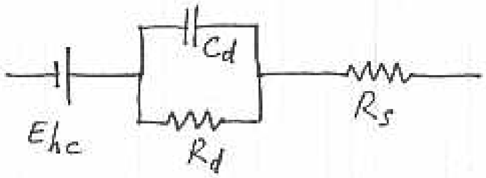
BIOELECTRIC AMPLIFIERS

Ag/AgCl Electrodes

These can be modeled as



$$Z_T = R_s + R_d // \left(\frac{1}{j\omega C_d}\right)$$

E_{hc} : Half cell potential (contact potential) generated at the metal-liquid interface (junction)
C_d : Capacitance of the metal-liquid interface
R_d : Leakage resistance of the metal-liquid interface
R_s : Series resistance associated with the metal-liquid interface and due to resistance in liquid (electrolyte) between metal and body

The total impedance, Z_T, is obviously frequency dependent. In addition, C_d and R_d have frequency dependence. C_d and R_d also depend on the current passing through the electrode. Modern amplifiers have very high input impedances and therefore current through the electrodes is negligible. Anyhow, up to $1 mA/cm^2$ current density on the electrode surface, dependence of R_d and C_d on current is negligible. Also for Ag/AgCl electrodes up to 100 KHz dependence of R_d and C_d on frequency can be neglected.

Typical Values for electrode parameters:

$$E_{hc} = 0.24 V, \; R_d = 20 k\Omega, \; C_d = 100 pF, \; R_s = 300 \Omega$$

At 10 Hz: $\frac{1}{\omega C} = \frac{1}{2\pi \times 10 \times 100 \times 10^{-9}} = 159 k\Omega \gg R_d$

and $Z_T \approx R_s + R_d$

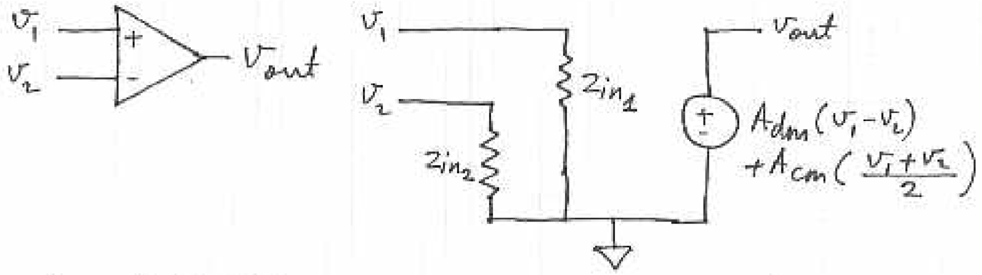
At 1 MHz: $\frac{1}{\omega C} = 15.9 \Omega \ll R_d$

and $Z_T \simeq R_s$.

1/11

Differential Amplifiers

Differential amplifiers are used to measure biopotential differences. A practical diff. amp. has the model

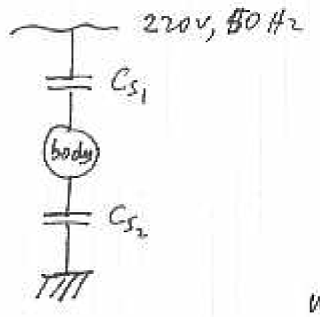


An ideal diff. amp.: $Zin_1 = Zin_2 = \infty$ and $A_{cm} = 0$.

There are of course other non-idealities such as input bias currents and offset voltages which are negligible for the analyses we shall undertake in these notes.

Common Mode 50 Hz Interference

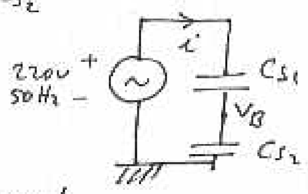
Due to unavoidable stray capacitances, the body has a large 50 Hz common mode voltage



Assuming body is conductive and equipotential, body voltage w.r.t. ⏚, V_B, is, in phasor notation,

$$V_B = 220 \times \frac{\frac{1}{j\omega C_{S_2}}}{\frac{1}{j\omega C_{S_1}} + \frac{1}{j\omega C_{S_2}}} = 220 \times \frac{C_{S_1}}{C_{S_1} + C_{S_2}}$$

With $C_{S_1} = C_{S_2}$,
$V_B = 110\,V$ (50 Hz)



Fortunately C_{S_1} and C_{S_2} are small enough so that low currents flow through the body. For $C_{S_1} = C_{S_2} = 100\,pF$,

$$|i| = \frac{220}{\left|\frac{1}{j\omega C_{S_1}} + \frac{1}{j\omega C_{S_2}}\right|} = \frac{220}{2}\,\omega C_{S_1} = 110 \times 2\pi \times 50 \times 100 \times 10^{-12}$$
$$= 3.46\,\mu A.$$

This value is much less than the safety limit of $100\,\mu A$ at 50 Hz.

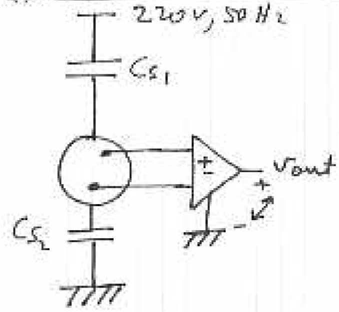
2/11

ECG amplifier configurations

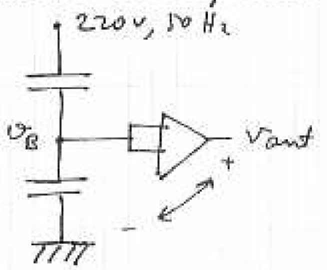
Non-isolated connections: (i) Two electrode configuration
(ii) Three electrode configuration

"Non-isolated" means that the diff. amp.'s common point is the same as (or connected to) actual earth ($\perp$).

(i) Two electrode non-isolated ECG amplifier:



Common Mode Equivalent Circuit:



Assuming very large common mode input impedances (Z_{in_1} and Z_{in_2}) for the amplifier, $|v_B|$ is large as exemplified previously.

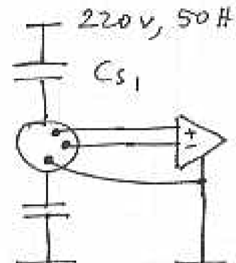
For $|v_B| = 110\,V$, $A_{cm} = \frac{1}{3000}$, $A_{dm} = 25$

$$v_{out} = \frac{110}{3000} \sin(2\pi \times 50 \times t) + 25\, v_{ecg}$$

$$= 37\,mV \sin(2\pi \times 50 \times t) + 25\, v_{ecg}$$

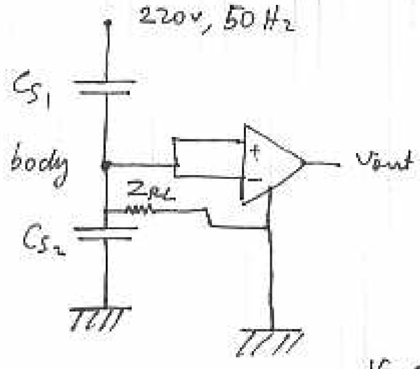
Thus ecg signals less than $\frac{37}{25}$ mV will be buried in 50 Hz interference. Considering that the peak of ecg is 1–2 mV, this amount of interference is not tolerable.

(ii) Three electrode non-isolated ECG amplifier:



In order to decrease the common mode voltage, v_B, we can connect the amplifier common to the body (usually to the Right Leg). Thus we are effectively grounding the body and v_B would ideally be zero. However due to finite electrode impedance of the RL electrode this is not achieved but v_B is significantly lowered. The equivalent common mode circuit is $\rightarrow$

3/11



where Z_{RL} is the RL electrode impedance.
In this case

$$v_B = 220 \times \frac{Z_{RL} // \frac{1}{j\omega C_{S_2}}}{Z_{RL} // \frac{1}{j\omega C_{S_2}} + \frac{1}{j\omega C_{S_1}}}$$

Since $Z_{RL} \lll \frac{1}{j\omega C_{S_1}}$ and $\frac{1}{j\omega C_{S_2}}$

$$v_B \simeq 220 \frac{Z_{RL}}{\frac{1}{j\omega C_{S_1}}} = 220\, j\omega C_{S_1} \times Z_{RL}$$

If $Z_{RL} = 10\,K\Omega$ and $C_{S_1} = 100\,pF$ $\left(\Rightarrow \frac{1}{\omega C_{S_1}} = 32\,M\Omega\right)$

then $|v_B| = 220 \times 10 \times 10^3 \times 2\pi \times 50 \times 100 \times 10^{-12} = 69\,mV$

Obviously the common mode output of the amplifier is $\frac{69\,mV}{3000} = 23\,\mu V$ and is negligible.

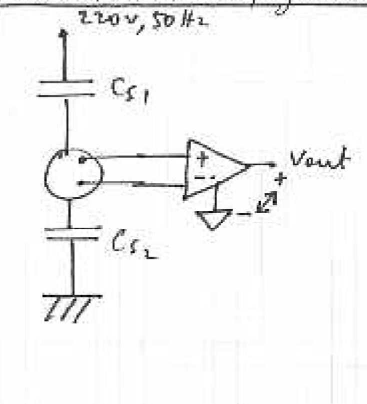
This is nice but there is yet another problem: SAFETY!
If the person, by accident, touches 220volts, then the current which will flow through the body is

$\frac{220\,v}{10\,K\Omega} = 22\,mA$ which is much much larger than the safety limit of $100\,\mu A$.

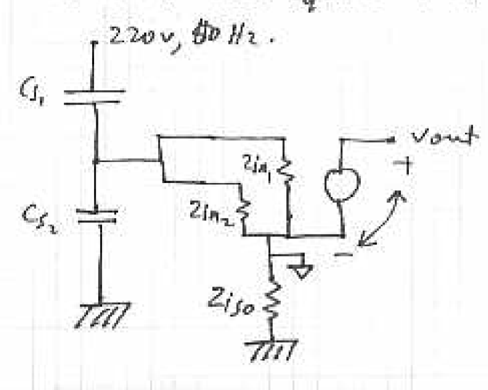
Therefore the above configuration is not safe. The solution is to use an isolated amplifier i.e. an amplifier whose common point (∇) is not connected to real earth ($\frac{|}{////}$).

Isolated connections: (i) Two electrode configuration
(ii) Three electrode configuration

(i) Two electrode configurations for isolated ECG amplifier

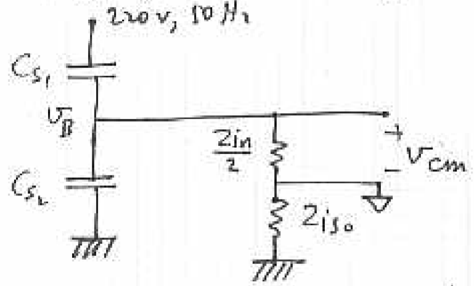


Common Mode Equivalent Circuit:



In reality between $\triangledown$ and $\underline{////}$ there is a large impedance, Z_{iso} (isolation impedance) which is mainly due to stray capacitance.
To find v_{out} due to the common voltage seen on the body w.r.t $\underline{////}$, we must first find the common mode voltage seen by the amplifier (because now $\triangledown$ and $\underline{////}$ are not the same).

Simplifying the circuit further



Assuming that $\frac{Z_{in}}{2} + Z_{iso} >\!>\!> \frac{1}{j\omega C_{s_2}}$ (worst case)

$$v_B = 220 \times \frac{C_{s1}}{C_{s_1}+C_{s_2}} \quad \text{as before.}$$

Then, the common mode voltage, v_{cm}, seen by the amplifier w.r.t. its own common ($\triangledown$) is

($Z_{in_1} = Z_{in_2} = Z_{in}$ is assumed)

$$v_{cm} = v_B \frac{\frac{Z_{in}}{2}}{\frac{Z_{in}}{2} + Z_{iso}}$$

To have small v_{cm} we need very high Z_{iso} or very small Z_{in}. Z_{iso} cannot be made infinitely large because of unavoidable stray capacitances. Z_{in} should not be made very small because in the differential signal model, diff. signal seen by the amp. will be attenuated. $Z_{in} = 10\,M\Omega$ is the minimum acceptable (by international standards) for ECG.

$Z_{iso} = 100\,M\Omega$ is a practically achievable isolation imp..

Thus for $v_B = 110\,v$, $Z_{iso} = 100\,M\Omega$, $Z_{in} = 10\,M\Omega$ we have $v_{cm} = 110 \times \frac{10}{105} = 10.5v$.

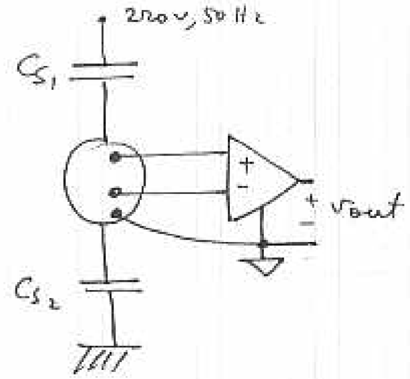
Output due to v_{cm} is, $v_{cm} \times A_{cm} = \frac{10.5}{3000} = 3.5$ mV

This is much better than the $110\,v \times \frac{1}{3000} = 37\,mV$.

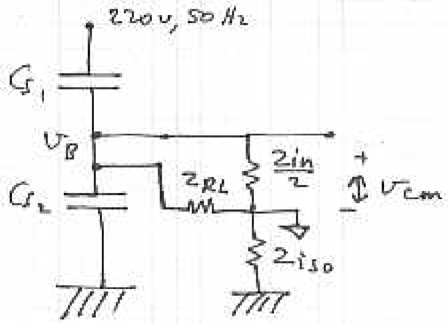
Thus $v_{out} = 3.5\,mV \sin(2\pi \times 50 \times t) + 25\,v_{ecg}$.

It would be nice to further decrease v_{cm}. This is achieved by using the RL connection to $\triangledown$ as shown in the next configuration. 5/11

(ii) Three electrode configuration for isolated ECG amplifier



Common Mode Equivalent Circuit:



Assuming Z_{RL} is much less then $\frac{Z_{in}}{2}$,

$$v_{cm} = V_B \times \frac{Z_{RL}}{Z_{RL} + Z_{iso}} \approx V_B \times \frac{Z_{RL}}{Z_{iso}}$$

For $V_B = 110V$, $Z_{RL} = 10\,K\Omega$, $Z_{iso} = 100\,M\Omega$, we have

$$v_{cm} = 110 \times \frac{10 \times 10^{+3}}{100 \times 10^{+6}} = 11\,mV$$ which is quite good.

Thus the whole output

$$v_{out} = \frac{11\,mV}{3000} \sin(2\pi \times 50 \times t) + 25\, v_{ecg}.$$

$$= 3.67\,\mu V \sin(2\pi \times 50 \times t) + 25\, v_{ecg}.$$

Safety consideration: If the person touches 220v by accident, current through the body is

$$\frac{220v}{Z_{RL} \,//\, \frac{Z_{in}}{2} + Z_{iso}} < \frac{220v}{Z_{iso}} = \frac{220\,v}{100\,M\Omega} = 2.2\,\mu A$$

which is O.K.

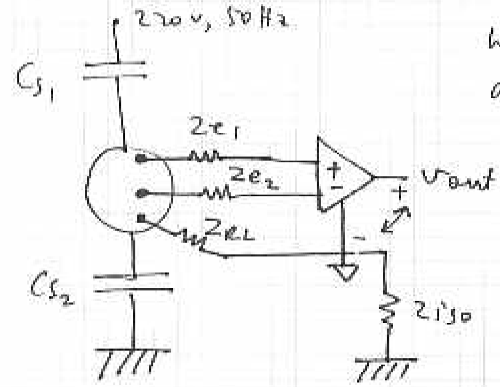
Therefore the isolated configurations are both safe and have smaller output due to common mode 50 Hz on the body.

Right-Leg-Drive Circuit: This technique can be used to further decrease V_{cm} by effectively lowering Z_{RL}. This technique which is used with 3-electrode configurations, is explained in Webster, page 256.

6/11

Complete Analysis of the isolated 3-electrode ECG amplifier including unbalance in electrode impedances

It is shown above that the three electrode isolated amplifier is best for ECG amplification. However in practice there is another problem which is the unbalance between the impedances of the two electrodes other than the RL electrode.



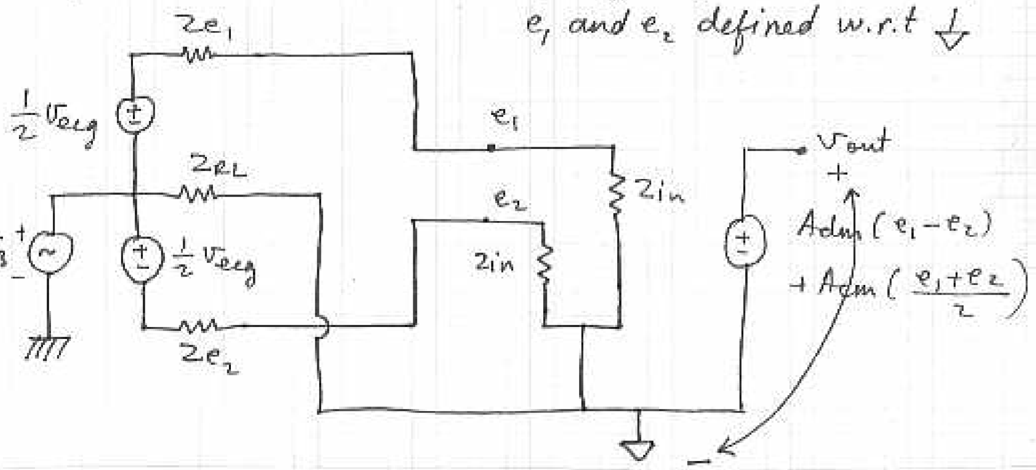
Where Ze_1, Ze_2 and Z_{RL} are the electrode impedances

In general $Ze_1 \neq Ze_2$

and $Ze_2 - Ze_1 \triangleq \Delta Z_e$

6/

Equivalent Circuit: ($Z_{in_1} = Z_{in_2} = Z_{in}$ is assumed)
e_1 and e_2 defined w.r.t ⏚

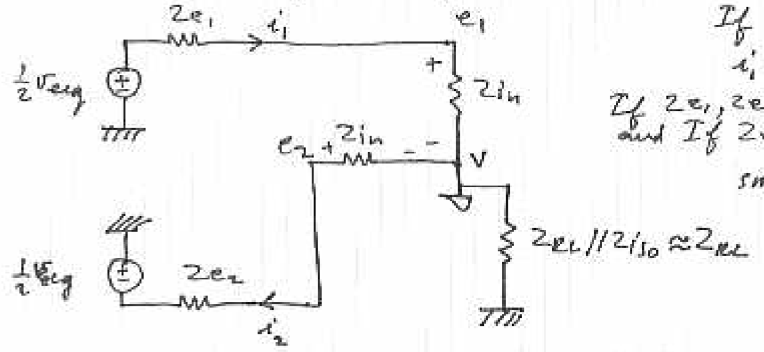


We can use superposition: (i) Differential input only i.e. $v_B = 0$, $v_{ecg} \neq 0$.

(ii) Common mode input only i.e. $v_B \neq 0$, $v_{ecg} = 0$.

7/11

(i) Differential input only:



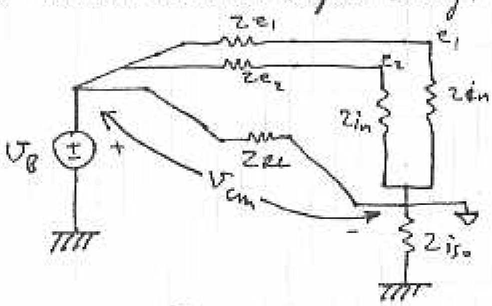
If $Z_{e_1} = Z_{e_2}$, then $i_1 = i_2$ and $V = 0$.
If $Z_{e_1}, Z_{e_2}, Z_{RL} << Z_{in}$ and If $Z_{e_1} \neq Z_{e_2}$ and ΔZ_e small, then $i_1 \simeq i_2$ and $V \approx 0$.

$$e_1 \simeq \frac{1}{2} v_{ecg} \quad e_2 \simeq -\frac{1}{2} v_{ecg}$$

$$\Rightarrow e_1 - e_2 = v_{ecg}$$

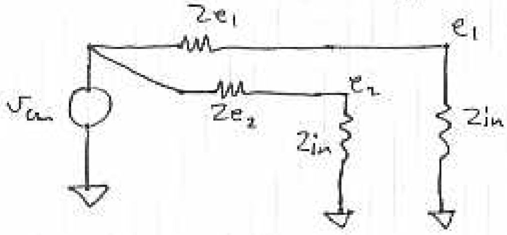
$$\Rightarrow v_{out} = A_{dm} v_{ecg}.$$

(ii) Common Mode Input only.



Since $Z_{RL} << Z_{e_1} + Z_{in}$ and $Z_{e_2} + Z_{in}$,

$$v_{cm} \simeq v_B \frac{Z_{RL}}{Z_{RL} + Z_{iso}} \simeq v_B \frac{Z_{RL}}{Z_{iso}}$$



$$e_1 = v_{cm} \frac{Z_{in}}{Z_{in} + Z_{e_1}}$$

$$e_2 = v_{cm} \frac{Z_{in}}{Z_{in} + Z_{e_2}}$$

$$e_1 - e_2 = v_{cm} \left(\frac{Z_{in}}{Z_{in} + Z_{e_1}} - \frac{Z_{in}}{Z_{in} + Z_{e_2}} \right)$$

$$\simeq \frac{Z_{e_2} - Z_{e_1}}{Z_{in}} v_{cm} = \frac{\Delta Z_e}{Z_{in}} v_{cm}$$

$$e_1 + e_2 \simeq 2 v_{cm}$$

$$CMRR \triangleq \frac{A_{dm}}{A_{cm}}$$

$$v_{out} = (e_1 - e_2) A_{dm} + \frac{e_1 + e_2}{2} A_{cm}$$

$$= v_{cm} \frac{\Delta Z_e}{Z_{in}} A_{dm} + v_{cm} A_{cm}$$

$$= v_{cm} A_{dm} \left(\frac{\Delta Z_e}{Z_{in}} + \frac{1}{CMRR} \right)$$

$$= v_B \frac{Z_{RL}}{Z_{iso}} \left(\frac{\Delta Z_e}{Z_{in}} + \frac{1}{CMRR} \right) A_{dm}$$

8/11

Combining the two cases, the total output is:

$$v_{out} = v_B \frac{Z_{RL}}{Z_{iso}} \left(\frac{\Delta Z_e}{Z_{in}} + \frac{1}{CMRR} \right) A_{dm} + v_{ecg} A_{dm}$$

For $\Delta Z_e = 1 K\Omega$, $Z_{iso} = 100 M\Omega$, $Z_{in} = 10 M\Omega$, $CMRR = 10^5$,
$v_B = 100 V$, $Z_{RL} = 10 K\Omega$

$$v_{out} = 100 \times \frac{10}{100\,000} \left(\frac{1}{10000} + \frac{1}{100\,000} \right) A_{dm} + v_{ecg} A_{dm}$$

$$= \frac{1}{1000} \cdot \left(\frac{1}{10000} \right) A_{dm} + v_{ecg} A_{dm}$$

$$= 1 \mu V \times A_{dm} + v_{ecg} \times A_{dm}.$$

$1 \mu V \times A_{dm}$ is the output voltage due to 50 Hz interference. The input referred value of this interference (i.e. divided by A_{dm}) is $1 \mu A$ which is much smaller than v_{ecg}.

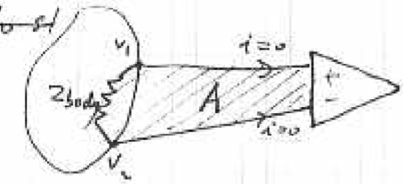
Note that this noise is primarily due to unbalance between Z_{e_1} and Z_{e_2}. Due to this unbalance v_{cm} is transferred into the two inputs of the amplifier (i.e. e_1, and e_2) unequally and a differential input appears at the amplifier input. As in the example above if $\frac{\Delta Z_e}{Z_{in}} \gg \frac{1}{CMRR}$, then conversion of v_{cm} to differential input has more pronounced effect that v_{cm} itself.

9/11

Other Sources of 50 Hz Interference

(i) Magnetic field, generated by current carrying 220 volt lines, causes an induced voltage in the loop formed by the electrode leads, the body and the amplifier inputs. Reduction of this interference can be significantly achieved by twisting the electrode leads (cables).

~~(ii) Due to st~~

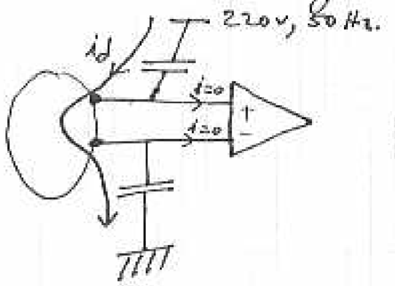


The induced voltage $v_1 - v_2$ is proportional to the area A and the frequency of the magnetic field (in our case 50 Hz).

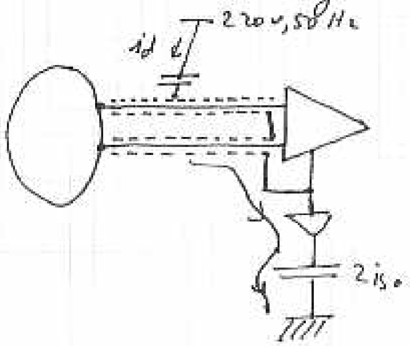
Twisting reduces A.

(ii) Due to stray capacitances to 220 v lines, displacement currents flow through the electrode leads via electrode impedances generating a differential input voltage. Remedy is to shield the electrode leads.

Without Shielding:



With shielding:



iii) Currents flowing through the body induced by stray capacitances generate differential voltages on the body due to the resistivity of the tissues. Careful electrode and body placement may remedy this problem.

Other interferences

EMG: Emg from muscles of the thorax and arms add on top of ECG. A low pass filter with 35 Hz cutoff frequency significantly lowers this interference but also

10/11

introduces some blunting of the ECG signal to an acceptable level.
It is best to record ECG while the muscles are relaxed as much as possible like when the person is relaxed in supine (lying) position. In exercise ECG testing relaxation of muscles is not possible.
BASELINE WANDER: Motion alters ionic concentrations under electrodes' metal-solution interface and thereby changes the contact potential. This change may be abrubt as in exercise ECG testing and high frequency interference is added to ecg. Electrodes and leads must be attached and fastened firmly to the body to avoid motion. During rest ECG this motion artifact is minimal and is only caused by breathing. A high pass filter with cut-off 0.05 Hz is sufficient to minimize this interference.

11/11