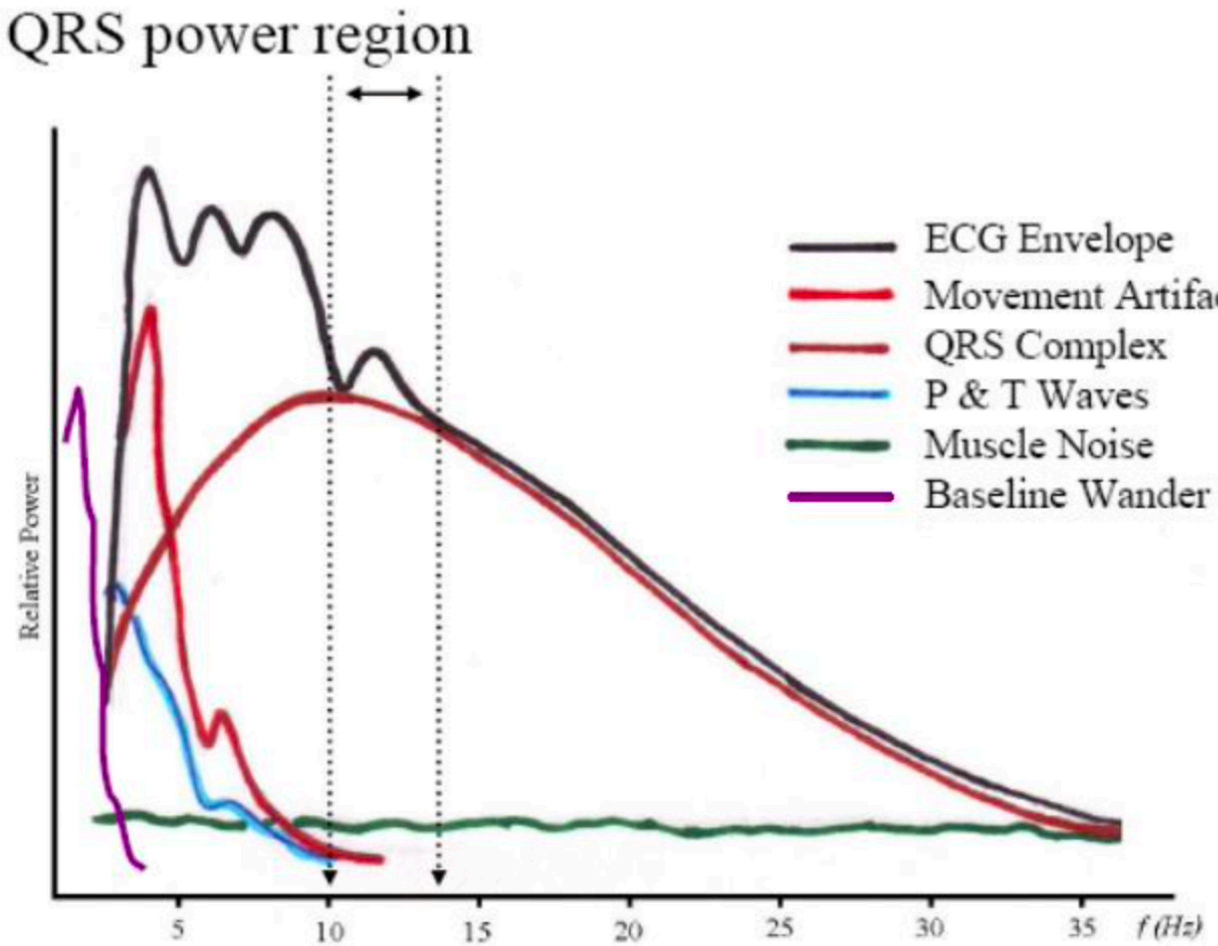
- There are 4 main problems in detecting the QRS complex in ECG traces:
  - Artifacts due to electrode motion
  - Baseline wander (mostly caused by breathing and torso movements)
  - Muscle artifact (broadband)
  - T-waves with high-amplitude content



QRS Detection

- The solution to these problems is to use a band-pass filter to remove:
  - Low-frequency changes such as baseline wander
  - High-frequency changes e.g. movement/muscle artifact
- Most of the frequencies in the QRS complex are around 5-20 Hz

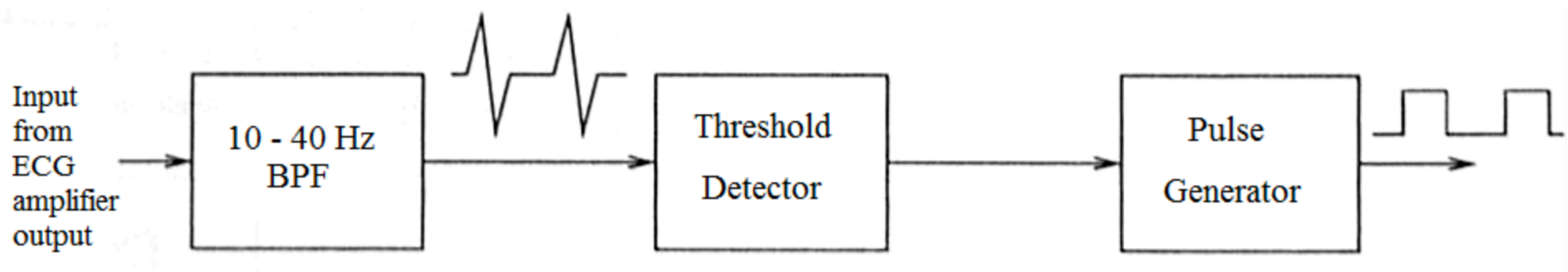
ECG Spectral Properties



- A pass-band of 10 – 40 Hz is therefore appropriate

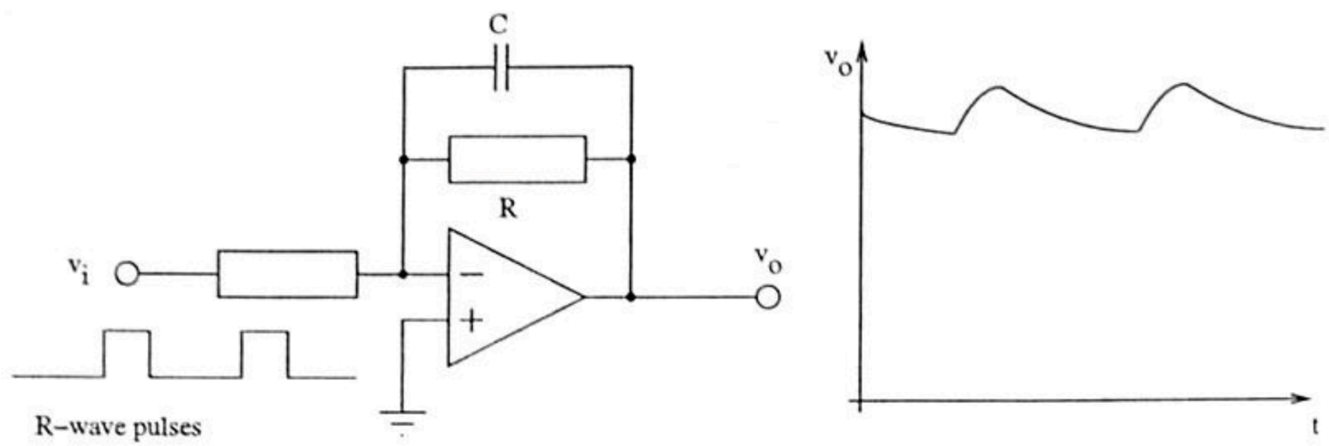
QRS Detection

- Once the "non-QRS" sections of the ECG have been attenuated, the QRS complex can be detected with a threshold detector

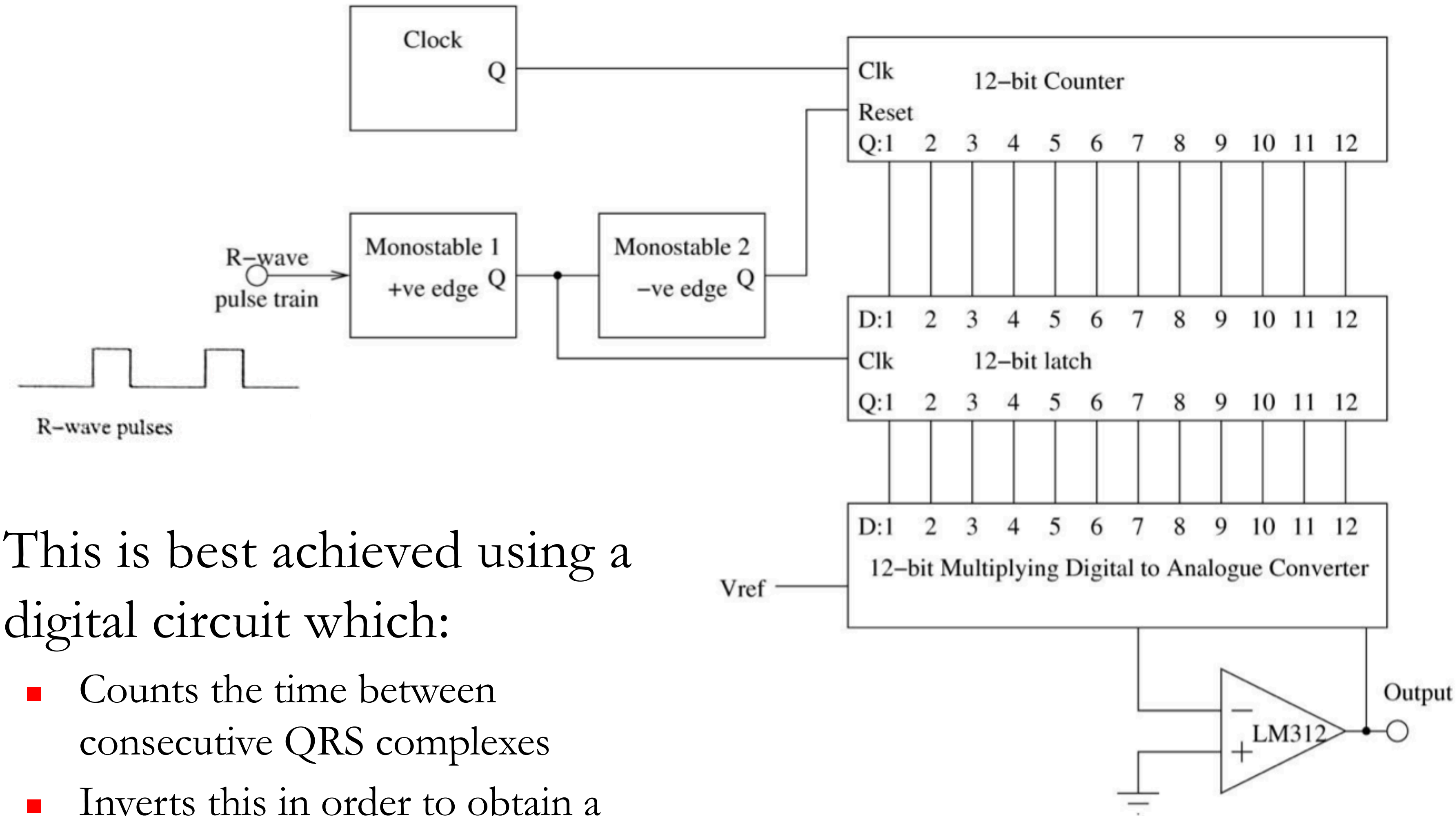


Averaging Heart Rate Meter

- The "average power" of the pulse train from the pulse generator circuit will be indicative of the heart rate
- This can be determined using a "leaky integrator" (a form of low-pass filter).
- The time-constant of the R-C circuit should be several beats long to minimize output ripple.

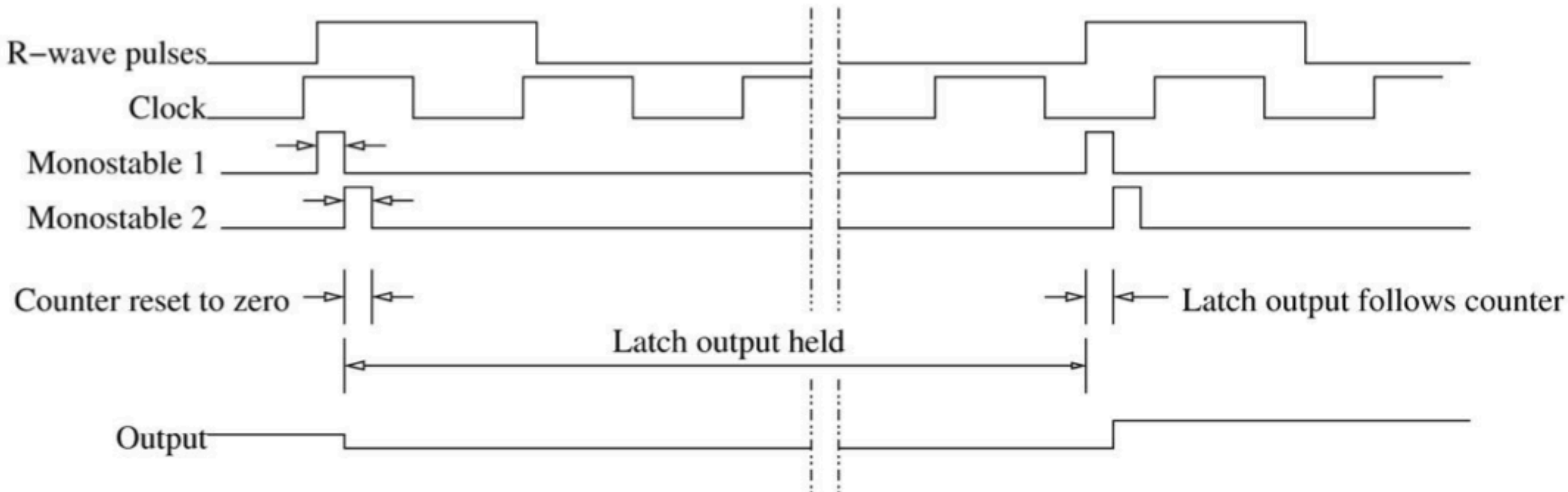


Beat-to-Beat Heart Rate Monitor



- This is best achieved using a digital circuit which:
  - Counts the time between consecutive QRS complexes
  - Inverts this in order to obtain a heart rate (rather than interval)

Beat-to-Beat Heart Rate Monitor



Electrical Safety

Significance of Safety

- Thousands of device related patient injuries in U.S every year
- Even a single harmful event can lead to significant damage in terms of reputation and legal action
- Different level of protection required as compared to household equipment.
- Minimum performance standards introduced in 1980s –relatively new practice.

Effects of Electricity

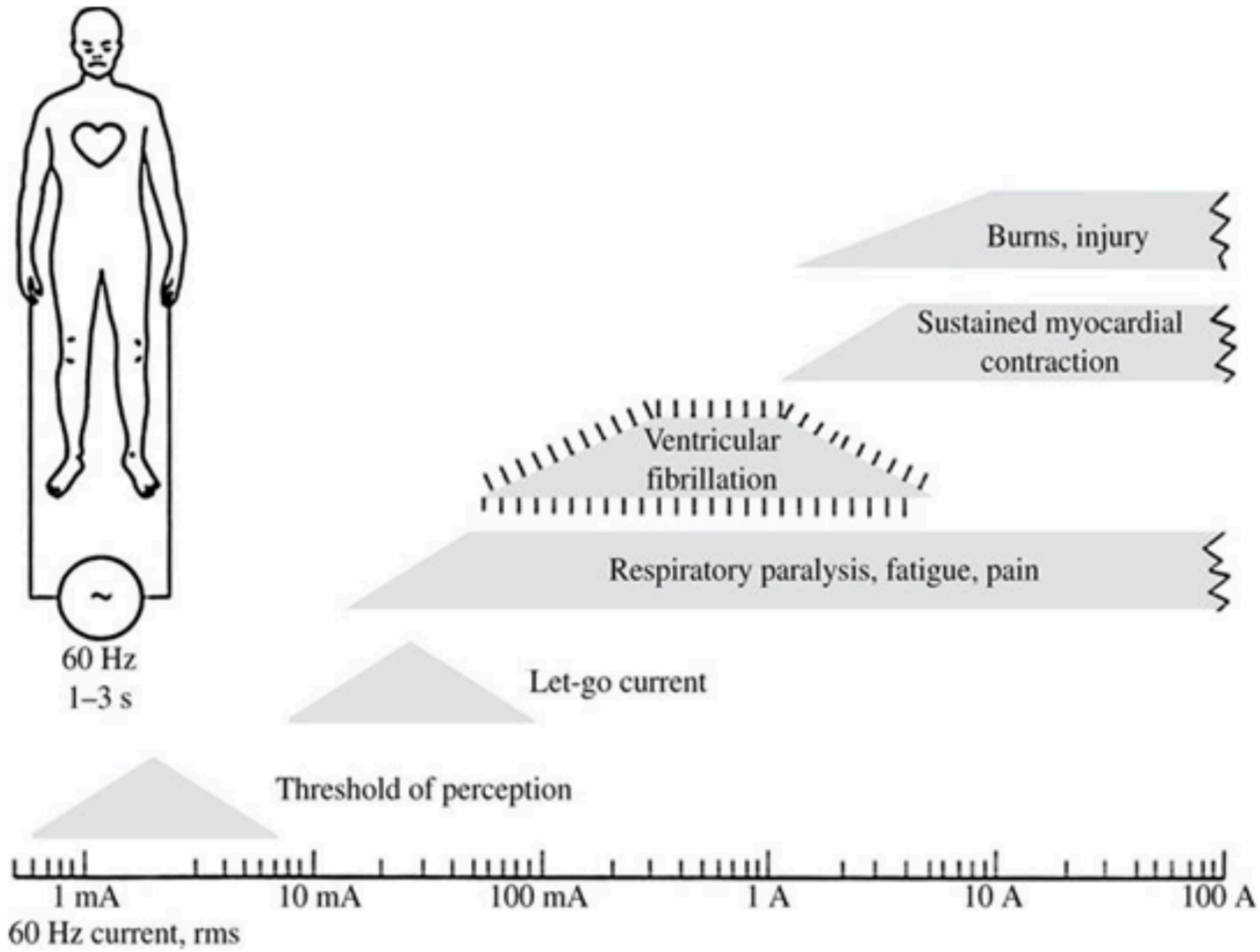
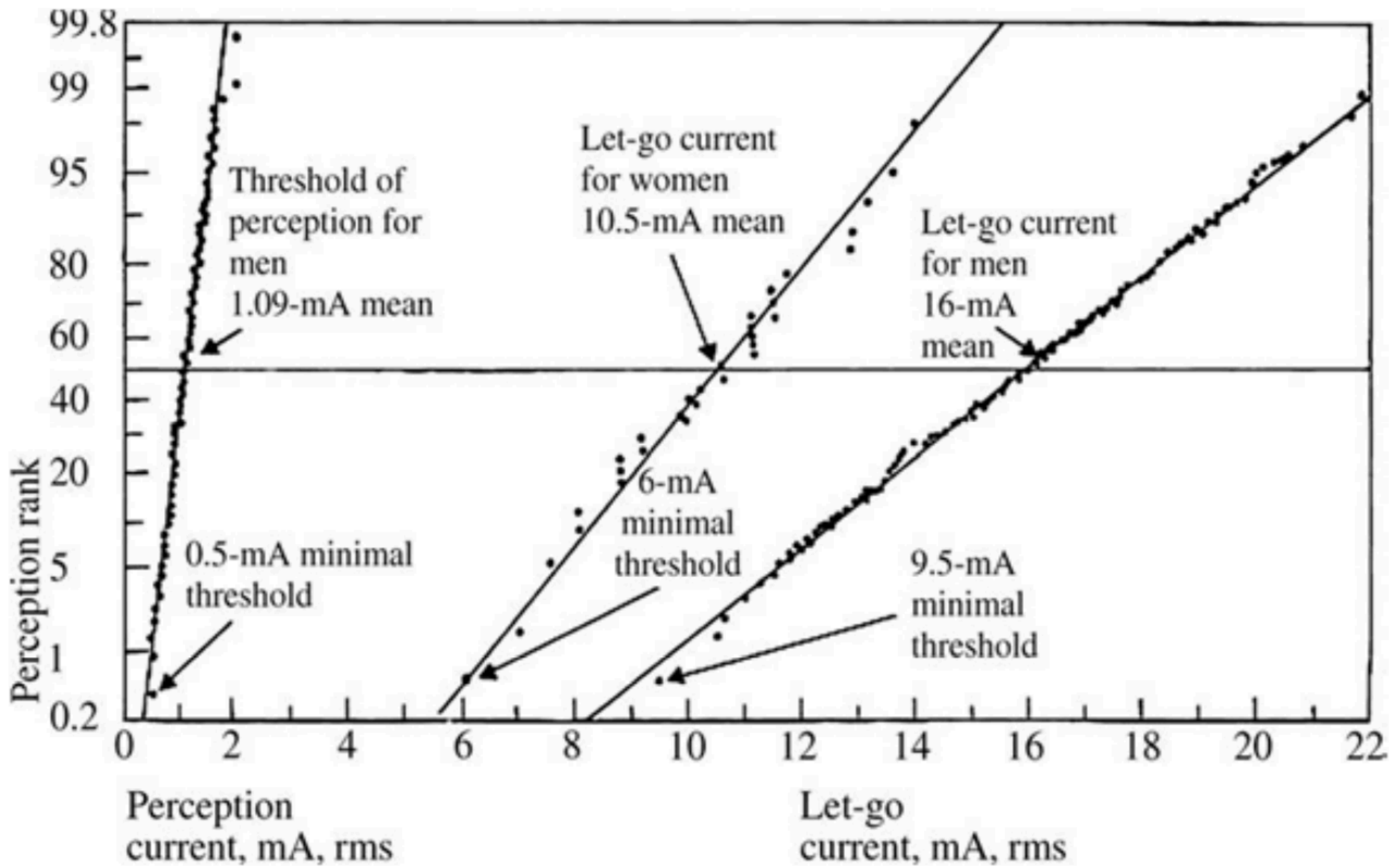
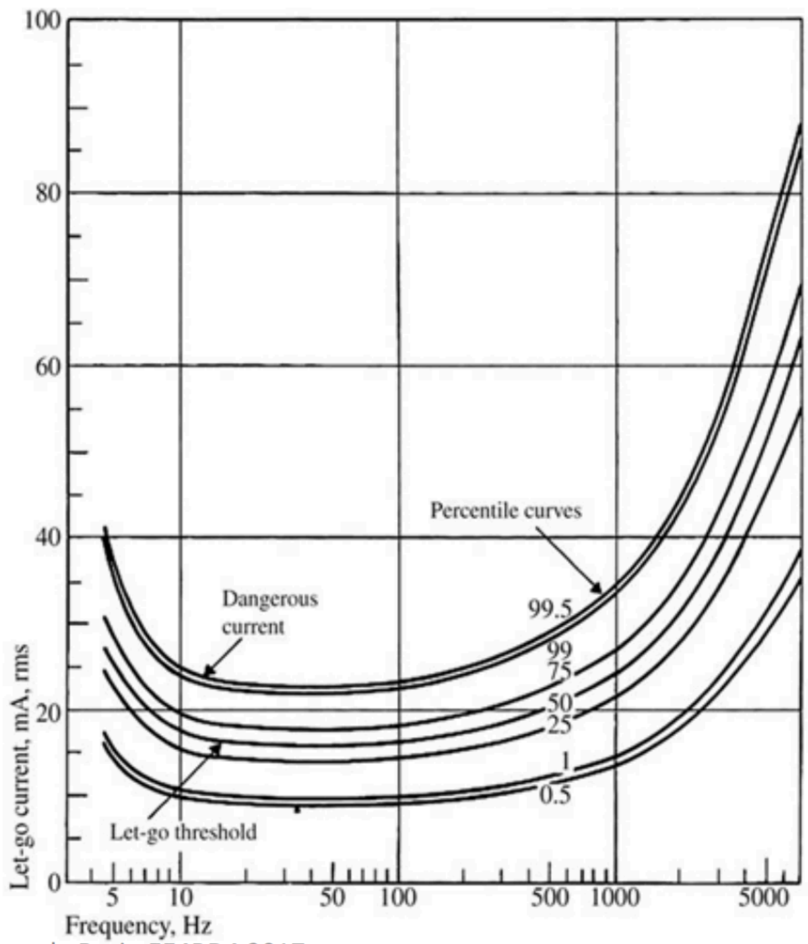


Figure 14.1 Physiological effects of electricity **Threshold or estimated mean values are given for each effect in a 70 kg human for a 1 to 3 s exposure to 60 Hz current applied via copper wires grasped by the hands.**

Variability of Threshold of Perception



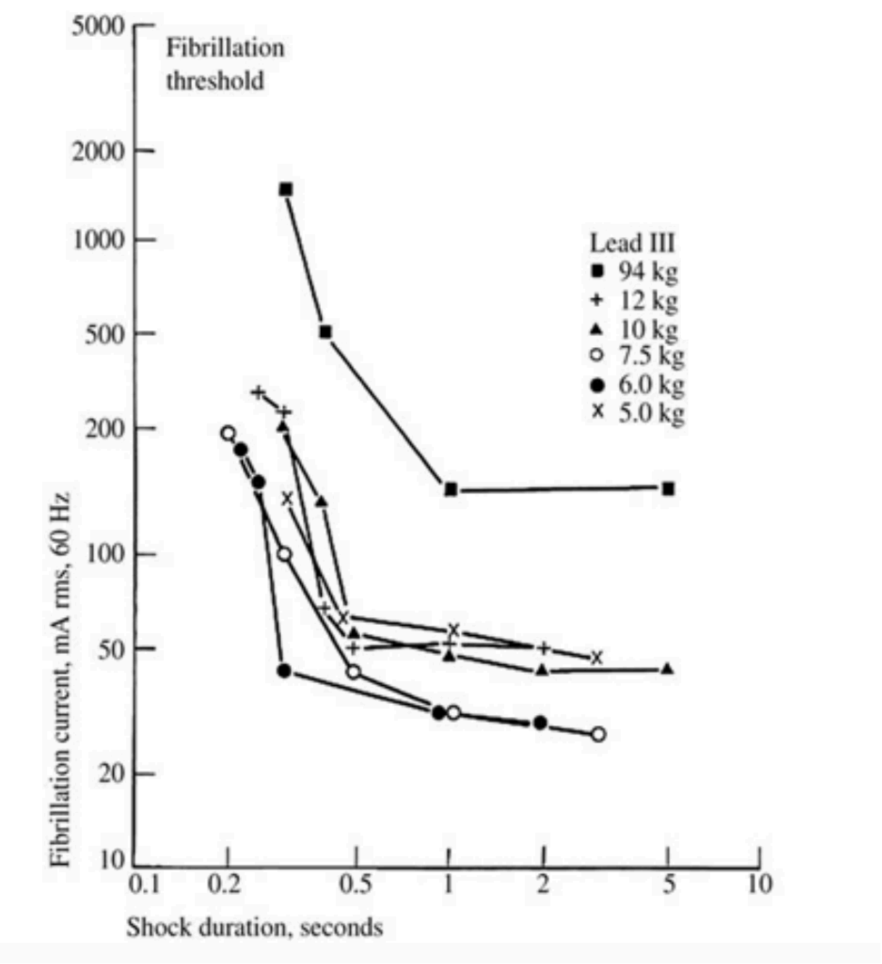
Frequency Effect on the Let-Go Current



de Bruin EE4BD4 2017

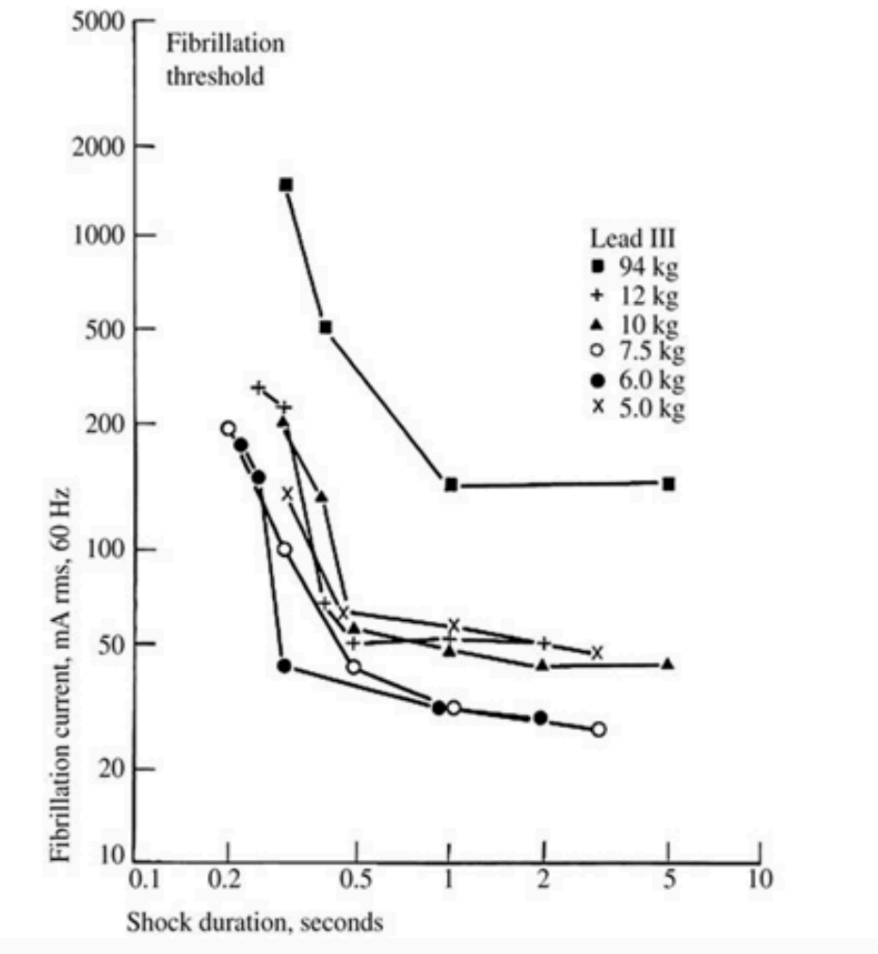
- Mean "**let-go current**"
  let-go current = max current where you can still release your grip
  - 10.5-16.5 mA
- Let-go current vs. frequency
  - Minimal let-go current occurs at commercial power-line frequencies of 50-60 Hz

Susceptibility Factors



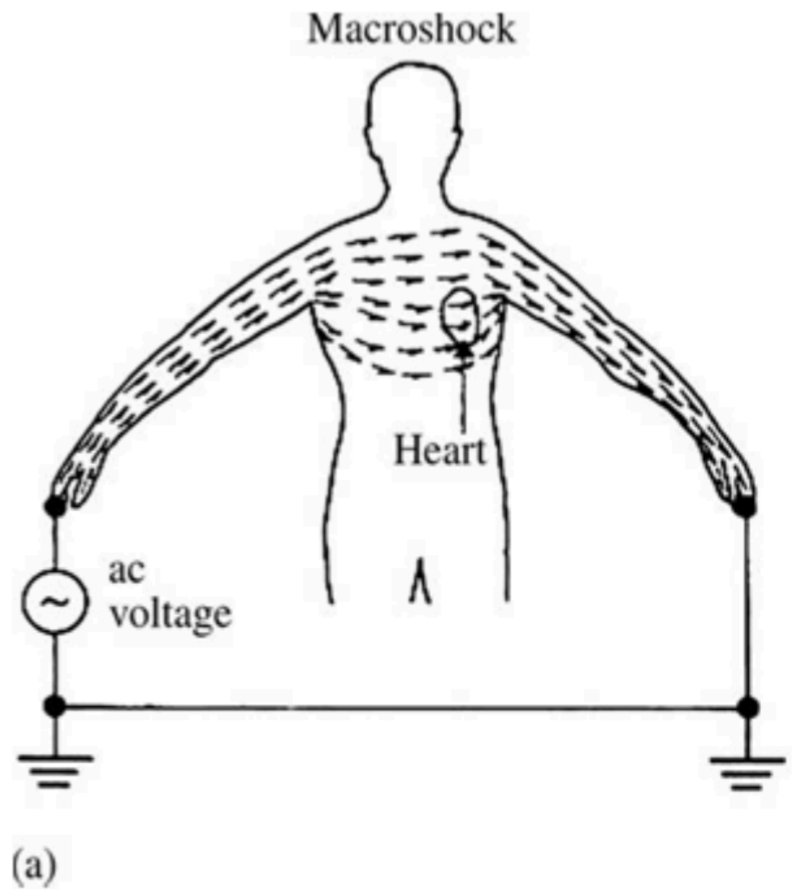
- Shock (stimulation) duration
  - Fibrillation current is inversely proportional to the shock pulse duration
  - Longer pulses → lower current does damage

Susceptibility Factors



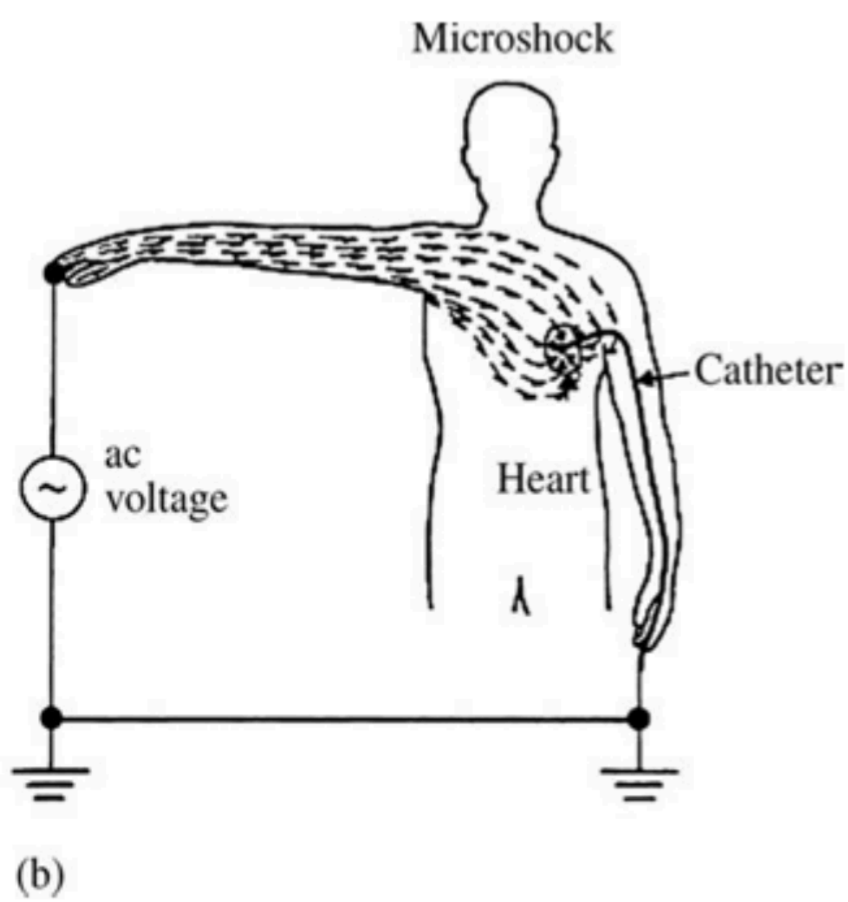
- Body weight
  - Fibrillation current increases with body weight
    - 50 mA RMS for 6 Kg
    - 130 mA RMS for 24 Kg
- Points of entry
  - Skin impedance varies: 15 kΩ to 1 MΩ
    - Resistive barrier that limits current flow
  - Tissue (beneath skin) has low impedance

Current Pathway



- Macroshock
  - Externally applied current
  - Spreads through the body and less concentrated

Current Pathway



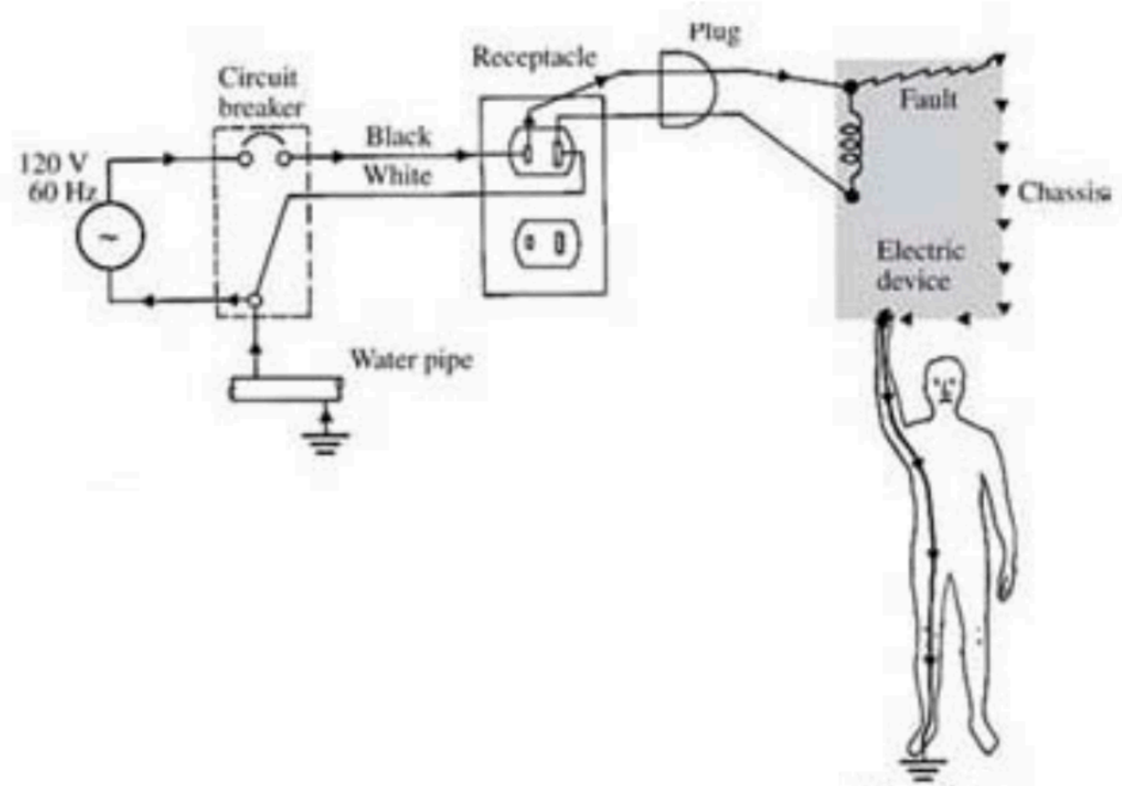
- Microshock
  - Current concentrated at an invasive point
  - Accepted safety only 10uA
  - Generally only dangerous if current flows through heart

Controlled Stimulation

- Electrical muscle stimulation
  - Low current & frequency
  - Not across heart
- Electrosurgery
  - high frequency (250 - 2000 kHz)
- Deep neural stimulation: very small current
- Defibrillation: as a last resort
- Electroshock therapy: last resort (if ever)

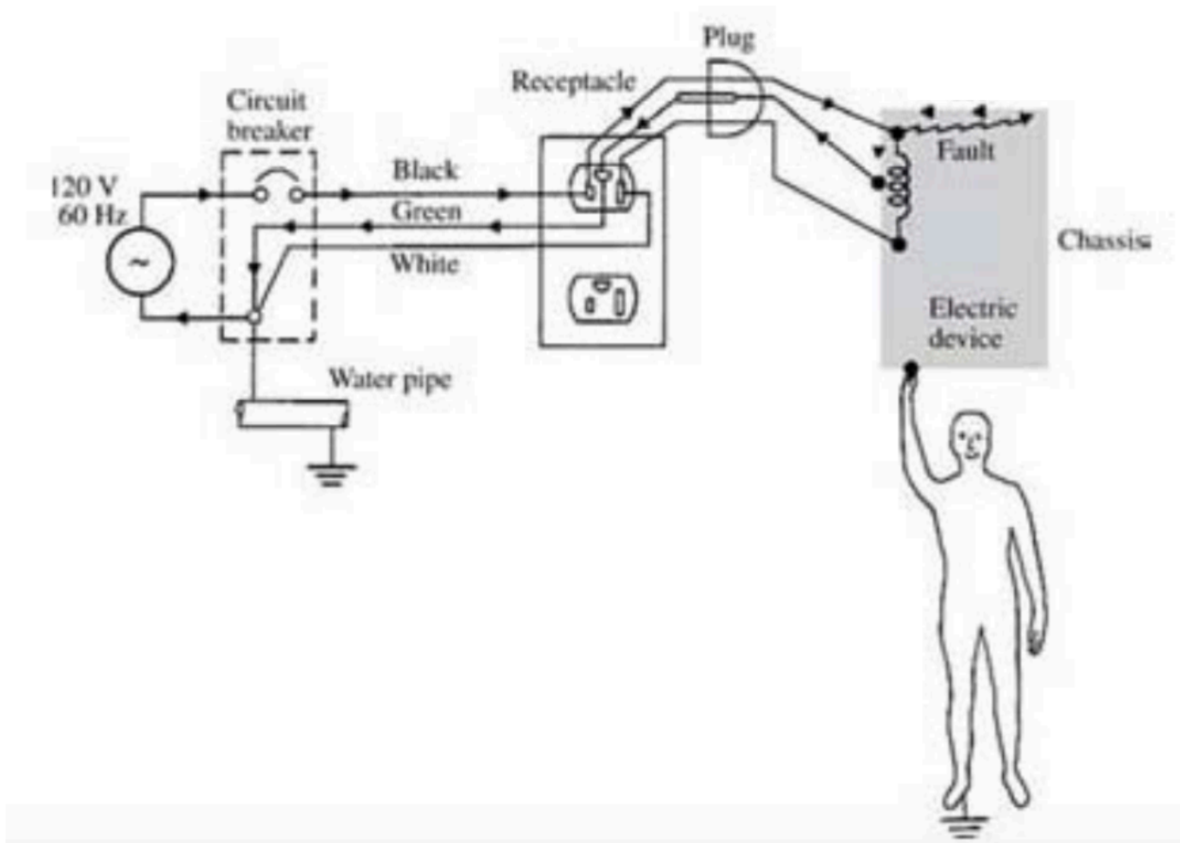
Macroshock

- Occur when equipment breaks down and the hot wire touches equipment case or other conductive pathway current flows through subject to ground but not enough to trip circuit breaker or breaker doesn't trip in time



Macroshock

- Grounded circuits (case grounded) provides an almost direct short to ground which will trip breaker but not necessarily in time



Macroshock Hazards

- Most probable cause of death
  - Ventricular fibrillation
- Factors
  - Skin/body resistance
  - Design of electrical equipment
- Skin and body resistance
  - dry skin has high resistance (~15kΩ-1MΩ)
  - wet/broken skin has low resistance (~1% that of dry skin)
  - Internal body resistance: ~200Ω for each limb, ~100Ω for trunk of body, ~500Ω resistance between two limbs
- Procedures that bypass skin resistance can be dangerous
  - Example: gel electrodes, surgery, oral/rectal thermometers

Microshock

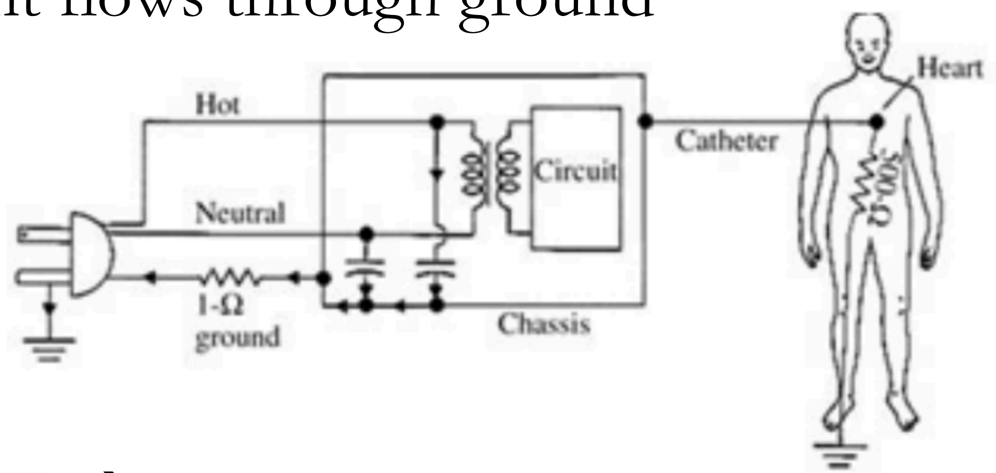
- Leakage currents are small currents (usually μA) that flow between insulated current carrying conductors during normal operation
  - Usually due to coupling capacitance between conductors with AC currents
  - Also could be due to resistive pathways established by moisture, dust or insufficient insulation
  - Especially dangerous when there are patient applied parts

Microshock Hazards

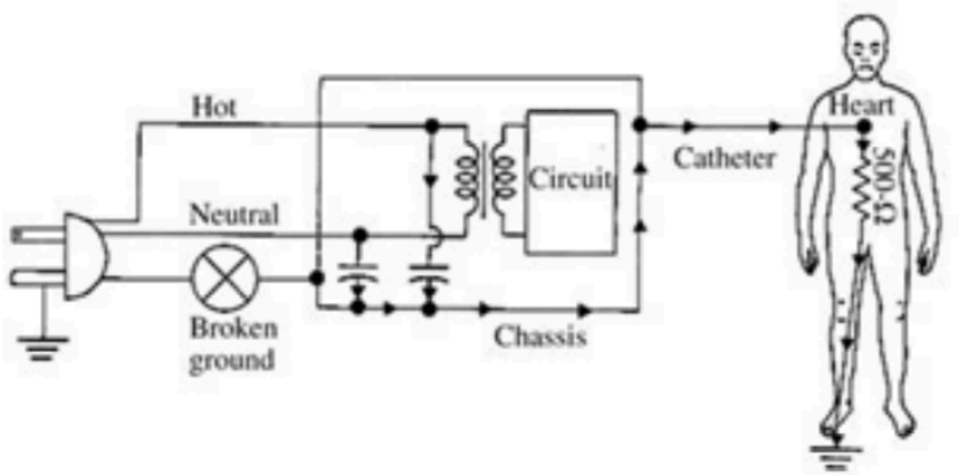
- Main causes
  - Leakage currents in line-operated equipment
    - Undesired currents go through insulated conductors at different potentials
  - Differences in voltage between grounded conductive surfaces

Microshock Hazards

- Leakage currents
  - If low resistance to ground is available → no problem, majority of current flows through ground



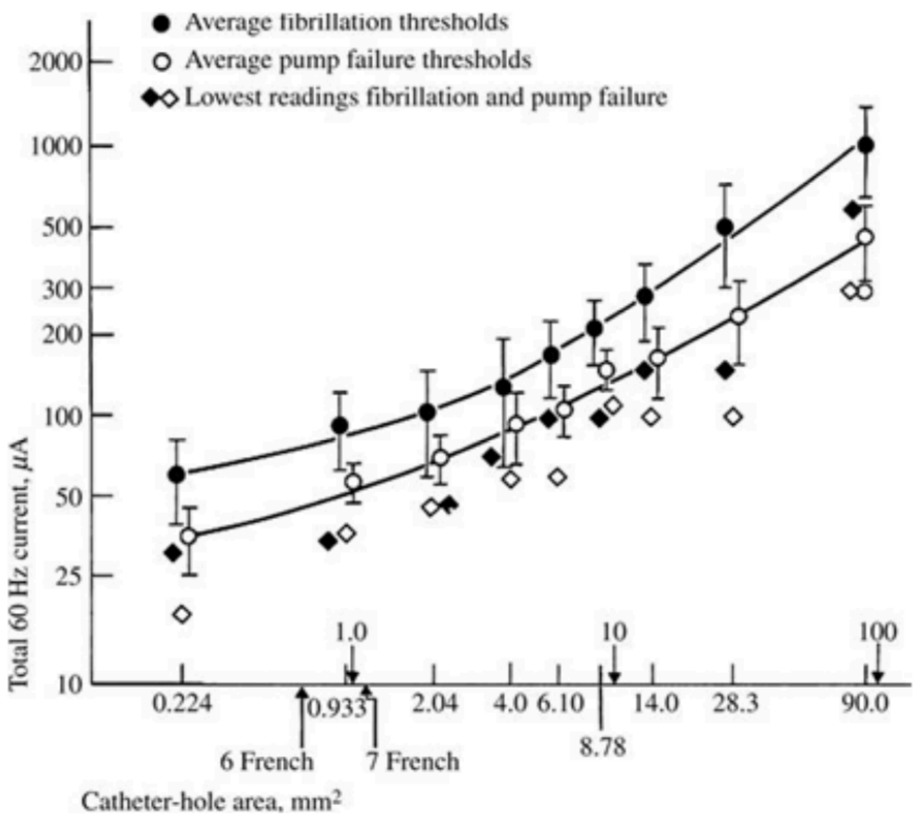
  - If ground is broken → all current flows through patient



Sources of Patient Leakage Currents

- All electrodes (and sensors with inputs to amplifiers) have leakage currents
- Any indwelling electrodes with pathways to or location close to heart are especially dangerous
  - epicardial or endocardial electrodes from an external cardiac pacemaker
- Liquid filled catheters for blood pressure, sampling or delivery of drugs (volumetric pumps which are line powered)
- Danger really only occurs when there is electrical connection to the heart

Electrode Current Density



- Experiments suggest smaller electrodes (or catheters) are more dangerous

What if No Modern Standards?

- Patient in ICU with right leg electrode grounded to avoid noise and left ventricle pressure conductive diaphragm also grounded (unrealistic scenario)
- A defective floor polisher plugged into the ECG Power supply injects 5 A into the ground wire

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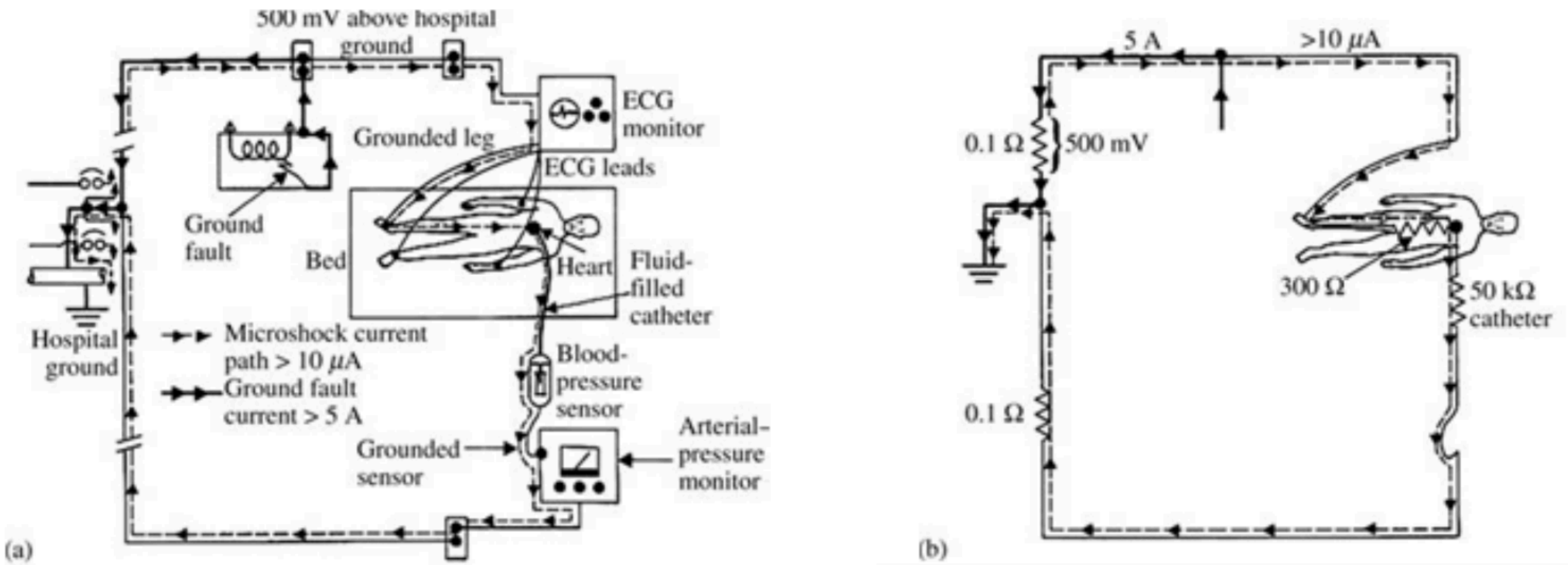
- With 0.1 Ω resistance in ground wire 500 mV is added to ground on ECG side
- Patient's body, ECG electrode, and catheter are <50 kΩ causing >10 μA through heart

Ground Loops



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Patient's Electrical Environment

- Any two conductive surfaces near a patient cannot have more than
  - 500 mV potential difference for general care areas in a hospital
  - 40 mV in a critical care area (NEC 2006)
- In general care areas patients have only incidental contact with electrical devices
- In critical care areas all exposed conductive surfaces must be grounded at a single point
- Other regulations exist for numbers and connections of outlets in each patient care area

Single-point Grounding System

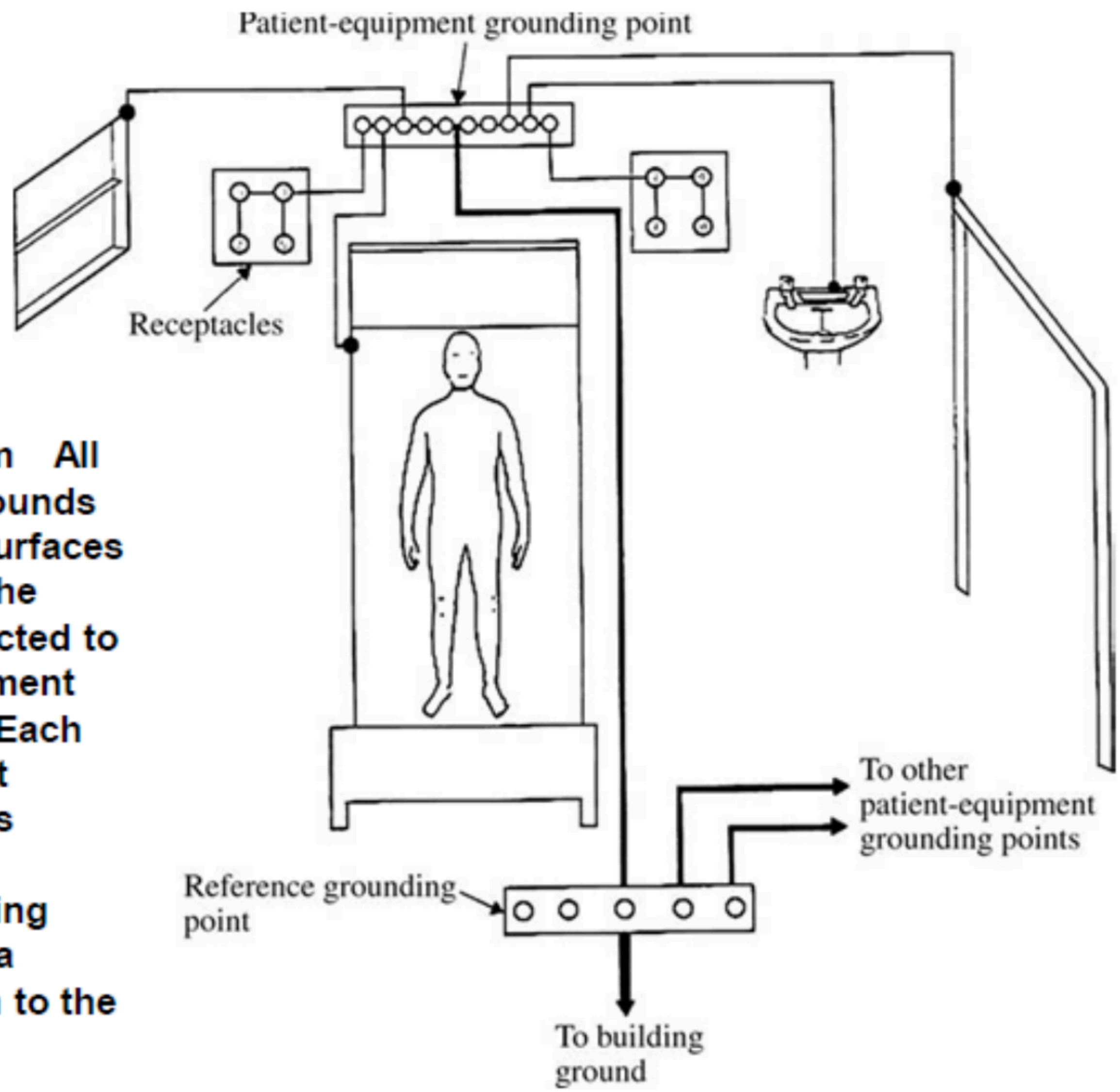
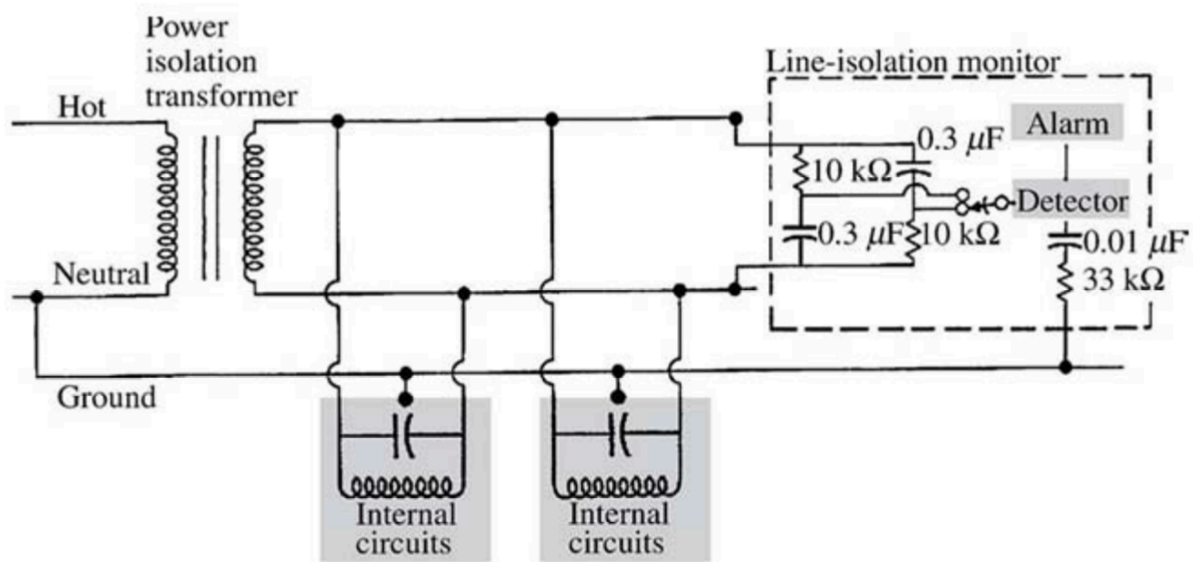


Figure 14.14
Grounding system All the receptacle grounds and conductive surfaces in the vicinity of the patient are connected to the patient-equipment grounding point. Each patient-equipment grounding point is connected to the reference grounding point that makes a single connection to the building ground.

Isolated Power Systems

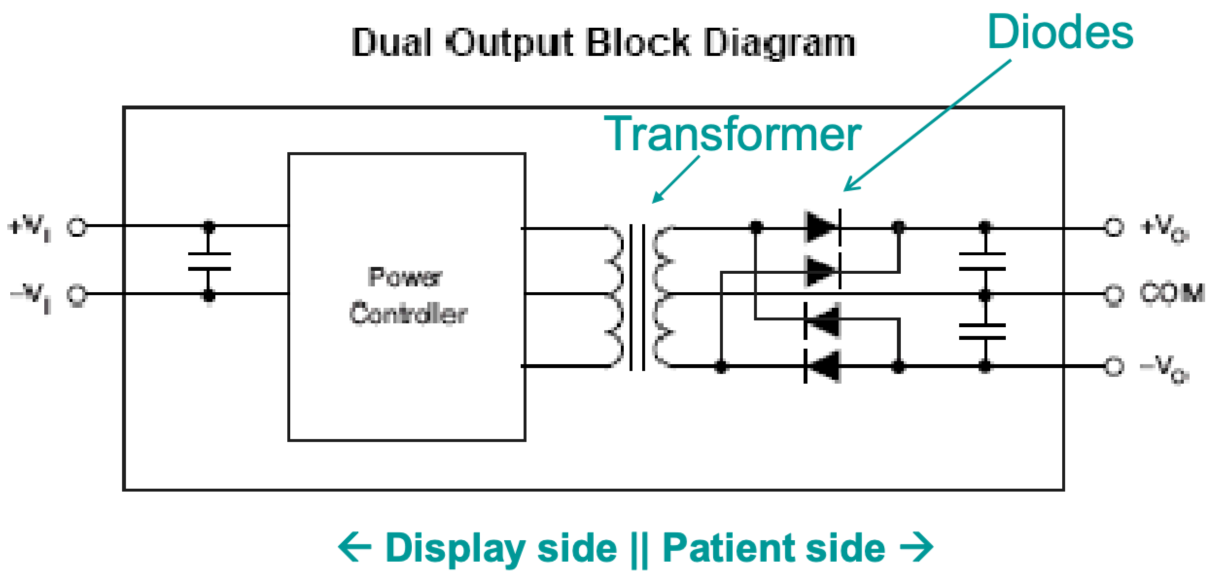
- Ground fault
  - Short circuit between hot conductor and ground
  - Injects large current into grounding system
  - Can create hazardous potentials on grounded surfaces
- Isolation transformer
  - Isolates conductors against ground faults
  - May include ground fault monitor/alarm



Electrical instruments

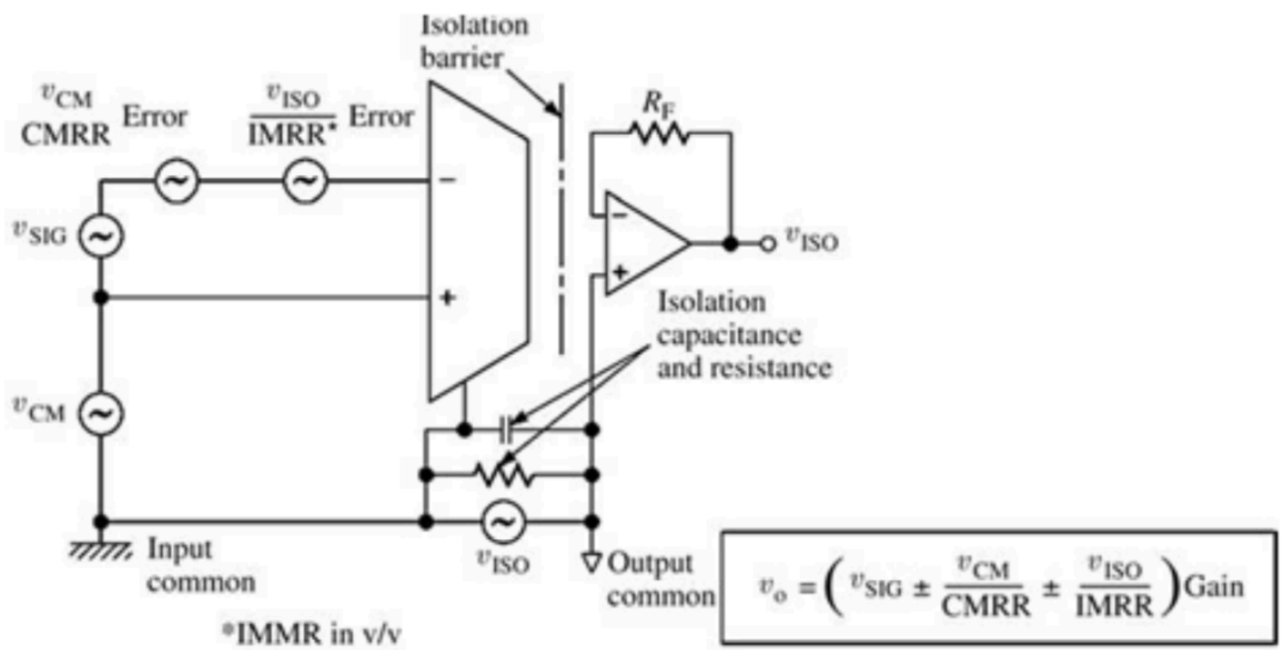
Isolated Power Supply

- DCH010505 Isolation Power Supply



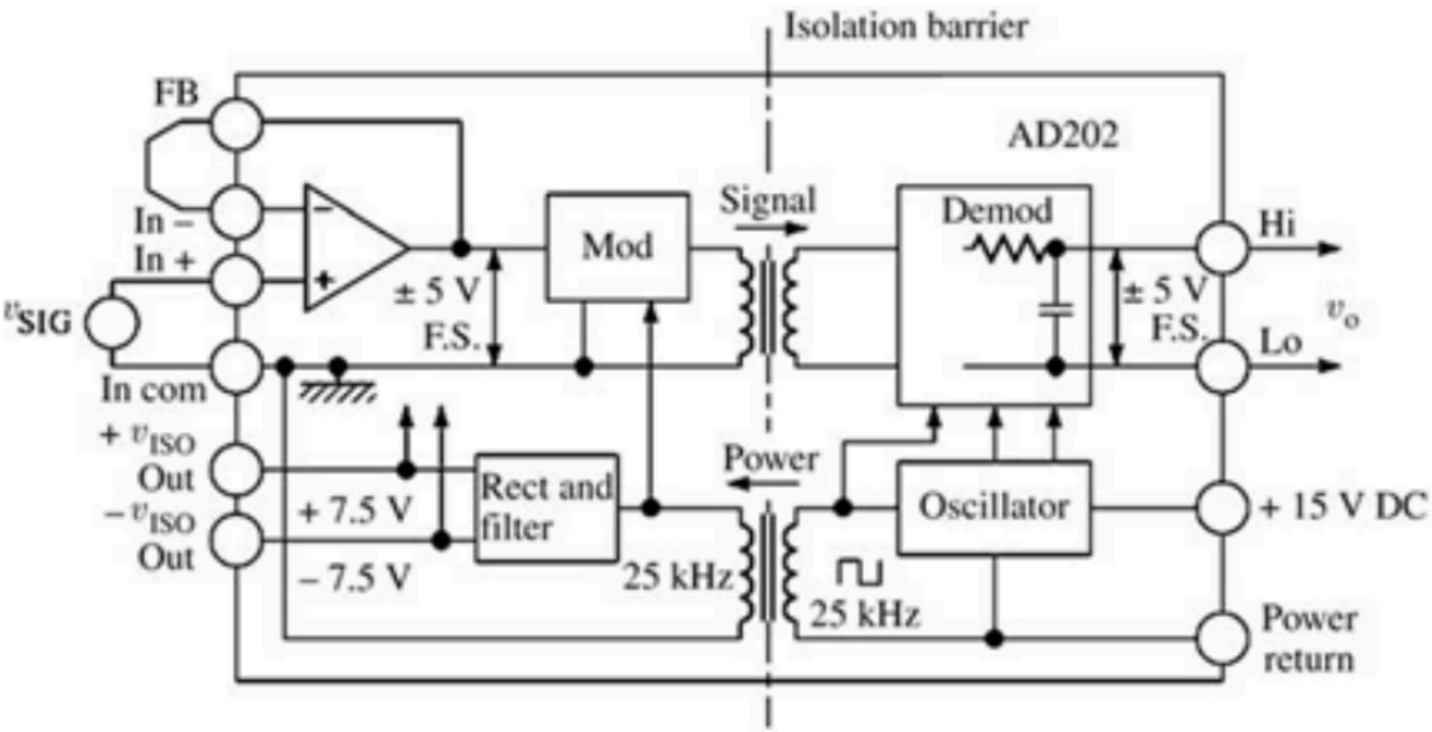
Isolation Amplifiers

- Isolation amplifiers
  - Devices that break ohmic continuity of electric signals between input and output of the amplifier
  - Different supply voltage sources and different grounds on each side of the barrier



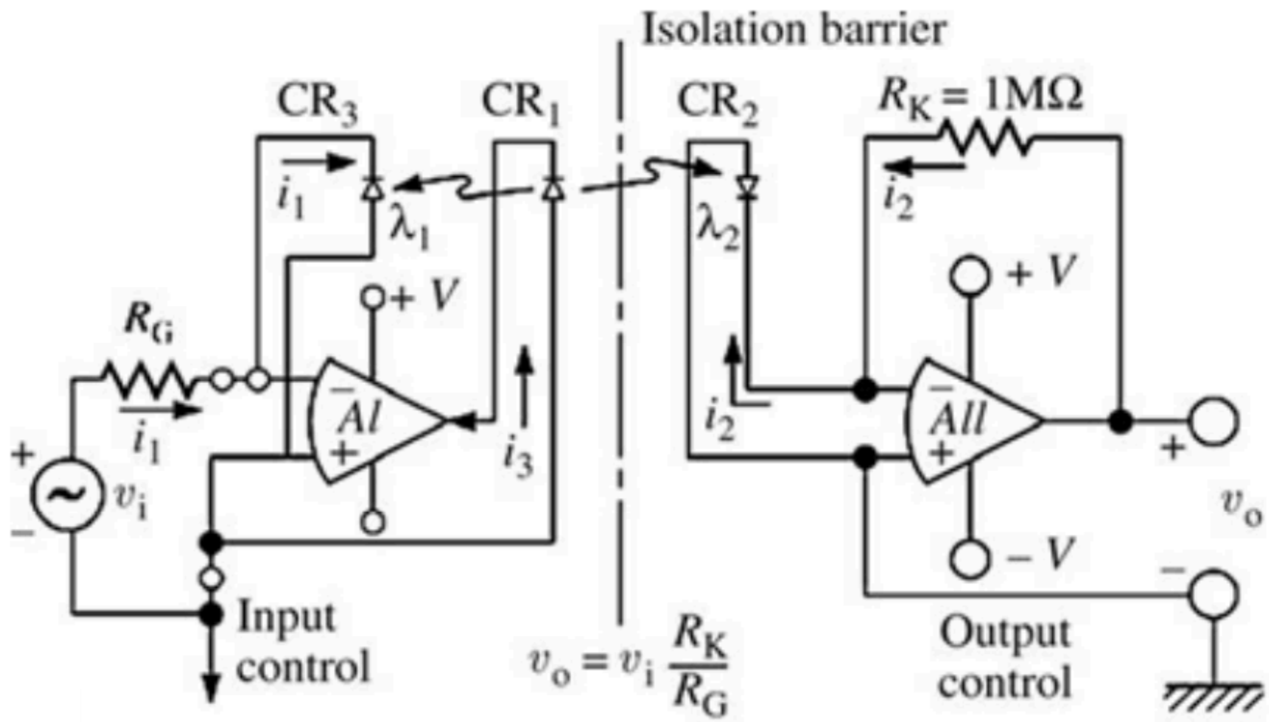
Isolation Amplifiers

- Transformer isolation
  - No current across barrier



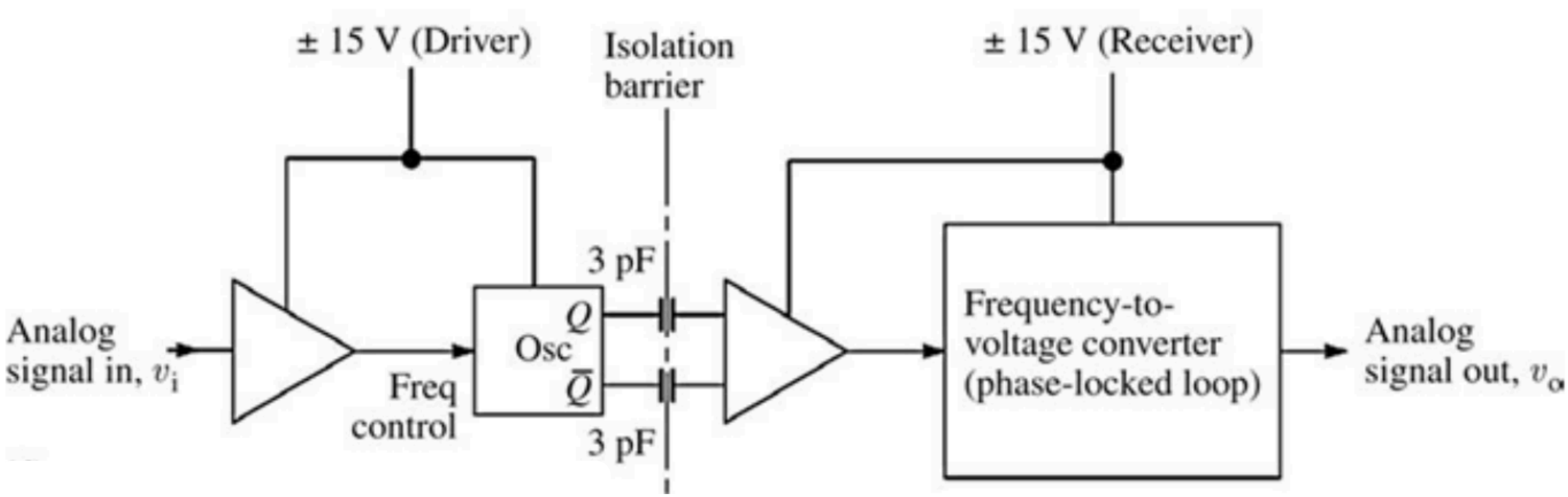
Isolation Amplifiers

- Optical isolation
  - No current across barrier



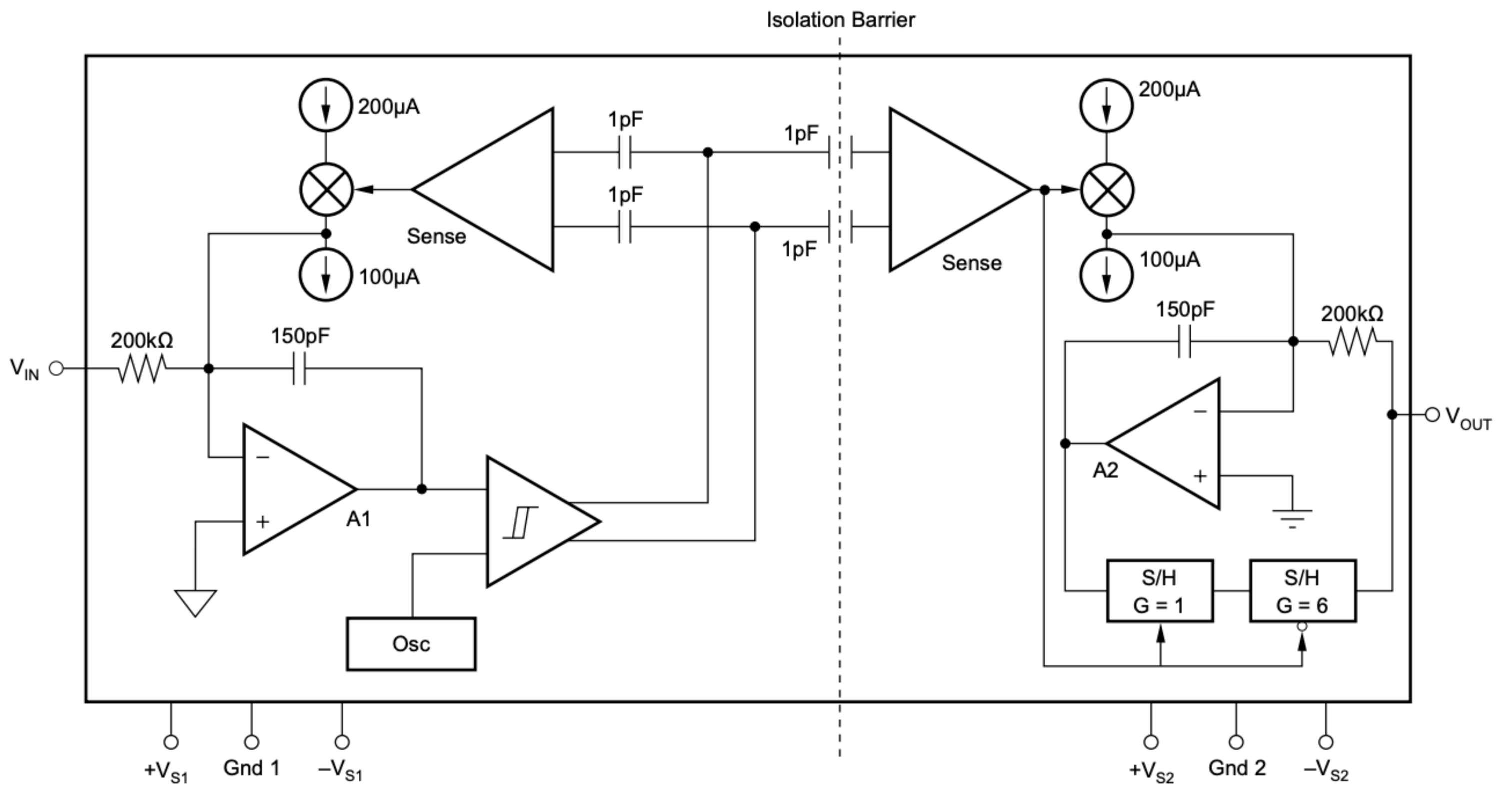
Isolation Amplifiers

- Capacitive isolation
  - No current across barrier
  - Functional diagram:



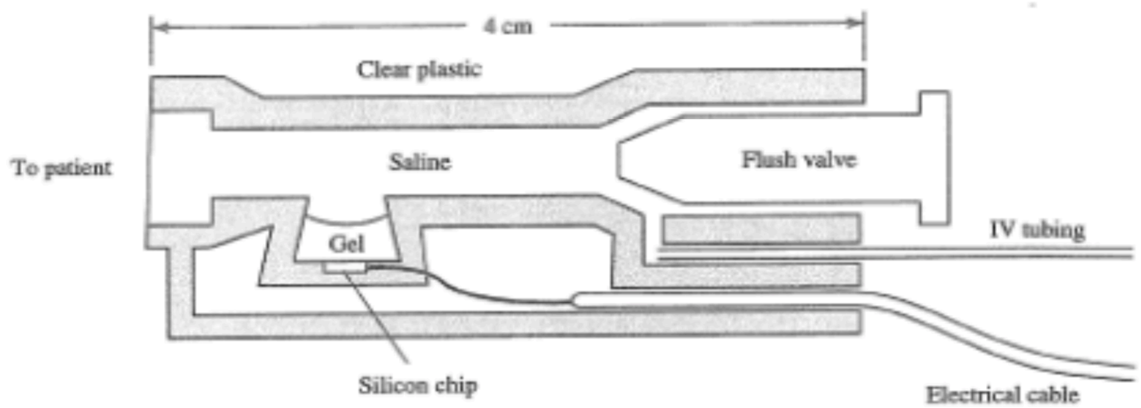
Isolation Amplifiers

- Capacitive isolation
  - ISO124

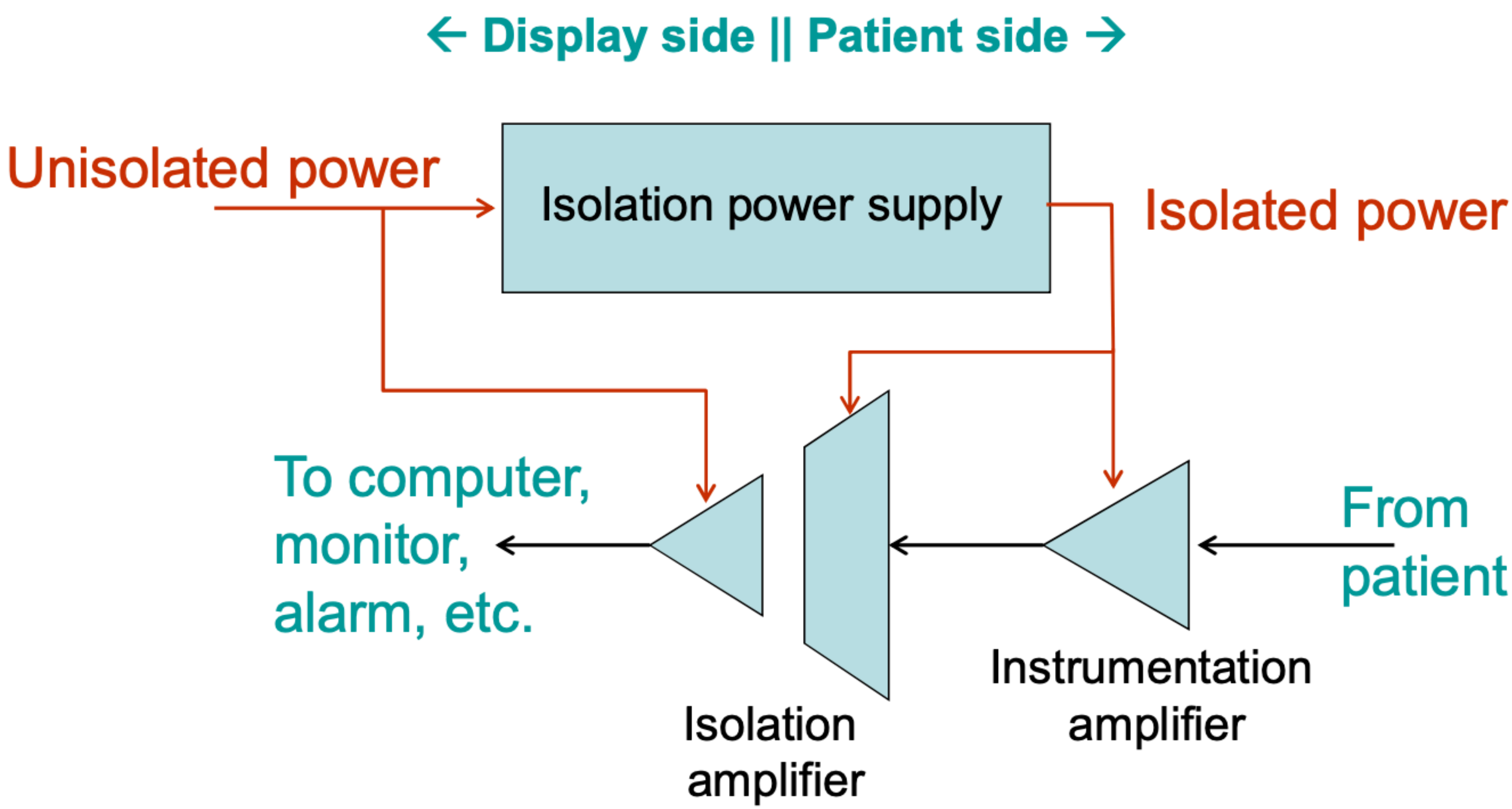


Implants

- Proper insulation required to prevent microschocks



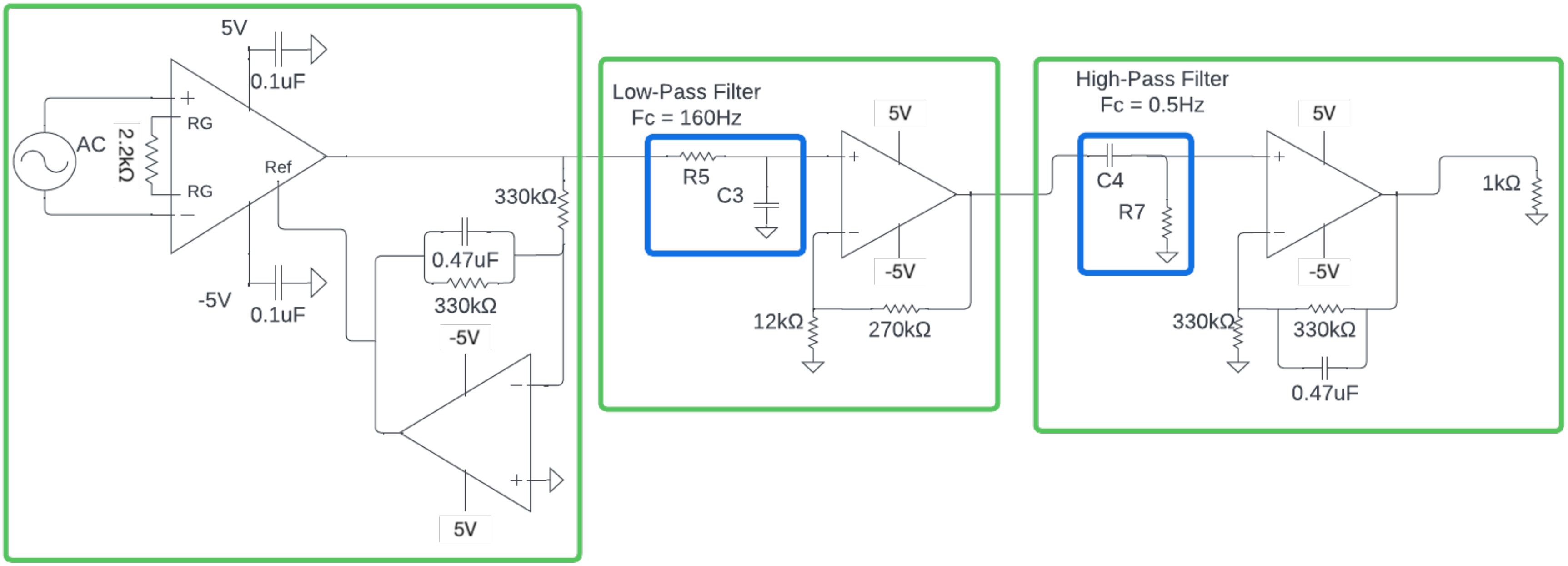
Basic Isolation System



Big Ideas

- ECG Signal used to diagnose heart conditions and potentially predict heart failure
  - Electrode placement important in monitoring
- Two kinds of heart rate monitors
  - Averaging and beat-to-beat
    - Use filters and circuitry to detect heart rate
- Two main safety problems
  - Macroschocks and microshocks from leakage currents
  - Really only a problem if going through heart
- Solutions
  - Electrical isolation
    - Isolation amplifiers and Barrier isolation
  - Good grounding

Lab 4 - Breadboarding



Admin

- Finish Lab 3 and submit deliverables in Canvas by next lab day at midnight