Outline

- Cardiac cycle
- Eindhoven’s triangle
- 12 lead EKG
- Biopotential amplifiers

Syllabus for Unit 3 - revised

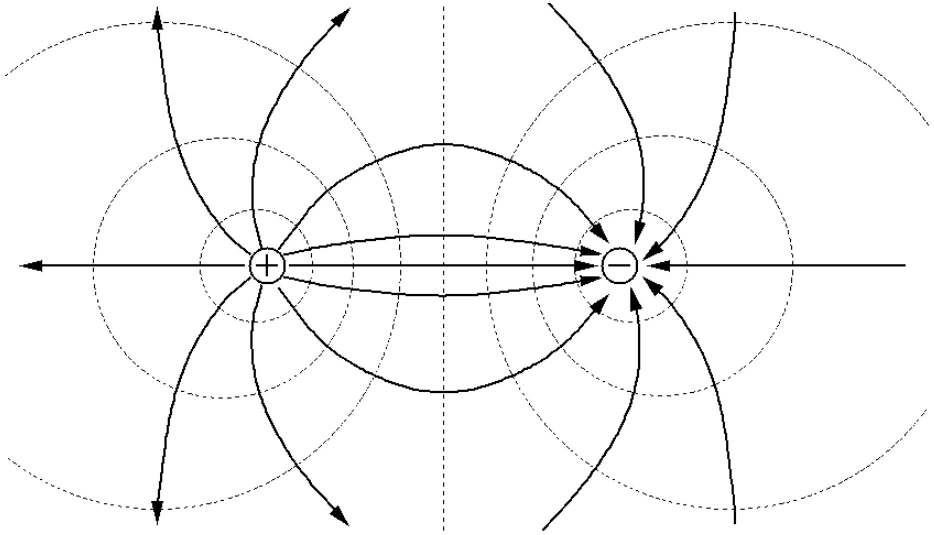
	Topics
Week 12	Chapter 2 Inductive, Piezoelectric and Capacitive Sensors, Digital Filters
Week 13	Capacitive Sensors (problems), Chapter 6 Biopotential Amplifiers, **(11/18) Homework #5**
Week 15	Chapter 6 EKG examples, EKG design - In class project **(12/2) MATLAB Assignment 3**
Week 16	Chapter 5 Biopotential Electrodes, Blood Pressure, Heart Sounds, Exam Review **(12/7) Homework #6, (12/7) EKG project (optional)**
Week 17	**Final Exam 12/14/21, 11:00 am – 1:45 pm, ECSN 2.126**

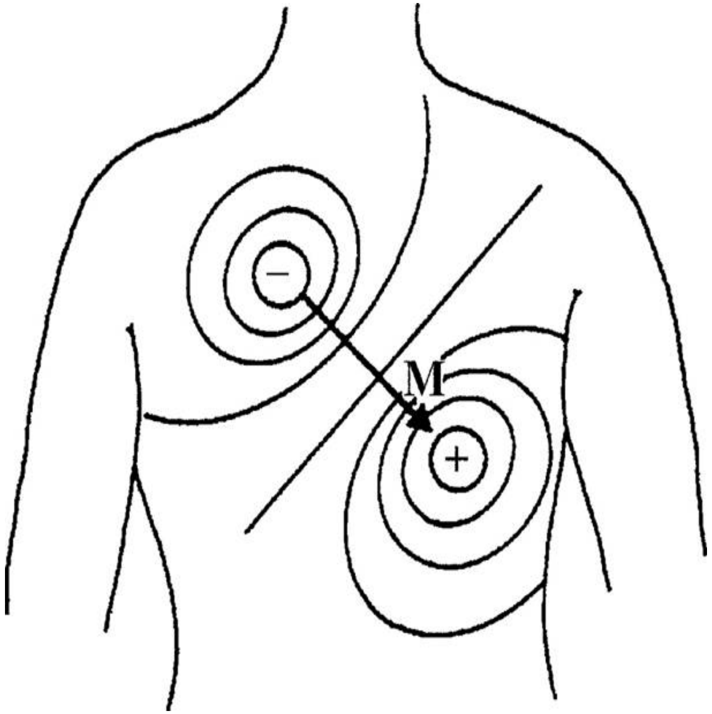
Cardiac Cycle Introduction

- **ECG Basics**
- **Animated ECG**
- Reference: Quantitative Human Physiology by Josef Feher

Understanding ECG Measurement

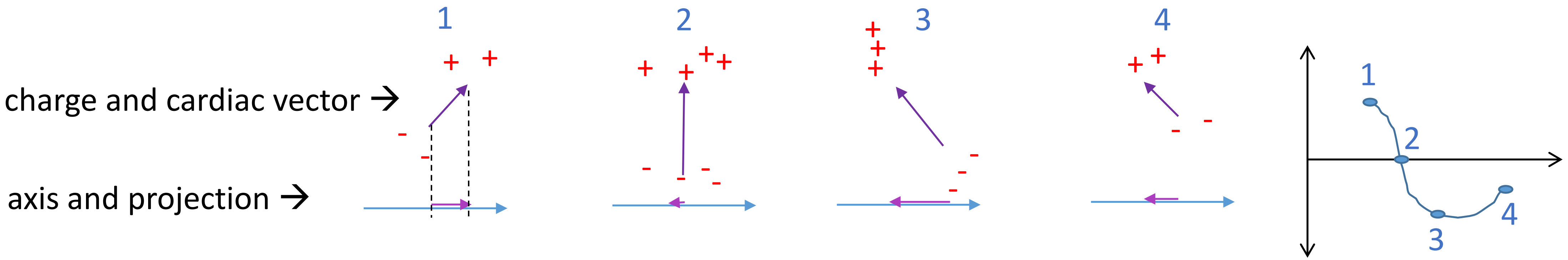
- **Cardiac vector: from – to + charge**
- **Electric dipole created by the electric field generated by the heart**
- **Represents the electrical field at a <u>specific instant</u>**
- **Magnitude and direction vary as the cardiac cycle progresses – it rotates**





Measuring voltage from charge spread

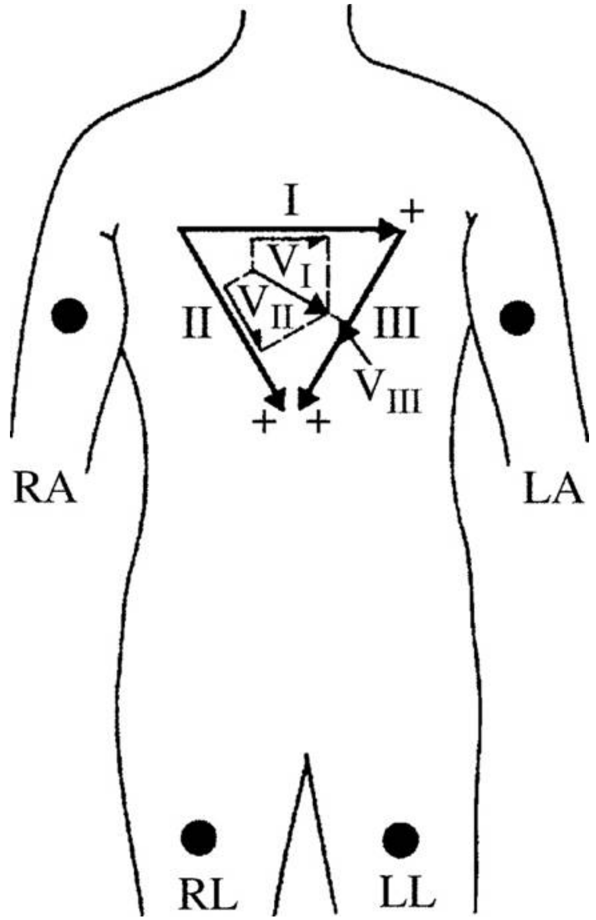
- Cardiac vector is also called a *dipole* in video and many texts
- Voltage is vector *pointing towards + charge*, magnitude depends on amount of separated charge and distance of separation.
- Cardiac vector is projected onto a measurement axis as below



- By having 3 or more axes, we get multiple views or projections to get a more complete picture. Ideally these are equally separated around 360°

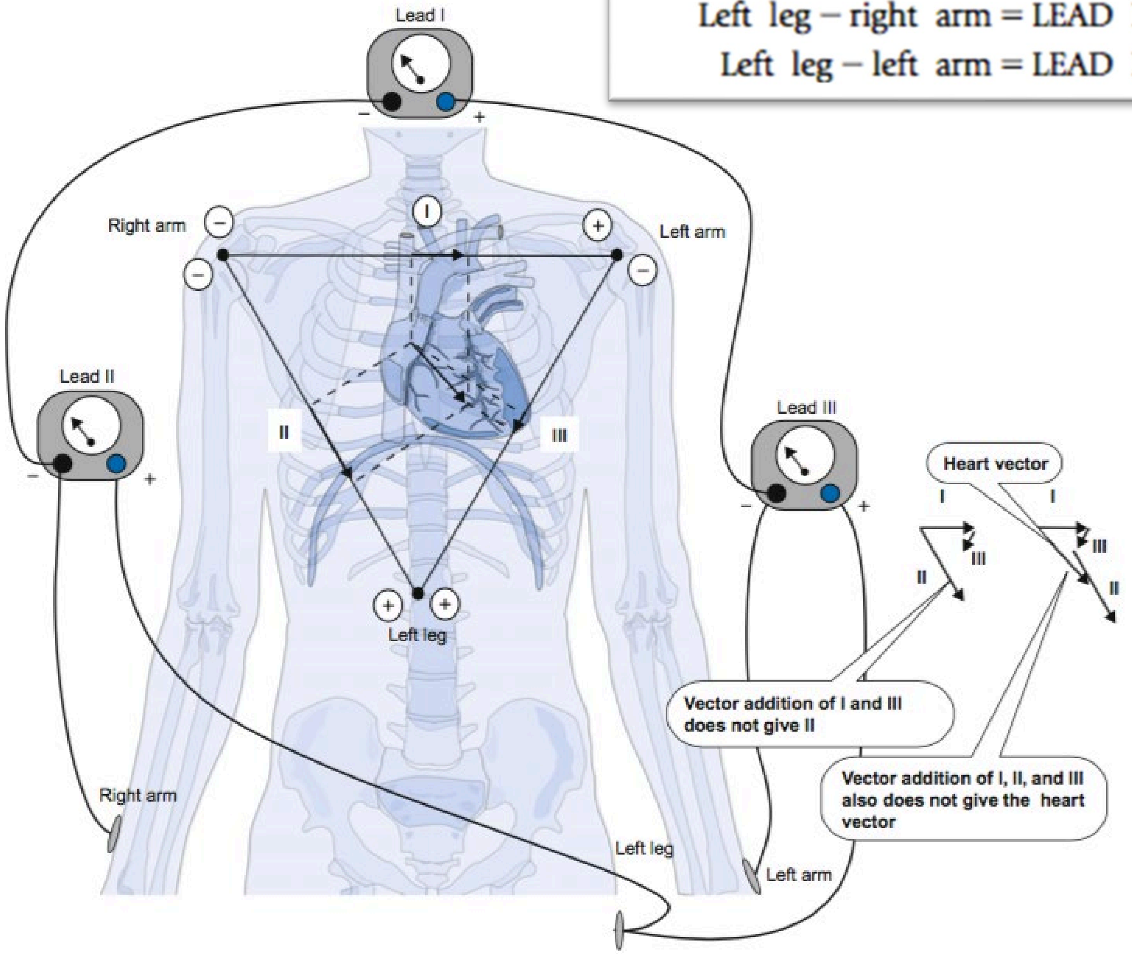
Basic 3 Lead ECG

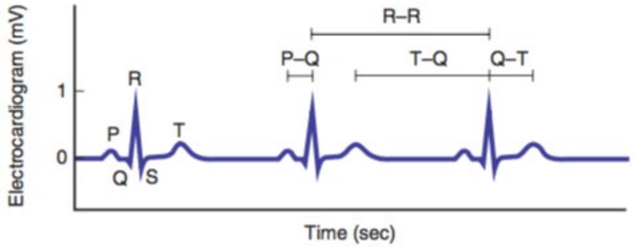
- **Standardized lead location**
- **Standardized naming convention**
  - **Lead I – RA to LA (0º)**
  - **Lead II – LL to RA (60º)**
  - **Lead III – LL to LA (120º)**
- **This is known as Einthoven's triangle**
- **KVL tells us that I – II + III = 0**
- **Using this we can determine the cardiac vector**

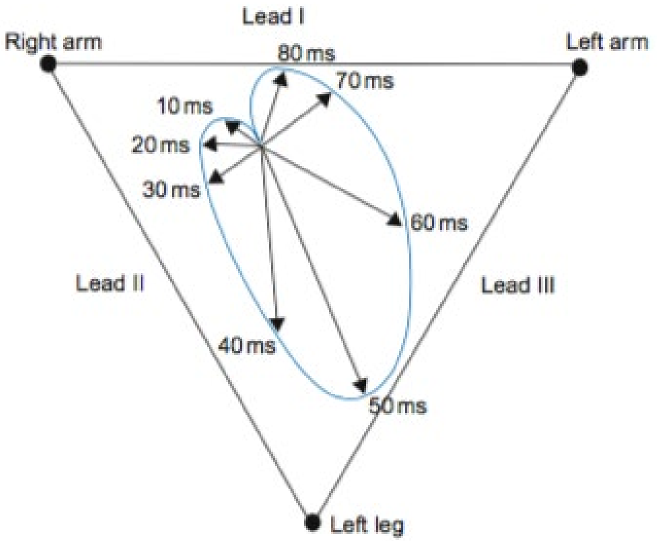


Cardiac Vector and Cardiac Cycle

Left arm – right arm = LEAD I
Left leg – right arm = LEAD II
Left leg – left arm = LEAD III







Cardiac dipole traces a closed curve during each heartbeat. This is QRST at Lead II.

P wave

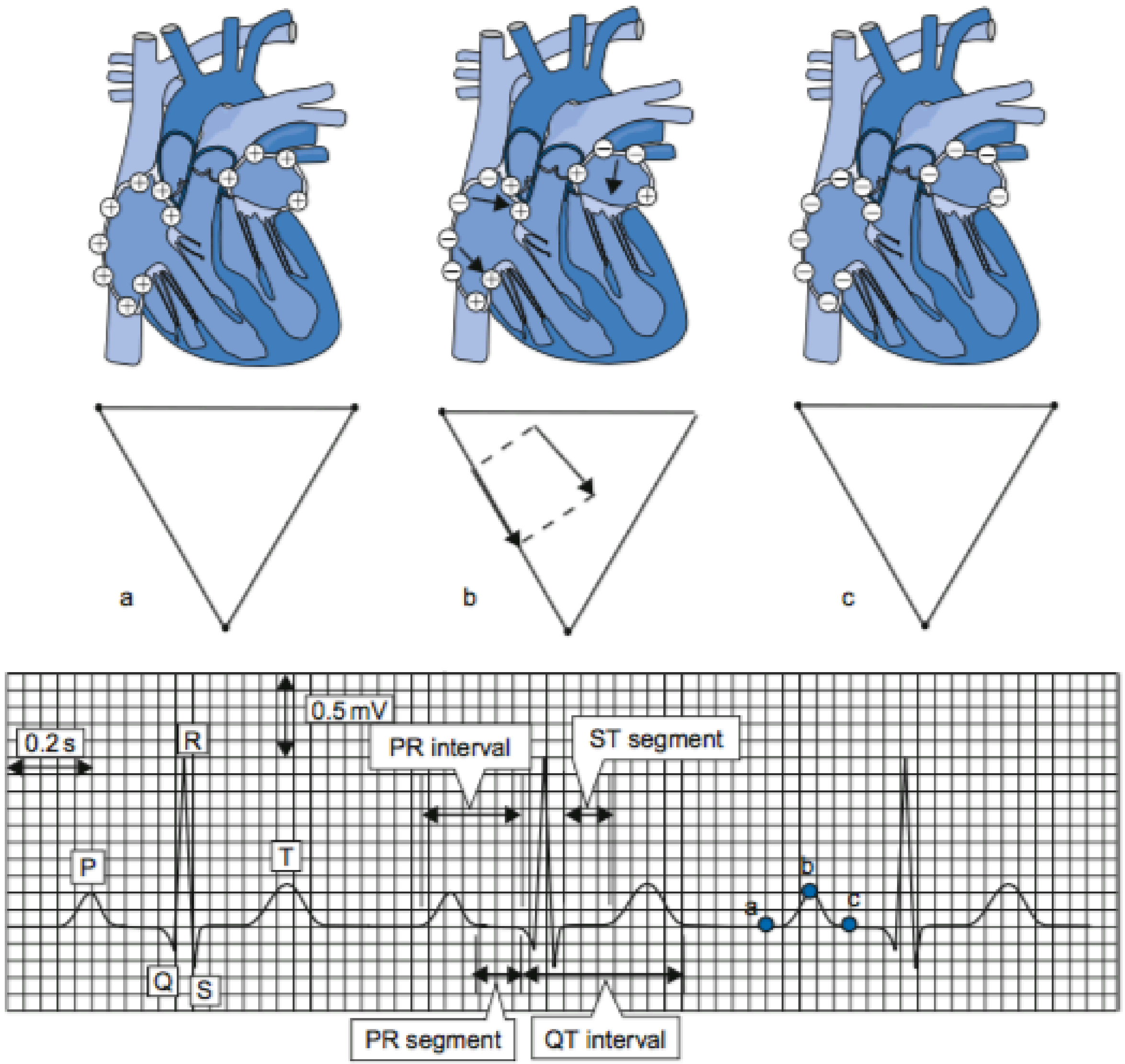


FIGURE 5.6.5 Origin of the P wave on the ECG. At rest all of the heart cells are polarized and there is no electric dipole. When the SA node depolarizes to threshold and initiates a cardiac impulse, the excitation is carried over the atria sequentially, with cells nearest the SA node depolarizing first. Bachmann's bundle simultaneously carries the excitation from the SA node to the left atrium, causing simultaneous activation of right and left atria. This pattern of depolarization creates an electric dipole directed more or less along the lead II axis and it is picked up by the ECG as the P wave. The magnitude of the lead II voltage at any time is the projection of the cardiac electric dipole moment onto the lead II axis, as shown in (b). This is always true, but the magnitude of the electric dipole is zero prior to activation (a) and after the atria are completely depolarized (c).

QRS complex and T wave

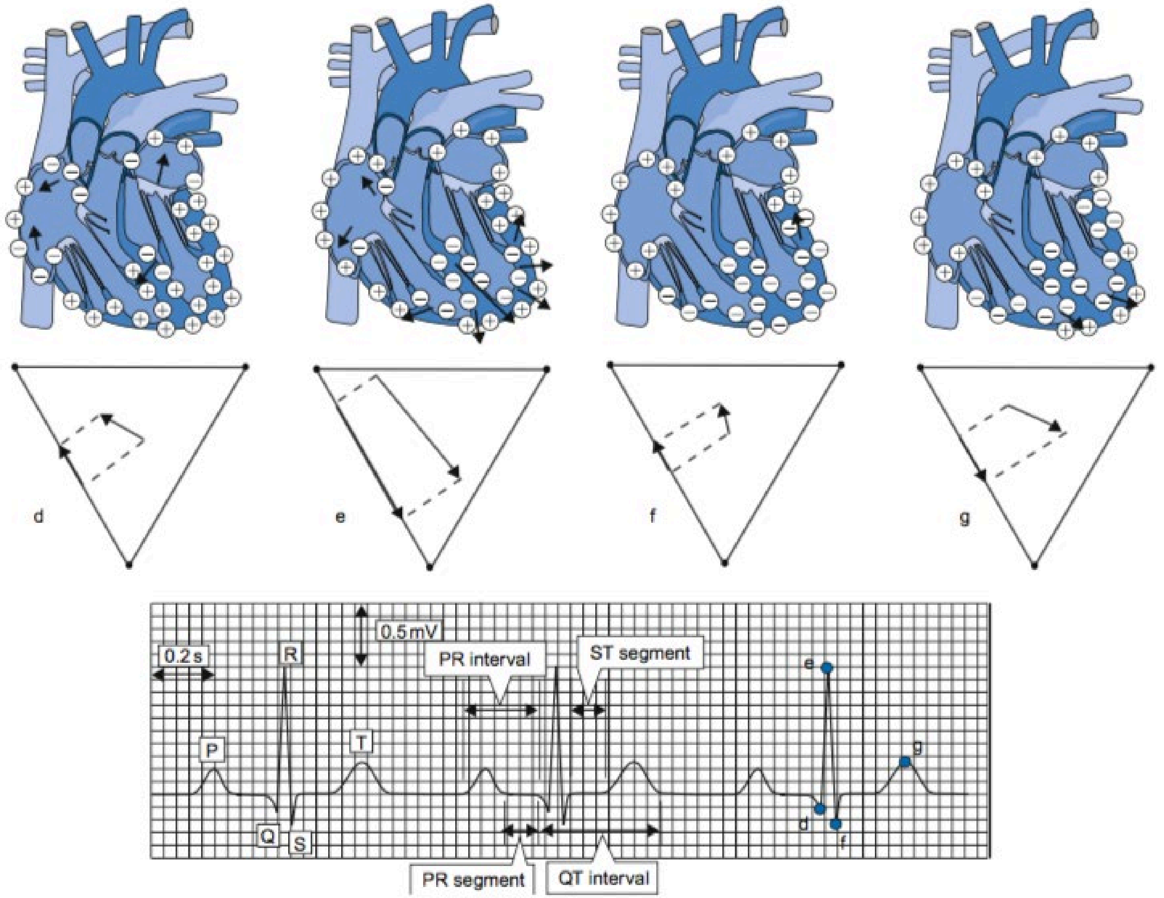
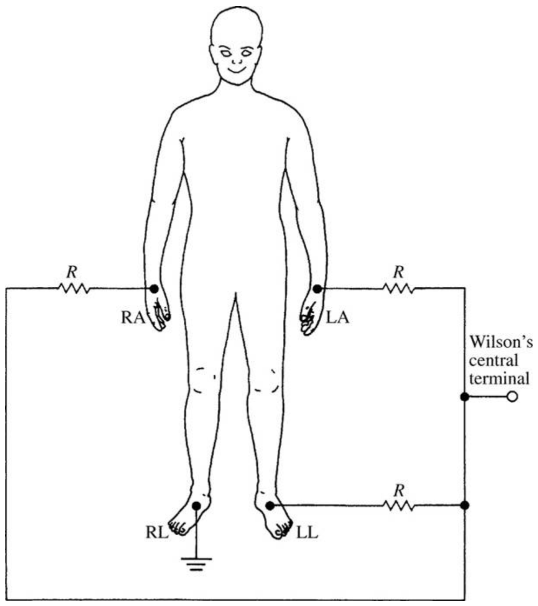
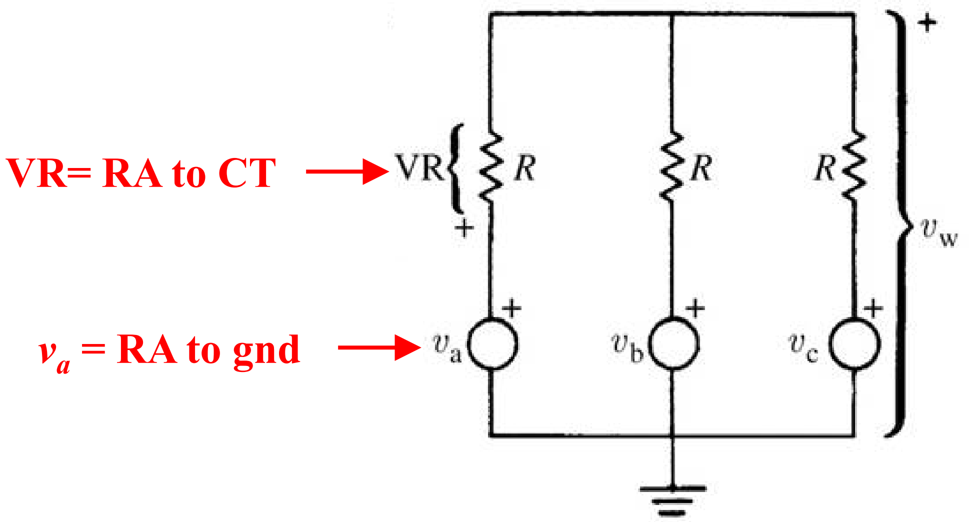


FIGURE 5.6.6 Origin of the QRS complex and T wave of the lead II scalar ECG. The spread of activation during ventricular activation creates a cardiac dipole that varies in magnitude and direction because of the sequence of activation produced by the left and right bundle branches and the Purkinje fibers. The Q wave is negative because the depolarization of the ventricles begins with the septum and the resulting dipole points away from the lead II axis (d). The largest vector arises from depolarization of the inner (subendocardium) apex of the heart, while the outer (subepicardium) apex remains polarized. This forms the R wave (e). The S wave is also negative and arises from the last depolarization of the free left ventricular wall near the left atrium. At this time the dipole vector points away from the lead II axis (f). Repolarization of the atria is buried in the QRS complex. Repolarization of the T wave is upright because the subepicardium has a shorter action potential and repolarizes before the subendocardium, creating a dipole pointing along the lead II axis (g).

Connections for Augmented Lead ECG

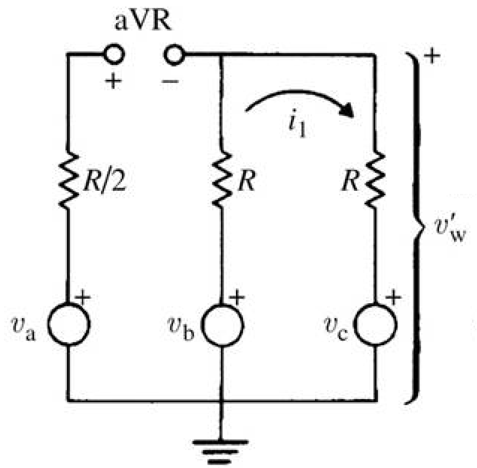
- Basic connections for the augmented leads are shown below
- Electrical equivalent circuit is to the right
- R shunts each circuit between central terminal and the lead, which <u>reduces the signal amplitude</u>
- Notice the right leg is grounded (all leads are unipolar)

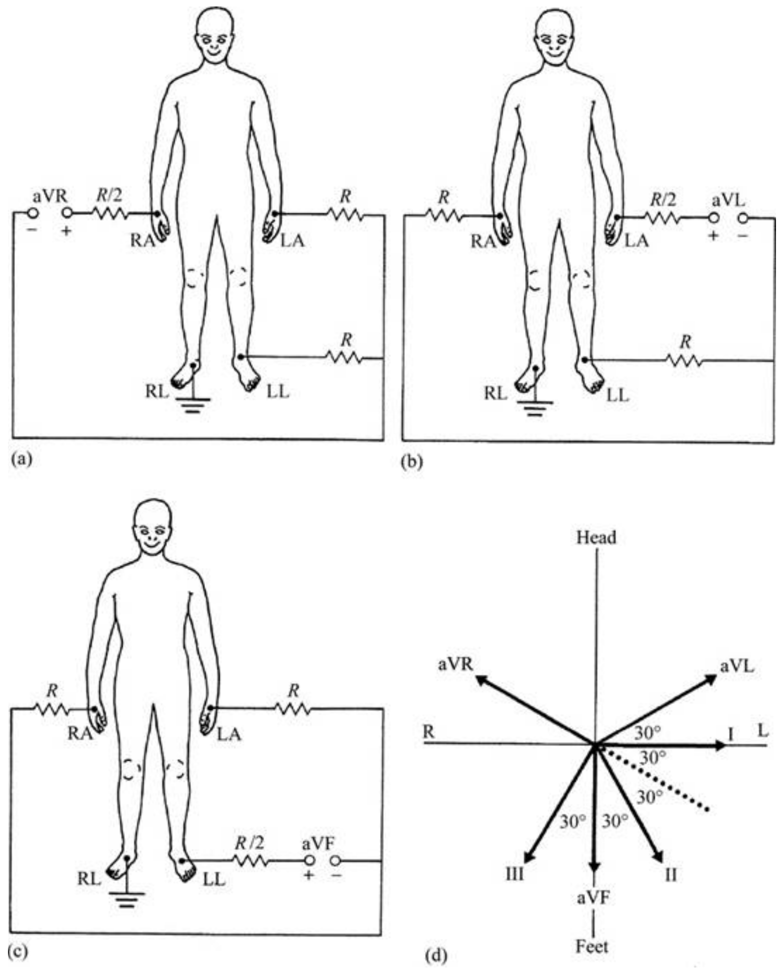




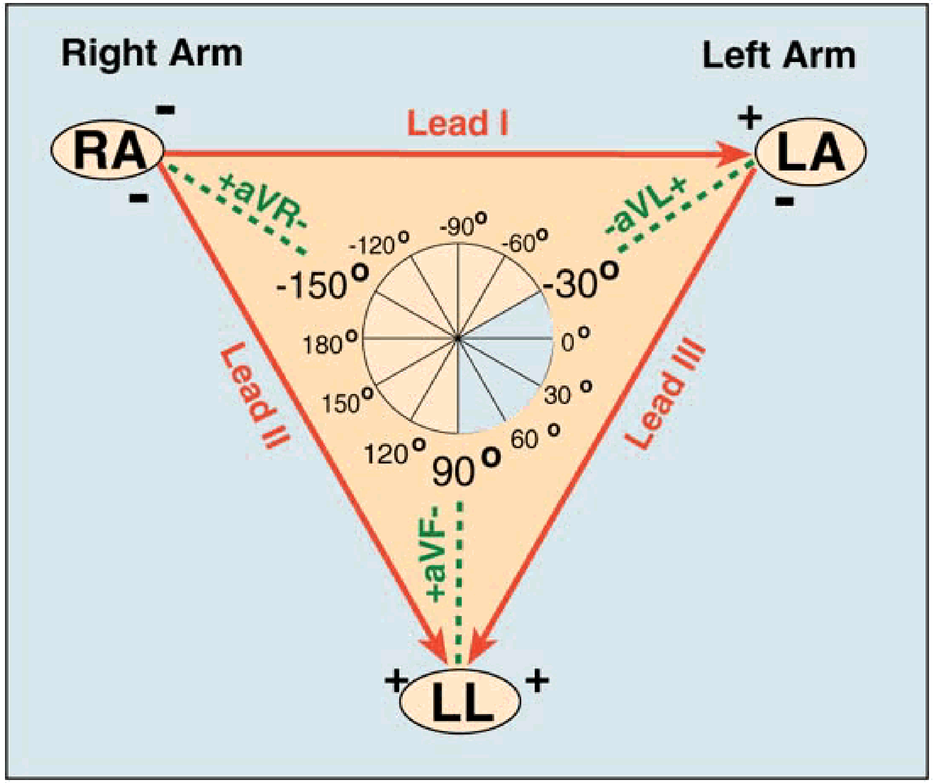
Augmented Leads - improved

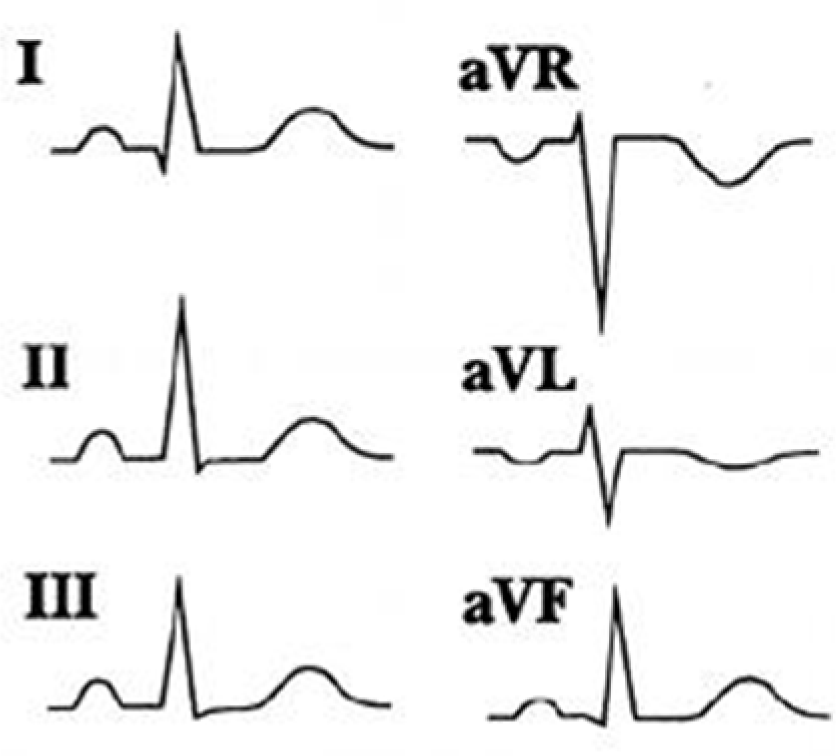
- If we disconnect the connection between the limb being measured and the central terminal, we can increase the signal amplitude by 50%
- This is an improvement via measurement technique
- Proof is in the text (Example 6.1)





Sample Results from Different Leads



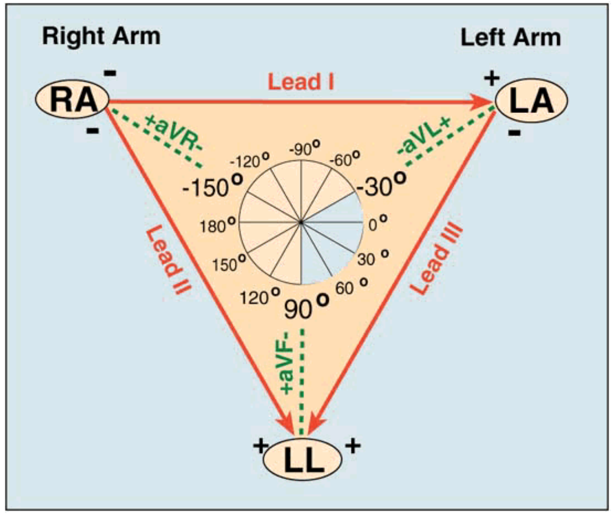


Video: [ECG Basics]

The Standard 12 Lead ECG

- **Frontal Plane:**

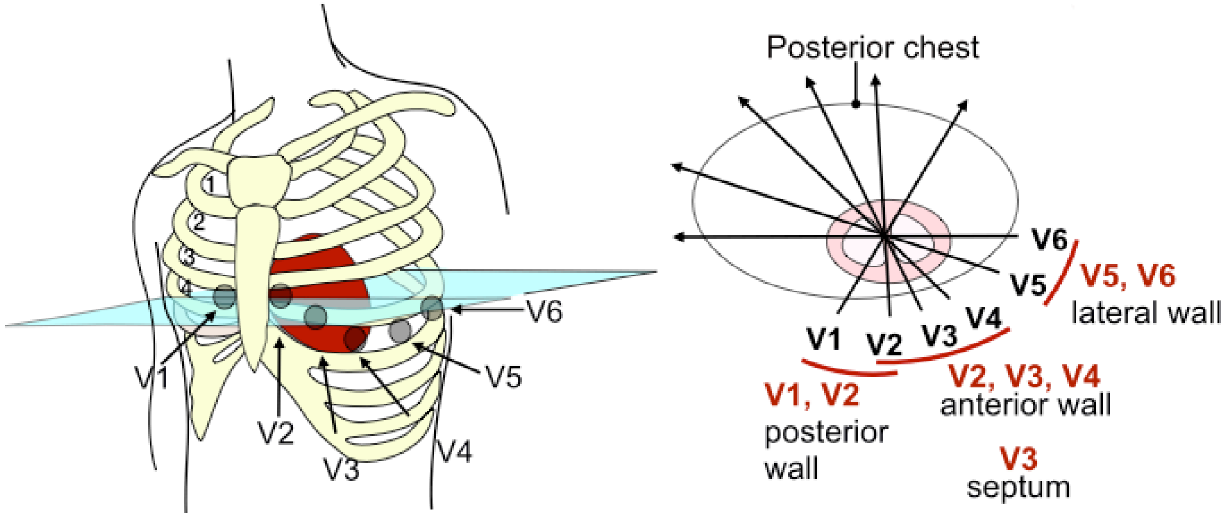
  3 Basic + 3 Augmented



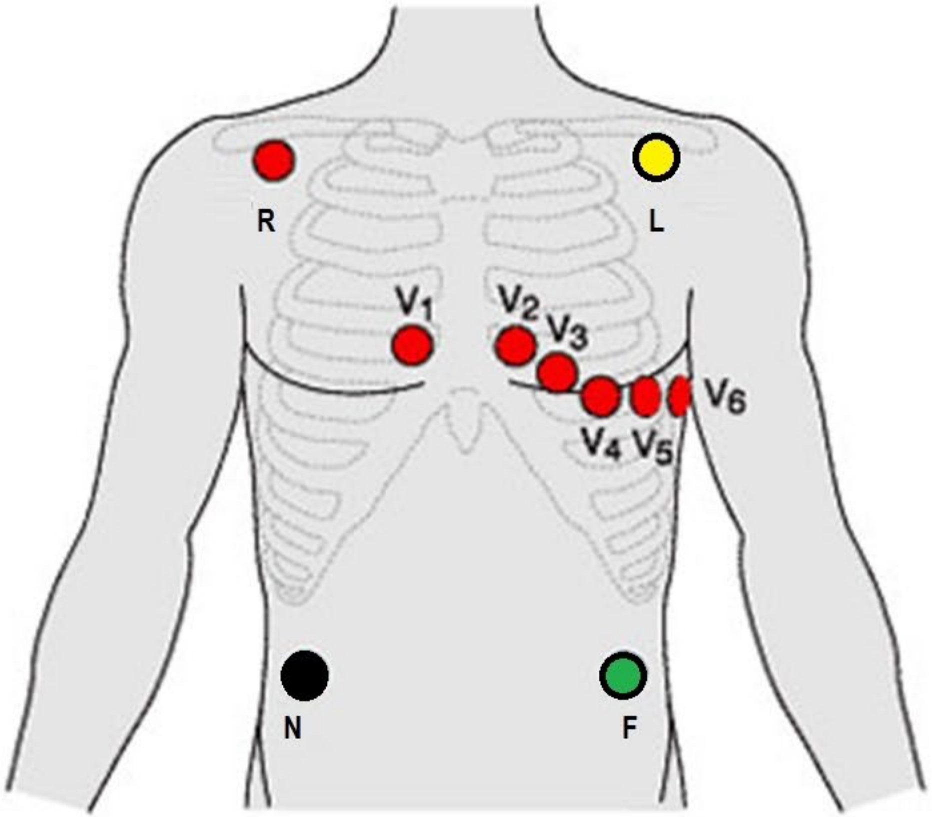
- **Transverse Plane:**

  6 Chest Leads

The 6 Left Chest Leads



Lead Placement - typical



I = L-R

II = F-R

III = F-L

aVR = R - (F+L)/2

aVL = L - (R+F)/2

aVF = F - (R+L)/2

V1 = C1 - (L+R+F)/3

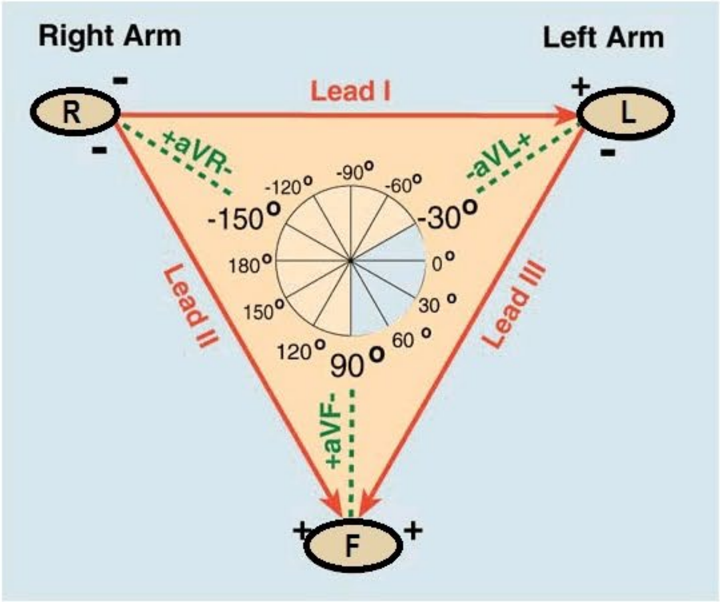
V2 = C2 - (L+R+F)/3

V3 = C3 - (L+R+F)/3

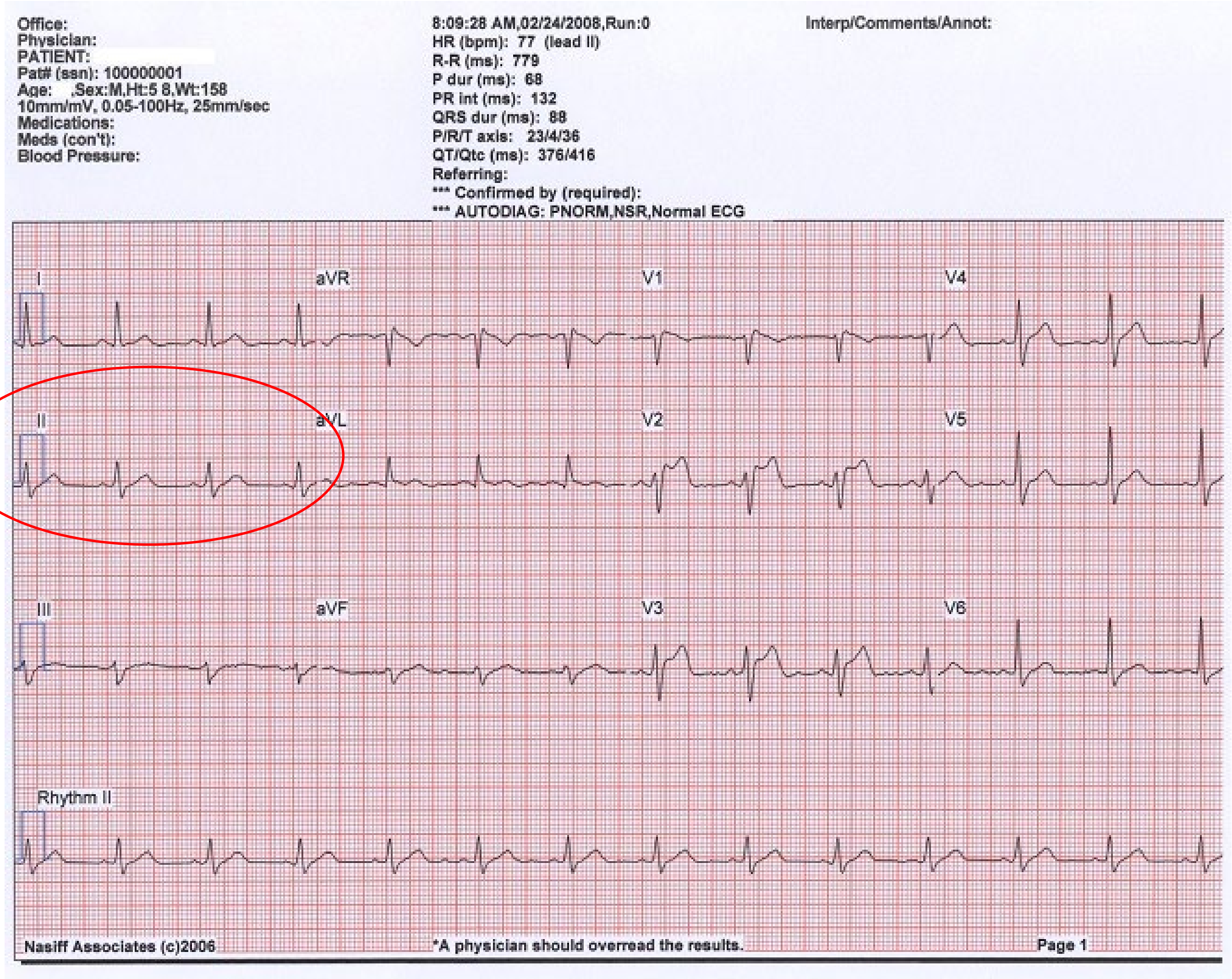
V4 = C4 - (L+R+F)/3

V5 = C5 - (L+R+F)/3

V6 = C6 - (L+R+F)/3



ECG Waveform – typical – Lead II is continuous

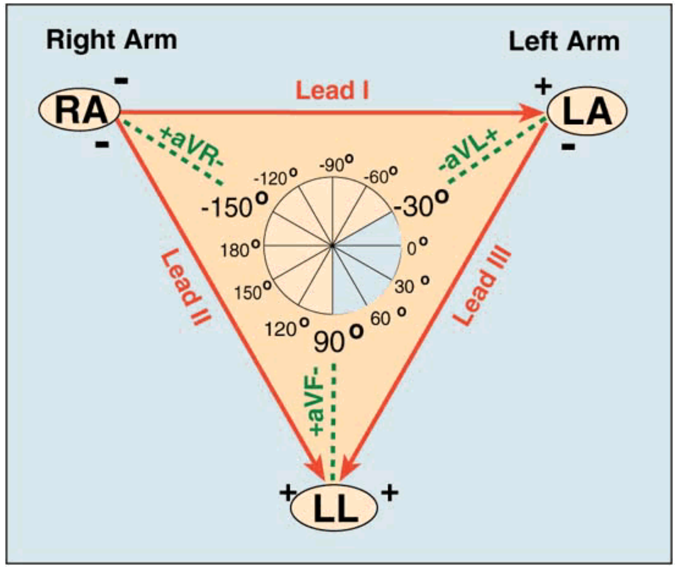


Biopotential Amplifiers: Problems

6.1 What position of the cardiac vector at the peak of the R wave of an electrocardiogram gives the greatest sum of voltages for leads I, II, and III?

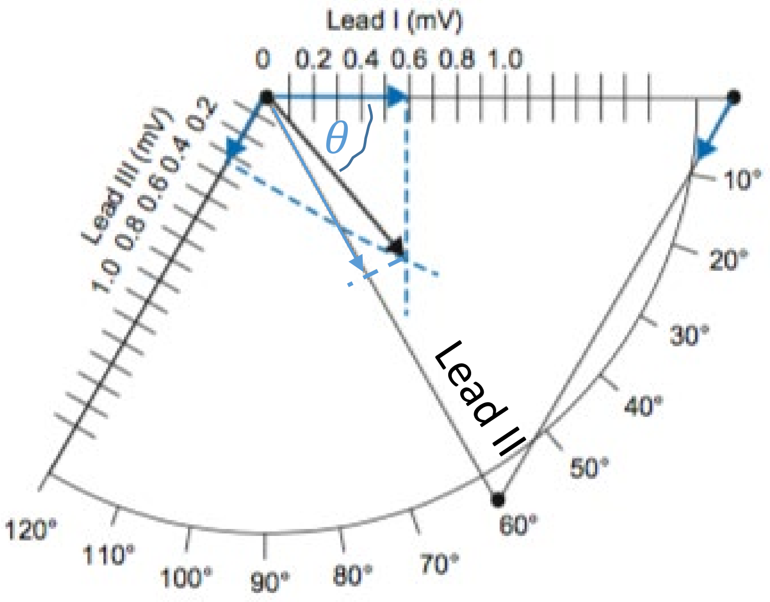
6.2 What position of the cardiac vector during the R wave gives identical signals in leads II and III? What does the ECG seen in lead I look like for this orientation of the vector?

6.3 An ECG has a scalar magnitude of 1 mV on lead II and a scalar magnitude of 0.5 mV on lead III. *Calculate* the scalar magnitude on lead I.



Problem 6.1

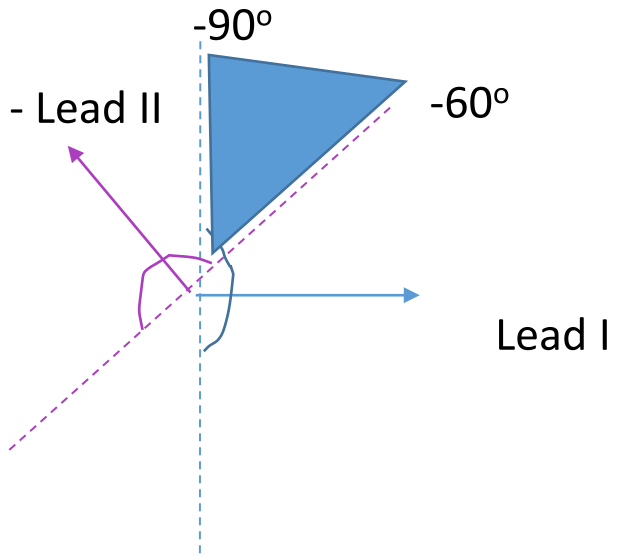
- Greatest sum of voltages for leads I, II and III:
- Maximize the sum of the projections:
  - M is the cardiac vector
  - $Mcos\theta + Mcos(60-\theta) + Mcos(120-\theta)$
  - For Lead II, Lead I, Lead III, in that order
  - take derivative and set equal to zero, see solution in Problem Set
- Or, by inspection, cardiac vector is strongest when aligned to Lead II



Problem 18

Problem 18. At a given instant, Lead I of an Electrocardiograph reads a positive voltage but Lead II reads a negative voltage. Find the upper and lower limits of the direction of the cardiac vector and sketch it.

- A positive voltage on Lead I is in the direction of 0 degrees.
- A negative voltage on Lead II is in the opposite direction of 60 degrees (in EKG space, which is clockwise from 0 degrees) or -120 degrees (in EKG space)
- Draw these and find an intersection:
  -60 to -90 degrees (EKG space)



Biopotential Amplifiers

- **Basic characteristics:**
  - **High input impedance**
    - **To minimize loading of the measured signal**
    - **Biopotential electrodes are highly sensitive to loading as they typically are required to measure very small signals**
  - **Low output impedance**
    - **It has to drive a recording/output device or A/D converter**
  - **High CMRR**
    - **Noise signals are often larger (sometimes much larger) than the signal we are trying to measure**
  - **High differential gain**
    - **Measured signals can be very small (μV to mV) and need to be amplified for use by the output device**

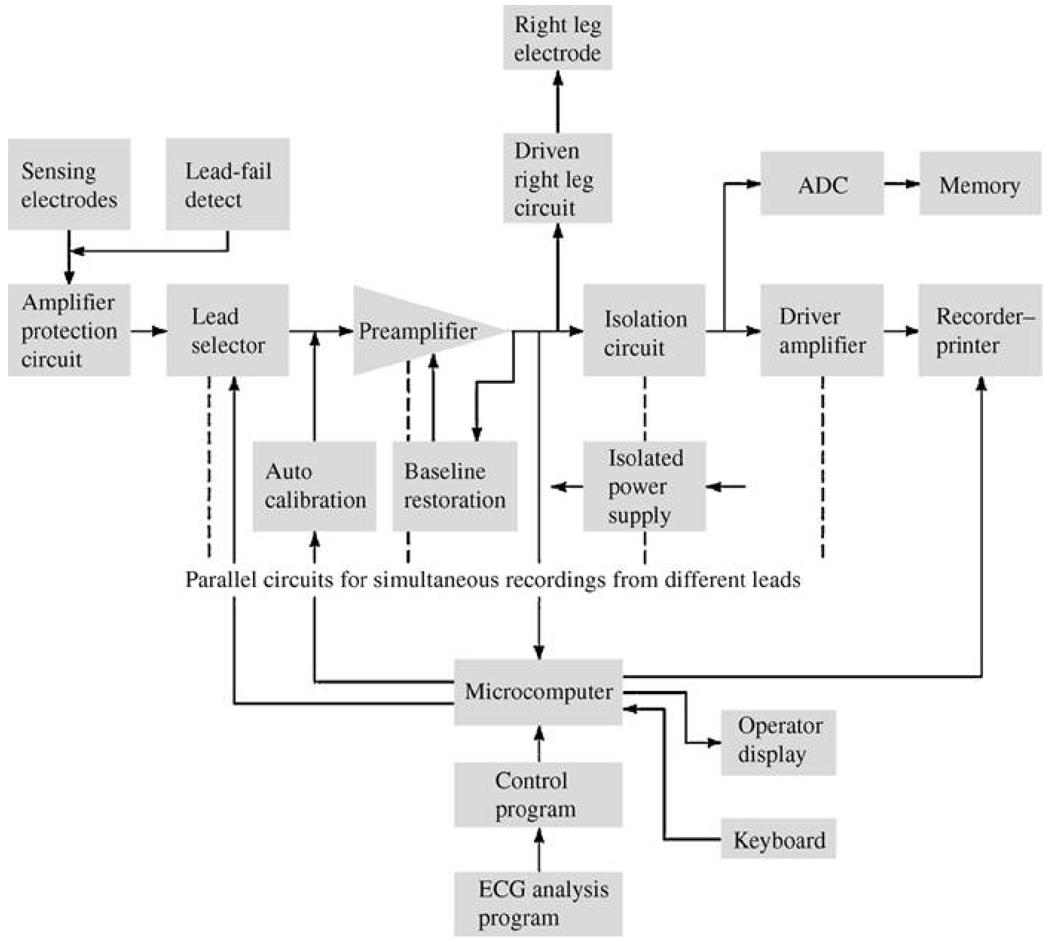
Biopotential Amplifiers (2)

- **More characteristics:**
  - **Limit bandwidth**
    - **Doing so allows us to increase signal-to-noise ratio (SNR) by eliminating noise signals that are at very different frequencies (and can be large in comparison to the measured signal)**
  - **Provide quick calibration**
    - **We need a method to verify that our circuit is functioning properly**
  - **Provide protection to the organism being measured**
    - **No current should flow back to the electrode and consequently to the organism (microshocks and macroshocks)**
    - **SAFETY!**

How Do We Accomplish All This?

- **Design**
  - **Common mode voltage rejection**
  - **Differential gain**
  - **Isolation techniques**
  - **Noise reduction**
- **Measurement techniques**
  - **How and where to place electrodes/leads**
  - **Measurement points**
  - **How to route leads**

ECG Block Diagram

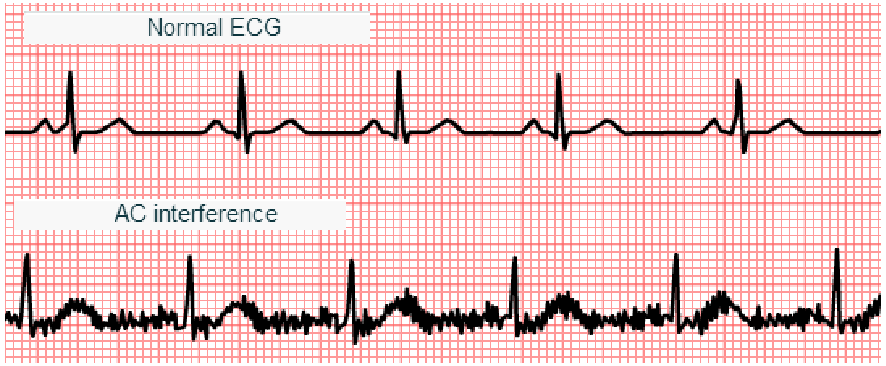


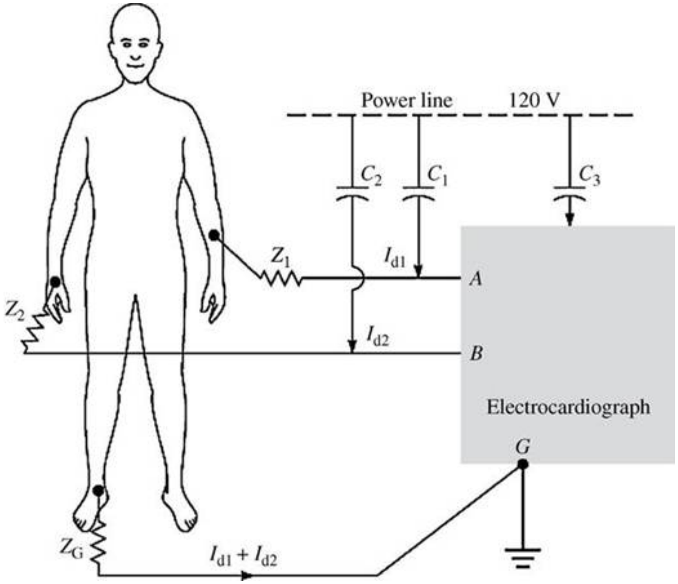
Problems Encountered

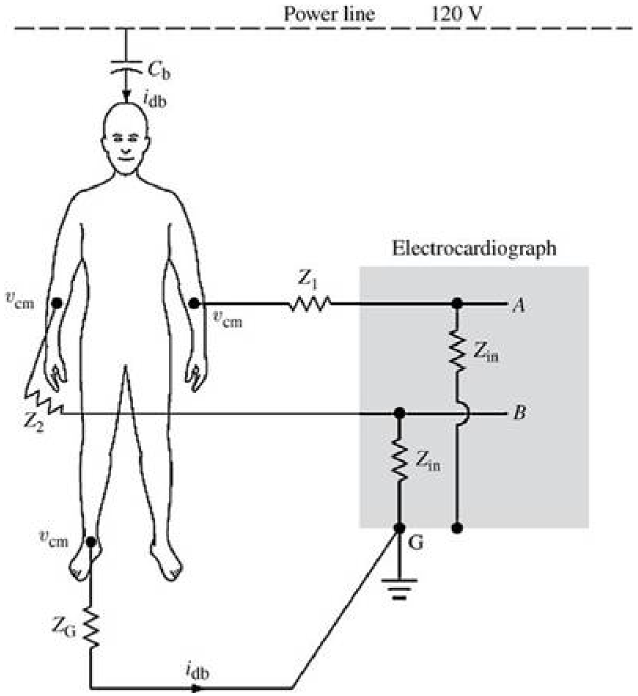
- **Saturation/Cutoff**
  - Need to properly design our amp so that input signals do not drive the amp into saturation
  - Main issue – reduction of the QRS peak (the largest measured voltage)
- **Ground Loops**
  - Multiple machines connected to a patient, all plugged into a different "ground"
  - Grounds at different potentials create another voltage (common mode) which will affect ECG readings
  - Can also become a SAFETY issue

Electrical Interference

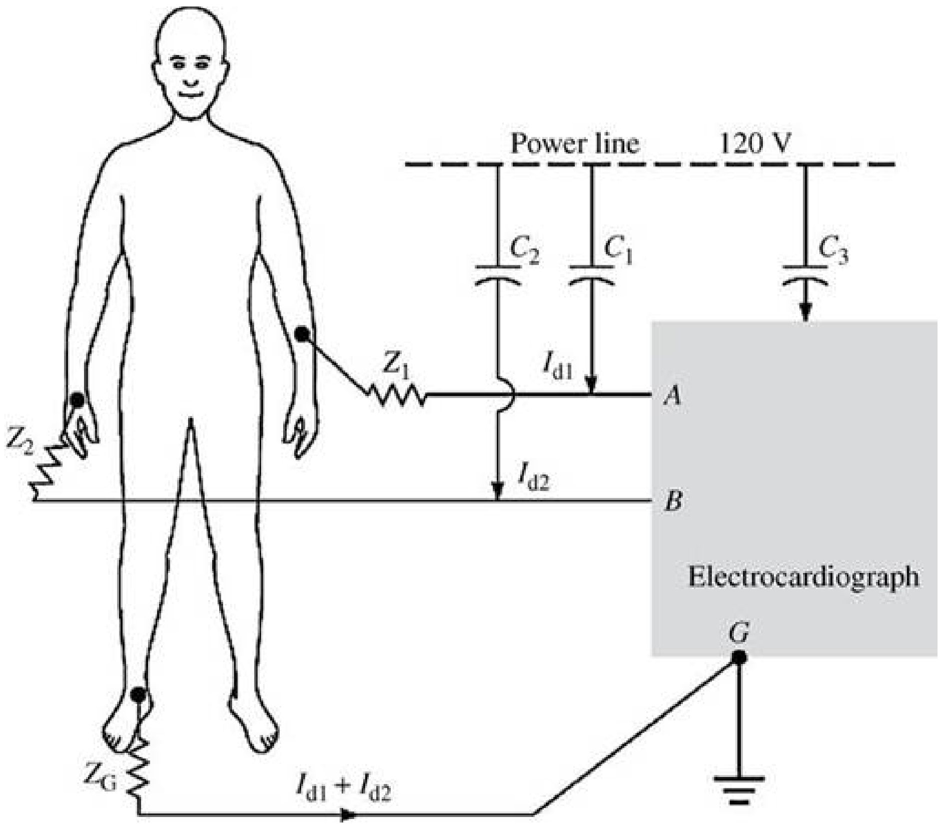
- 60Hz power-line noise on our ECG trace
  - Through the ECG machine itself
  - Through the person







Electrical Interference: Through the ECG machine



$$v_A - v_B = i_{d1}Z_1 - i_{d2}Z_2$$

$i_{d1} \cong i_{d2}$ if the two leads run near each other,

$$v_A - v_B = i_{d1}(Z_1 - Z_2)$$

Values measured for 9 m cables show that $i_d \cong 6\,\text{nA}$

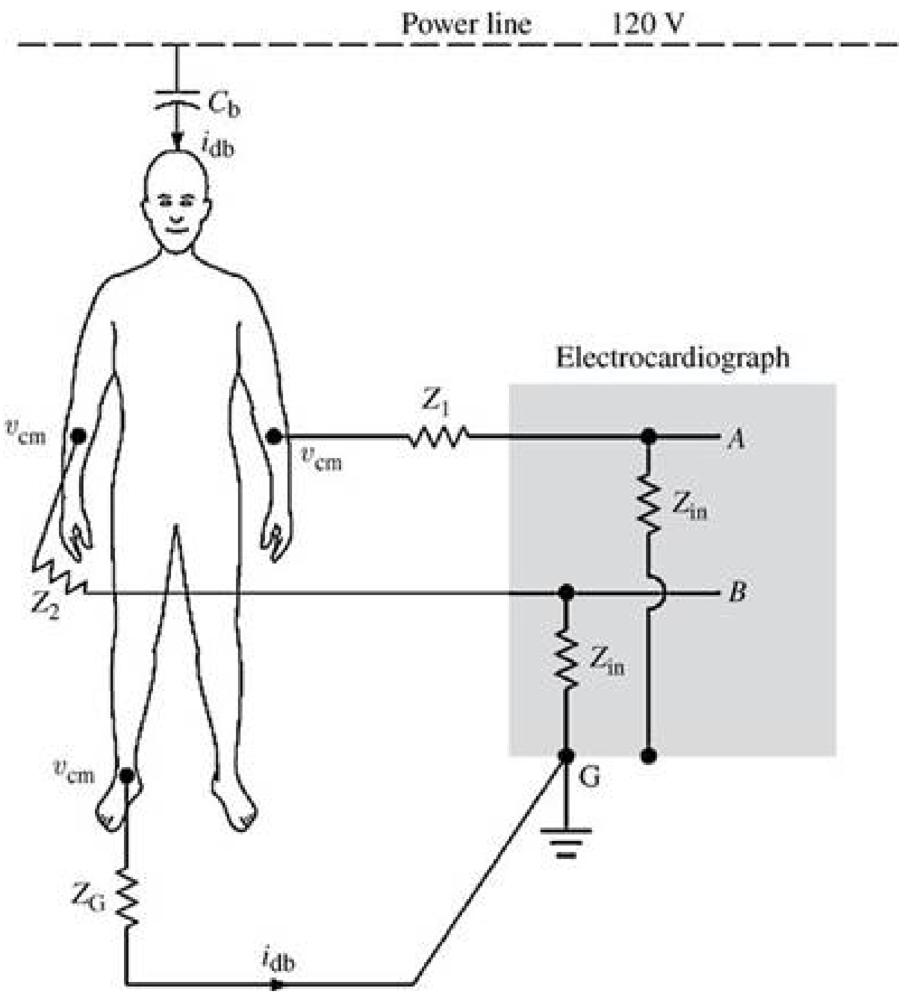
Skin–electrode impedances may differ by 20 kΩ.

$$v_A - v_B = (6\,\text{nA})(20\,\text{k}\Omega) = 120\,\mu\text{V}$$

This can be minimized by shielding the leads and grounding each shield at the electrocardiograph.

Lowering skin-electrode impedances is also helpful.

Electrical Interference: Through the person



$$v_{cm} = i_{db} Z_G$$

Typical values

$$v_{cm} = (0.2\,\mu A)(50\,k\Omega) = 10\,mV$$

$$v_A - v_B = v_{cm}\left(\frac{Z_{in}}{Z_{in}+Z_1} - \frac{Z_{in}}{Z_{in}+Z_2}\right)$$

Z_1 and Z_2 are much less than Z_{in}.

$$v_A - v_B = v_{cm}\left(\frac{Z_2 - Z_1}{Z_{in}}\right)$$

Typical values

$$v_A - v_B = (10\,mV)(20\,k\Omega/5\,M\Omega) = 40\,\mu V$$

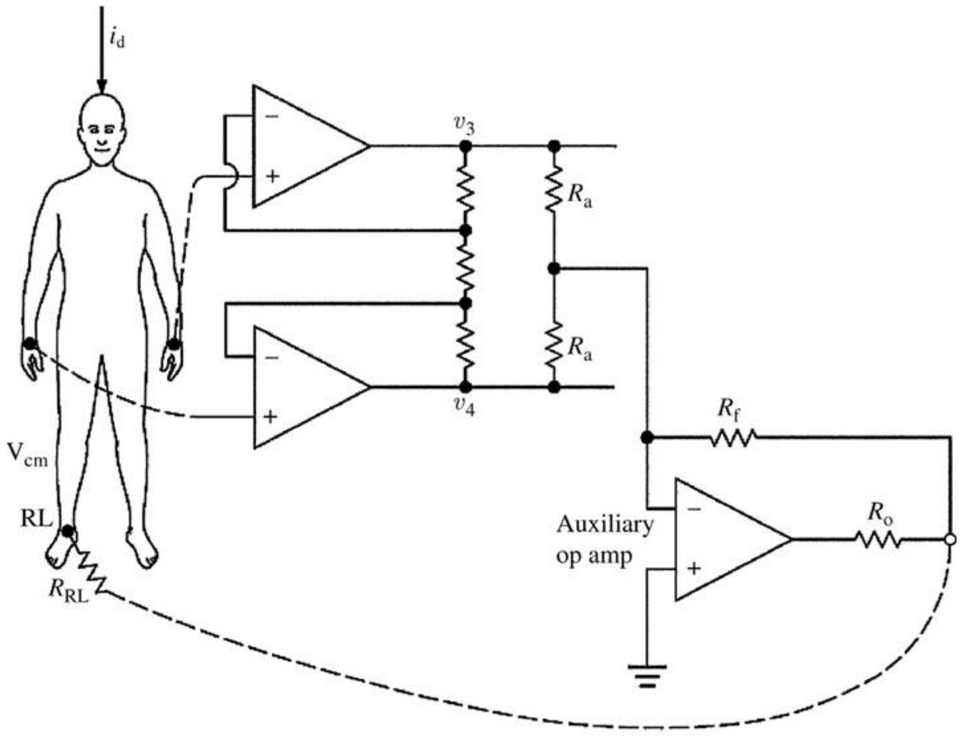
This interference can be minimized by

lowering skin–electrode impedance

raising amplifier input impedance

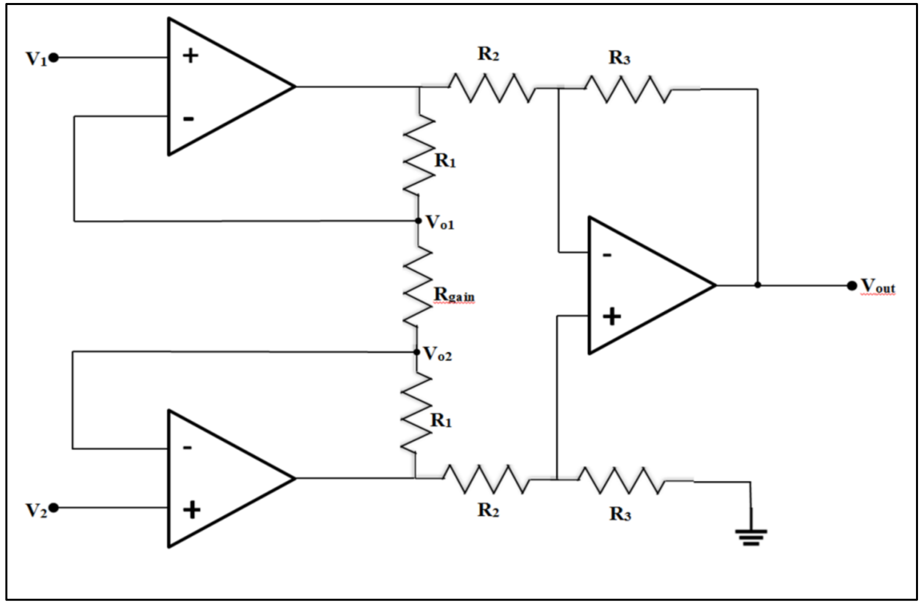
Reducing Common Mode Voltage

- Driven Right Leg System
- This is the typical system in use today
- RL is no longer grounded
- Now it's connected to the output of an auxiliary amp
- Which inverts and drives the common mode voltage back into the subject
- This helps cancel out v_{cm}



Basic Biopotential Amp

- This is the instrumentation amp from Chapter 3
- Front pair of op amps form the preamplifier
- Helps reject v_{cm}
- We can adjust the gain of this stage by changing R_{gain} which is normally external
- We can also add more gain in the final stage



Biopotential Amp with Filtering

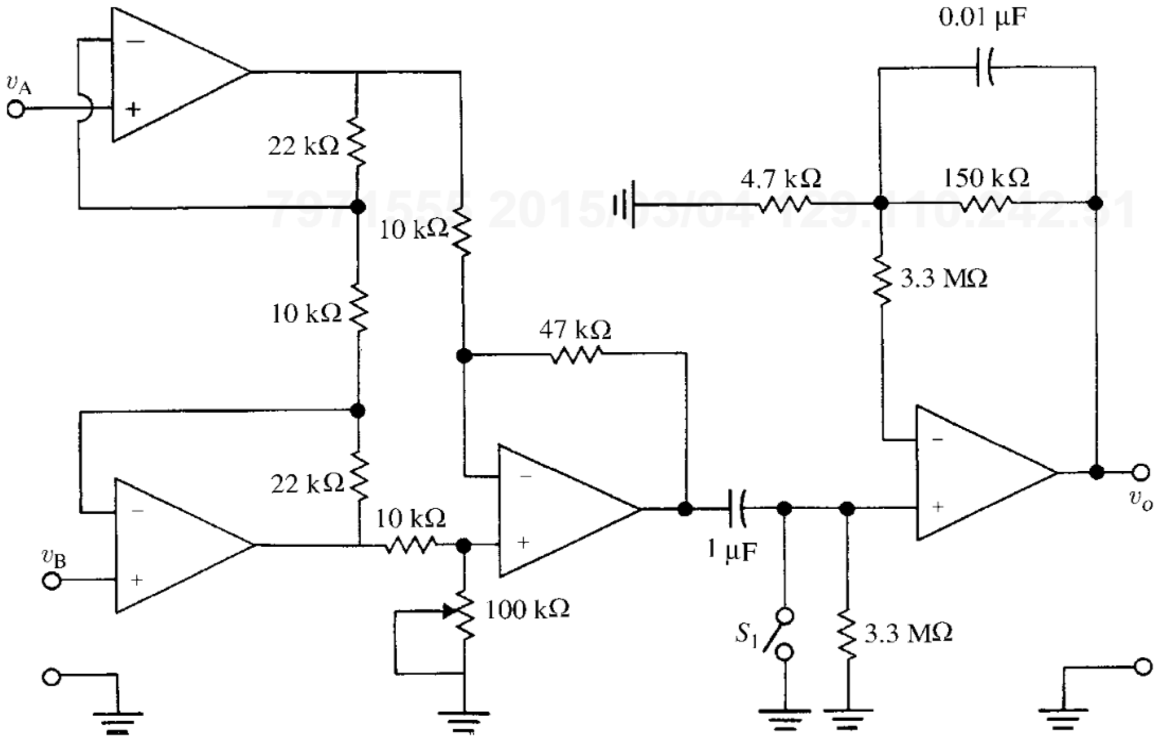
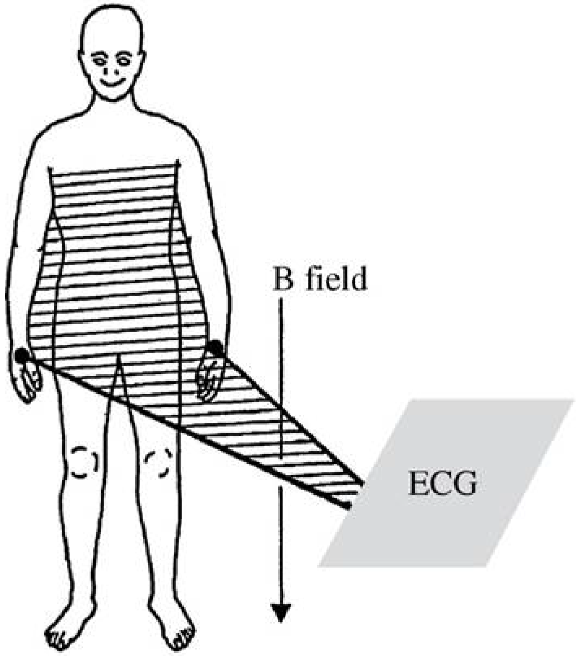
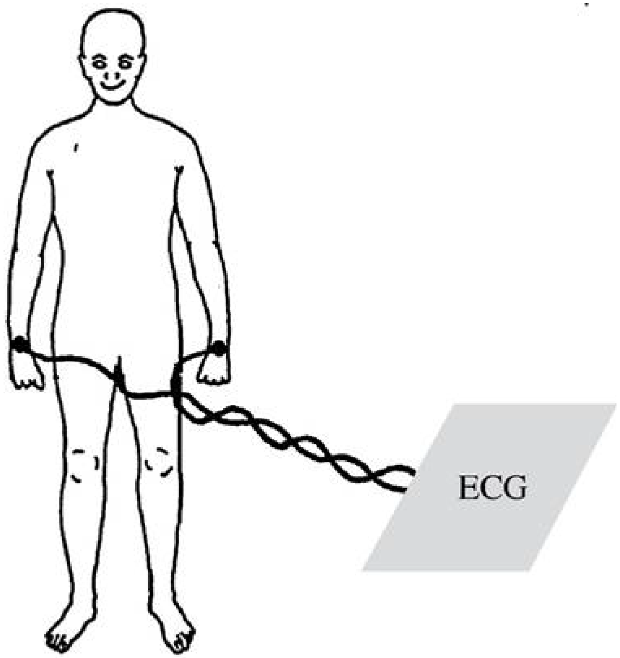


Figure 6.18 This ECG amplifier has a gain of 25 in the dc-coupled stages. The high-pass filter feeds a noninverting-amplifier stage that has a gain of 32. The total gain is $25 \times 32 = 800$. When μA 776 op amps were used, the circuit was found to have a CMRR of 86 dB at 100 Hz and a noise level of 40 mV peak to peak at the output. The frequency response was 0.05 to 106 Hz for ±3 dB and was flat over 4 to 40 Hz. A single op-amp chip, the LM 324, that contains four individual op amps could also be used in this circuit reducing the total parts count.

Magnetic Field Pickup

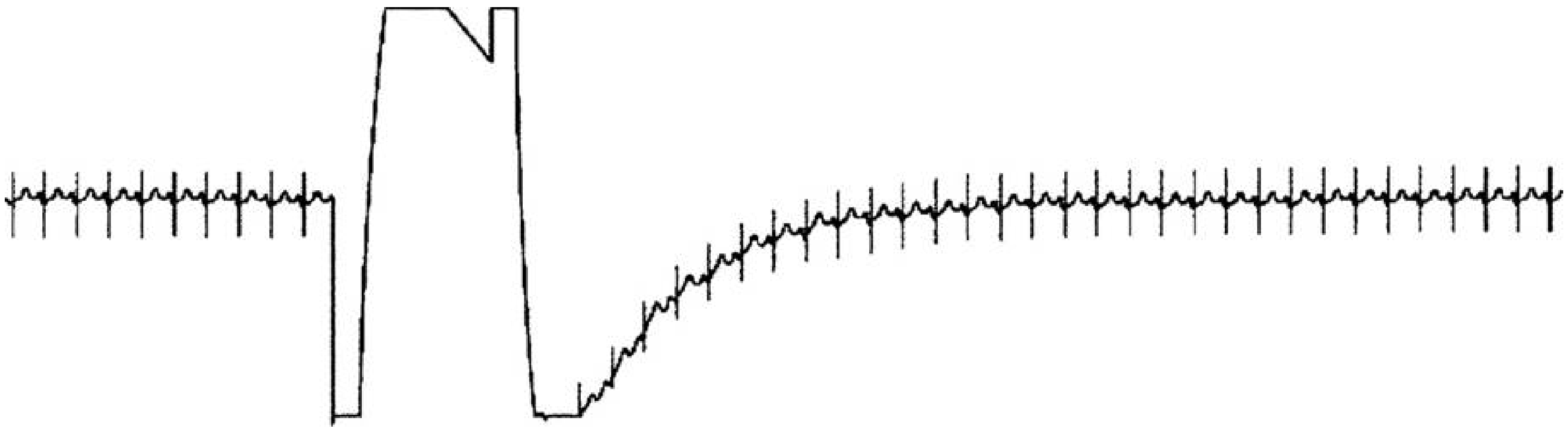
- We can also have magnetic field interference
- Induces an electric current (common mode)
- Easy solution!





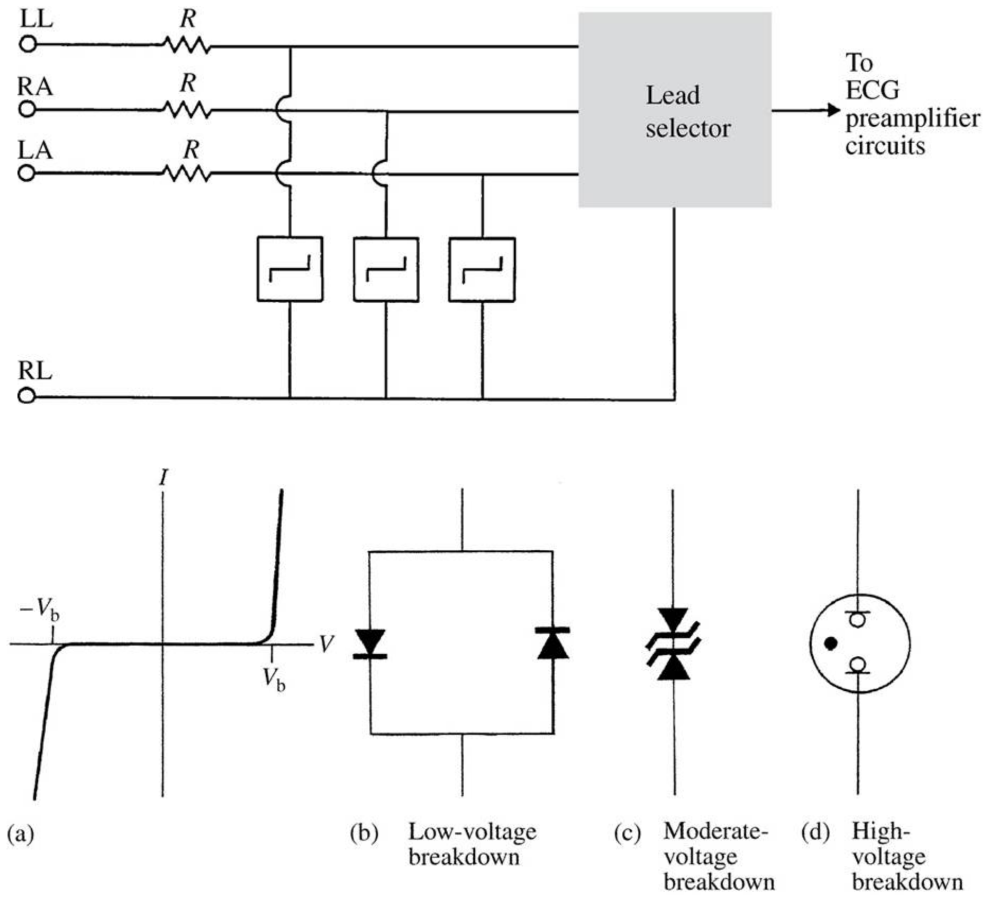
Transient Artifacts

- **Large transient voltage (e.g., from a defibrillator) will be detected and saturate our amp**
- **Due to the capacitances in our amp, our readings will be affected for a time constant based on the R and C of the amp before it returns to normal readings**



Transient Protection

- How to prevent this problem?
- Typical way is by using back-to-back zener diodes (c)
- This limits the voltage that can be passed to our amp



PROBLEMS

Biopotential Amplifiers: Problems

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6.2 What position of the cardiac vector during the R wave gives identical signals in leads II and III? What does the ECG seen in lead I look like for this orientation of the vector?

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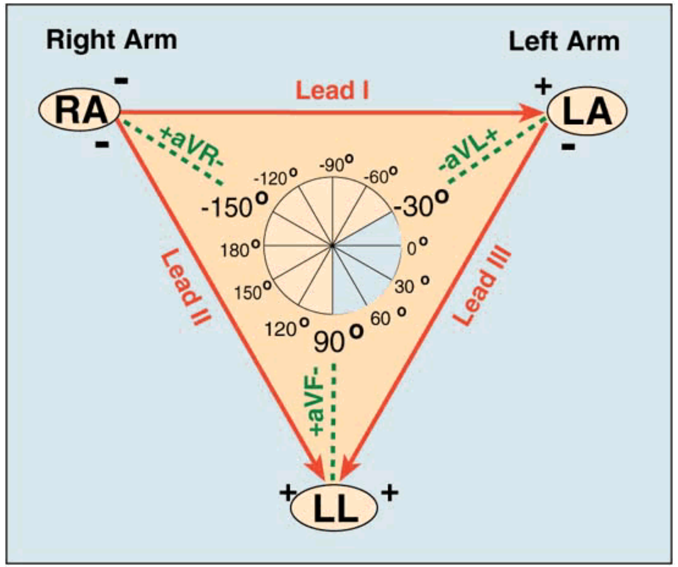
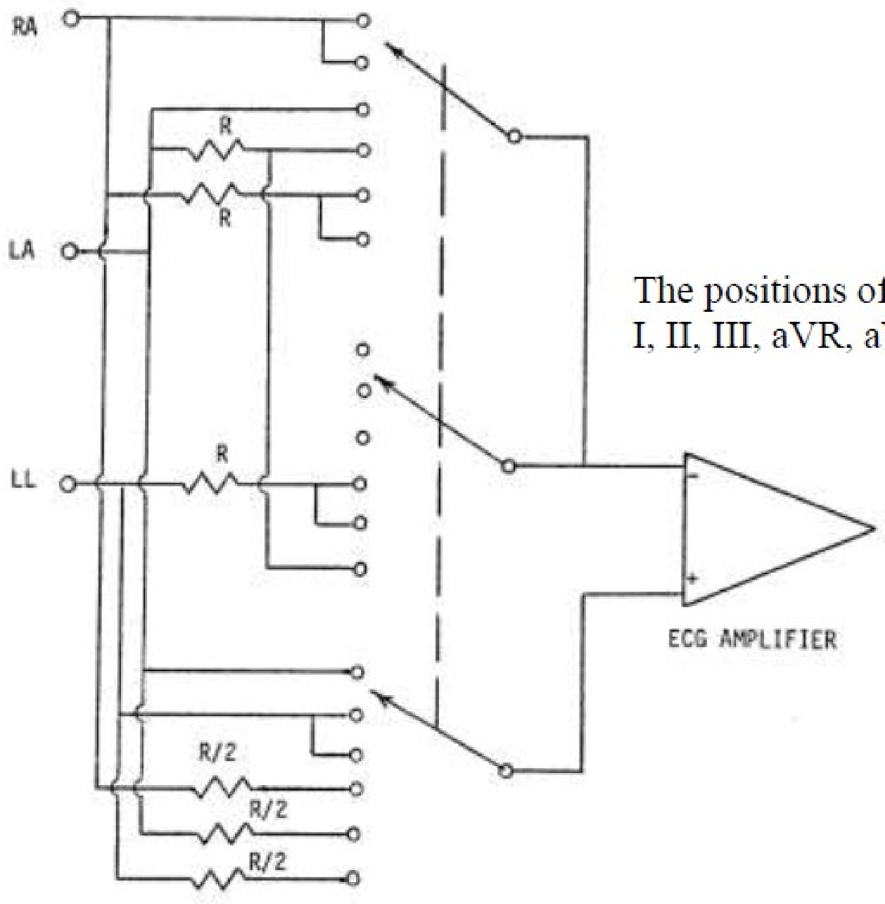


6.7 Design an electrocardiograph with an input-switching system such that we can record the six frontal-plane leads by means of changing the switch.

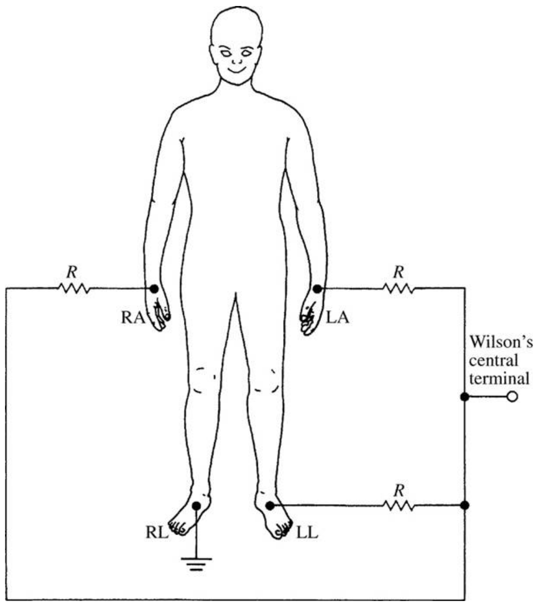


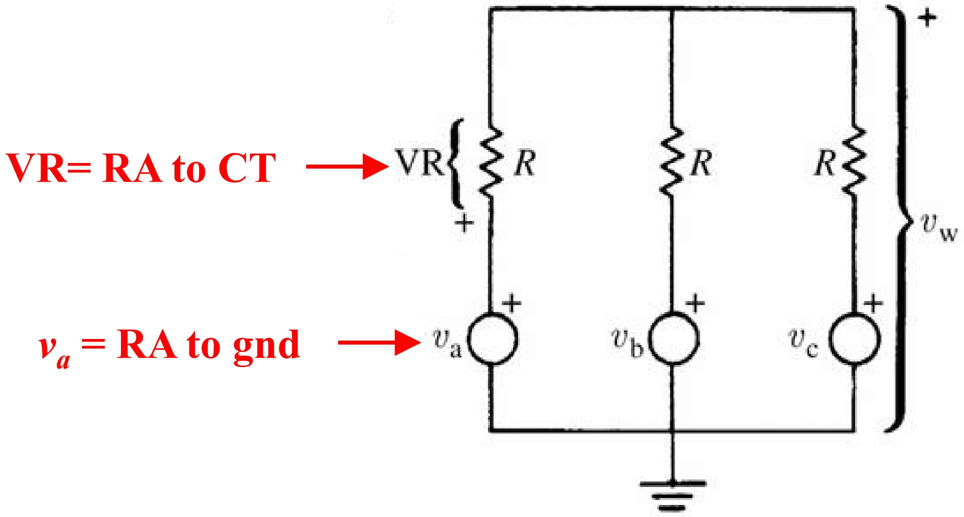
The positions of the selector switch from top to bottom are:
I, II, III, aVR, aVL and aVF.

6.9 The central terminal requirements for an electrocardiograph that meets the recommendations of Table 6.1 sets the minimal value of the resistances at 1.7 MΩ.

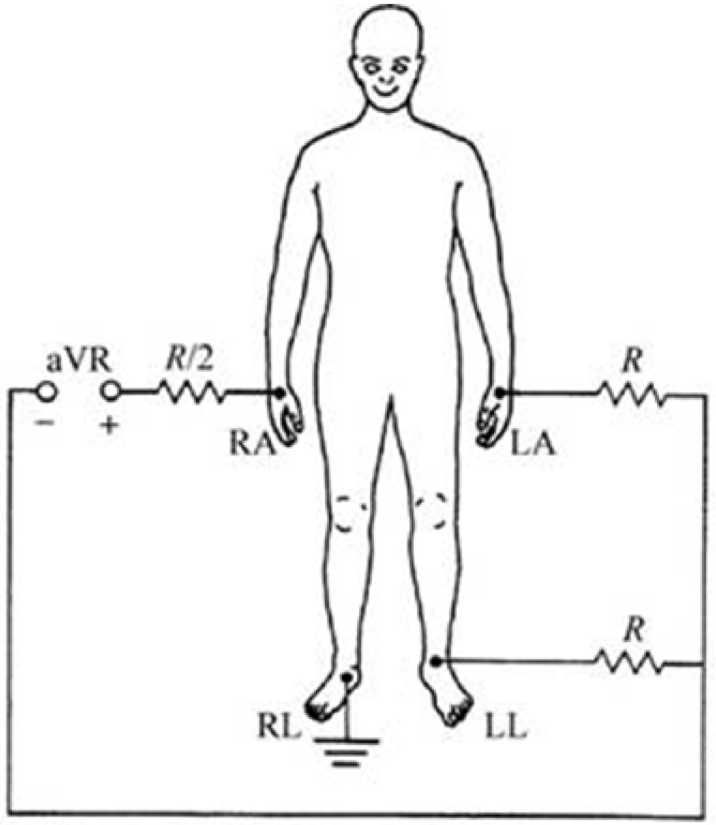
Show that this value is a result of the specification given in Table 6.1:

the input impedance between an electrode terminal and ground should be no less than 2.5 MΩ

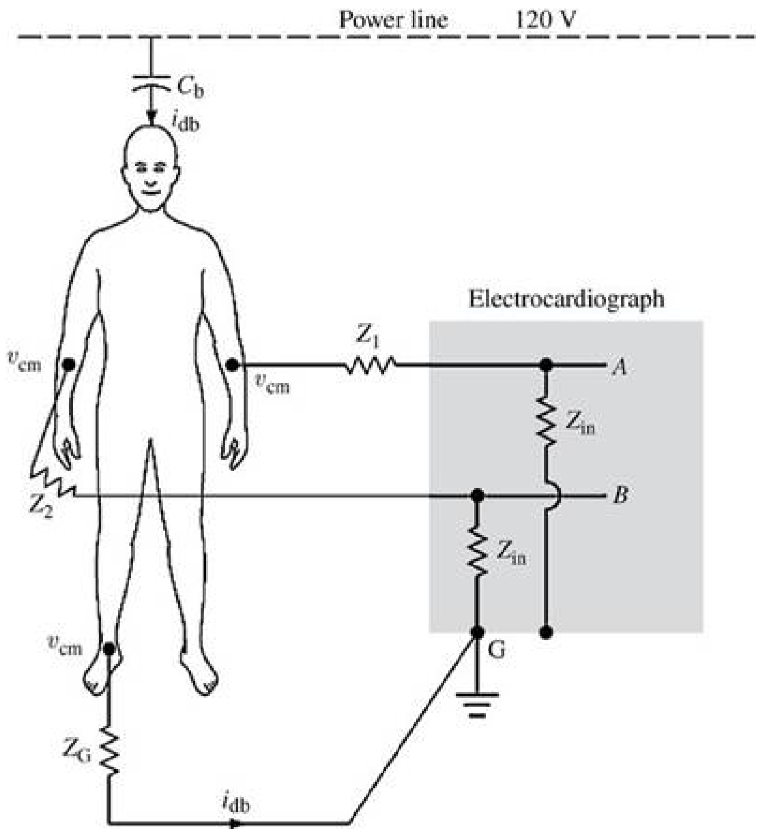




6.12 An engineer sees no purpose for $R/2$ in Figure 6.5(a) and replaces it with a wire in order to simplify the circuit. What is the result?



6.10 A student attempts to measure his own ECG on an oscilloscope having a differential input. For Figure 6.11, $Z_{in} = 1\,\mathrm{M\Omega}$, $Z_1 = 20\,\mathrm{k\Omega}$, $Z_2 = 10\,\mathrm{k\Omega}$, $Z_G = 30\,\mathrm{k\Omega}$, and $i_{db} = 0.5\,\mu\mathrm{A}$. Calculate the power-line interference the student observes.

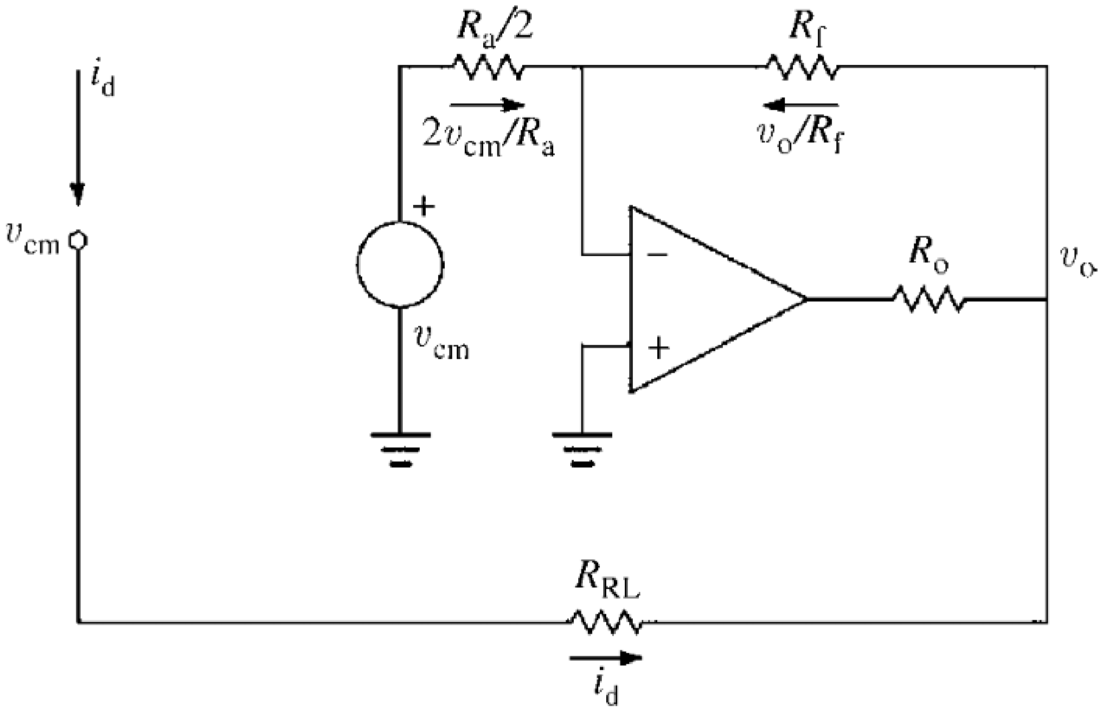


EXAMPLE 6.3 A clinical staff member has attached a patient to an electroencephalograph (EEG machine) for a sleep study that continuously displays that patient's EEG on a computer screen and stores it in memory. This staff member accidently used two different types of electrodes for the EEG lead, and each electrode had a different source impedance. One had a relatively low impedance of 1500 Ω at EEG frequencies, while the other had a higher impedance of 4700 Ω. A ground electrode having an impedance of 2500 Ω was also used. The input impedance of each differential input of the EEG machine to ground was 10 MΩ, and the instrument had a CMRR of 80 dB. The power-line displacement current to the patient was measured at 400 nA. The amplitude of the patient's EEG was 12 μV.

a. How much common-mode voltage will be seen on this patient and will it significantly interfere with the EEG signal?

b. How much power-line interference will be seen on the patient's EEG?

EXAMPLE 6.4 Determine the common-mode voltage v_{cm} on the patient in the driven-right-leg circuit of Figure 6.15 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 and there is only a high-resistance path to ground when the auxiliary op amp saturates. What is v_{cm} for this circuit when $i_d = 0.2\ \mu A$?

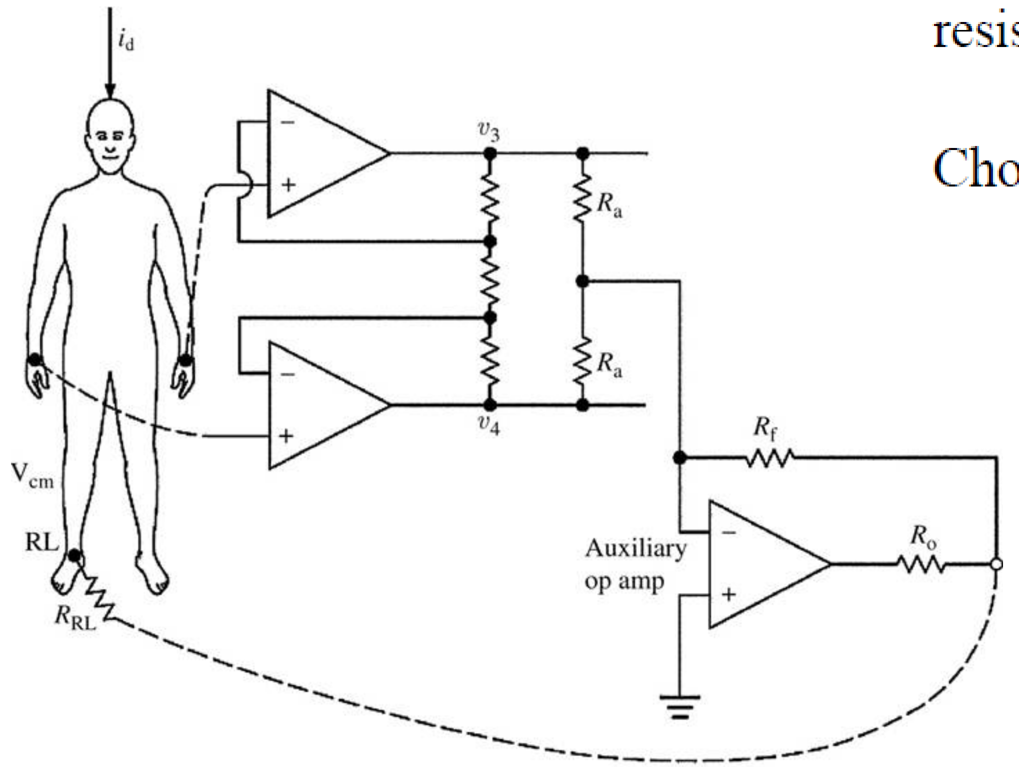


$$v_{cm} = \frac{R_{RL} i_d}{1 + 2R_f/R_a}$$

Previously:

$$v_{cm} = i_{db} Z_G$$

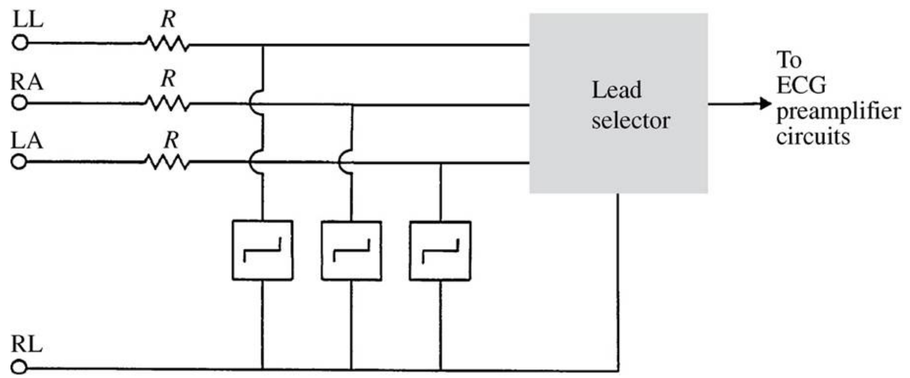
6.11 Design a driven-right-leg circuit, and show all resistor values. For 1 μA of 60 Hz current flowing through the body, the common-mode voltage should be reduced to 2 mV. The circuit should supply no more than 5 μA when the amplifier is saturated at ±13 V.

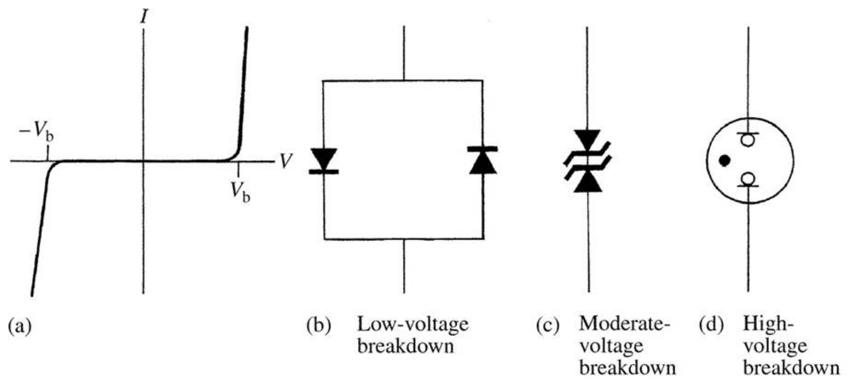


The typical max value of skin–electrode resistance is assumed to be 100 kΩ.

Choose Ra = 25 kΩ as in the book.

6.17 Silicon diodes having a forward resistance of 2 Ω are to be used as voltage-limiting devices in the protection circuit of an electrocardiograph. They are connected as shown in Figure 6.14(b). The protection circuit is shown in Figure 6.13. If voltage transients as high as 500 V can appear at the electrocardiograph input during defibrillation, what is the minimal value of R that the designer can choose so that the voltage at the preamplifier input does not exceed 800 mV? Assume that the silicon diodes have a breakdown voltage of 600 mV.





Problem 18. At a given instant, Lead I of an Electrocardiograph reads a positive voltage but Lead II reads a negative voltage. Find the upper and lower limits of the direction of the cardiac vector and sketch it.

Which of the following measures can help reduce the effect of interference caused by the electric-field coupling between the power-line and the lead wires? *(circle 'YES' if it helps and 'NO' if it doesn't)*

YES NO Shielding the wires

YES NO Reducing the difference between the electrode impedances

YES NO Reducing the input impedance of the electrocardiograph

YES NO Employing a driven right leg system

YES NO Increasing the CMRR of the amplifier

YES NO Using a 60 Hz Notch filter

Problem 15. The input to an electroencephalograph (the EEG machine) contains an EEG signal with an amplitude of $15\ \mu V$ and a common mode noise that can go as high as 200mV.

i. What is the input SNR?
ii. If the common-mode noise at the output of the electroencephalograph is to be restricted to less than 0.5%, what should its CMRR be?