Subject Name: Biomedical Instrumentation Design I_2

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Lecture No.: 3

Lecture Title: ECG PART 2.

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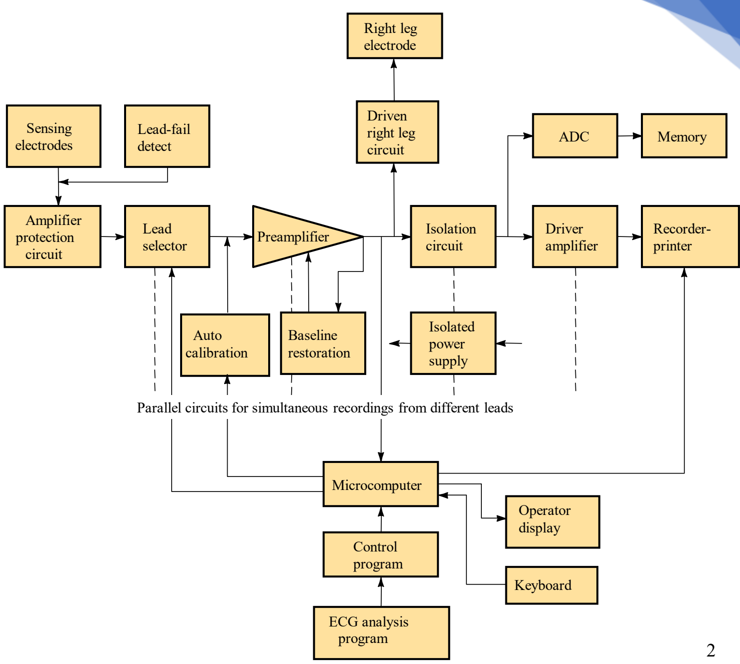
Electrocardiograph

- Sensing electrodes
- Lead fail detect
- Amplifier protection circuit
- Lead selector
- Auto calibration
- Preamplifier
- Baseline restoration
- Driven right leg circuit
- Isolation circuit
- ADC & Memory system
- Driver amplifier
- Recorder-printer
- Microcomputer
- Control software



- *Lead selector:*

✓ Determine which electrodes are necessary for a particular lead and to connect them to the remainder of the circuit

- *Preamplifier*

✓ Carries out the initial amplification of the ECG.

✓ Have very high input impedance and a high CMRR

✓ Three-op-amp differential amplifier

- *Isolation circuit*

✓ To block dangerous currents (e.g. from 120V power line (50 or 60 Hz)) from flowing from the patient through the amplifier to the ground of the recorder or microcomputer.

- *Driven right leg circuit*

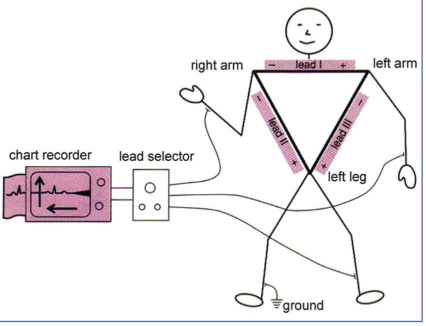
✓ provides a reference point on the patient that normally is at ground potential

- *Driver amplifier*

✓ Amplifies the ECG to a level at which it can appropriately record the signal.

✓ Its input is AC-coupled so that offset voltages amplified by the preamplifier are not seen at its input.

✓ carries out bandpass filtering of the ECG



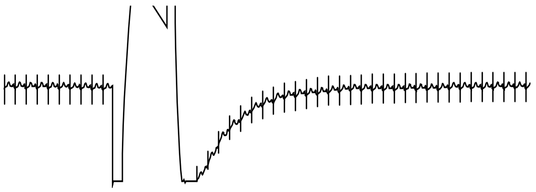
Frequent Problems

To be considered in the design and application of the ECG machine and other biopotential amplifiers

- **Frequency Distortion**
  - ✓ High-frequency loss rounds the sharp edges of the QRS complex.
  - ✓ Low-frequency loss can distort the baseline (no longer horizontal) or cause monophasic waveforms to appear biphasic.
- **Saturation/cutoff Distortion**
  - ✓ Combination of input signal amplitude & high offset voltage (at the electrodes) drives amplifier into saturation
  - ✓ Positive case: clips off the top of the R wave
  - ✓ Negative case: clips of the Q, S, P, and T waves
- **Ground Loops**
  - ✓ Patients are connected to multiple pieces of equipment; each has a ground (power line or common room ground wire)
  - ✓ If more than one instrument has a ground electrode connected to the patient, a ground loop exists. Power line ground can be different for each item of equipment (one higher than the other), sending current through the patient, elevating body potential, and introducing common-mode noise on ECG.
  - ✓ Hospitals and clinics usually have established grounding systems for medical equipment.
- **Open Lead Wires**
  - ✓ Disconnected electrode to the machine, induce high potential in open wire
  - ✓ Can be detected by impedance monitoring.

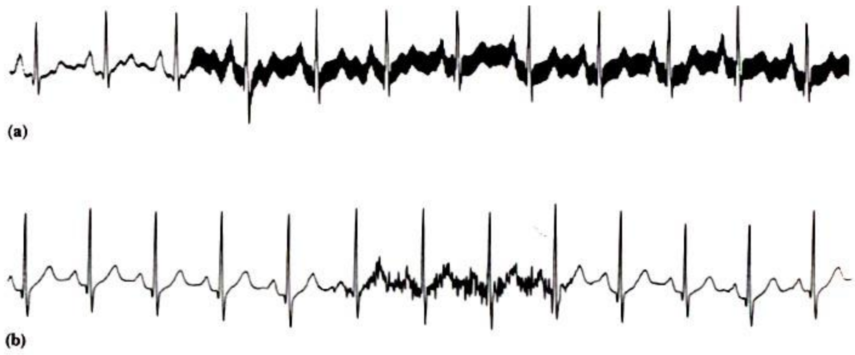
Artifacts

- Unwanted voltage transients
  - ✓ Electrical stimulation signals (high-voltage –current pulse), like defibrillation
  - ✓ Higher than ECG potentials
- Amplifier saturates, charge build-up on the coupling capacitor.
- Prolonged recovery to baseline
  - ✓ Recovery time set by the low-frequency corner of the bandpass amplifier
- Other sources
  - ✓ Motion of electrodes (body movement)
  - ✓ Static charges of patients
- Solution
  - ✓ Protection circuitry, discharge of patients, use of electrodes



Effect of a voltage transient on an ECG recorded on an electrocardiograph in which the transient causes the amplifier to *saturate*, and a finite period of time is required for the charge to bleed off enough to bring the ECG back into the amplifier's active region of operation. This is followed by a *first-order recovery of the system*.

Artifacts: Interference from Electric Devices



- Upper figure: coupling of 60 Hz power line noise
  - ✓ Electric-field coupling between the power lines and the instrument, patient, and lead wires, like small capacitors joining these entities to the power lines
- Lower figure: coupling of electromyographic (EMG) noise
  - ✓ An example is tensing chest muscles while an ECG is being recorded.

Power-Line Coupling

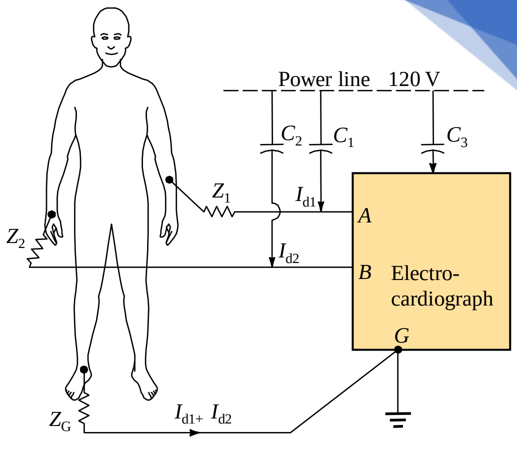
- Small parasitic capacitors (arise from the inherent electric field surrounding any charged conductor) **connect the power line to the RA and LA leads, and the grounded instrument case**
- Small ac displacement currents **I_{d1} and I_{d2} are generated**
- **The body impedance is about 500 Ω and can be neglected**

  $v_A - v_B = i_{d1} Z_1 - i_{d2} Z_2$ (6.3)
- If I_{d1} and I_{d2} are approximately equal, and values measured for 9m cables show that id = 6nA, although this value will depend on the room and the location of other equipment and power lines. Skin-electrode impedances may differ by as much as 20 kΩ. Hence:

  $v_A - v_B = i_{d1} (Z_1 - Z_2)$ (6.4)

  $= (6\ nA)\ (20\ K\ \Omega)$

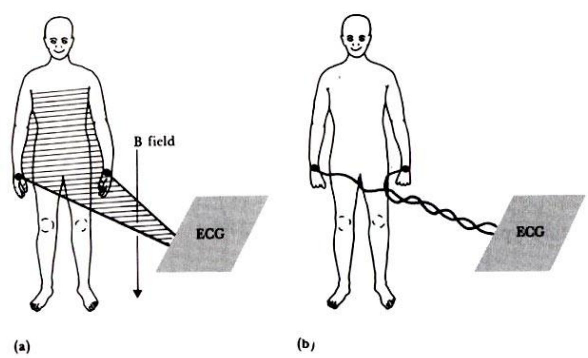
  $= 120\ \mu V$
- Remedies
- Shield electrodes & connect to electrocardiograph (grounding tree) to reduce i_d
- Reduce or match the electrode skin impedances (minimize $Z_1 - Z_2$)



A mechanism of electric-field pickup of an electrocardiograph resulting from the power line. Coupling capacitance between the hot side of the power line and lead wires causes current to flow through skin-electrode impedances on its way to ground.

Magnetic Field Coupling

- Sources
- Power lines
- Transformers and ballasts in fluorescent lights
- Remedies
- Shielding
- Route leads away from potential sources
- Reduce the effective area of the single-turn coil (twist the lead wires)

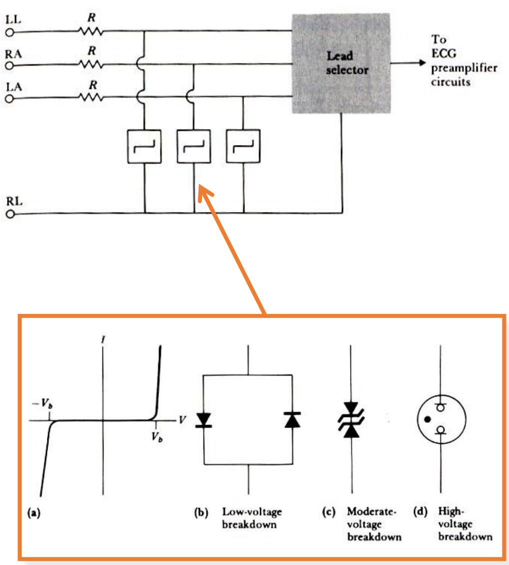


Magnetic-field pickup by the elctrocardiograph (a) **Lead wires make a closed loop (shaded area) when patient and electrocardiograph are considered in the circuit. The change in magnetic field passing through this area induces a current in the loop.**
(b) **This effect can be minimized by twisting the lead wires together and keeping them close to the body in order to subtend a much smaller area.**

Other Sources of Interference

- Electromagnetic radiation
  - ✓ Patient leads become antennas, especially if detached.
- Sources
  - ✓ Radio
  - ✓ Television
  - ✓ Radar
  - ✓ High-freq generators
  - ✓ Research equipment
  - ✓ Electrosurgical devices
  - ✓ Arching fluorescent lights (needing replacement)
- Remedy
  - ✓ Employ capacitors shunting the inputs to the ECG amplifier to ground (eg., 200 pF).
  - ✓ Do not lower the input impedance of the amplifier.
- Other interferences: electrophysiological noise e.g. electromyographic (EMG) signal from muscle contraction, also picked up by ECG leads

Transient Protection

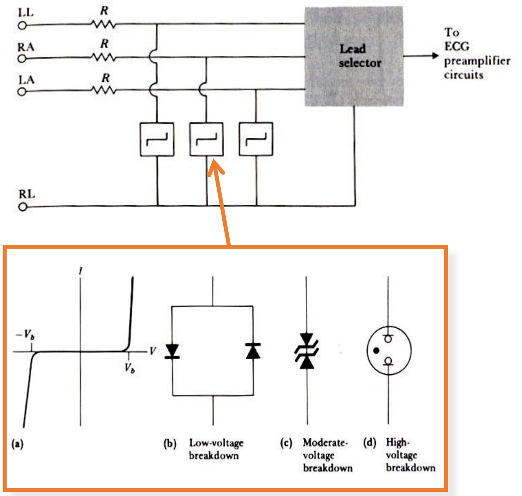


- High voltages due to electrosurgical equipment into patients and entering the ECG machine and cardiac monitor, causing damage and transient artifacts.
- Voltage limiting devices on each input lead are used to protect the equipment.

Figure 1 A voltage-protection scheme at the input of an electrocardiograph to protect the machine from high-voltage transients. Circuit elements connected across limb leads on left-hand side are voltage-limiting devices.

Figure 2 Voltage-limiting devices:
(a) Current–voltage characteristics of a voltage-limiting device, At voltages less than v_b, the breakdown voltage, the device allows very little current to flow and ideally appears as an open circuit. Once the voltage across the device attempts to exceed v_b, the characteristics of the device sharply change, and current passes through the device to such an extent that the voltage cannot exceed v_b as a result of the voltage drop across the series resistors R, and the device appears to behave as a short circuit in series with a constant-voltage source of magnitude v_b.

Transient Protection



- High voltages due to electrosurgical equipment into patients and entering the ECG machine and cardiac monitor, causing damage and transient artifacts.
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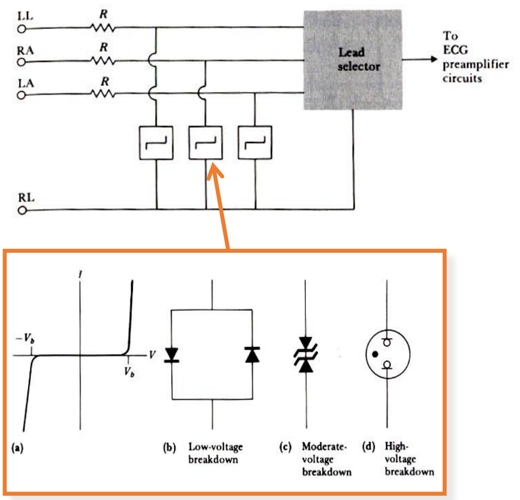
Figure 3 A voltage-protection scheme at the input of an electrocardiograph to protect the machine from high-voltage transients. Circuit elements connected across limb leads on left-hand side are voltage-limiting devices.

Figure 4 Voltage-limiting devices
(b) Parallel silicon-diode voltage-limiting circuit, The diodes are connected such that the terminal voltage on one has a polarity opposite that on the other. The breakdown voltage is approximately 600 mV; thus, one of the diodes is forward-biased when the voltage reaches approximately 600 mV.

Transient Protection

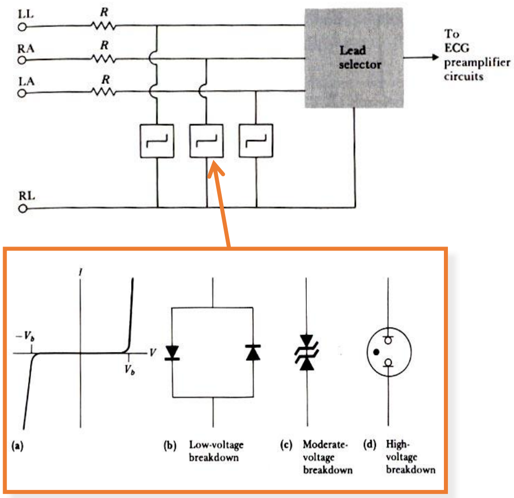


- High voltages due to electrosurgical equipment into patients and entering the ECG machine and cardiac monitor, causing damage and transient artifacts.
- Voltage limiting devices on each input lead are used to protect the equipment

Figure 5 A voltage-protection scheme at the input of an electrocardiograph to protect the machine from high-voltage transients. Circuit elements connected across limb leads on left-hand side are voltage-limiting devices.

Figure 6 Voltage-limiting devices
(c) Back-to-back silicon Zener-diode voltage-limiting circuit. When a voltage is connected across this circuit, one of the diodes is biased in the forward direction and the other in the reverse direction. The breakdown voltage in the forward direction is approximately 600 mV, but that in the reverse direction is much higher. It generally covers the range of 2 to 20 V. Thus , this circuit does not conduct until its terminal voltage exceeds the diode's reverse breakdown by approximately 600 mV.

Transient Protection

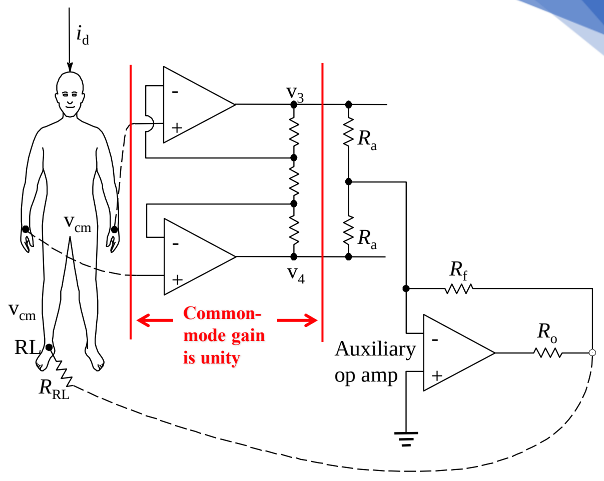


- High voltages due to electrosurgical equipment into patients and entering the ECG machine and cardiac monitor, causing damage and transient artifacts.
- Voltage limiting devices on each input lead are used to protect the equipment

Figure 7 A voltage-protection scheme at the input of an electrocardiograph to protect the machine from high-voltage transients. Circuit elements connected across limb leads on left-hand side are voltage-limiting devices.

Figure 8 Voltage-limiting devices
(a) Current–voltage characteristics of a voltage-limiting device,
(b) Parallel silicon-diode voltage-limiting circuit,
(c) Back-to-back silicon Zener-diode voltage-limiting circuit,
(d) Gas-discharge tube (neon light) voltage-limiting circuit element.

Driven Right Leg Circuit



- Patient is not grounded
- Common mode voltage is sensed by two averaging resistors (R_a), inverted, amplified, and fed back to the right leg.
- Negative feedback drives the common mode voltage to a low value.
- Body's displacement current flows to the inverting OpAmp.
- *Provides safety:* if the OpAmp saturates, an alarm sounds; R_o limits current out of the feedback OpAmp.

Minimizes common- mode interference. The circuit derives common-mode voltage from a pair of averaging resistors connected to v_3 and v_4 in the instrumentation amp. The right leg is not grounded but is connected to output of the auxiliary op amp.

Example 1

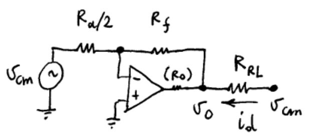
Determine the common-mode voltage v_{cm} on the patient in the driven right-leg circuit of Figure 9 when a displacement current i_d flows to the patient from the power lines. Choose appropriate values for the resistances in the circuit so that the common-mode voltage is minimal and there is only a high-resistance path to ground when the auxiliary operational amplifier saturates. What is v_{cm} for this circuit when $i_d = 0.2\ \mu A$?

Sol. Since the common-mode gain of the input stage is 1 and because the input stage has a very high input impedance, v_{cm} at the input is isolated from the output circuit. R_{RL} represents the resistance of the right-leg electrode. Summing the currents at the negative input of the op amp, we get:

$$\frac{2v_{cm}}{R_a} + \frac{v_o}{R_f} = 0$$ This gives $$v_o = -\frac{2R_f}{R_a} v_{cm}$$

Since $$v_{cm} = R_{RL} i_d + v_o$$

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



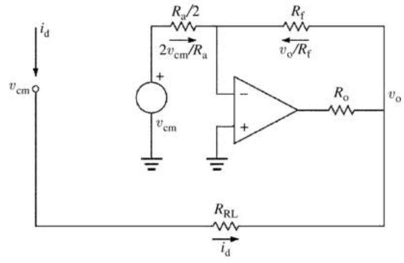


Figure 10 Equivalent circuit of driven-right-leg system of Figure 9.

Right Leg resistance

The effective resistance between the right leg and ground is the resistance of the right-leg electrode divided by 1 plus the gain of the auxiliary op-amp circuit.

- When the amplifier saturates, as would occur during a large transient v_{cm}, its output appears as the saturation voltage v_s. The right leg is now connected to the ground through this source and the parallel resistances R_f and R_o. To limit the current, R_f and R_o should be large Values as high as 5 MΩ are used.
- When the amplifier is not saturated, v_{cm} to be as small as possible. This can be achieved by making R_f large and R_a relatively small. R_f can be equal to R_o, but R_a can be much smaller.
- A typical value of R_a would be 25 kΩ. A worst-case electrode resistance R_{RL} would be 100 kΩ. The effective resistance between the right leg and ground would then be

$$\frac{100\,\text{k}\Omega}{1 + \frac{2 \times 5\,\text{M}\Omega}{25\,\text{k}\Omega}} = 249\,\Omega$$

For the 0.2 μA displacement current, the common-mode voltage is

$$v_{cm} = 249\,\Omega \times 0.2\,\mu\text{A} = 50\,\mu\text{V}$$

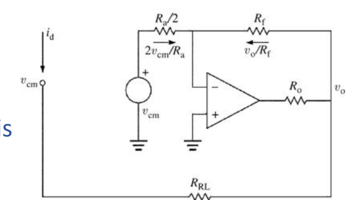


Figure 10 Equivalent circuit of driven-right-leg system of Figure 9.

Preamplifiers

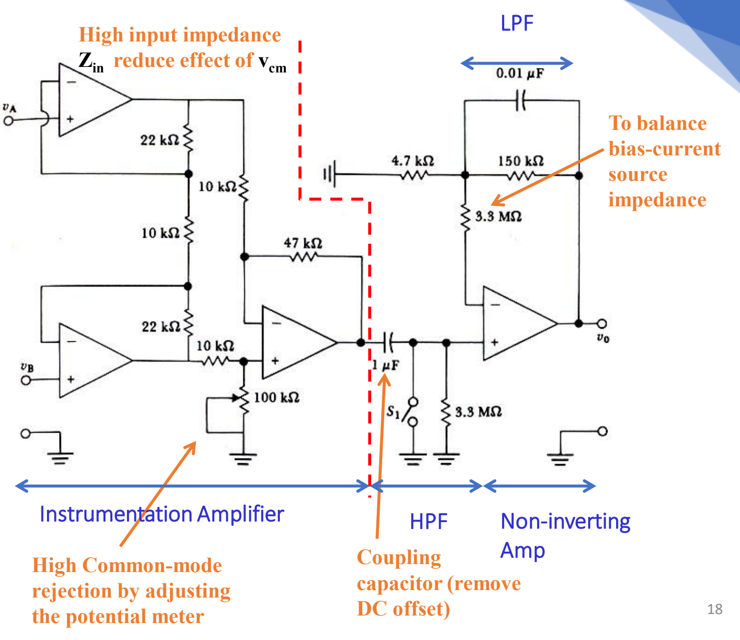
The main tasks are to sense the voltage between two measuring electrodes while rejecting the common mode signal and minimizing the effect of electrode polarization overpotentials.

The first stage of the amplifier circuit

- Important common factor to all amplifiers for various bio-potential signals
- Must be a low-noise device
  - Its output is amplified many times, so any noise injected here also gets amplified many times!
- Should be dc coupled to the electrodes
  - Include no series capacitors in the input leads (input bias currents build the charge on series input capacitors).
  - To preserve the low-frequency content of the input signals.
- Use relatively low gain for the preamplifier
  - Input bias currents can build the charge on polarizable electrodes, creating a dc offset in the input signals.
  - High gain will saturate the output of the preamplifier.
  - The pre-amp can be capacitor-coupled to the later stages of the amplifier circuit to eliminate the saturation effects of this DC potential.
- Use a high-input impedance OpAmp to reduce these charging effects.
- Electrically isolated from the remaining amplifier stages (and hence from power lines)

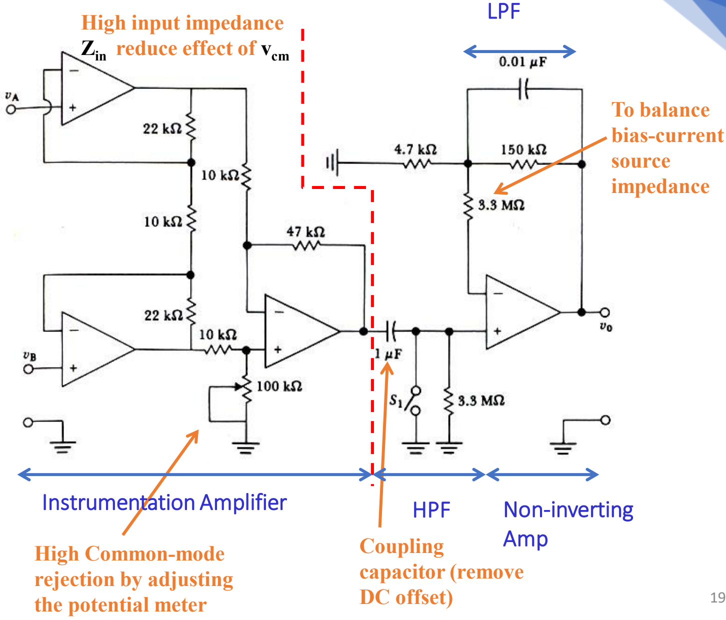
An ECG Amplifier

- The instrumentation amplifier of Figure 3.5 is used to provide very high input impedance.
- High common-mode rejection is achieved by adjusting the potentiometer to about 47kΩ. Electrodes may produce an offset potential of up to 0.3V.
- Thus, to prevent saturation, the dc-coupled stages have a gain of only 25. Coupling capacitors are not placed at the input because this would block the op-amp bias current.
- Adding resistors to supply the bias current would lower the Z_{in}. Coupling capacitors placed after the first op amps must be impractically large. Therefore, the single 1pF coupling capacitor and the 3.3MΩ resistor form a high-pass filter.
- The resulting 3.3 s time constant passes all frequencies above 0.05 Hz. The output stage is a noninverting amplifier with a gain of 32.



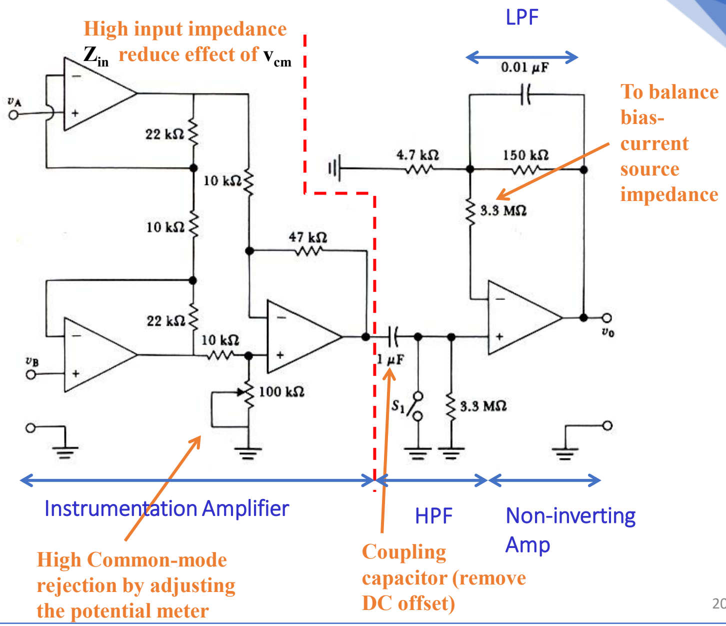
An ECG Amplifier

- A second 3.3 MΩ resistor is added to balance bias-current source impedances. The 150 kHz and 0.01 pF low-pass filter attenuate frequencies above 106 Hz. Switch 51 may be momentarily closed to decrease the discharge time constant when the output saturates.
- This is required after defibrillation or lead switching to charge the 1 pF capacitor rapidly to the new value and return the output to the linear region. We do not discharge the capacitor voltage to zero. Rather, we want the right end to be at 0 V when the left end is at the dc voltage determined by the electrode offset voltage.
- Switch closure may be automatic via a circuit that detects when the output is in saturation, or it may be manual.



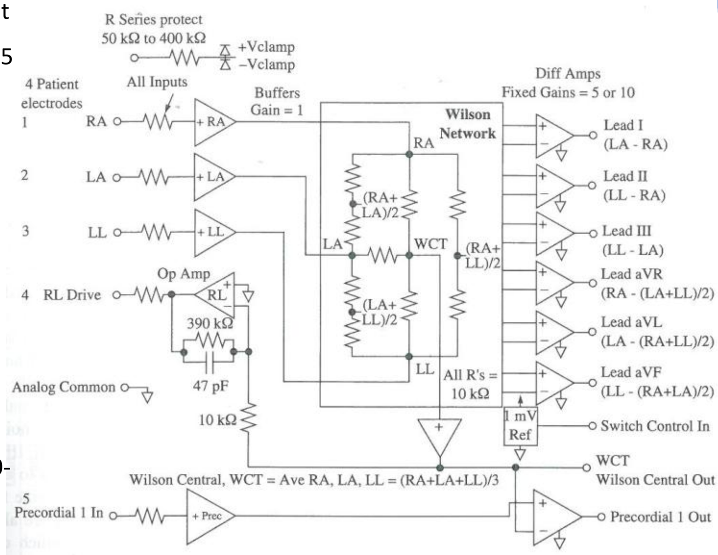
An ECG Amplifier

- Gain: 800
  - *DC-coupled stage:*
    - To prevent saturation due to offset potential from electrode (up to 0.3 V)
    - low gain of G=25
  - *AC coupled band-pass stage*: Non-inverting amp: G=32
- With μA 776 OpAmps
  - CMRR: 86 dB at 100 Hz
  - Noise: 40 mV p-p
- Frequency response
  - .04 to 150 Hz for +-3dB
  - Flat over 4 - 40 Hz



Five electrode (6-lead) ECG Front end

- Back of six diff amps (Gain must be low to prevent electrode offset voltage from saturating them – G=5 or 10V/V)
- The diff. Amps remove the 60Hz common-mode (CM) noise, by subtracting the equal noise voltage and only amplify the differential voltage
- The Wilson central ECG zero and common-mode interference (dc and 60 CM voltage), used as one input to precordial diff amps for removing 60-Hz interference
- The gain of the right-leg driver is usually set to 30-50 V/V



12-Lead ECG front-end

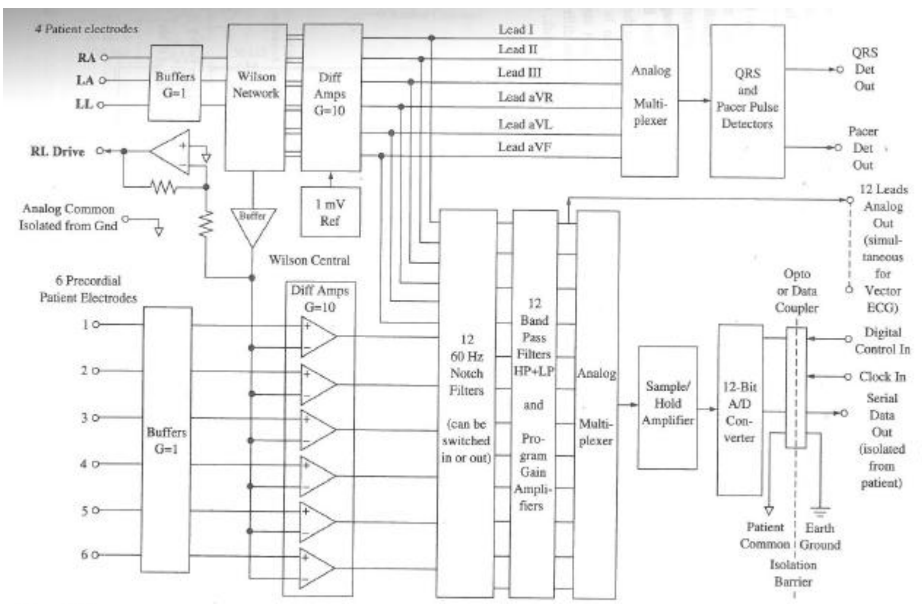
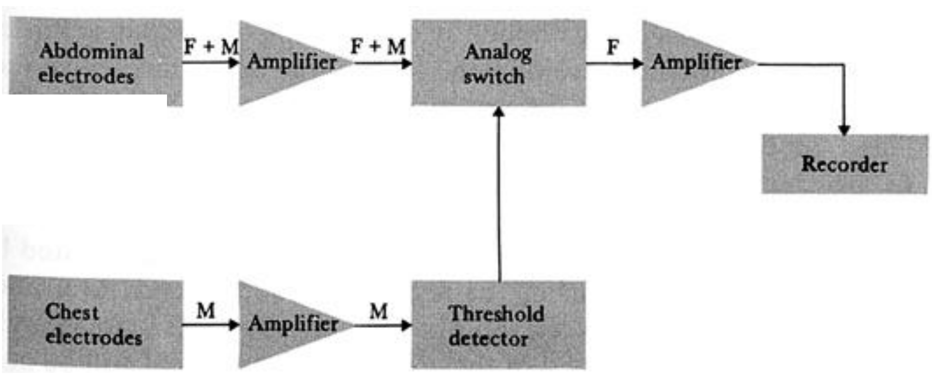


Figure 8-14
Ten-patient electrode (12-lead) ECG block diagram.

Maternal Abdominal ECG

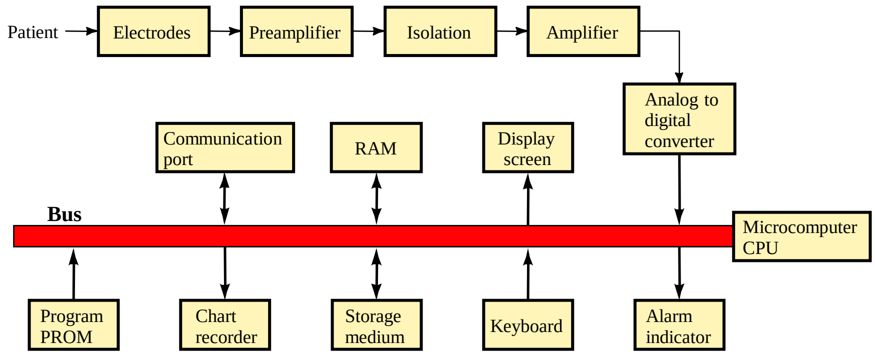
Typical fetal ECG obtained from maternal abdomen. ***F represents fetal QRS*** **complexes;** ***M represents maternal QRS*** **complexes. Maternal ECG and fetal ECG (recorded directly from the fetus) are included for comparison.**

Fetal ECG

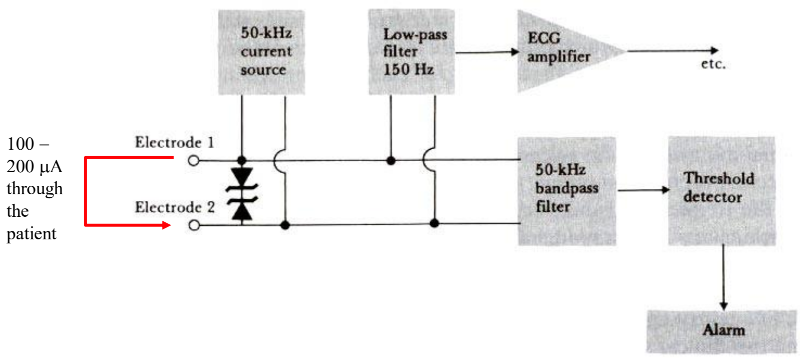


Block diagram of a scheme for isolating fetal ECG from an abdominal signal that contains both fetal and maternal ECGs.

Cardiac Monitor

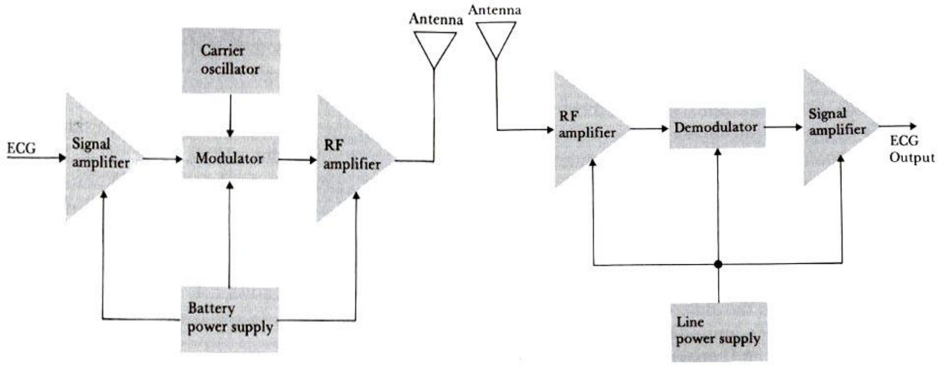


Lead-Failure Alarm



Block diagram of a system used with cardiac monitors to detect increased electrode impedance, lead wire failure, or electrode fall-off. When the electrode begins to fall off, the impedance increases and the voltage at 50 Hz rises towards the threshold. When the threshold is crossed, the alarm sounds. The back-to-back Zener diodes limit the voltage at the current source output and protect the patient and other electronics from high voltage values.

Biotelemetry



Block diagram of a single-channel radiotelemetry system

THANK YOU