Republic of Iraq Ministry of Higher Education and Scientific Research
Almaarif University
Department of Medical Instrumentation Engineering Technique

Biomedical Signals Recorders and Monitors

Prepared by
Walaa Ahmed Salih
M.Sc. Biomedical Engineering
BSc. Biomedical Engineering

September 2024

Fundamentals of medical Instrumentation

Introduction

Biomedical Instrumentation focuses on the development and application of devices that measure electrical signals, such as current or voltage, produced by different parts of the body. These signals are typically very small and need to be amplified and analyzed to provide useful information. By using these instruments, medical professionals can better diagnose patient conditions and determine the most effective treatment.

Devices like ECGs, EEGs, and EMGs allow for the monitoring of heart, brain, and muscle activity, respectively. This technology enhances diagnostic accuracy, enabling physicians to make more informed decisions regarding patient care. Biomedical and medical devices engineers are essential in creating and refining these systems to ensure their effectiveness and safety.

The Basic Features of a Biomedical Instrumentation System

A typical medical instrumentation system consists of the following essential components:

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

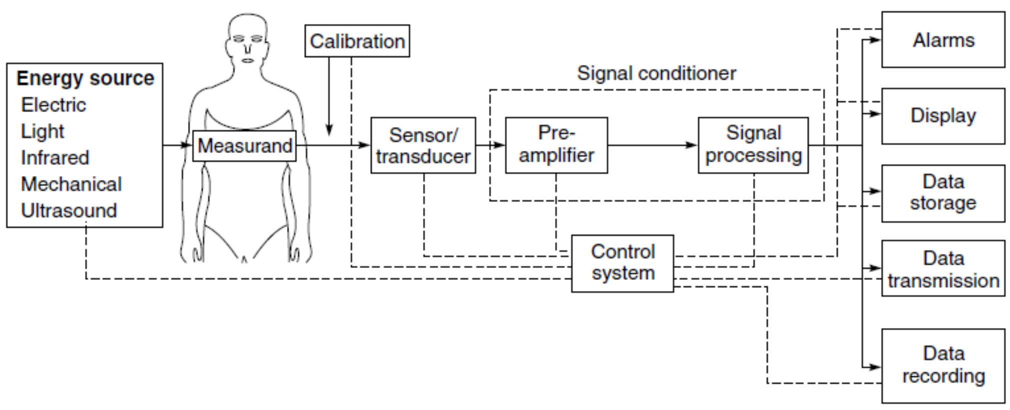

Figure 1: General block diagram of a medical instrumentation system.

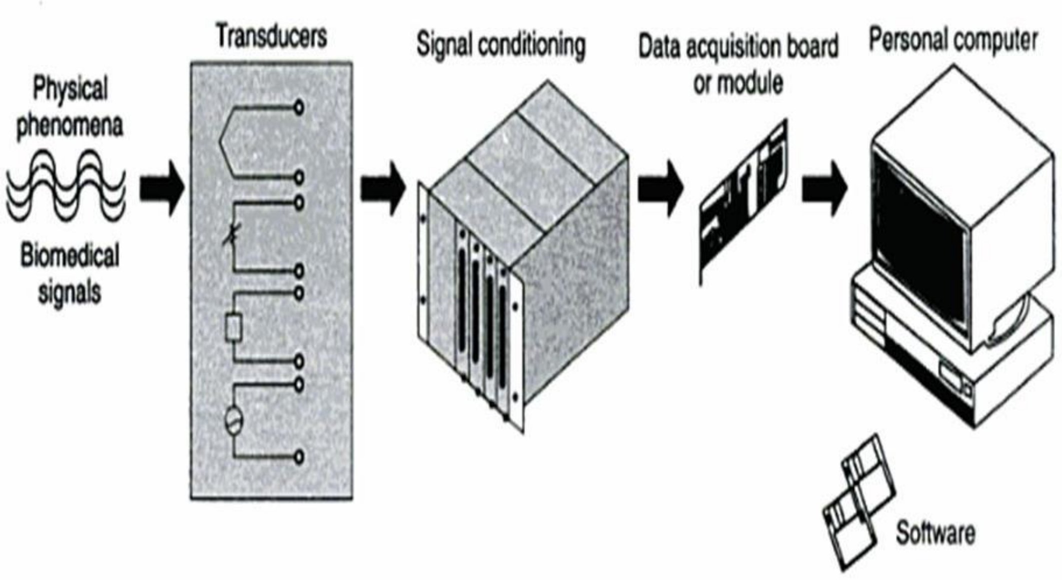

Figure 2: Typical configuration of a PC based medical instrument.

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 transforms one form of energy into another. In biomedical instrumentation, it converts a physical signal into an electrical output. The main purpose of the transducer is to produce a usable output in response to the measurand. In some cases, the term "**sensor**" is also used in medical systems, performing the same role of converting the physical measurand into an electrical signal.

Signal Conditioner

The signal conditioner transforms the transducer's output into an electrical signal that can be used by the display or recording system. Signal conditioning typically involves processes such as amplification, filtering, and converting signals between analog and digital forms. This component enhances the sensitivity of the instrumentation by amplifying the original signal, which is often very small, or its converted form.

Display System

This component offers a visual representation of the measured quantity, either as a displacement on a scale, a recorder's chart, a CRT screen, or in numerical format. In addition to the display unit, the conditioned signal can also be directed to:

1. **Alarm System**: Equipped with adjustable upper and lower thresholds to signal when the measurand exceeds preset limits.
2. **Data Storage**: Stores data for future reference, either as a hard copy (on paper) or in magnetic/semiconductor memory.
3. **Data Transmission**: Uses standard interfaces to transfer data to other parts of an integrated system or across different locations.

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 produced by the body during the activity of various systems, providing valuable data that can be analyzed to assess the performance of these systems. Information extraction from these signals can range from straightforward methods, such as checking the pulse to determine heart rate, to more complex approaches, like using ultrasound to examine internal soft tissue structures. Biomedical or physiological signals are typically categorized based on their source within the body.

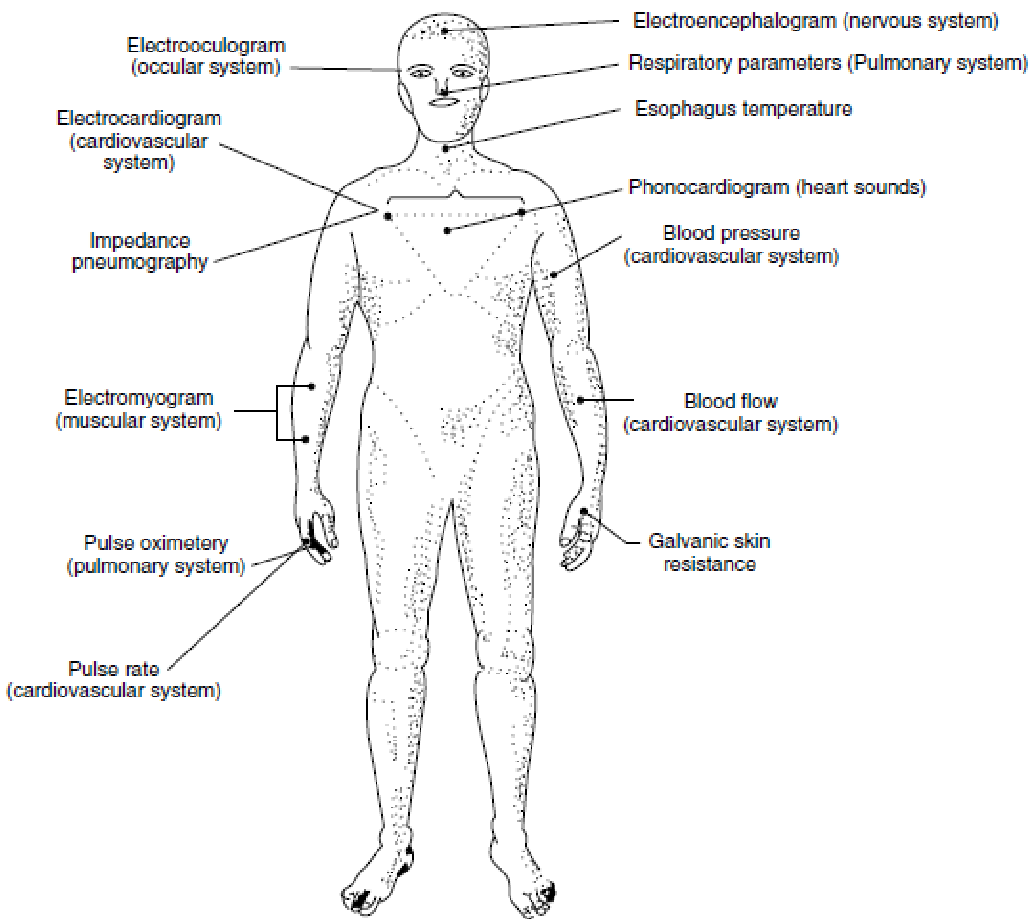

Figure 3: Sources of biomedical signals

<u>Biomedical signals are classified as follows</u>:

1. **Bioelectric Signals**: These are produced by nerve and muscle cells, originating from the cell membrane, which can become excited under certain conditions, generating an action potential. The collective electrical activity from multiple cells creates a bioelectric signal. Common examples include electrocardiographic (ECG) and electroencephalographic (EEG) signals.
2. **Biomechanical Signals**: These signals result from the mechanical activities of physiological systems, encompassing all types of motion, displacement, pressure, and flow signals. For instance, chest movements during respiration can be measured and analyzed as biomechanical signals.
3. **Biocoustic Signals**: Generated by systems where blood or air flows, these signals accompany unique sounds, such as blood flow in the heart or the process of breathing (inspiration and expiration) in the lungs.
4. **Bio-impedance Signals**: Skin impedance depends on factors like skin composition, blood distribution, and blood volume. Measuring impedance helps assess skin health and physiological system function. The voltage drop caused by tissue impedance forms a bio-impedance signal.
5. **Biochemical Signals**: These arise from chemical measurements either directly from living tissues or through laboratory sample analysis. Examples include measuring partial pressures of carbon dioxide (pCO_2), oxygen (pO_2), and the concentration of ions in blood.
6. **Bio-optical Signals**: Produced by optical changes within physiological systems, these signals are used to measure parameters like blood oxygenation by assessing light transmission and reflection through blood vessels.
7. **Bio magnetic Signals**: Very weak magnetic fields, generated by organs like the brain, heart, and lungs, provide unique insights not captured by bioelectric signals. An example is magnetoencephalography, which records the biomagnetic signals from the brain.

Key Considerations When Using Biomedical Instrumentation Systems:

In many medical instrumentation systems, periodic calibration is essential to ensure accurate operation. Calibration is typically performed by applying a signal to the sensor input or as early in the signal processing chain as possible. In numerous medical measurement scenarios, a form of stimulus or energy is applied to the patient, and its effects are then monitored. This stimulus can be visual, such as a flash of light, or involve stimulation of the nervous system. In certain cases, automatic control of the transducer, stimulus, or signal conditioning components may be necessary. This control is achieved through a feedback loop, where a portion of the output from the signal conditioning or display device is fed back to the input stage. The control and feedback mechanisms can either be automatic or manually operated.

Key Factors to Consider when Designing Biomedical Instruments:

1. **Patient Safety**: Medical instruments must be designed to prevent electric shock hazards since they are physically connected to patients. Adequate safety measures are crucial during operation.
2. **Transducer Interface Issues**: The transducer's presence can affect the measurement system, especially in living systems, potentially altering readings or impacting other physiological responses. The design should minimize the transducer’s loading effect.
3. **Measurement Range**: Biomedical signals are typically small, often in the microvolt range, so instruments must be sensitive enough to accurately measure these low-level signals.
4. **Frequency Range**: Physiological signals are generally in the audio-frequency range or lower, often containing direct current (DC) or low-frequency components, which should be considered in the design.
5. **Artifact Risks**: Artifacts, such as electrical interference or noise, can distort measurements. Designers must incorporate methods to filter or prevent these unwanted signals.
6. **Reliability**: Instruments, especially life-saving devices like defibrillators, must be dependable, easy to use, and capable of withstanding physical stresses and exposure to harsh environments.
7. **Safe Energy Levels**: Medical instruments apply energy (e.g., X-rays in CT scans) to tissues. Designers should adhere to established safe energy levels during equipment development.

Types of Amplifiers used in Biomedical Measurement Applications:

Signal amplification plays a crucial role in biomedical measurements. Since bioelectric signals are typically low-level, often in the microvolt range, amplification is necessary to enhance the input signal. This ensures compatibility with recording and display systems, or it helps match the signal to the input range of an analog-to-digital converter, thereby improving the measurement's resolution and sensitivity. Below, we will explore various types of amplifiers commonly used in biomedical measurement applications.

- **Carrier Amplifiers**

Carrier amplifiers are utilized with transducers that need an external excitation source. They are known for their high gain, minimal drift, extremely low noise, and ability to work with resistive, inductive, or capacitive transducers. A typical carrier amplifier consists of a carrier oscillator, a bridge balancing system with a calibration circuit, a high-gain AC amplifier, a phase-sensitive detector, and a DC output amplifier.

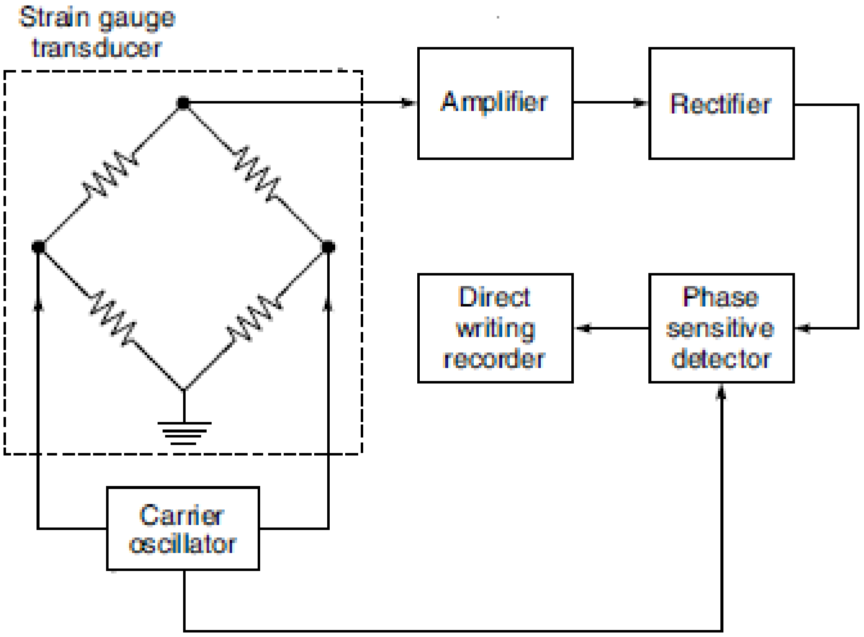

Figure 4: A block diagram of a carrier amplifier.

• Chopper Amplifiers

Chopper amplifiers are designed to amplify very small DC signals, typically in the microvolt range. They are used to eliminate the drift problem commonly seen in direct-coupled amplifiers. A chopper amplifier employs a chopping device that converts a slowly varying DC signal into an alternating voltage by modulating the DC into a square wave. The amplitude of this AC signal corresponds to the input DC, while its phase reflects the polarity of the original signal. This AC square wave is then amplified by an AC amplifier and demodulated to produce an amplified DC output. Chopper amplifiers come in both single-ended and differential input configurations and are widely used in medical applications to amplify small DC signals, such as those from temperature sensors (like thermistors and thermocouples) and strain gauges.

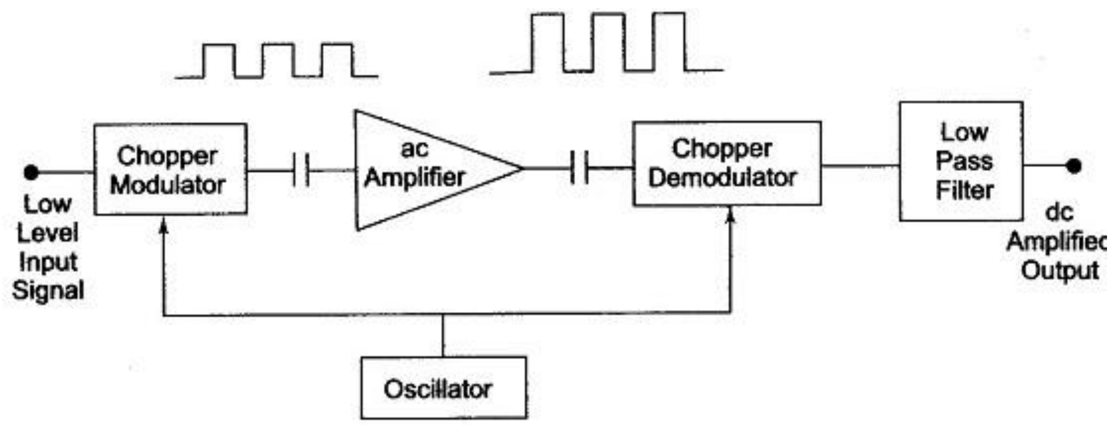

Figure 5: Chopper stabilized amplifier.

- **Isolation Amplifiers**

Isolation amplifiers are employed to safeguard against leakage currents by disrupting the direct electrical connection between the input and output signals. There are three main methods of isolation that can be used:

- Optical isolation
- Transformer isolation
- Capacitive isolation

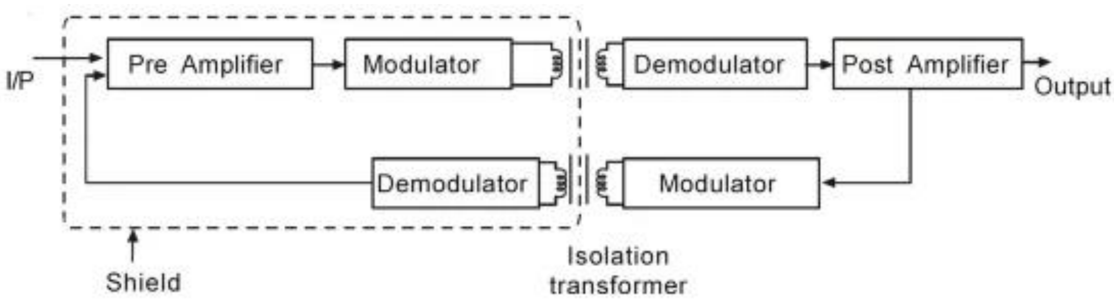

Figure 6 : A block diagram of Isolation Amplifier (Transformer type)

- **Optical Isolation**

In the diagram, as the input signal changes, the light intensity of the LED in the final amplification stage also fluctuates. An optocoupler transfers this light to a phototransistor, where the phototransistor's collector current is directly proportional to the light intensity. To enhance stability, feedback from the output may be introduced. Electrical isolation is used to protect patients from electrical hazards. Biomedical devices like pacemakers, electrocardiographs, pressure monitors, and pressure transducers are designed to electrically isolate the part of the circuit connected to the patient from the section connected to the AC power line and ground.

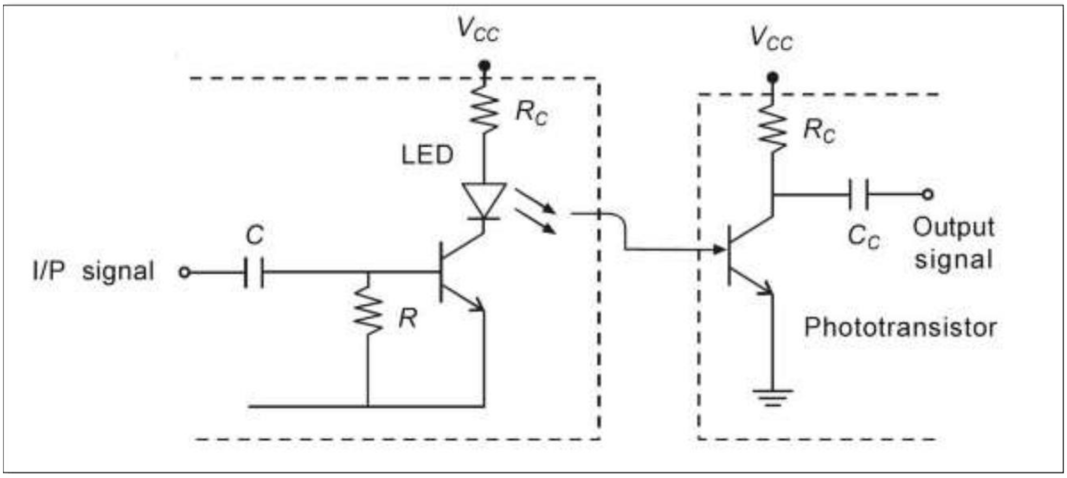

Figure 6: Optical isolation

Differential Amplifiers

Biomedical amplifiers used in the input stage of biomedical measurement systems are typically differential amplifiers. These amplifiers have three input terminals: one is set at the reference potential, while the other two are active terminals. Differential amplifiers are ideal for measuring the voltage difference between two points, where both points may vary in amplitude at different rates and follow different patterns. Examples of signals requiring differential amplifiers include heart-generated voltages detected by bioelectrodes placed on the arms and legs, and brain-generated voltages recorded by bioelectrodes on the scalp.

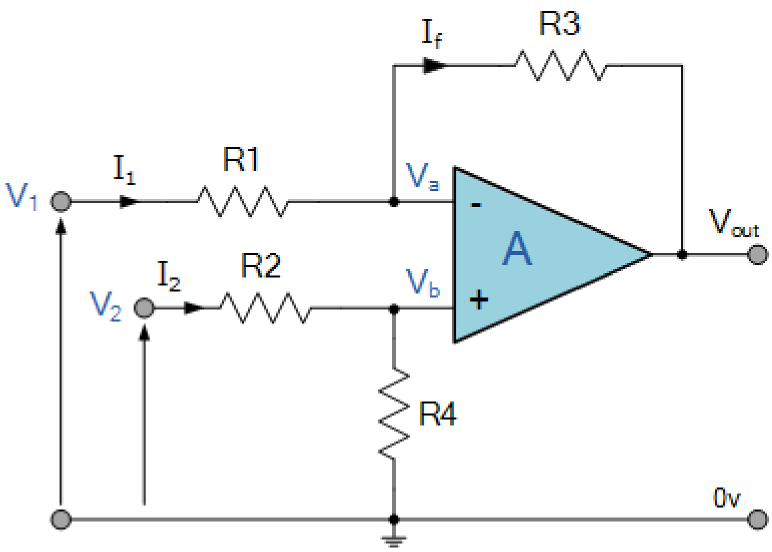

Figure 7: Differential Amplifier using an Operational Amplifier.

Reasons why Differential amplifier is preferred over other electronic amplifiers

The differential amplifier is highly effective at rejecting common-mode interferences, which are often picked up by electrodes along with the desired bioelectric signals from the body. As a direct-coupled amplifier, it offers excellent stability and versatility. Its stability is enhanced by its insensitivity to temperature changes, which are a common cause of excessive drift in other configurations. Its versatility allows it to be adapted for various applications, including those requiring floating or grounded inputs and outputs.

The differential amplifier's ability to reject common voltages present on both input leads is known as Common-Mode Rejection (CMR), quantified by the Common-Mode Rejection Ratio (CMRR). This ratio represents the proportion of common-mode input to differential input needed to produce the same output response and is typically expressed in decibels (dB). In biomedical instrumentation, a high CMRR is crucial to ensure that only the desired signals pass through the amplifier while unwanted signals are filtered out in the preamplifier stage.

A high rejection ratio is typically achieved using a matched pair of transistors in the preamplifier's input stage and a large "tail" resistance in the long-tailed pair, which provides maximum negative feedback for in-phase signals. To reduce the effects of varying electrode impedance, it is important to use an input or preamplifier stage with high input impedance. Low input impedance can lead to significant distortion in the recorded data.

High-gain integrated DC amplifiers with differential inputs and external feedback options are called operational amplifiers because they can perform mathematical operations. These amplifiers are available in integrated circuit form.

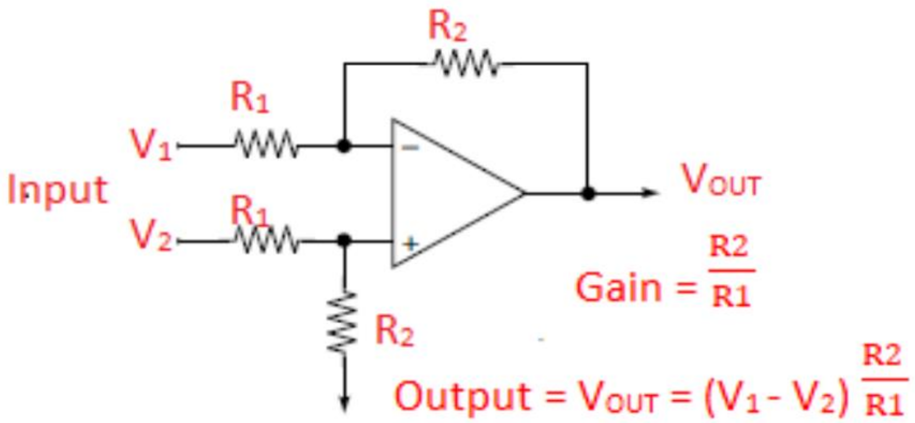

Figure 8 A single op-amp in a differential configuration

The common-mode rejection (CMR) of most operational amplifiers (op-amps) typically ranges between 60 dB and 90 dB, which may be insufficient to filter out common-mode noise often present in biomedical measurements. Additionally, the input impedance of op-amps may not be high enough to effectively process signals from high-impedance sources. One method to enhance the input impedance is to incorporate field-effect transistors (FETs) in the differential input stage of the op-amp. However, the optimal 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.

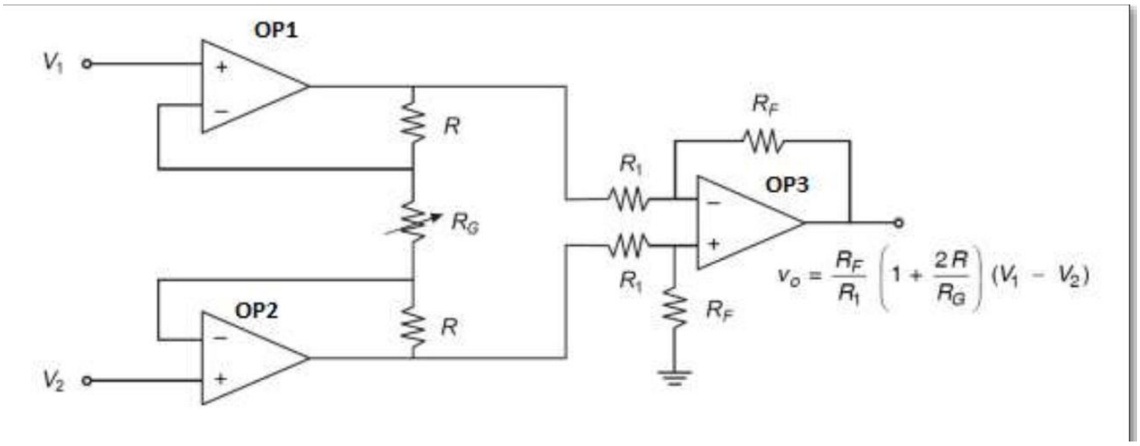

Figure 9 :Instrumentation amplifier

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 opamp 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.

Keywords:

1. **Biomedical Instrumentation**
2. **Transducer**
3. **Measurand**
4. **Signal Conditioner**
5. **Display System**
6. **Bioelectric Signals**
7. **Biomechanical Signals**
8. **Biocoustic Signals**
9. **Bio-impedance Signals**
10. **Biochemical Signals**
11. **Bio-optical Signals**
12. **Bio-magnetic Signals**
13. **Carrier Amplifiers**
14. **Chopper Amplifiers**
15. **Isolation Amplifiers**
16. **Differential Amplifiers**
17. **Common-Mode Rejection Ratio (CMRR)**
18. **Instrumentation Amplifiers**
19. **Biopotential Amplifiers**
20. **Calibration**
21. **Patient Safety**
22. **Cardiac**
23. **ECG**
24. **EEG**
25. **EMG**
26. **Signal**
27. **Sensor**