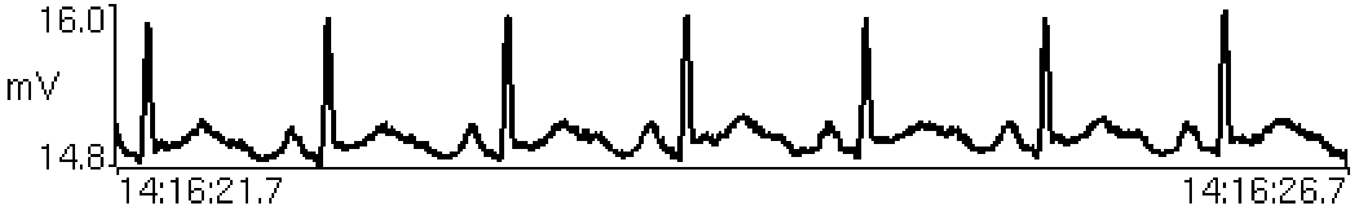
Biomedical Instrumentation

1. The Electrocardiogram (ECG)

The Electrocardiogram

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



- This is the electrocardiogram or ECG

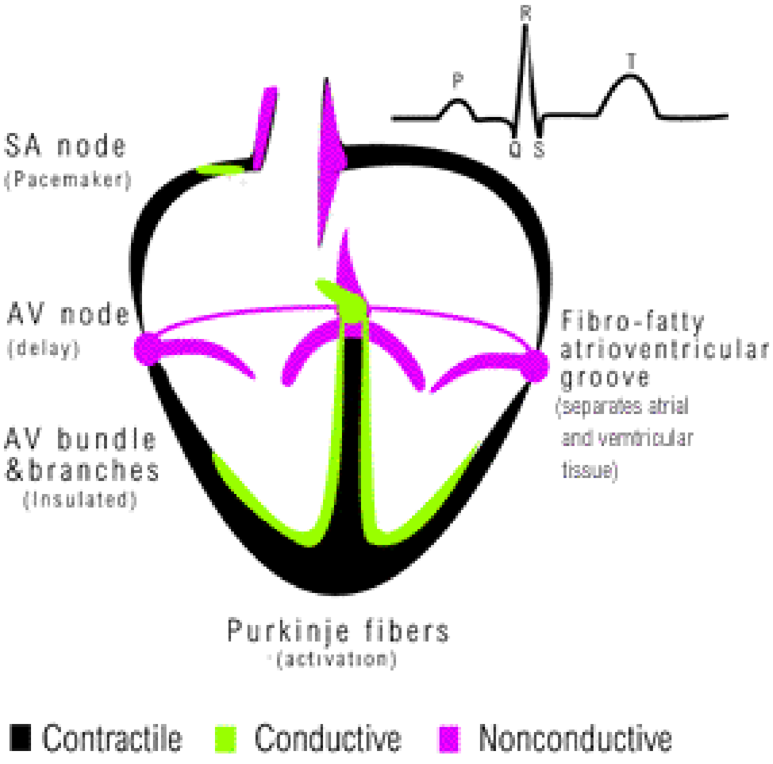
The origin of the ECG

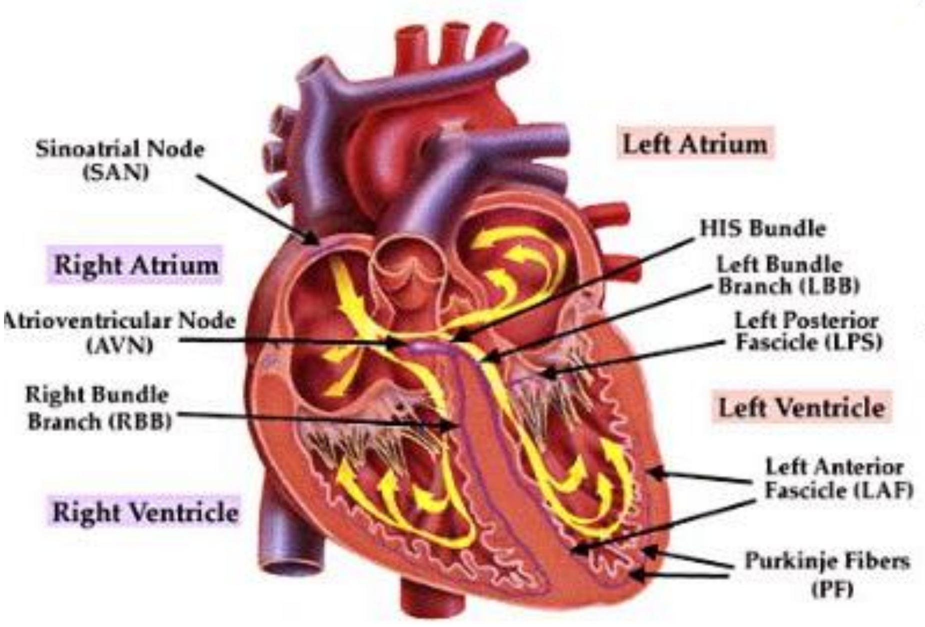
- Atrial and ventricular contractions are the result of carefully timed *depolarisations* of the cardiac muscle cells

- The timing of the heart cycle depends on:
  - Stimulus from the pacemaker cells
  - Propagation between muscle cells
  - Non-excitable cells
  - Specialised conducting cells (Atrio-Ventricular Node)

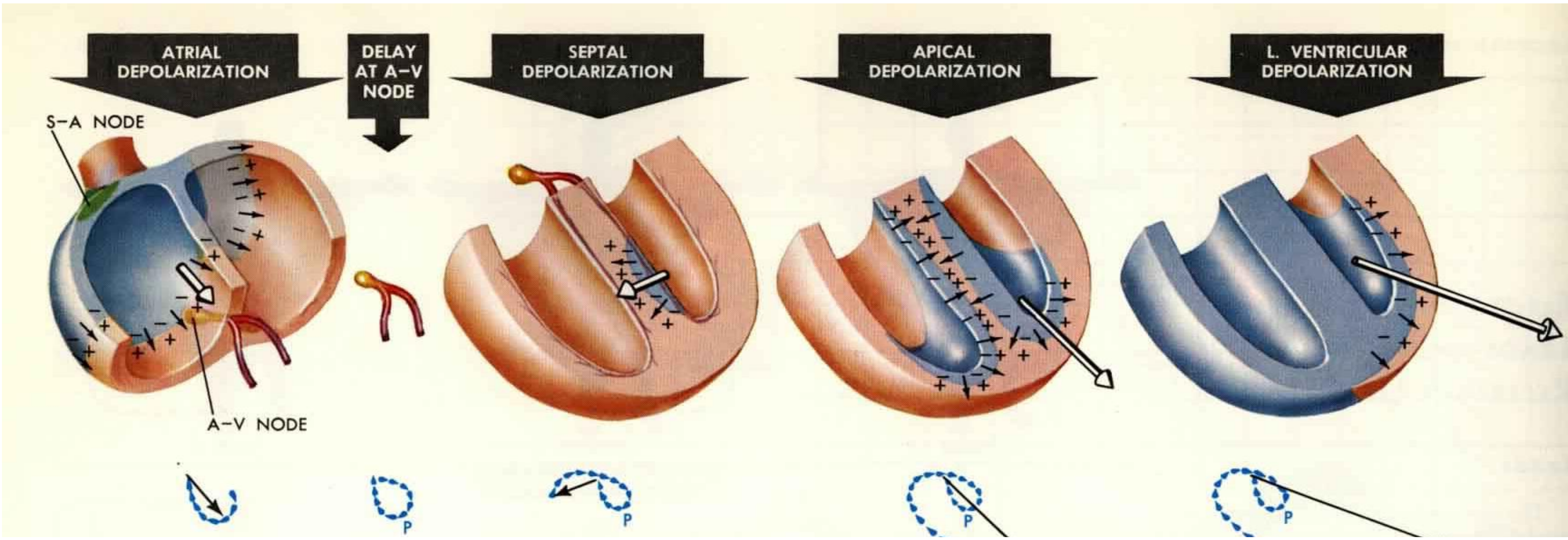
Important specific structures

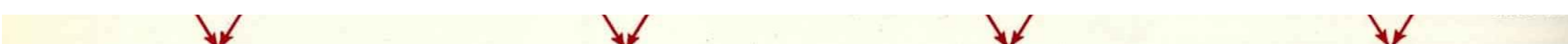
- Sino-atrial node = pacemaker (usually)
- Atria
- After electrical excitation: contraction
- Atrioventricular node (a tactical pause)
- Ventricular conducting fibers (freeways)
- Ventricular myocardium (surface roads)
- After electrical excitation: contraction



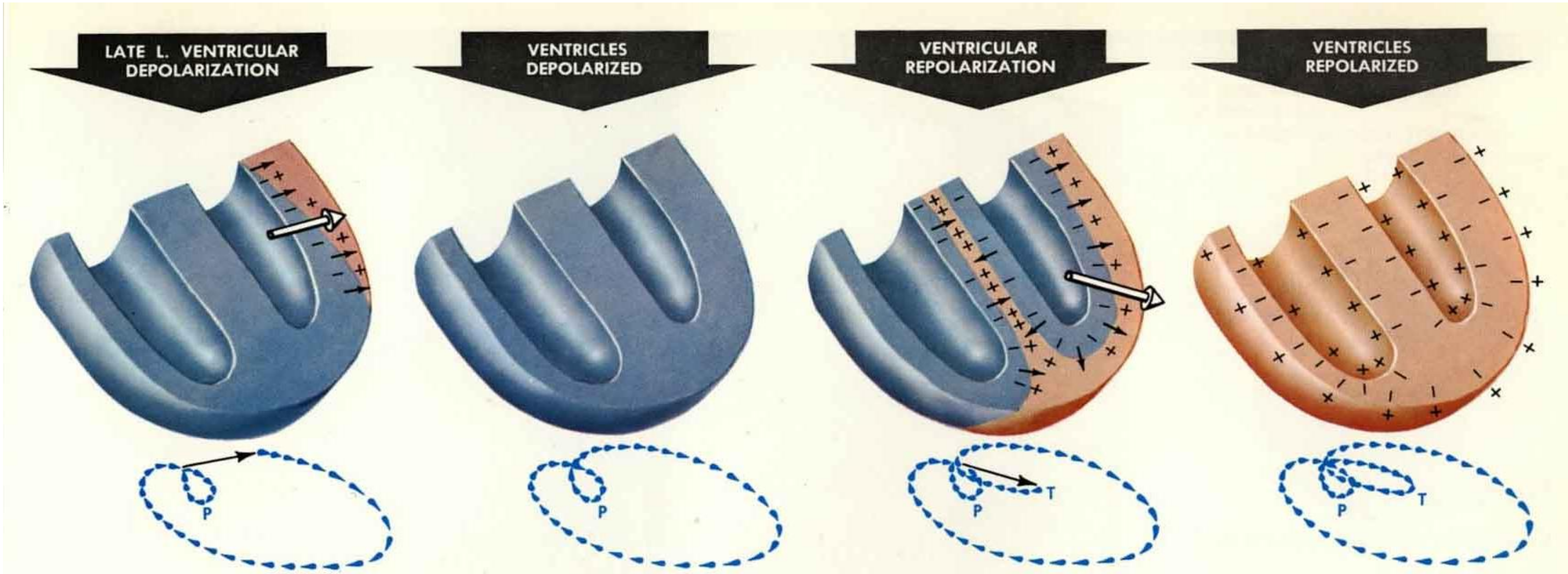


Excitation of the Heart



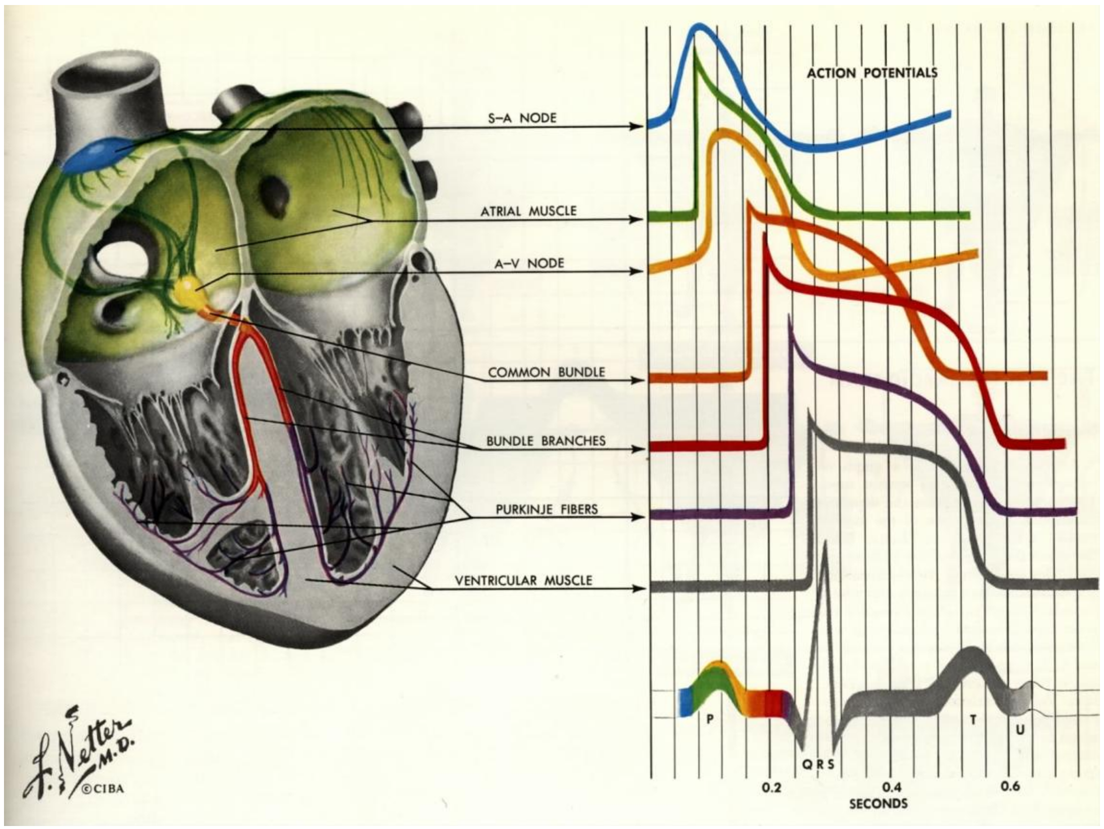


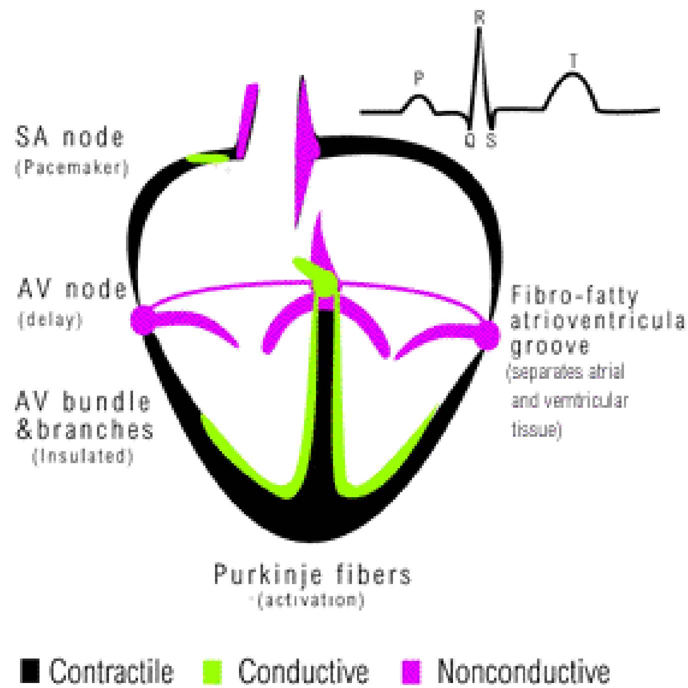
Excitation of the Heart



Cardiac Electrical Activity

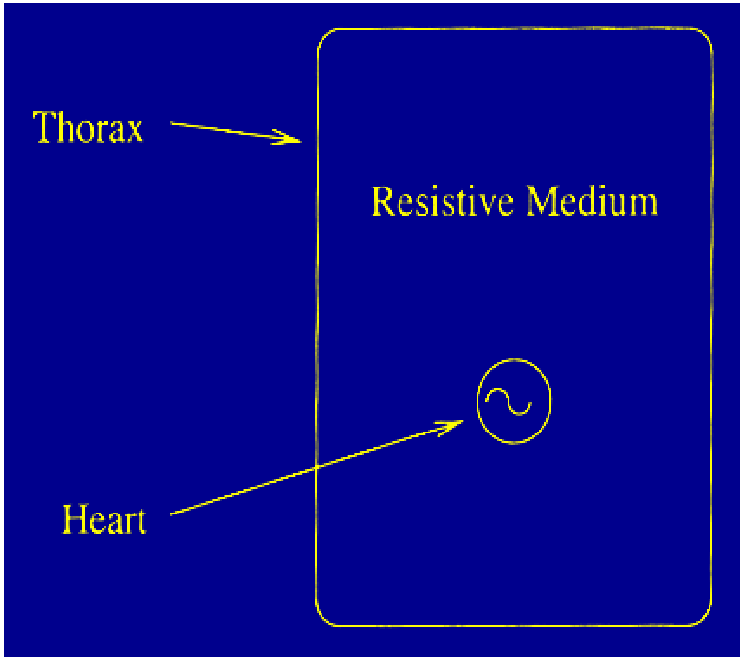
- Putting it al together:



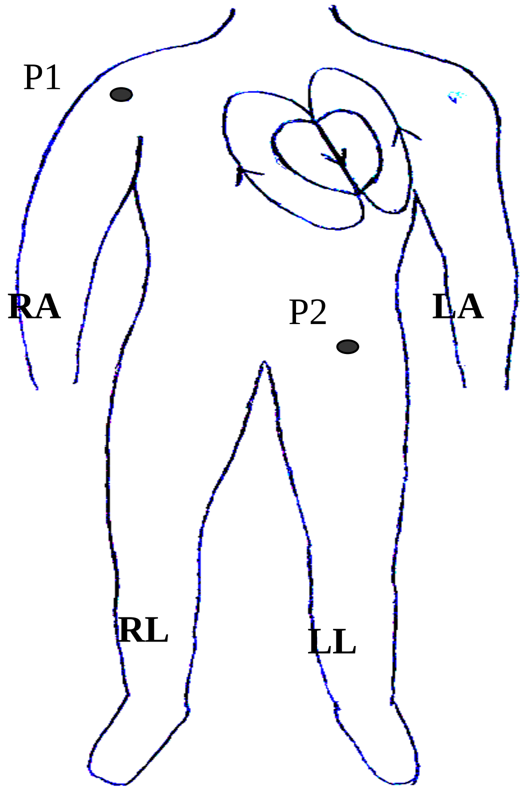


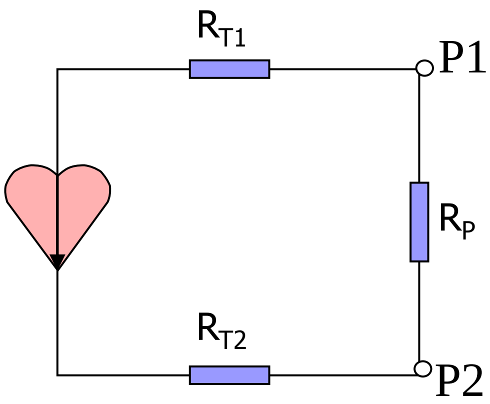
Approximate model of ECG

- To a first approximation, the heart can be considered to be an electrical generator.
- This generator drives (ionic) currents into the upper body (the thorax) which can be considered to be a passive, resistive medium
- Different potentials will be measured at different points on the surface of the body



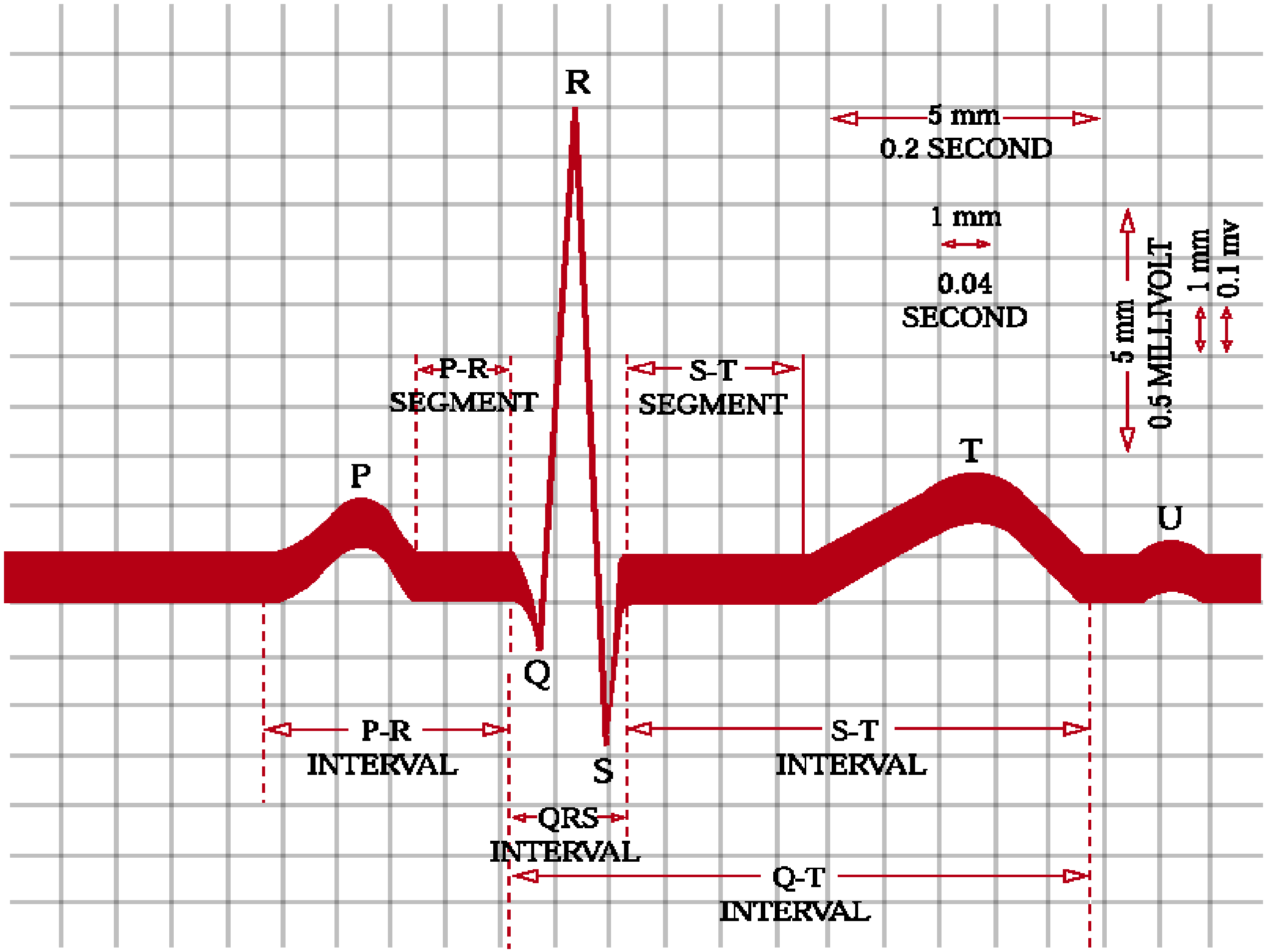
Recording the ECG





Points P1 and P2 are arbitrary observation points on the torso; R_P is the resistance between them, and R_{T1} , R_{T2} are lumped thoracic medium resistances.

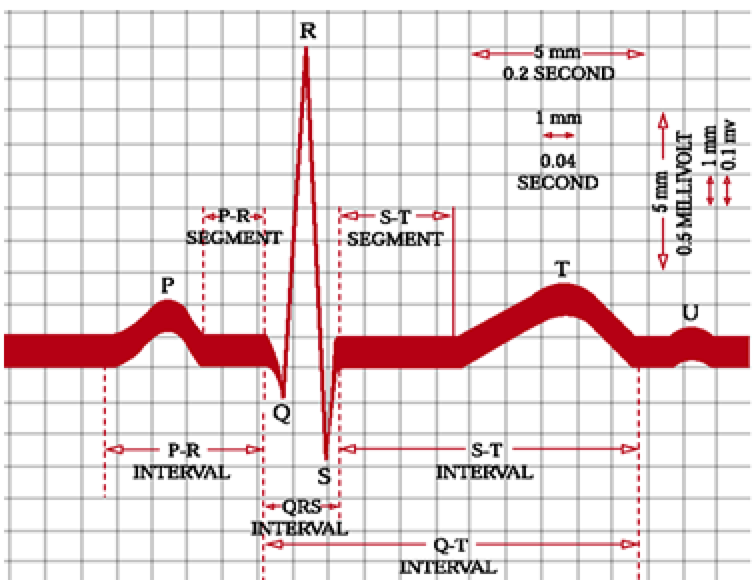
Typical ECG signal



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

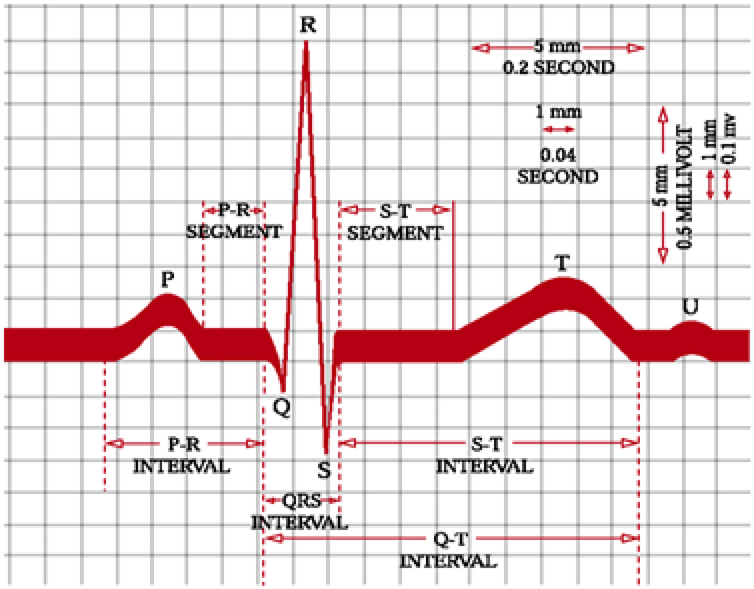
Components of the ECG waveform

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



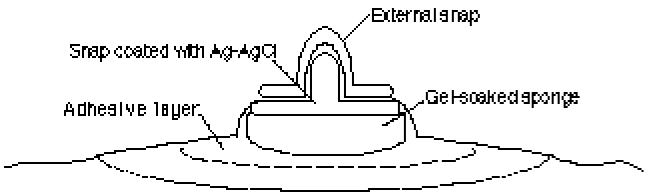
Components of the ECG waveform

- T-wave: ventricular repolarisation.
- P-Q interval: the time interval between the beginning of the P wave and the beginning of the QRS complex.
- Q-T interval: characterises ventricular repolarisation.



Recording the ECG

- To record the ECG we need a transducer capable of converting the ionic potentials generated within the body into electronic potentials
- Such a transducer is a pair of electrodes and are:
  - Polarisable (which behave as capacitors)
  - Non-polarisable (which behave as resistors)
  - Both; common electrodes lie between these two extremes
- The electrode most commonly used for ECG signals, the *silver-silver chloride* electrode, is closer to a non-polarisable electrode.



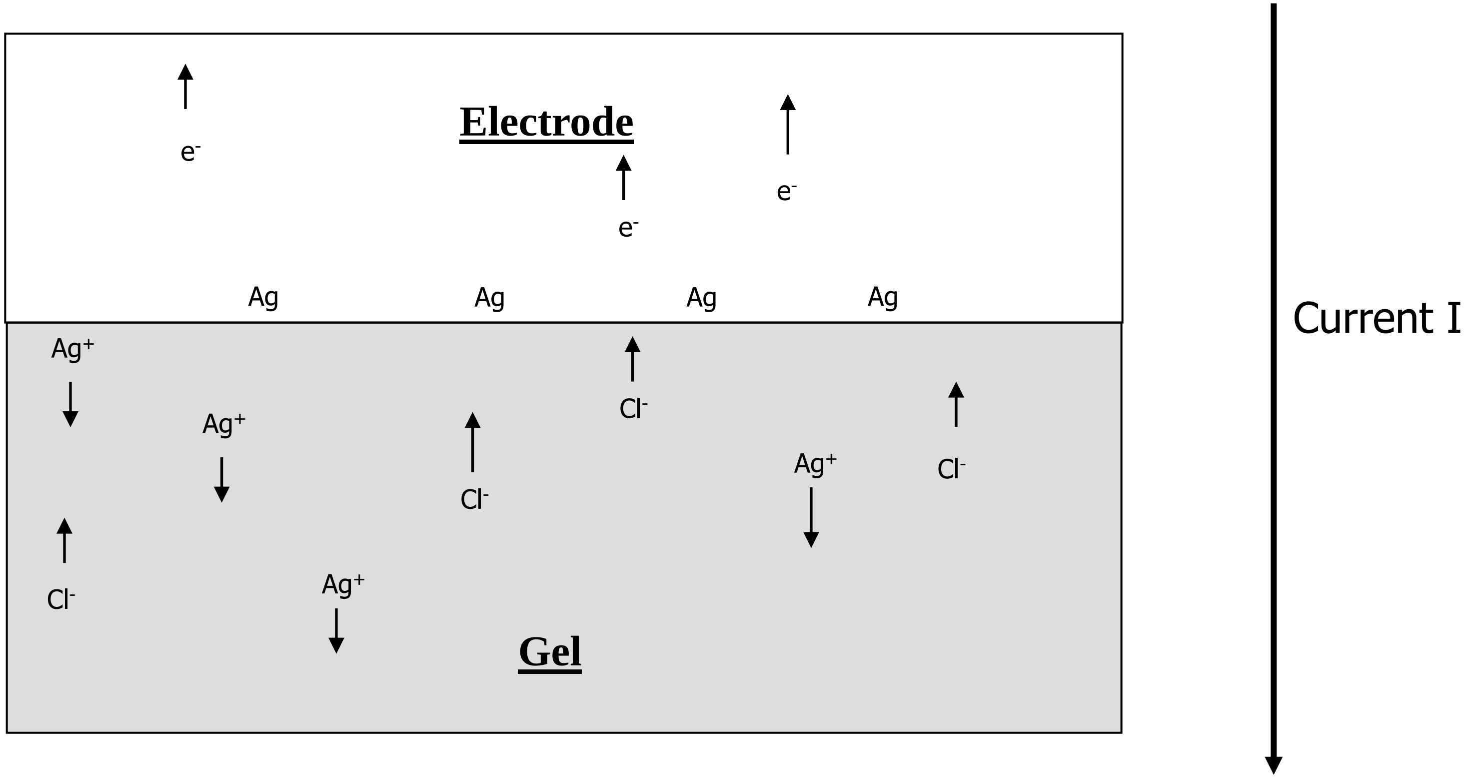
Silver-silver chloride electrode

- Electrodes are usually metal discs and a salt of that metal.
- A paste is applied between the electrode and the skin.
- This results in a local solution of the metal in the paste at the electrode-skin interface. Some of the silver dissolves into solution producing Ag^+ ions:

$$Ag \rightarrow Ag^+ + e^-$$

- Ionic equilibrium takes place when the electrical field is balanced by the concentration gradient and a layer of Ag^+ ions is adjacent to a layer of Cl^- ions.

Electrode-electrolyte interface

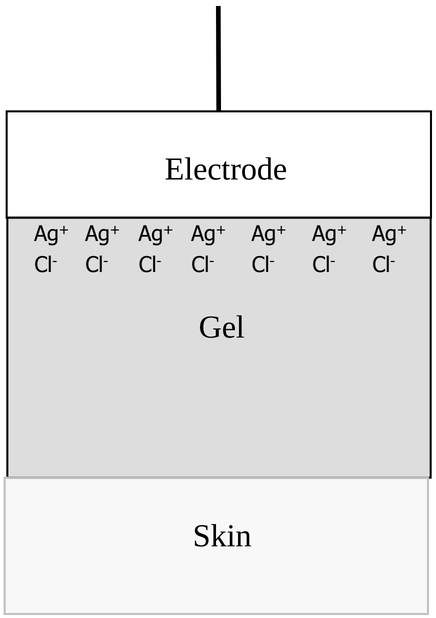


Illustrative diagram of electrode-electrolyte interface in case of Ag-AgCl electrode

Silver-silver chloride electrode

- Electrodes are usually metal discs and a salt of that metal.
- A paste is applied between the electrode and the skin.
- This results in a local solution of the metal in the paste at the electrode-skin interface.
- Ionic equilibrium takes place when the electrical field is balanced by the concentration gradient and a layer of *Ag+* ions is adjacent to a layer of *Cl-* ions.
- This gives a potential drop E called the *half-cell potential* (normally 0.8 V for an *Ag-AgCl* electrode)

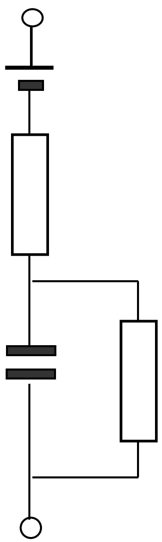
Silver-silver chloride electrode



$$Ag \rightarrow Ag^{+} + e^{-}$$

- The double layer of charges also has a capacitive effect.
- Since the *Ag-AgCl* electrode is primarily non-polarisable, there is a large resistive effect.
- This gives a simple model for the electrode.
- However, the impedance is not infinite at d.c. and so a resistor must be added in parallel with the capacitor.

Silver-silver chloride electrode



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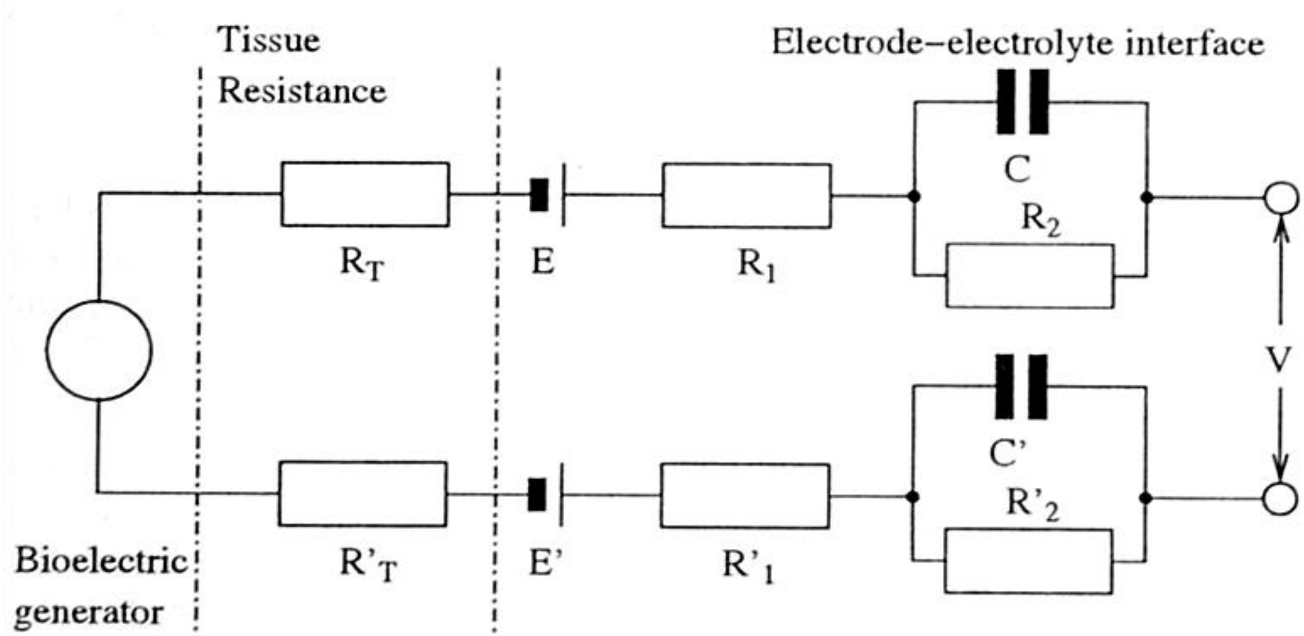
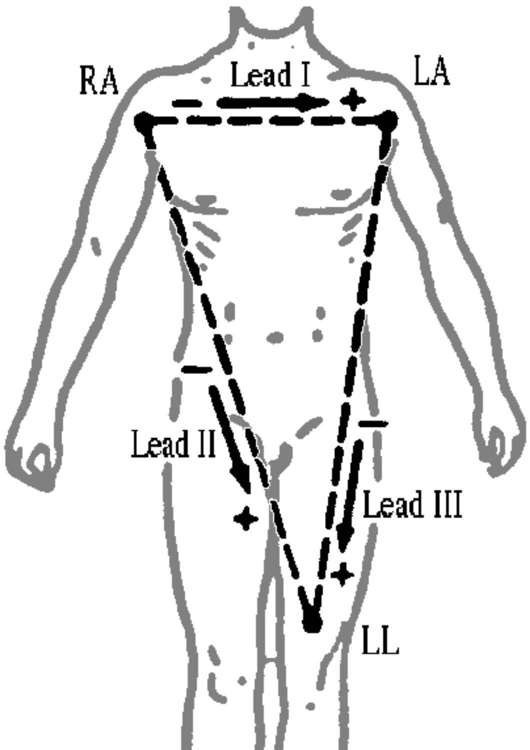
The Overall Model



- The resistors and capacitors may not be exactly equal.
- Half cell potentials E and E' should be very similar.
- Hence V should represent the actual difference of ionic potential between the two points on the body where the electrodes have been placed.

Electrode placement

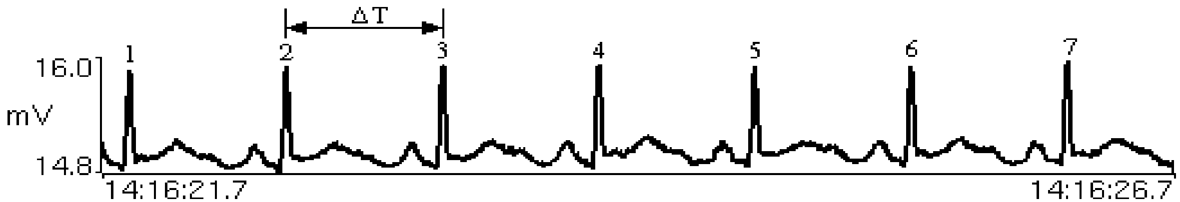


V_I = (potential at LA) – (potential at RA)

V_{II} = (potential at LL) – (potential at RA)

V_{III} = (potential at LL) – (potential at LA)

The right leg is usually grounded (but see later)

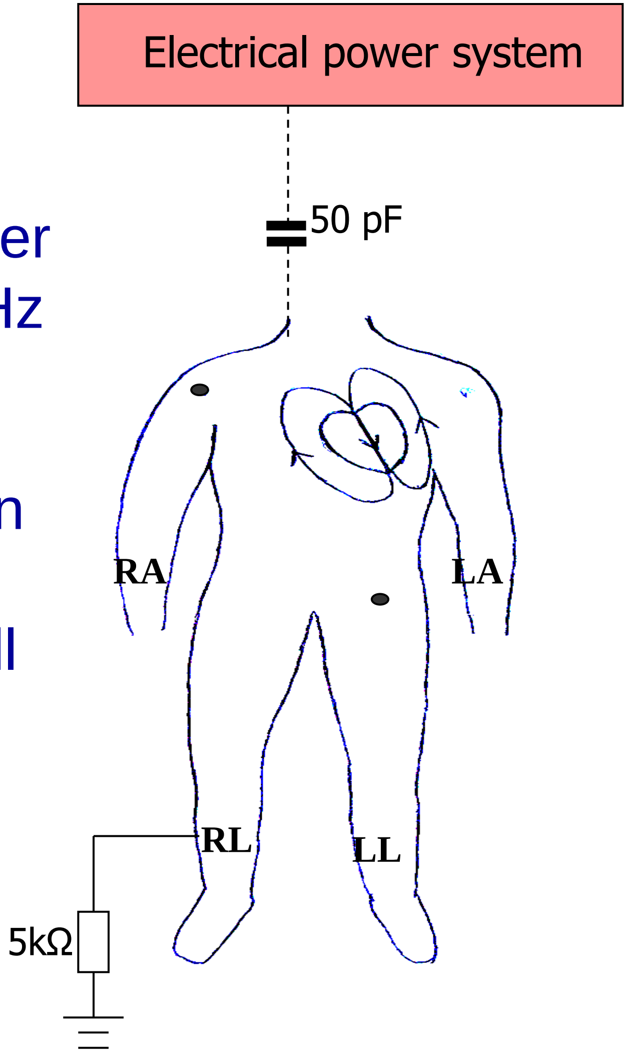


ECG Amplification

- Problems in ECG amplification
  - The signal is small (typical ECG peak value ~1mV) so amplification is needed
  - Interference is usually larger amplitude than the signal itself

1st Problem: Electric Field Interference

- Capacitance between power lines and system couples current into the patient
- This capacitance varies but it is of the order of 50pF (this corresponds to 64MΩ at 50Hz ... recall $X_C = 1/\omega C$)
- If the right leg is connected to the common ground of the amplifier with a contact impedance of 5kΩ, the mains potential will appear as a ~20mV noise input.



the 50 Hz interference is common to both measuring electrodes !

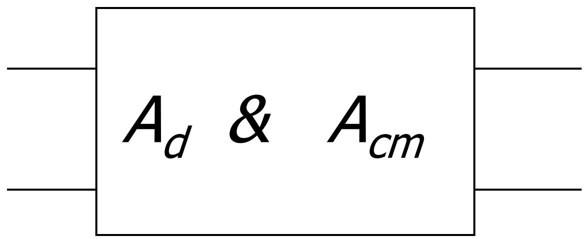
(common mode signals)

The solution

- The ECG is measured as a *differential* signal.
- The 50Hz noise, however, is common to all the electrodes.
  - It appears equally at the Right Arm and Left Arm terminals.
- Rejection therefore depends on the use of a *differential amplifier* in the input stage of the ECG machine.
- The amount of rejection depends on the ability of the amplifier to reject *common-mode* voltages.

Common Mode Rejection Ratio (CMRR)

$v_{in} = v_{cm} + v_d$

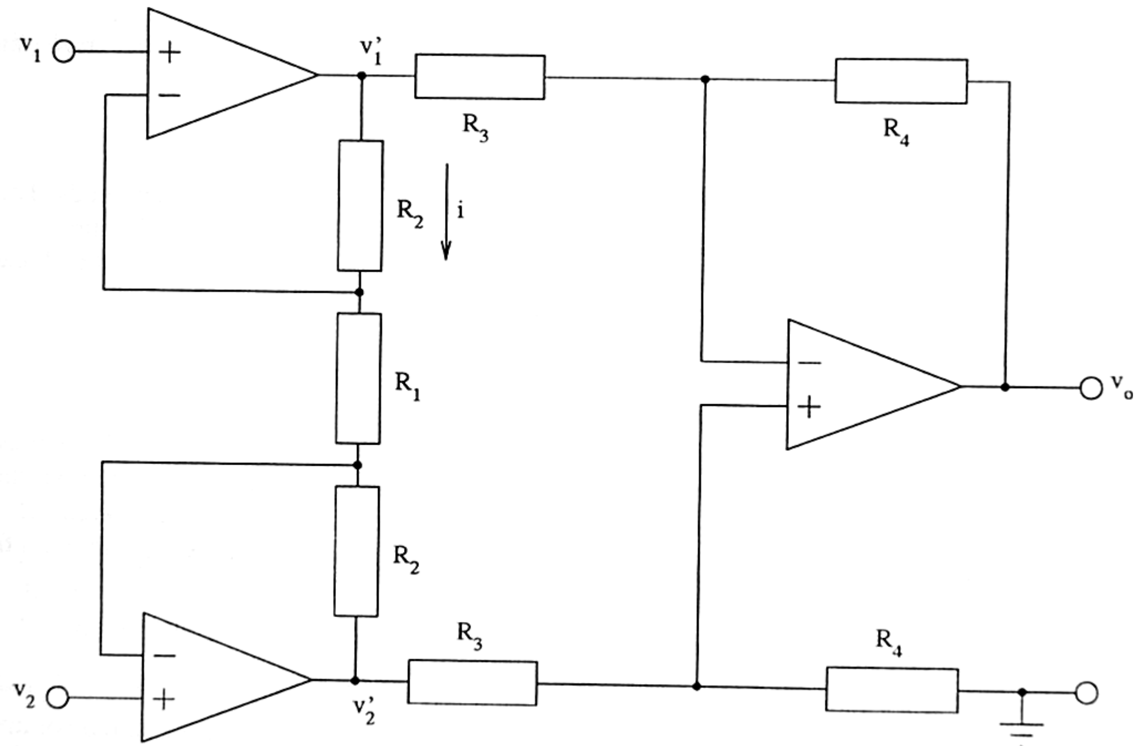


$v_{out} = A_{cm}v_{cm} + A_d v_d$

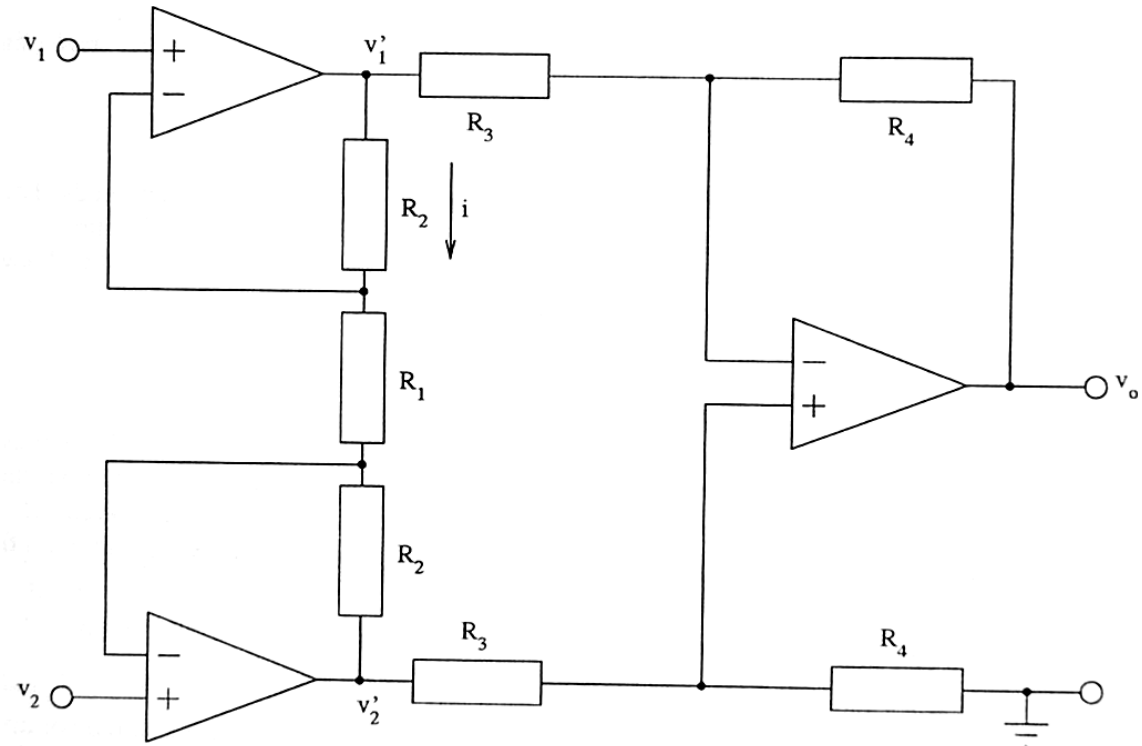
$$CMRR = A_d / A_{cm}$$

(ratio of differential gain to common mode gain)

Three Op-Amp Differential Amplifier



Three Op-Amp Differential Amplifier



$$i = \frac{v_1' - v_1}{R_2} = \frac{v_1 - v_2}{R_1} = \frac{v_2 - v_2'}{R_2}$$

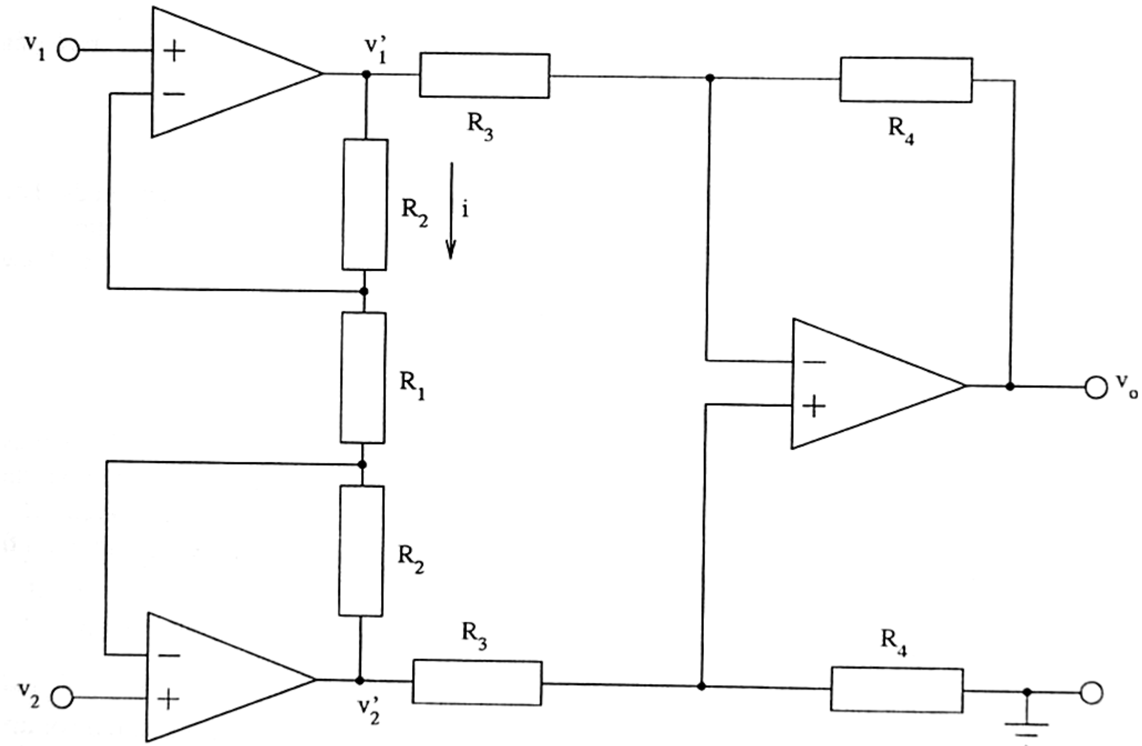
$$v_1' = (1 + \frac{R_2}{R_1})v_1 - \frac{R_2}{R_1}v_2$$

$$v_2' = (1 + \frac{R_2}{R_1})v_2 - \frac{R_2}{R_1}v_1$$

$$v_2' - v_1' = (v_2 - v_1)(1 + \frac{2R_2}{R_1})$$

$$A_{d1} = 1 + \frac{2R_2}{R_1}$$

Three Op-Amp Differential Amplifier



$$i = \frac{v_1^{'} - v_1}{R_2} = \frac{v_1 - v_2}{R_1} = \frac{v_2 - v_2^{'}}{R_2}$$

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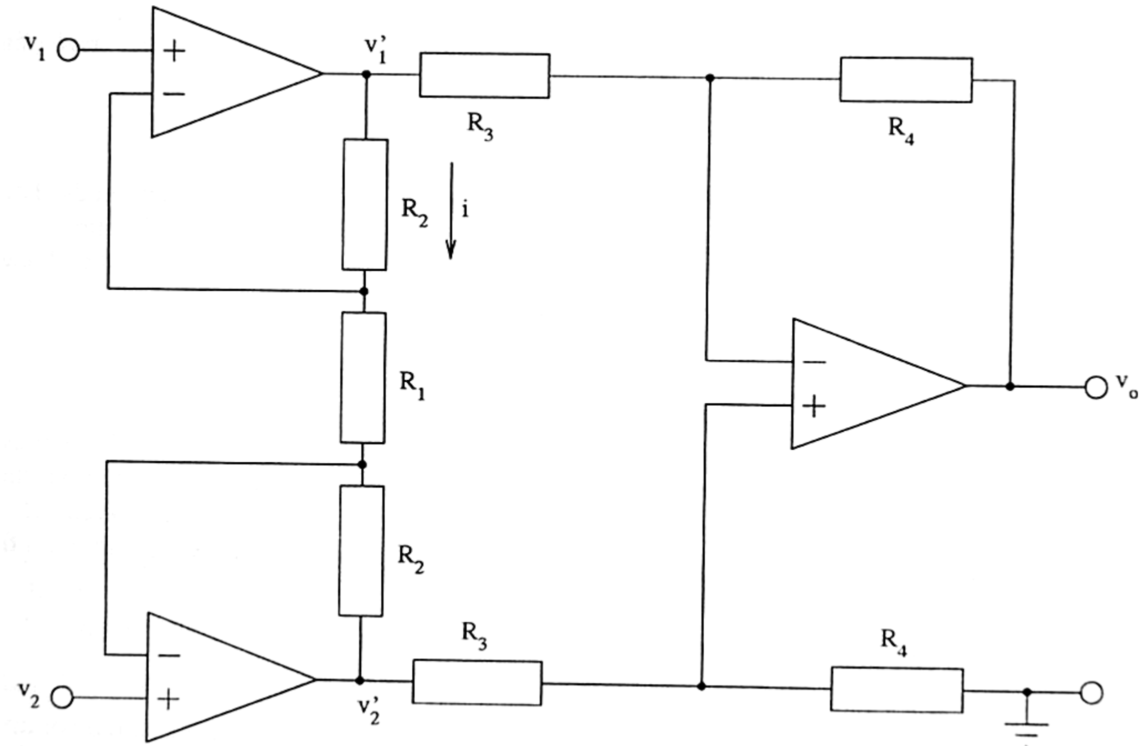
$$v_2^{'} - v_1^{'} = (v_2 - v_1)(1 + \frac{2R_2}{R_1})$$

When $v_1 = v_2 = v_{cm}$, $A_{cm} = 1$

Three Op-Amp Differential Amplifier



$$i = \frac{v_1' - v_1}{R_2} = \frac{v_1 - v_2}{R_1} = \frac{v_2 - v_2'}{R_2}$$

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$$v_2' = (1 + \frac{R_2}{R_1})v_2 - \frac{R_2}{R_1}v_1$$

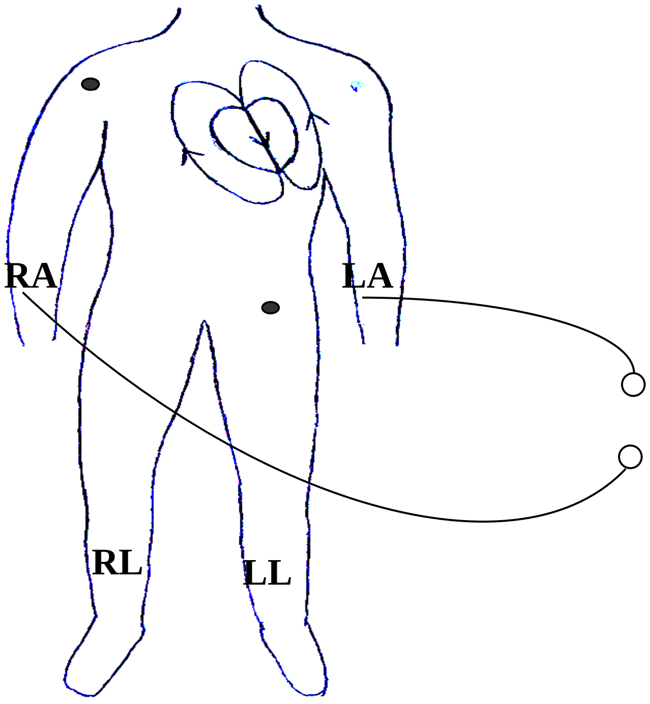
$$v_2' - v_1' = (v_2 - v_1)(1 + \frac{2R_2}{R_1})$$

$$\text{CMRR} = \frac{A_{d1} \cdot A_{d2}}{A_{cm1} \cdot A_{cm2}}$$

CMRR is product of CMRR for each input amplifier

2nd problem: Magnetic Induction

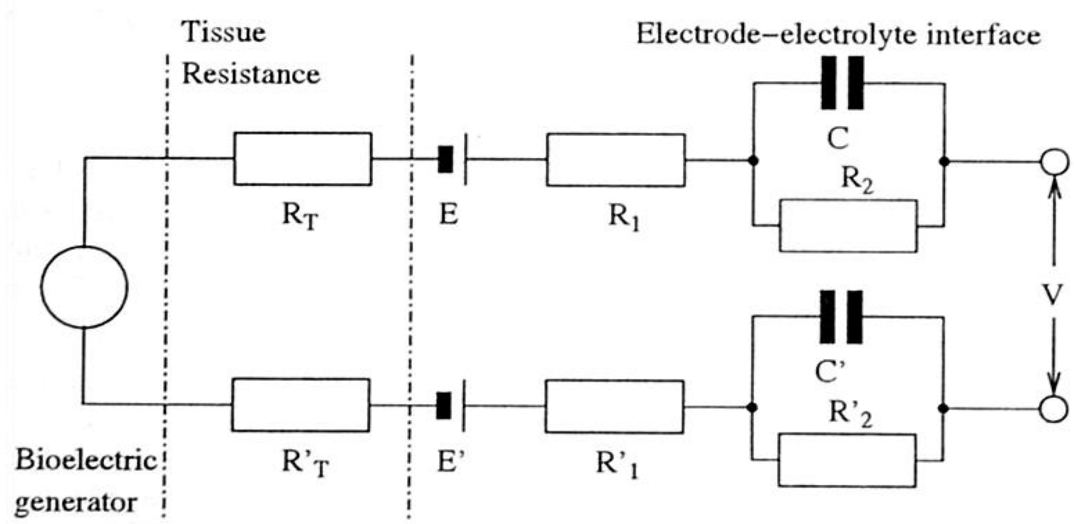
- Current in magnetic fields induces voltage in the loop formed by patient leads



- The solution is to minimise the coil area (e.g. by twisting the lead wires together)

3^{rd} problem: Source impedance unbalance

- If the contact impedances are not balanced (i.e. the same), then the body's common-mode voltage will be higher at one input to the amplifier than the other.



3rd problem: Source impedance unbalance

- If the contact impedances are not balanced (i.e. the same), then the body's common-mode voltage will be higher at one input to the amplifier than the other.

- Hence, a fraction of the common-mode voltage will be seen as a differential signal.
  - see problem on example sheet

Summary

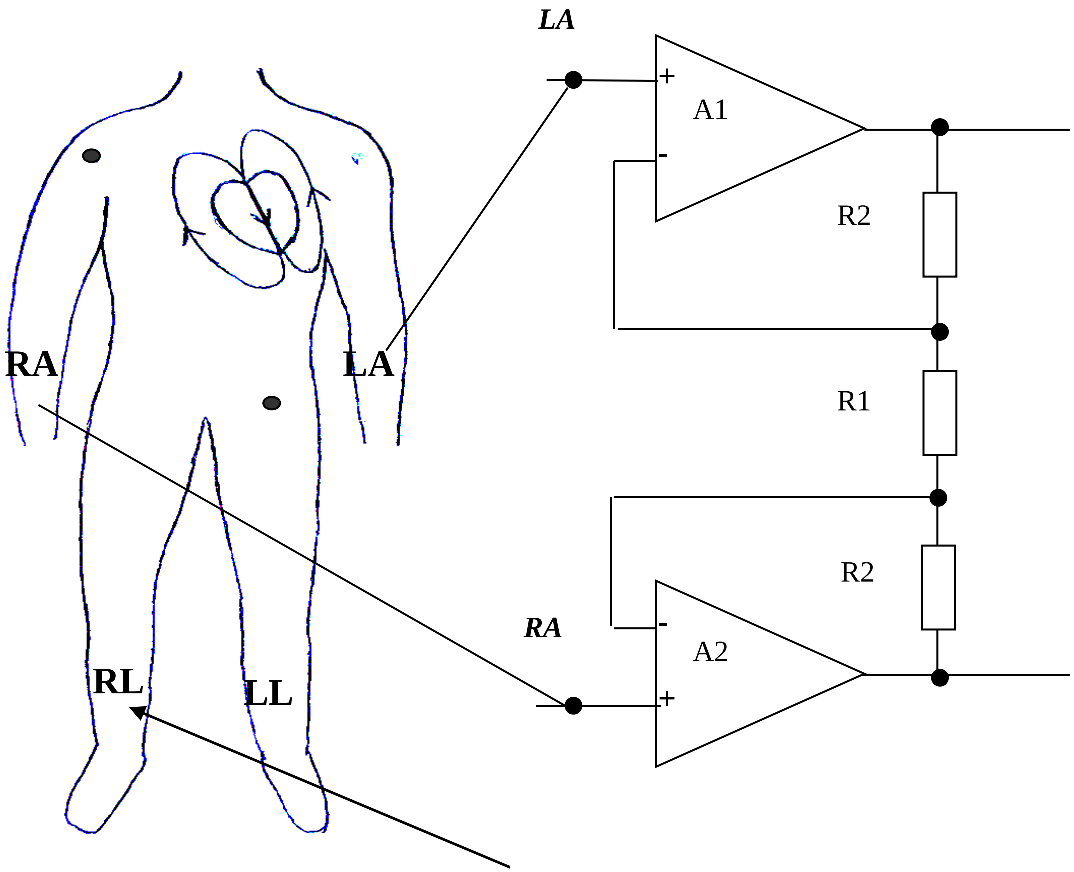
- Output from the differential amplifier consists of three components:
  - The *desired* output (ECG)
  - *Unwanted* common-mode signal because the common-mode rejection is not infinite
  - *Unwanted* component of common-mode signal (appearing as pseudo-differential signal at the input) due to contact impedance imbalance

Driven right-leg circuitry

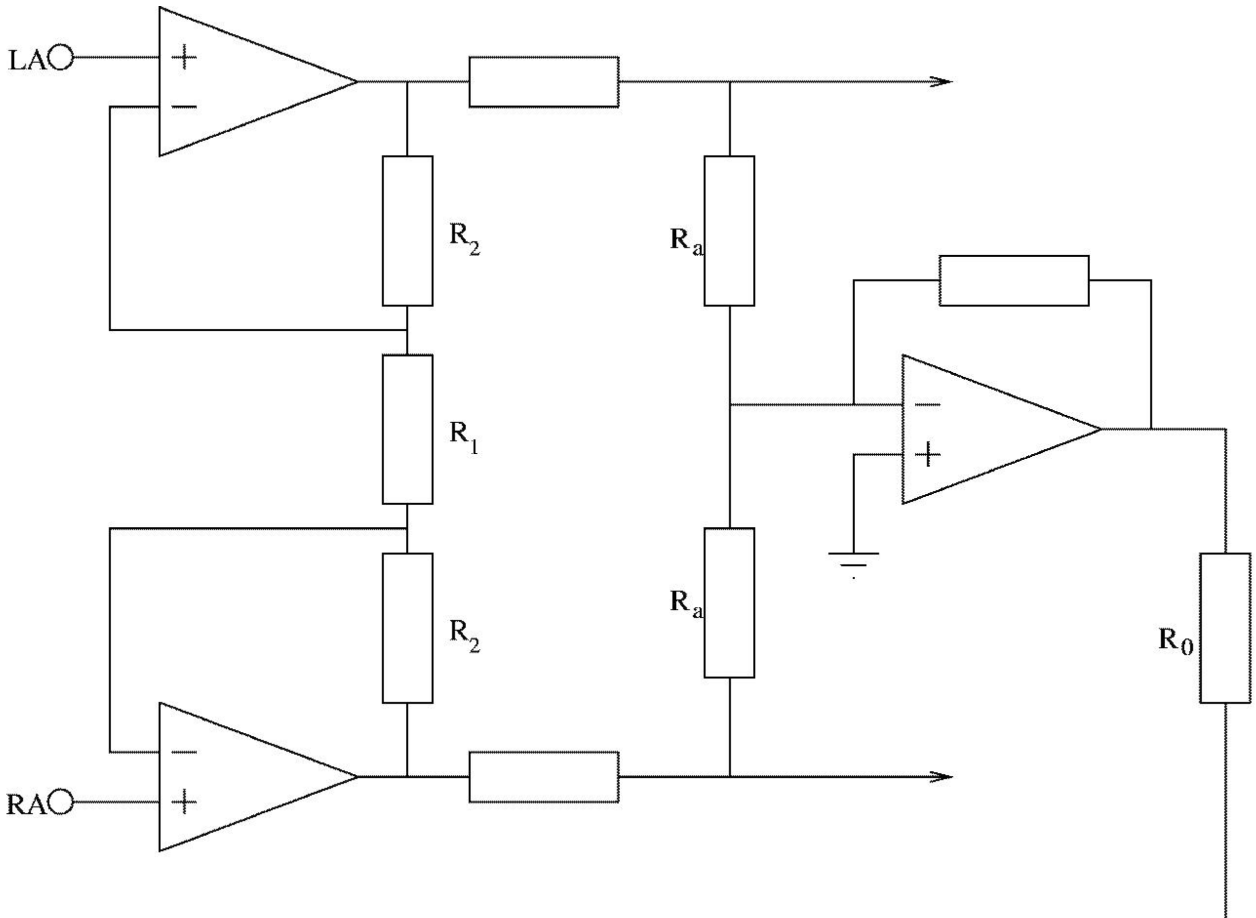
- The common-mode voltage can be controlled using a *Driven right-leg circuit*.

- A small current (<1μA) is injected into the patient to equal the displacement currents flowing in the body.

Driven right-leg circuitry



Driven right-leg circuitry

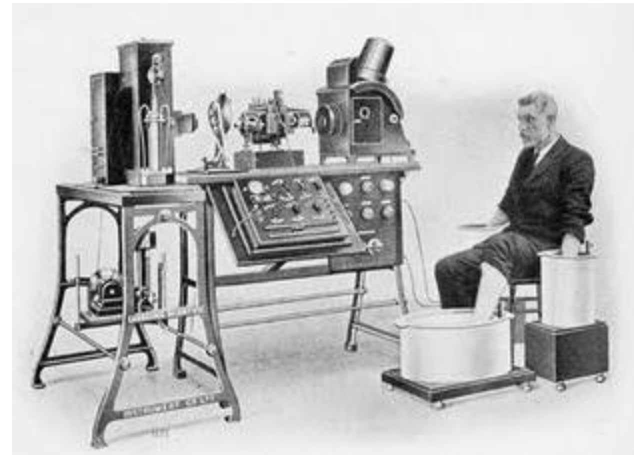


Driven right-leg circuitry

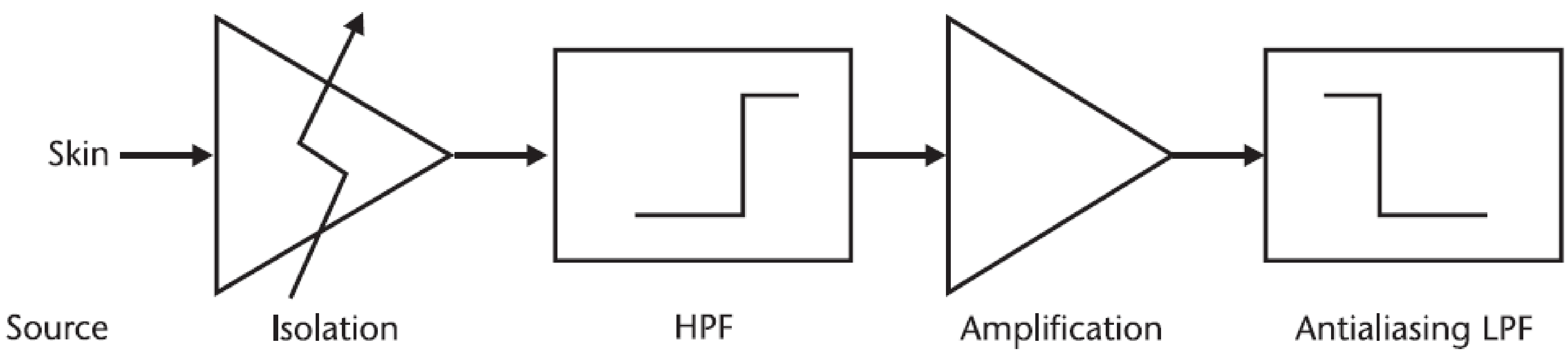
- The common-mode voltage can be controlled using a *Driven right-leg circuit*.
- A small current (<1μA) is injected into the patient to equal the displacement currents flowing in the body.
- The body acts as a summing junction in a feedback loop and the common-mode voltage is driven to a low value.
- This also improves patient safety (R_0 is v. large – see notes).

Other patient protection

- (**[Defib Protection]**)
- **Isolation**
- Filtering
- Amplification
- Anti-alias filtering
- Digitization

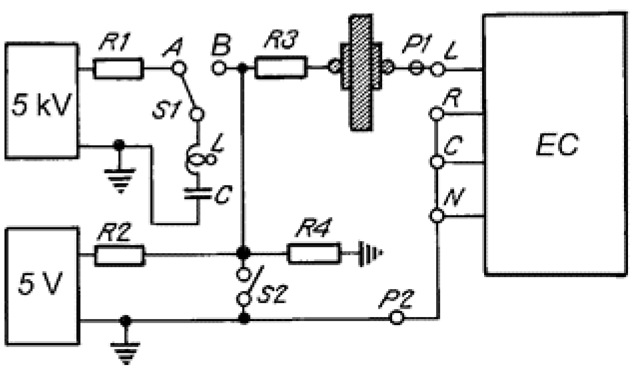


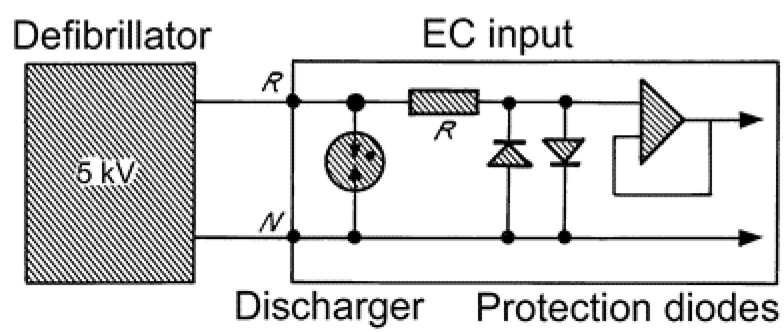
Photograph of a Complete Electrocardiograph, Showing the Manner in which the Electrodes are Attached to the Patient, In this Case the Hands and One Foot Being Immersed in Jars of Salt Solution



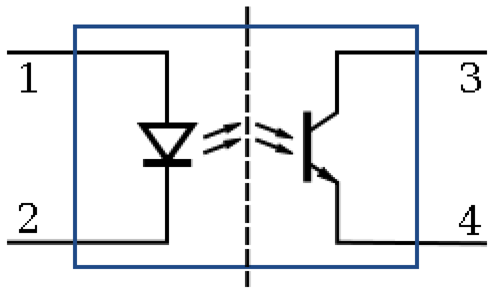
Static defibrillation protection

- For use in medical situations, the ECG must be able to recover from a 5kV, 100A impulse (defibrillation)
- Use large inductors and diodes

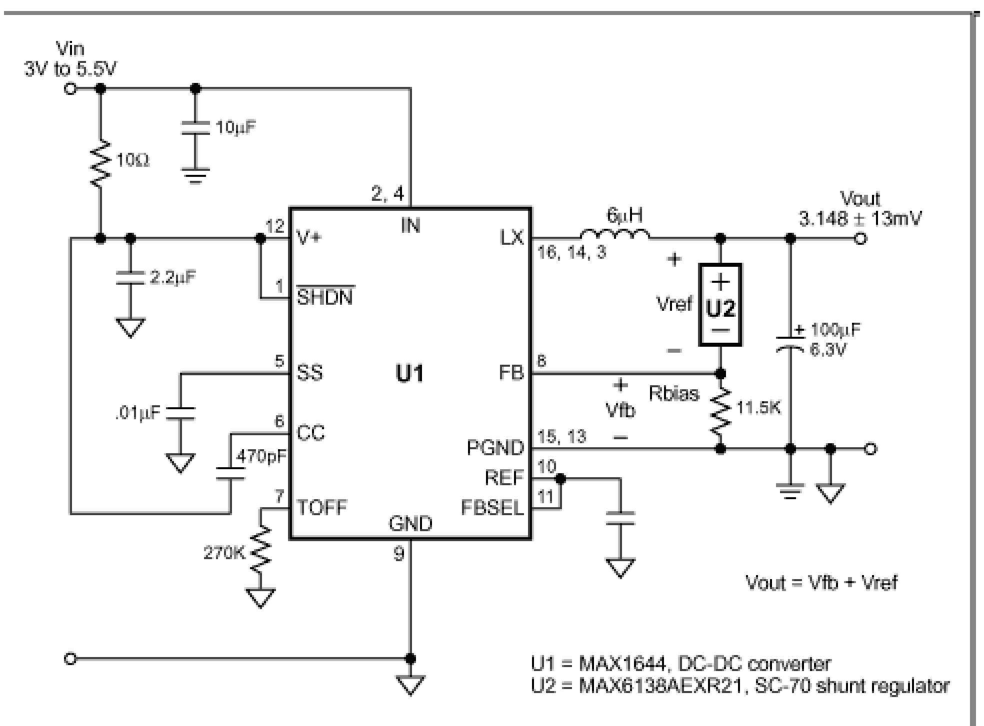




Patient Isolation



- Opto-isolators



- DC-DC Converters

RF Shielding & Emissions

- **Electromagnetic compatibility (EMC)**
  - the ability of a device to function (a) properly in its intended electromagnetic environment, and (b) without introducing excessive EM energy that may interfere with other devices
- **Electromagnetic disturbance (EMD)**
  - any EM phenomenon that may degrade the performance of equipment, such as medical devices or any electronic equipment. Examples include power line voltage dips and interruptions, electrical fast transients (EFTs), electromagnetic fields **(radiated emissions), electrostatic discharges**, and **conducted emissions**
- **Electromagnetic interference (EMI)**
  - degradation of the performance of a piece of equipment, transmission channel, or system (such as medical devices) caused by an electromagnetic disturbance
- **Electrostatic discharge (ESD)**
  - the rapid transfer of electrostatic charge between bodies of different electrostatic potential, either in proximity in air (air discharge) or through direct contact (contact discharge)
- **Emissions**
  - electromagnetic energy emanating from a device generally falling into two categories: conducted and radiated. Both categories of emission may occur simultaneously, depending on the configuration of the device

Testing

Electrical safety
(from Lecture B)

Physiological effects of electricity:

- Electrolysis
- Neural stimulation
- Tissue heating

Electrolysis

- Electrolysis takes place when direct current passes through tissue.
- Ulcers can be developed, for example if a d.c. current of 0.1 mA is applied to the skin for a few minutes.
- IEC601 limits the direct current (< 0.1 Hz) that is allowed to flow between a pair of electrodes to 10 μA.

Neural stimulation

- An action potential occurs if the normal potential difference across a nerve membrane is reversed for a certain period of time.

- This results in a sensation of pain (if sensory nerve has been stimulated) or muscle contraction (if motor nerve has been simulated).

Hazards of neural stimulation

- The effects of neural stimulation depend on the amplitude and frequency of the current, as well as the location of the current injection.
- If the current is injected through the skin, 75 mA – 400 mA at 50 Hz can cause ventricular fibrillation.

  Beware: under normal (dry) conditions, the impedance of the skin at 50 Hz is usually between 10 kΩ and 100 kΩ; if the skin is wet, the impedance can be 1 kΩ or less.

- If the current is directly applied to the heart wall (e.g. failure of circuitry in a cardiac catheter), 100μA can cause ventricular fibrillation.

Tissue heating

- The major effect of high-frequency (> 10 kHz) electrical currents is heating.
- The local effect depends on the current amplitude and frequency as well as the length of exposure.
- *Think about your mobile phone usage…*

Electricity can also be good for you…

- Electrical shock is also applied to patients in clinical practice for therapeutic purposes.
- These applications make use of the *neural stimulation* effect:
  - Pacemakers (to stimulate the heart)
  - Defibrillators (to stop ventricular fibrillation)
  - Implantable Stimulators for Neuromuscular Control (to help paralysed patients regain some neuromuscular control).

Electricity can also be good for you…