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Amplification and Filtering Of ECG Signal Using Instrumentation Amplifier

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Abstract
This paper deals with the process of generation of ECG signal and discusses the general shape of the ECG waveform and its generation by using the three bipolar limb lead method based on Einthoven's Triangle. Since the ECG signal has amplitude in mV range, its observation requires the use of Instrumentation Amplifier and moreover, filter is also used for smoothening the signal.
Index Items: Einthoven's Triangle, Sinoatrial Node, Electrostatic Discharge (ESD), Instrumentation Amplifier, Butterworth filter

I. Introduction

Normal Electrocardiogram (ECG) is composed of a P wave, a QRS complex and a T wave as shown in Figure 1. Both P wave and QRS complex are depolarization waves. P wave is caused by electrical potential generated when atria depolarize before a trial contraction begins. QRS complex is caused by potentials generated when ventricles depolarize before contraction. T wave is caused by potentials generated as ventricles recover from state of depolarization and is called repolarization wave.

An ECG is used to measure the electrical activity of the heart treated as vector quantity. It measures the rate and regularity of heart beat. The cardiac signal typically 5mV peak-to-peak is an AC signal with a bandwidth of 0.05 Hz-100 Hz. P wave occurs at the beginning of contraction of atria and QRS complex occurs at beginning of contraction of ventricles. The ventricles remain contracted until after repolarization has occurred, that is, until the end of T wave, [1, 4, 7, and 8].

An electrical impulse is necessary to stimulate the contraction of heart. The *Sinoatrial Node (SA)* is responsible for producing these impulses. When a heart is at rest it is polarized (i.e., there is balance of charge in and out of each cell within the heart muscle) and therefore no electricity flows. A resting heart has negative charge. When a stimulus occurs, positive ions enter the cell, changing the charge to positive. This is depolarization and occurs in every heart cell causing the fibres to shorten. This leads to contraction of heart, pumping out the positive ions and returning the heart to its relaxed normal shape (repolarization). Figure 2 depicts the various parts of human heart and their respective electrical waveforms, [2, 4, 11].

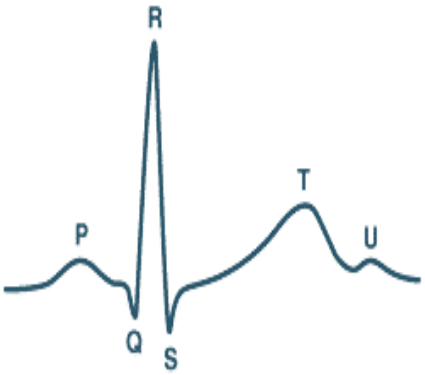

Fig 1: Typical ECG waveform

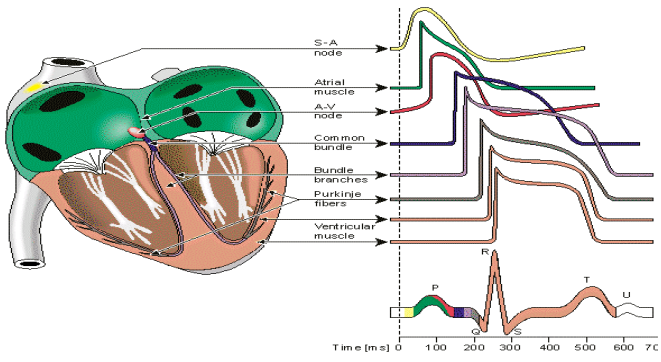

Fig. 2: Electrophysiology of the heart

Figure 3 represents the most basic form of electrode placement (three lead) which is based on Einthoven's Triangle. Each apex of triangle represents where the fluids around the heart connect electrically with the limbs. Lead-I measures the differential potential between right and left arms, Lead-II between right and left leg, Lead-III between left arm and left leg.

Einthoven's law also states that value of any point can be computed from values of the other two points.

Lead I: $V_1 = P_l - P_r$

Lead II: $V_2 = P_f - P_r$

Lead III: $V_3 = P_f - P_l$

Thus,
Lead I + Lead III = Lead II

where,
P_l= Potential of left arm
P_f = Potential of left leg
P_r = Potential of right arm

The peak to peak voltage from top of R wave to bottom of S wave is 1-1.5 mV, the voltage of P wave is between 0.1-0.3 mV and that of T wave is 0.2-0.3 mV. The PR interval (or PQ interval) is 0.16 sec and QT interval is 0.35 sec. Normal interval between two successive QRS complexes in adult is 0.83 seconds, that is, heart rate is 60/0.83, which is 72 beats per min.

In the three bipolar limb leads, the negative terminal of Lead I is connected to right arm and positive terminal to left arm. The ECG records positively if portion of chest connected to right arm is electronegative with respect to point where left arm connects to chest else it records negatively. For Lead II, the negative terminal is connected to right arm and positive to left leg. For Lead III, the negative terminal is connected to left arm and positive terminal to left leg.

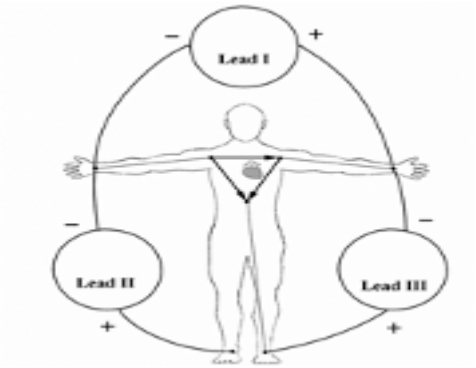

Fig3: The Three Leads

In augmented unipolar limb, two limbs are connected to negative terminal of ECG and third limb to positive terminal of ECG. When third limb is right arm, it is called VR lead, when left arm it is called VL lead, when left leg it is VF lead. They are all similar graphs except that graph recordings from VR lead are inverted.[2, 3, 5, and 9].

In case of chest leads (precordial leads), one electrode is placed on anterior surface of heart (connected to positive terminal of heart) and negative electrode is connected to right arm, left arm and left leg. The different recordings are known as leads. In leads V1 and V2, the QRS recordings are negative because they are nearer to base of heart than to apex (base of heart is negative) and for V4, V5, V6, they are positive.

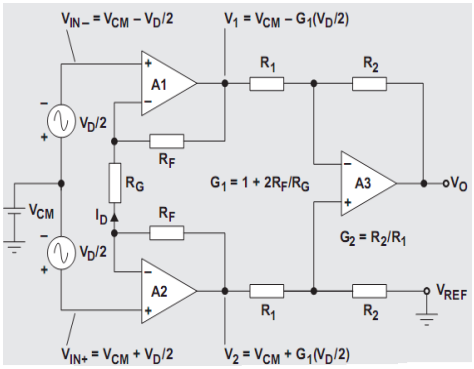

Fig. 4: Instrumentation Amplifier

II. ECG Interference Sources

ECG signals are typically in the mV range. Hence they are highly susceptible to large amounts of interference from a variety of sources. The interference sources can be divided into 3 distinct groups:

(i) Noise originating from sources external to the patient
(ii) Interference originating from the patient
(iii) Unwanted potentials as well as interference originating from patient-electrode contact.

i) Noise originating from sources external to the patient

A. Electrostatic Sources

When a charged body is brought up close to an uncharged one, an equal & opposite charge develops on the uncharged body. For example if an unearthed body is close to any electronic device that is connected to the mains supply voltage, the body will develop a surface charge of equal & opposite potential even though no current is flowing between the two bodies. This phenomenon is commonly known as ESD (Electrostatic Discharge). ESD has been well documented in the recent past and extends a lot further than this particular case. The process of electron transfer as a result of two objects coming into contact with each other and then separating is known as 'triboelectric charging'. As the mains potential has a frequency of 50 Hz, the induced potential will also have this frequency. Other sources of electrostatic charge include the operating table, other persons, electronic equipment, [3, 4, and 7].

B. Electromagnetic Induction

It is an interference that occurs in the vicinity of wires carrying AC currents. Due to the generation of a magnetic field by the flow of a current, all conductors carrying mains currents are surrounded by electromagnetic fields. The 50 Hz mains interference is a difference in potential relative to ground, that is imposed upon any patient/subject in proximity to the wire carrying alternating (50Hz) main supply current; the patient takes on a potential that is neither that of

ground, nor that of the mains, but rather, somewhere in between. Since the mains current is fluctuating (AC), the induced voltage of the subject is also fluctuating. This effect is however minimized by the fact that the electromagnetic field generated by the live wire is to a large degree cancelled out by the neutral cable flowing adjacent to the live cable but in the opposite direction.

ii) Interference originating from the patient

An electromyogram (EMG) measures the electrical activity of muscles at rest and during contraction. Analysis of the EMG shows that the frequency (Hz) components of both the EEG & ECG lie within the same band. The EMG signal however is typically five times larger (up to 30mV) than that of the ECG signal. Muscular activity (especially shivering) can lead to large interference in any ECG signal since they occupy the same frequency band.

iii) Noise originating from patient-electrode contact

ECG electrodes do not act as a passive non-invasive conductor. The placement of any metal adjacent to an electrolytic solution (gel on ECG pads combined with surface of skin) produces an electrochemical half-cell, similar to (although a lot less complex) than that of a battery, resulting in potentials on the surface of the skin. If a differential amplifier is connected to a pair of such electrodes it will amplify any difference in potentials. Ideally if the cells are identical the output will be zero. If the potentials however are not identical, any difference between the two electrodes will be amplified. Additionally, the small current produced by the offset potential may result in polarization. Polarization of the electrode will further distort any signal.

III. The Main New Findings

We first describe amplification of ECG signal. For our principal goal, we use the following instruments:

(a). Hewlett Packard 54602B Oscilloscope

Frequency limit: 150 MHz
Sampling Frequency: 1Gs/s

(b). Tektronix TDS 2012B Two Channel Digital storage Oscilloscope

Frequency Limit: 100MHz

(c). Hewlett Packard E3631A; adjustable regulated DC power supply
(0±25V/ 1A, 0-6V/5A)

(d) Agilent 3325OA, 80 MHz Function/ Arbitrary Waveform Generator

ECG signal is very less in amplitude and hence it requires amplification. On the other hand ECG signals cannot be amplified by ordinary amplifiers as they require precision high gain (more then 500) and high Common-mode Rejection. Hence to overcome these we make use of Instrumentation amplifier which has high Common-mode Rejection Ratio, high gain and high input impedance. The schematic diagram of the Op-amp instrumentation amplifier is shown in figure 4.

$V_{CM} = (V_{IN+} + V_{IN-}) / 2$

$V_D = (V_{IN+} - V_{IN-})$

where V_{CM} and V_D represents the common mode voltage and differential voltage respectively .
Thus,
$V_{IN+} = V_{CM} + V_D/2$
$V_{IN-} = V_{CM} - V_D/2$

In the non-saturated mode, the a pomp action of A1 and A2 applies the differential voltage V_D across the gain resistor R_G, generating input current I_D.

$I_D = (V_{IN+} - V_{IN-})/R_G$

Output voltages of A_1 and A_2 are thus,

$V_1 = V_{CM} – V_D/2 – I_D R_F$
$V_2 = V_{CM} + V_D/2 + I_D R_F$

Thus,
$V_1 = V_{CM} - (V_D G_1)/2$
$V_2 = V_{CM} + (V_D G_1)/2$

Where the input gain, $G1 = 1 + 2R_F/R_G$

Thus only the differential component $V_D/2$ is amplified by the input gain G1, while V_{CM} passes the input stage with unity gain.

$V_O = (V_2 – V_1)*G_1$

If we define $G_2 = R_2/R_1$, then $V_O/V_D = G_1G_2 = G_{TOT}$

Because, V_{CM} and V_D can change their polarities, the maximum voltage either output can assume before reaching saturation is

$\pm |V_{1,2}| = \pm (|V_{CM}| + |V_D/2|) \leq \pm |V_{sat}|$

The variables refer only to magnitude values. Assuming that $V_{1,2}$ and V_D are constant, the only way to increase the input common–mode voltage V_{CM} to V_{CM}' is to reduce the input gain from G_1 to G_1' so that

$V_{1,2} = \text{Const} = V_{CM} + V_D/2 = V_{CM}' + V_D'/2$
$V_{CM}' = V_{CM} + V_D \times (G_1 – G_1')/2$

Reducing G_1 reduces the range of the amplified differential component $G_1'(V_D/2)$, thus providing an expansion range for $V_{CM.}$ Standard INAs, using unity-gain difference amplifiers, have $R_2 = R_1$ and $G_2 = 1$. The total INA gain is then placed into the input stage making $G_1 = G_{TOT}$. Reducing G_1 from G_{TOT} to G_1', while preserving $G_{TOT,}$ requires an increase in difference amplifier gain from $G_2 = 1$ to $G_2' = G_{TOT}/G_1'$. Replacing G_1 with G_{TOT} and G_1' with G_{TOT} / G_2' results in the extended common–mode range:

$$V_{CM}' = V_{CM} + (V_D/2) \times G_{TOT}(1 - 1/G_2')$$

$$= V_{CM} + (V_D/2) \times G_1' \times (G2' - 1)$$

From the above expression it is clear that the three op-amp instrumentation amplifier, amplifies only the differential signal and first buffer stage improves the impedance of the overall amplifier.

IV. Design and observations

The concept of instrumentation amplifier has been made use of in the amplification of ECG signal by putting a gain of 500. To maintain the high input impedance we select the IC TL072 (FET Op-amp) for the design of instrumentation amplifier. Referring to the Figure.4 the component values are

$R_1 = 100\ \Omega$
$R_2 = 10K$
$R_F = 2K$
$R_G = 1K$

Therefore,

$$G_{TOT} = V_0/V_{IN} = (1+2R_F/R_G) \times (R_2/R_1)$$
$$= 5*100$$
$$= 500$$

The observed frequency response of the designed instrumentation amplifier is given in table 1 and figure 5.

Table 1: Frequency response of Instrumentation Amplifier
(Input voltage, V_{IN} = 10 mV)

Frequency(Hz)	V_{OUT}(V)	Gain(dB)
1	4.73	53.50
10	4.73	53.50
20	4.73	53.50
100	4.73	53.50
200	4.73	53.50
500	4.73	53.50
1K	4.73	53.50
2K	4.68	53.40
5K	4.33	52.73
9K	3.75	51.48
9.5K	3.70	51.36
10K	3.63	51.20
11K	3.48	50.83
12K	3.33	50.45
13K	3.20	50.10
15K	2.93	49.30
20K	2.43	47.71
25K	2.07	46.32

0.707*4.73V= 3.33V which corresponds to f_C=12K (constant peak voltage=4.73V)

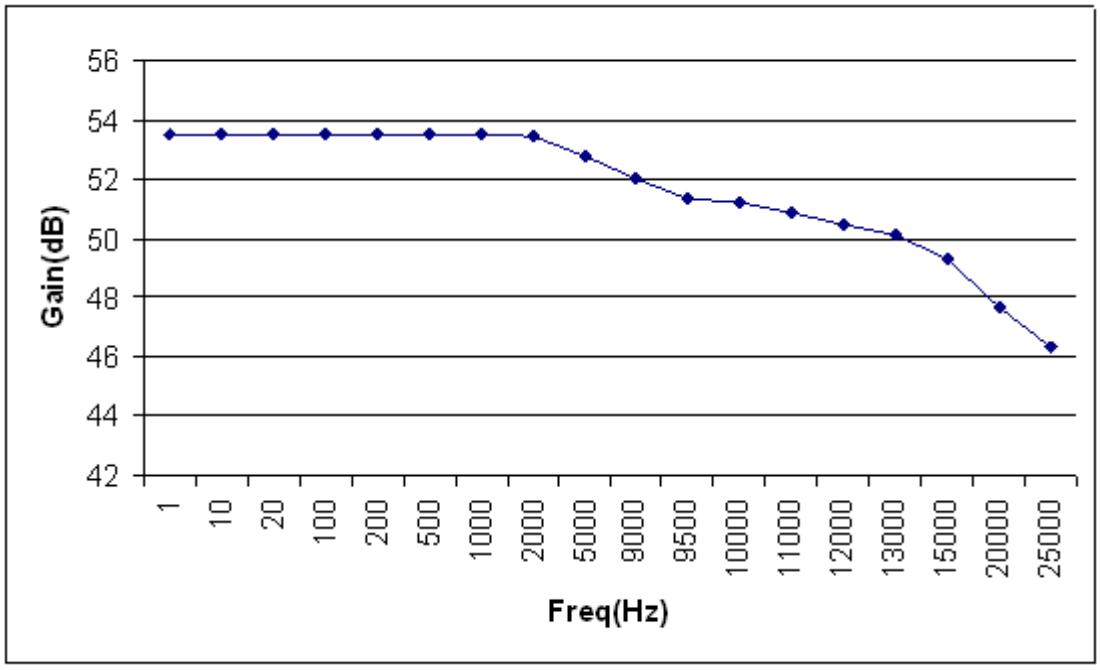

Figure 5: Frequency Response without filter

V. Filters

To remove the noises we make use of different types of filters.

- Third order low-pass Butterworth filter with cut-off at 30 Hz

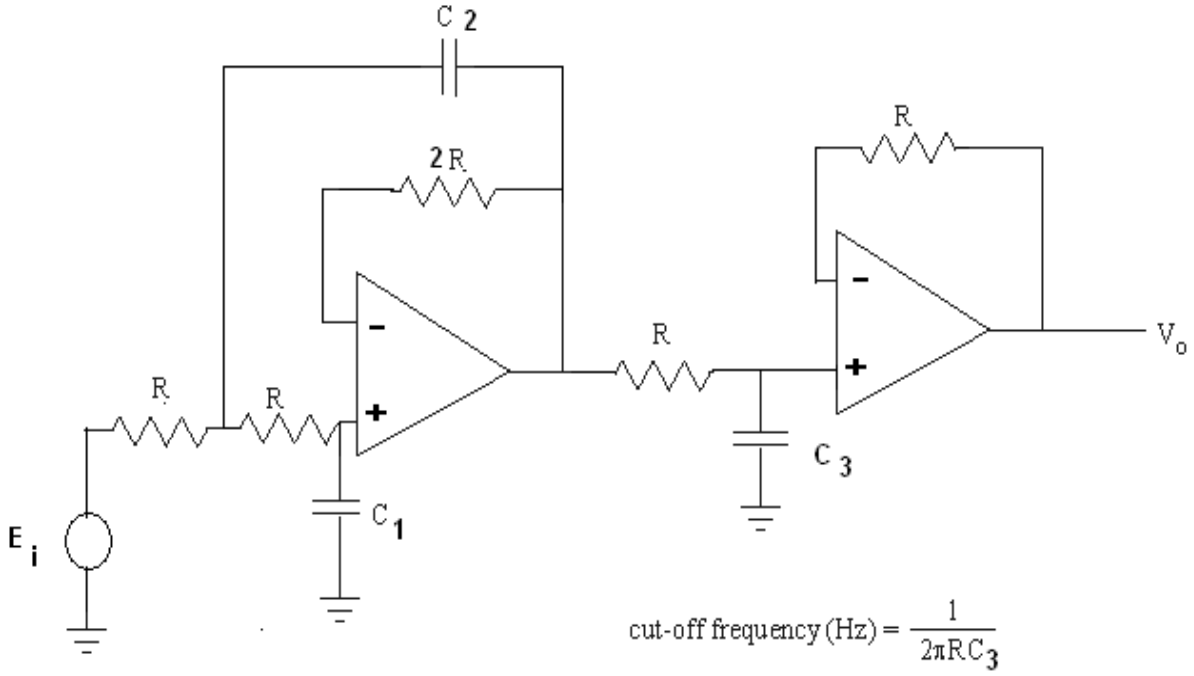

Figure 6: Third order filter

A third order Butterworth filter is made by cascading a first order and a second order filter .Filters are designed with the use of 741 general purpose op-amp for 30 Hz cutoff and the component values for 3rd order filter are given below

$C3 = 0.1 * 10^{-6}$ F
C1 = 0.5*C3=50nF
$C2 = 2C3=0.2 * 10^{-6}$ F
R = 53.05K
2R = 106.1K

Here R1=R2=R; therefore cutoff = f_c =(2* pi* R*C1)$^{-1}$ = 30Hz. Measured frequency response of the 3rd order filter is given in the table 2.

Table 2: Frequency response of third order Butterworth filter

Frequency(Hz)	V_{OUT}(V)	Gain(dB)
1	10.45	0.38
5	10.45	0.38
10	10.45	0.38
15	10.45	0.38
20	10.00	0
22	9.68	-0.29
25	8.90	-1.01
28	8.13	-1.8
30	7.50	-2.5
31	7.38	-2.64 → f_c
35	5.78	-4.77
38	5.00	-6.02
40	4.53	-6.88
50	2.80	-11.05

0.707*10.45V=7.38V which corresponds to f_c =31 Hz practically (peak constant voltage =10.45 V)

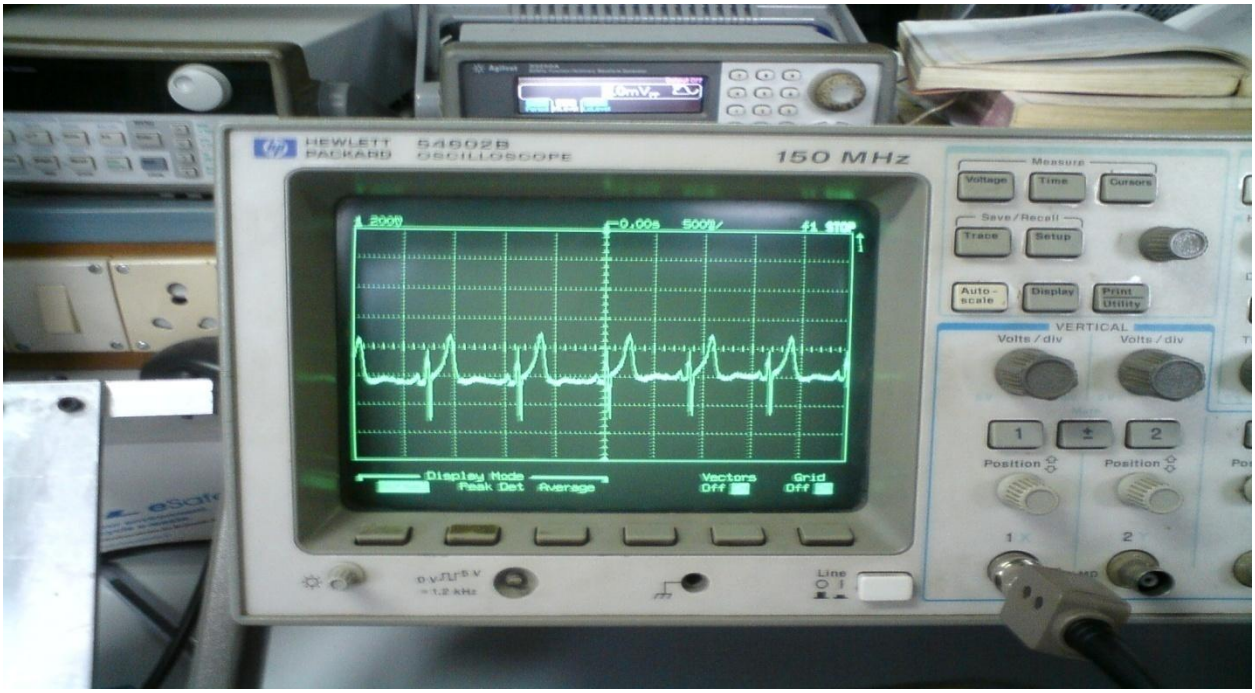

Fig. 7: ECG signal produced (two of the leads are on chests)

VI. Conclusions

ECG signal is very less in amplitude and hence instrumentation amplifier is very essential. On the other hand ECG signals cannot be amplified by ordinary amplifiers as they require precision high gain (more then 500) and high Common-mode Rejection. Hence to overcome these we make use of Instrumentation amplifier which has high Common-mode Rejection Ratio, high gain and high input impedance. Again, the small ac signal voltage (less than 5 mV) detected by the sensor on the electrodes is accompanied by a large ac common-mode component (up to 1.5 V) and a large variable dc component (300 mV). Moreover, electrical activity of the heart can be approximated by a dipole (a vector drawn between two opposite electrical charges) with time varying amplitude and orientation. We have also observed that **t**he Bio-Radio physiological monitor provides a standardized method of wireless ECG measurement with a compact amplifier and several options for acquisition and ECG analysis.

In case of wavelet transform, thresholding should be carefully done so that it does not remove the underlying EEG data components; whether thresholding should be applied to entire signal or only artifacts or the detail coefficients should also be taken into consideration. New techniques such as adaptive filter algorithms can be implemented and many potential applications can be studied. Table 1 regarding frequency response of Instrumentation Amplifier (input voltage, V_{IN} = 10 mV), Table 2 regarding frequency response of third order Butterworth, figure 5 and figure 6 are significant support for our results .Three bipolar limb lead method based on Einthoven's Triangle can be applied very efficiently for our results .

Acknowledgment

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