Fundimentals of medical Instrumentation

Introduction

Biomedical Instrumentation deals with the measurement and analysis of current or voltage signals from different parts of the body. The human body generates a variety of voltages which are usually very small. Biomedical instrumentation helps medical personnel or physicians to make a better diagnose of the problem in a patient and provide the appropriate treatment.

The Basic Features of a Biomedical Instrumentation System

Certain characteristics, which are common in most instrumentation systems are also applied in Biomedical Instrumentation Systems. Any medical instrumentation system would be made up of the following key components:

1. Measurand
2. Transducer or sensor
3. Signal Conditioner
4. Display system

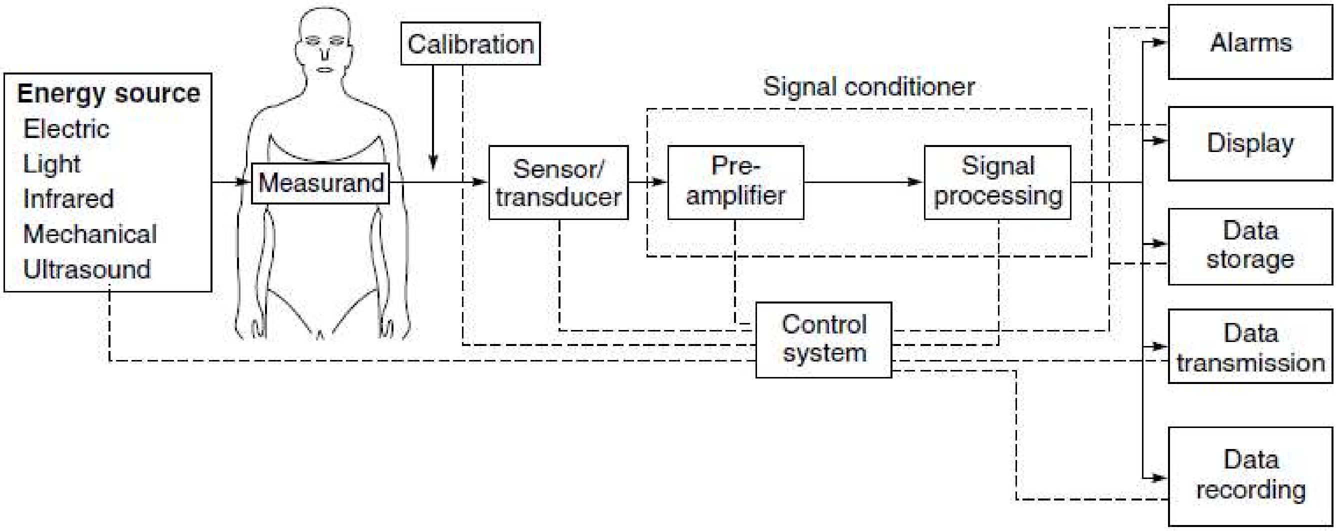

Figure 1 General block diagram of a medical instrumentation system.

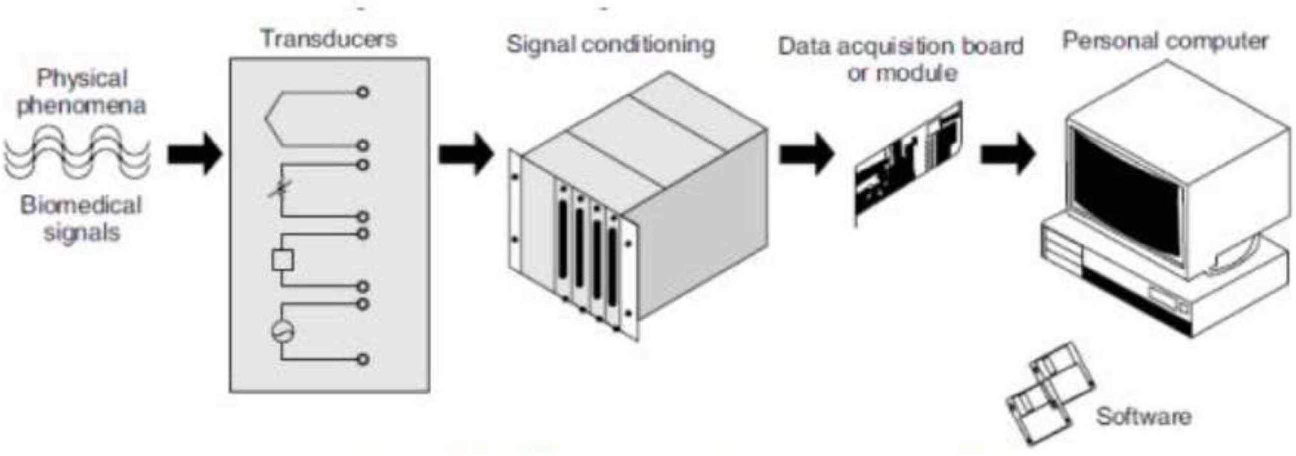

Figure 2 Typical configuratin of a PC based medical instrument

Measurand

This is the physical quantity or condition that the instrumentation system measures. The source of the Measurand is the human body which generates a variety of signals. The Measurand for example can be on the surface of the body (electrocardiogram potential) or may be blood pressure in the chambers of the heart.

Transducer/Sensor

A transducer is a device that converts one form of energy to another. A transducer converts a physical signal into an electrical output. The primary function of the transducer is to provide a usable output in a response to the Measurand. Sometimes another term, ‘’sensor’’ maybe used in medical instrumentation systems. When used here it does the same function of converting the physical Measurand to an electrical signal.

Signal Conditioner

The signal conditioner converts the output of the transducer into an electrical quantity that is suitable for operation of the display or recording system. Signal conditioning usually include functions such as amplifications, filtering, analog-to-digital conversions, digital-to-analog conversions etc. This component of the medical instrumentation system helps in increasing the sensitivity of instruments by amplification of the original signal (which is usually extremely small) or its transduced form.

Display System

This provides a visible representation of the quantity as a displacement on a scale or on the chart of a recorder the screen of CRT or in a numerical form. Besides the display unit, the processed signal after signal conditioning maybe passed to:

Alarm system:

With upper and lower adjustable thresholds to indicate when the measurand physical variable goes beyond the preset limits.

Data Storage:

To keep data for future reference, this may be a hard copy on a paper or on magnetic or semiconductor memories.

Data Transmission:

Using standard interface connections so that information obtained may be carried to other parts of an integrated system or transmits it from one location to another.

Sources of Biomedical Signals

Biomedical signals/physiological signals are those signals (phenomenon that conveys information) which are used primarily for extracting information on a biological system under investigation. Our body produces various physiological signals. The accessibility to these signals is important because these signals:

- Can be internal (Blood pressure)
- May emanate from the body (infrared radiation)
- Maybe derived from tissue sample (Blood or tissue biopsy)

All physiological signals can grouped as:

- Bio potential
- Pressure
- Flow
- Dimensions (imaging)
- Displacement (velocity, force, acceleration)
- Impendence
- Temperature
- Chemical concentration and composition

A transducer converts a physical signal into an electrical output. A transducer should only respond to the targeted form of energy existing in the physiological signal and it must exclude all other energies. It should also interface with the living system in such a way that it extracts minimum energy and it should not be invasive.

How are Physiological Signals generated

Physiological signals are generated by the body during the functioning of various physiological systems. Hence, physiological signals hold information which can be extracted from these signals to find out the state of the functioning of these physiological systems. The process of extracting information can be either a simple as feeling the pulse to find the state of heart beats or it can be complex as analysing the structure of internal soft issues by an ultrasound. (link to ultrasound article)

Biomedical signals/Physiological signals are classified according to where they originate from within the body.

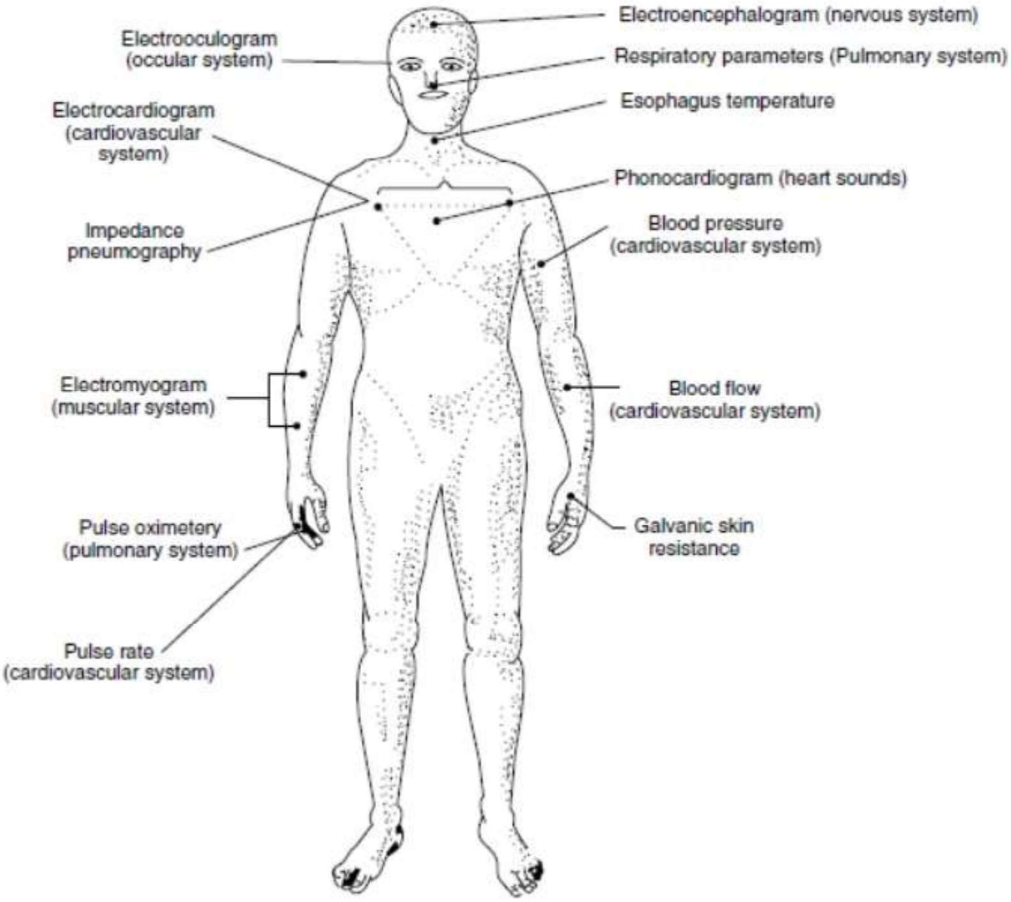

Figure 3 Sources of biomedical signals

Biomedical signals are classified as follows:

1. **Bioelectric signals:** These signals are generated by the nerve and muscle cells. Their basic source is the cell membrane which under certain conditions maybe excited to generate an action potential. The electric field generated by the action of many cells constitutes the bioelectric signal. The most common examples of bioelectric signals are the ECG (Electrocardiographic) and EEG (Electroencephalographic) signals. (Link to amazon products for ECG and EEG)
2. **Biomechanical signals:** These signals are generated due to some mechanical function of a physiological system. They include all types of motion and displacement signals, pressure, flow signals etc. in the physiological system. The respiratory physiological system performs its function by the chest movement. This movement can be measure and analysed.
3. **Biocoustic signals:** These signals are created by the physiological system in which either flow of blood or air takes place. The flow of the blood in the heart as well as inspiration and expiration of the lungs takes place accompanied with unique acoustic signals.
4. **Bio-impedance signals:** The impedance of the skin depends upon; the composition of the skin, blood distribution and blood volume through the skin. The measurement of impedance helps in finding the state of skin and functioning of various physiological systems. The voltage drop due to the tissue impedance is a bio-impedance signal.
5. **Biochemical signal:** The signals which are obtained as a result of chemical measurements from the living tissue or from samples analysed in the laboratory. The examples of these include; measurement of partial pressure of carbon-dioxide (pCO2), partial pressure of oxygen (pO2) and concentration of various ions in the blood.
6. **Bio-optical signals:** These signals are produced by the optical variation by the functioning of the physiological system. The blood oxygenation can be determined by measuring transmitted and reflected light occurring from the blood vessel.
7. **Biomagnetic signals:** Extremely weak magnetic fields are produced by various organs such as the brain, heart and lungs. The measurement of these signals provides information which is not available in other types of bio-signals such as bioelectric signals. A typical example is the Magnetoencephalography which is obtained by recording the biomagnetic signals from the brain .

Key Points to Note when using a Biomedical Instrumentation System

In most of the medical instrumentation systems, some calibration is necessary at regular intervals during their operation. The calibration signal is applied to the sensor input or as early in the signal processing chain as possible. In many measurement applications in the medical field, some form of stimulus or energy is given to the patient and the effect it has on the patient is measured. This stimulus can be visual in the form of flash or light or stimulation of some part of the nervous system. In some situations, automatic control of the transducer, stimulus or signal conditioning part of the system may be required. This is achieved by using a feedback loop in which part of the output from the signal conditioning or a display device is fed back to the input stage. Note, the control and feedback may be automatic or manual.

Key Factors to Consider when Designing Biomedical Instruments

1. Some of the important factors that are considered when designing a medical measuring instrument include:
2. Patient safety considerations –Since medical instruments have to be physically connected to the patient, there is the possibility of an electric shock hazard in cases where there is electric or electronic equipment unless adequate measures have been taken in the design of the medical equipment to prevent such kind of hazards. All safety measures need to be ensured during the operation of the medical instrument.
3. Transducer interface problems –All instrumentation systems are affected in some way by the presence of the measuring transducer. This problem may get compounded while making measurement on the living system where the physical presence of the transducer may change the reading significantly. Besides, the presence of a transducer in one system can affect response in other system. Therefore, adequate care needs to be taken while designing a medical measuring system to ensure that the loading effect of the transducer is minimal on the source of the measured variable.
4. Measurement range –Generally, physiological signals measurement ranges are quite low to other parameters outside the medical field. The biomedical signals are usually very small in the microvolt range. Therefore, it is important to consider this when designing any medical instrument.
5. Frequency range –Most of the physiological signals are in the audio-frequency range or below. Also, many signals contain dc and very low frequency components.
6. The high possibility of artifacts –An artifact is undesirable signal that is extraneous to the physiological variable under measurement. This may come from electrical interference, cross talk or noise generated within the measurement system. Designers of biomedical instruments, put in ways to remove/filter or avoid these kinds of artifacts.

7. Reliability –In cases of life saving instrument like the defibrillators, their failure to operate or provide the desired output can cause a potential life threat to the patient. Hence, the biomedical equipment must be reliable, easy to operate and able to withstand physical stress like transportation within the hospital or in the ambulance and or exposure to corrosive chemicals.
8. Safe levels of applied energy –Biomedical instruments require some form of energy to be applied to the living tissue e.g. CT scan requires X-rays (a form of electromagnetic waves energy). Safe levels of some of these energies have been established by scientific researchers; designers can use this information when they are designing the medical equipment.

Types of Amplifiers used in Biomedical Measurement Applications

Signal amplification is essential part of any biomedical measurement. Bioelectric measurements are usually low-level i.e. microvolt level measurements, therefore amplification is required to boost the level of the input signal to match the requirements of recording/display systems or to match the range of the analog-to-digital convertor, thus increasing the resolution and sensitivity of the measurement.

We will discuss some of the amplifiers that are used in biomedical measurement applications.

• Carrier Amplifiers

The carrier amplifiers are used with transducers which require an external source of excitation. They are characterized by high gain, negligible drift, extremely low noise and the ability to operate with resistive, inductive or capacitive transducers. A carrier amplifier is made up of a carrier oscillator, a bridge balance, with a calibration circuit, a high gain ac amplifier, a phase-sensitive detector, and a dc output amplifier.

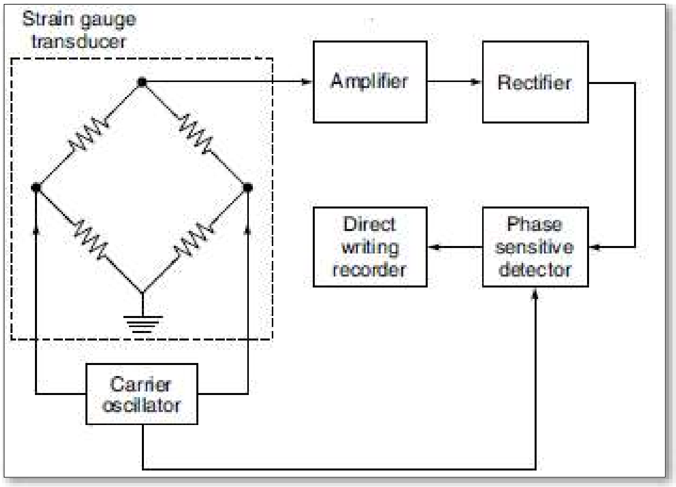

Figure 4 A block diagram of a carrier amplifier

• Chopper Amplifiers

The chopper amplifier is used to amplify very small dc signals of the order of microvolts. To avoid the drift problem that is characterized by the direct coupled amplifier, the chopper amplifier is used. The amplifier uses a chopping device that converts a slowly varying direct current to an alternating voltage (the dc is chopped into a square wave with a chopper modulator). The resulting alternating voltage has amplitude that is proportional to the input direct current and with phase dependent on the polarity of the original signal. The resulting ac square wave is amplified with an ac amplifier and then demodulated to get an amplified dc. Chopper amplifiers are available in both single-ended as well as differential input configurations. Chopper amplifiers are used in medicine in amplification of small dc signals of a few microvolts. They are used with transducers such as temperature sensors (thermistors, thermocouples), strain gauge, etc.

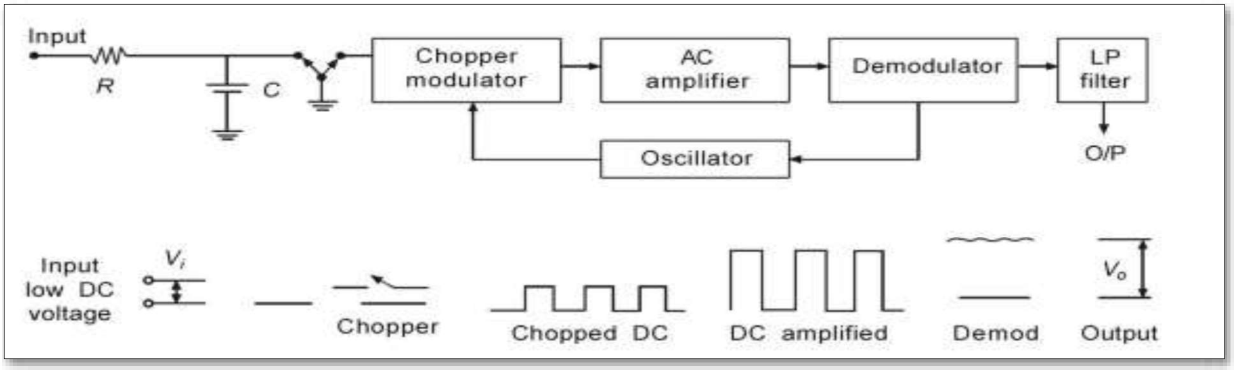

Figure 5 Chopper stabilized amplifier

Isolation Amplifiers

Isolation amplifiers are used to provide protection against leakage currents. They break the ohmic continuity of electric signals between the input and output of the amplifier.
We have 3 methods of isolation that can be used:

- Optical isolation
- Transformer isolation
- Capacitive isolation

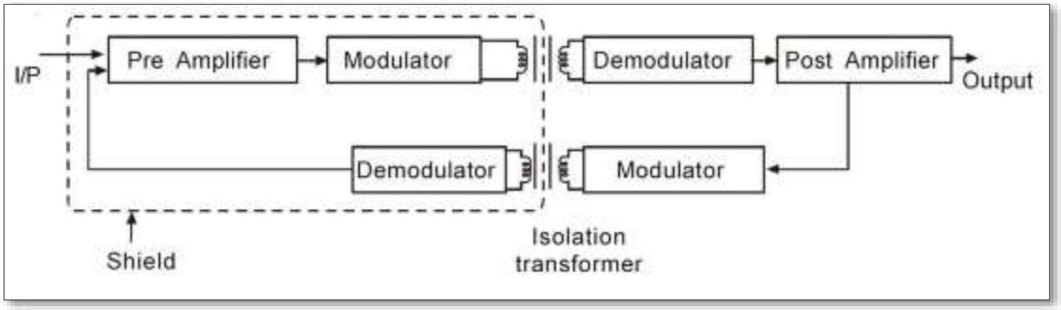

Figure 6 A block diagram of Isolation Amplifier (Transformer type)

Optical Isolation

From the above diagram, as the input signal varies, the light intensity of the LED shown in the last stage of amplification also varies. An optocoupler is used to couple this light to the phototransistor. This light falls on a phototransistor. The collector current of the phototransistor is proportional to the light intensity. For stabilization purposes, a feedback from the output may be provided. Electrical isolation is used to ensure patient protection against electrical hazards. Biomedical instruments such as pacemakers, electrocardiographs, pressure monitors, pressure transducers, etc. are designed to electrically separate the portion of the circuit to which the patient is connected from the portion of the circuit connected to the ac power line and ground.

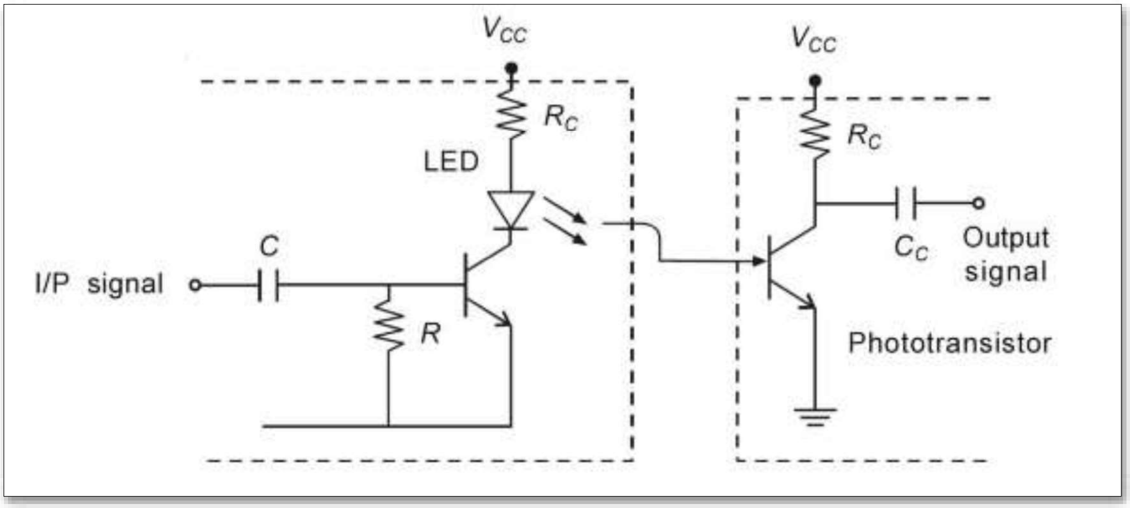

Figure 6 Optical isolation

Differential Amplifiers

Biomedical amplifiers employed in the input stage of a biomedical measurement system are mostly of the differential type. Differential amplifier has three input terminals out of which one is arranged at the reference potential and the other two are live terminals. The differential amplifier is used when it is necessary to measure the voltage difference between two points, both of them varying in amplitude at different rates and in different patterns.
Heart-generated voltages that are picked up by means of Bioelectrodes on the arms and legs and brain-generated voltages picked up by the Bioelectrodes on the scalp are typical examples of signals whose measurements needs the use of differential amplifier.

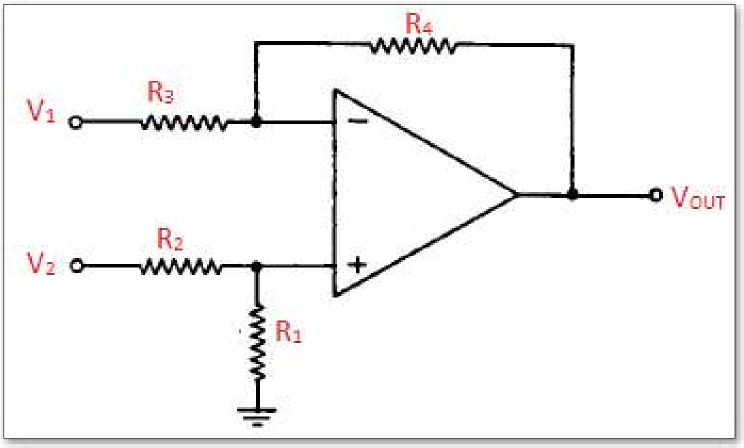

Figure 7 Differential Amplifier using an Operational Amplifier

Reasons why Differential amplifier is preferred over other electronic amplifiers

Its ability to reject common-mode interferences which are invariably picked up by electrodes from the body along with the useful bioelectric signals. As a direct coupled amplifier, it has good stability and versatility. High stability is achieved because it can be insensitive to temperature changes which is often the source of excessive drift in other configurations It is versatile in that it may be adapted for many applications e.g. applications requiring floating inputs and outputs or applications where grounded inputs and or outputs are desirable. The ability of the differential amplifier to reject common voltages on its two input leads is known as Common-mode rejection and is specified as the ratio of common-mode input to differential input to derive the same response. It is abbreviated as CMRR (Common-mode rejection ratio). CMRR is an important specification with regard to differential amplifiers and is usually expressed in decibels.

CMRR for the input stage of biomedical instrumentation systems should be as high as possible so that only the wanted signals find a way through the amplifier and all unwanted signals get rejected in the preamplifier stage. A high rejection ratio is normally achieved by the use of a matched pair of transistors in the input stage of the preamplifier and a large ‘’tail’’ resistance in the long-tailed pair to provide maximum negative feedback for in phase signals. In order to minimize effects of changes occurring in the electrodes impedances, it is necessary, to use an input stage amplifier or preamplifier with a high input impedance. It has been established that a low value of input impedance give rise to a considerable distortions of the data recordings.

High gain integrated dc amplifiers, with differential input connections and a provision for external feedback are termed to as operation amplifiers because of their ability to perform mathematical operations. They come in integrated circuit form.

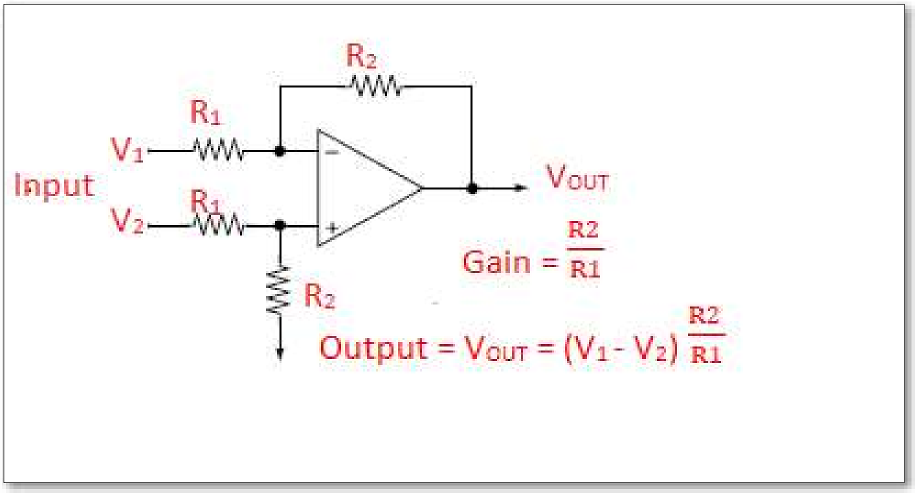

Figure 8 A single op-amp in a differential configuration

The common-mode rejection for most op-amps is typically between 60 dB and 90 dB. This may not be enough to reject common-mode noise that is usually encountered in biomedical measurements. In addition, the input impedance is not very high to handle signals from high impedance sources. One way to increase the input impedance of the op-amp is to use Field effect transistors (FET) in the input differential stage. Alternatively, the best solution is to use an Instrumentation amplifier in the preamplifier stage.

Limitations of Differential amplifiers

Although the differential amplifier is well suited for most of the applications in biomedical measurements, it has the following limitations:

- The amplifier has limited input impedance and therefore, draws some current from the source and loads them to some extent.
- The common-mode rejection ratio (CMMR) of the amplifier may not exceed 60 dB in most of the cases, which is inadequate in modern medical measurement systems.

The Instrumentation amplifier, which is an improved version of a differential amplifier, overcomes the limitations of the differential amplifier. In fact connecting a buffered amplifier to a basic differential amplifier makes an instrumentation amplifier!

Instrumentation Amplifiers

Instrumentation amplifier is a differential voltage gain device optimized for operation in an environment that is hostile to precision measurements. It is consists of 3 op-amps and 7 resistors.The instrumentation amplifier is made up of 2 parts: a buffered amplifier (OP1, OP2) and a basic differential OP3.

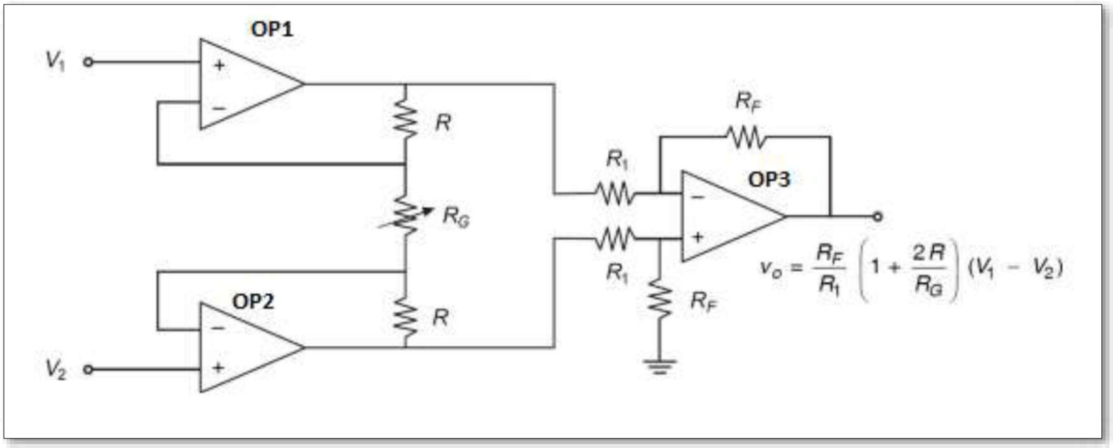

Figure 9 Instrumentation amplifier

The differential amplifier part is essential for biomedical sensors; this is because a sensor produces a signal between its terminals however, in some applications neither terminal may be connected to the same ground as your measuring circuit hence the terminals may be biased at a high potential or might be riding on a noise voltage. The differential amplifier fixes this problem by directly measuring the difference between the sensors terminals. The buffered amplifier OP1 and OP2 provides gain and also prevents the sensor resistance from affecting the resistors in the op-amp circuit.

Key Characteristics of Instrumentation Amplifiers

- Voltage gain from differential input (V1-V2) to single ended output is set by one resistor (RG).
- The input resistance of both inputs is very high and does not change as the gain is varied.
- Vo does not depend on common-mode voltage but only on their difference i.e. output voltage is proportional to the difference between the two input voltages.

Reasons why Instrumentation Amplifiers are Preferred in Biomedical Applications

- They have high input impedance
- They have high common mode rejection ratio (CMRR)
- Low bias and offset currents
- Low power consumption
- High slew rate
- Less performance deterioration if source impedance changes
- Possibility of independent reference levels for source and amplifier.

The Essential Requirements of Biopotential Amplifiers for Medical applications

Biopotential amplifiers are also termed to as Bioamplifiers. Bioelectric measurements are normally low-level voltages with high source impedances therefore signal amplification is essential part of biomedical measurement systems. The signal amplification is needed to boost or increase the strength of the input signal to match the requirements of recording/display systems. We have specialized amplifiers designed to do signal amplification in biomedical measurement applications and are known as biopotential amplifiers. Biopotential amplifiers are usually in the form of voltage amplifiers because they are capable of increasing the voltage levels of a signal. However, voltage amplifiers also serve to increase power levels so they can be considered power amplifiers too. In some circumstances biopotential amplifiers are employed in isolating the load from the source. In this case, the amplifiers provide only current gain, leaving the voltage levels principally unchanged. Examples of biopotential amplifiers include Chopper amplifier, Differential amplifier, Instrumentation amplifier, etc. These examples and more are covered in details in the Types of Amplifiers used in Biomedical Measurement Applications.

Let's look at some of the essential features and requirements of biopotential amplifiers as discussed below: To be used in medical measurement applications, all biopotential amplifiers must meet the necessary requirements. Biopotential amplifiers must have high input impedance so that they provide minimal loading of the signal being measured. The characteristic of biopotential electrodes can be affected by the electric load they see; which in addition to signal loading, can result in distortion of the signal. Loading effects are minimized by making the amplifier input impedance as high as possible thereby reducing the signal distortion. Modern bioamplifiers have input impedances of at least 10 MΩ. Biopotential amplifiers must operate in that portion of the frequency spectrum in which the bioelectric potentials that they amplify exist. Because of the low level voltages of these kinds of signals, it is important to limit the bandwidth of the amplifier so that is just great enough to process the signal adequately. This way, we can obtain optimal signal-to-noise signal (SNRs). Bioelectric potentials normally have amplitudes of the order of a few millivolts or less, therefore such signals must be amplified to levels compatible with recording and displaying devices. This implies that most biopotential amplifiers must have gains of the order of 1000 or greater.

The input circuit of a biopotential amplifier must provide protection to the organism being studied. The current or potential appearing across the amplifier input terminals which is produced by the amplifier is capable of affecting the biological potential being measured. These electric currents from input terminals of a biopotential amplifier can result in microshocks or macroshocks in the patient being studied. To prevent these problems, the amplifier should have an isolation and protection circuitry so that the current through the electrode circuit can be kept at safe levels and any artifact generated by such current can be minimized. The main function of the amplifier output circuit is to drive the amplifier load i.e. an indicating instrument or recording device with maximum range and reliability in the readout. Hence the output impedance of the amplifier must be low with respect to the load impedance, and the amplifier must be able to supply the power required by the load. In most cases, biopotential signals are obtained from bipolar electrodes, these electrodes are often symmetrically located, electrically with respect to the ground. Under such conditions, the most proper biopotential amplifier is a differential one. Since such bipolar electrodes frequently have common-mode voltage with respect to the ground, which is much larger than the signal amplitude and as the symmetry with respect to ground can be distorted; such biopotential differential amplifiers must have high common mode-rejection ratios to minimize the interference due to the common-mode signal. Lastly, for biopotential amplifiers that are employed both in medical applications and in the laboratories, they should make quick calibration possible.