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A Handbook of Internet of Things in Biomedical and Cyber Physical System

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Preface

The purpose of this edited book is to inform and educate its audience about the power of biomedical, cyber-physical system with Internet of things. With the recent thrust in the Internet of things and wearable electronics, it is expected that all the conventional medical instruments would be highly unobtrusive as well as connected to the Internet in the near future. However, this imposes several fundamental challenges in their design like low power consumption, low-noise design, EMI immunity, motion artifact tolerance, and low-radiation biosignal communication; one aspect of this edited book is to identify the work carried out by researchers in the biomedical and cyber-physical system. We are sure that cyber-physical system and IoT will give an added boost to biomedical engineering and will be very useful to the new researchers for solving and supporting to open their research challenges. The book is organized into twelve chapters:

Chapter 1 provides the fundamental information regarding the most important physiological data for the development of a ubiquitous IoT healthcare system that can ensure more accurate diagnosis, real-time evidence-based treatment, lower hospital visits, and optimal utilization of resources.

Chapter 2 discusses specifically the case of crypto-hash Bloom filter incorporation in network intrusion detection system (NIDS) in security applications and privacy-preserving record linkage in medical research applications and shows the improved and comparable performance of the proposed system. The hardware implementation of the variants in various FPGA devices is also discussed. This work provides better results in applications than the previously existing systems and paves the way for huge future research scope for the research community.

Chapter 3 presents a security analysis of medical cyber-physical system, provides a layer-to-layer solution to the security issues, and recapitulates the security issues of MCPS from independent perspectives.

The objective of Chap. 4 is to focus on computerized security perspective on the earth and contraptions of the Internet of things. The amount of IoT contraptions is growing continually, and these devices are used fundamentally in each part of standard everyday presence. As such, mooring the IoT contraptions is expanding progressively more hugeness.

Chapter 5 covers the wearable/IoT device evolution and uses. This chapter will help to understand about the IoT protocols and security challenges. There are so many factors we need to take care during IoT solution design. We must follow security guidelines during designing and implementation of the IoT solutions. There are ten major security checkpoints to take care during designing phase. There are always two sides of a coin; IoT is not the exception, and having its own advantages and disadvantages depends upon case to case and applications. Advantage for one solution may be the disadvantage for the other. We need to understand the same how we can take care this during the designing and implementation.

Chapter 6 reduced by using an IoT-based fall detection system, in which a SVM algorithm and PCA features are applied. In addition, datasets collected from tri-axial accelerometer sensors and/or Kinect camera systems are transferred to a central hub via zigbee interface and are updated continuously to a cloud server for processing and detecting fall states. In addition, fall messages can be sent to relatives through smart phones and/or healthcare centers for alerting and supporting soon. The experimental results illustrate the effectiveness of the proposed system.

The goal of Chap. 7 is to indicate how Internet of things (IoT) is affecting therapeutic administrations and the piece of information technology in social protection. The developing people and the extending social protection cost in centers are inciting the approach of remote well-being checking frameworks. Physiological advances recognizing devices and the ascent of strong low-control remote framework developments have engaged the arrangement of remote well-being checking frameworks. The new time Internet, normally insinuated as (IoT) Internet of things, depicts a device-populated world that can recognize process and react through the Internet.

Chapter 8 enumerates their comparative review, proposes extensibility from IoMT perspective which will in turn be useful for real-time analysis of chronic disease data, personalized treatments, obtaining recommendation patterns, and so on, valuable for all types of healthcare professionals.

Chapter 9 proposes an IoT-based diagnostic system for heart disease classification. This system is designed to transmit classified data to server for storage and diagnosis. In particular, ECG devices are connected to Internet systems through Wi-fi or 3G/4G technologies for transmitting ECG data to a cloud-based processing system for storing patient's profiles. Therefore, datasets are preprocessed for extracting features using a WPD algorithm. In addition, a WKPCA method and a deep learning framework are employed for classifying heart diseases. The experimental results and the IoT-based system description are shown to illustrate the effectiveness of the proposed method.

Chapter 10 contributes toward understanding the recent research work, issues, challenges, and opportunities in applying enabling technologies for IoT. Also, how well the security and privacy can be incorporated is also discussed.

Chapter 11 reviews IoT healthcare data integration semantic techniques and secondly overviews the machine learning algorithms for integration of IoT healthcare data. Finally, the major research areas are discussed to integrate the IoT healthcare data. The processes and corresponding algorithms of the proposed framework are presented in detail with layer-by-layer including the raw data acquisition, semantic annotation, resources data extraction, semantic reasoning, and clustering.

Chapter 12 dissects IoT security and protection highlights, including security necessities, and threat models, from the medicinal services point of view. Further, this paper talks about how extraordinary advancements, for example, enormous information and wearables, can be utilized in a medicinal service setting. The examination gives roads to future research on IoT-based healthcare insurance alongside set of open issues and difficulties. The research is beneficial for the beginners who want to learn IoT and Big Data from scratch as well as professionals who are ready to develop applications and devices using IoT. The journey will take from the overview of IoT to applications in healthcare industry.

There have been several influences from our family and friends who have sacrificed lot of their time and attention to ensure that we are kept motivated to complete this crucial project. The editors are thankful to all the members of Springer (India) Private Limited especially Prof. (Dr.) Lakhmi C. Jain and Aninda Bose for giving the opportunities to edit this book.

Arad, Romania — Valentina E. Balas
Hyderabad, India — Vijender Kumar Solanki
Jabalpur, India — Raghvendra Kumar
Dhaka, Bangladesh/Osaka, Japan — Md. Atiqur Rahman Ahad

About This Book

The book is aimed to do a project based on biomedical and cyber-physical system research work in association with Internet of things. Today, we see that IoT is covering the major segment of technology and automation. This book focuses on the recent work happening in biomedical and cyber-physical system with IoT. We are sure that this subjective work will attract the reader as it is not easily available in the market. The biomedical is expanding the phase in the many-fold growth; in the same pace, the cyber-physical system is taking a grip on more new domains, so we felt that this edited book will help the researchers to know about the computing power to explore cyber-physical system and different biomedical aspects' execution with IoT.

Key Features

1. Covering the biomedical and cyber-physical system work with IoT.
2. Covering the biomedical systematic growth with cyber-physical and IoT system.
3. Contributors belong to different parts of the world working with multidisciplinary laboratory will be supporting us by contributing their research work in our book.
4. Containing insightful approach for interdisciplinary approach of IoT, e.g., wearable, sensor-enabled environment, cyber-tech IoT, etc.
5. Presenting several chapters' emphasis on improving the efficiency and growing deed of cyber-physical system through IoT/Big Data approach.
6. Exploration of cutting-edge technologies through sensor-enabled environment in biomedical industry.
7. Discussion about the mobile IoT and cyber-physical system.
8. Security and privacy of cyber-physical and biomedical system in preview of IoT and Big Data.
9. Case studies: in line of biomedical, cyber-physical, and IoT/Big Data.

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He has been involved with some academic and editorial activities: e.g., Editorial Board Member, *Scientific Reports*, *Nature*; Associate Editor, *Frontiers in ICT*; Editorial Board Member, *Encyclopedia of Computer Graphics and Games, Springer*; Editor, *International Journal of Affective Computing;* Associate Technical Editor (former), *IEEE ComSoc Magazine*; Editor-in-Chief: *International Journal of Computer Vision and Signal Processing* http://cennser.org/IJCVSP; General Chair, *2019 8th International Conference on Informatics, Electronics and Vision, 2019, Japan*, *3rd International Conference on Imaging, Vision and Pattern Recognition* http://cennser.org/ICIEV, *International Conference on Activity and Behavior Computing*, 2019 https://abc-research.github.io; Workshop Chair, *17th IEEE PiCom*; Publication Chair, *2018 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*; Vice Publication Co-Chair and Vice Award Chair, *Joint 17th World Congress of International Fuzzy Systems Association (IFSA) and 9th International Conference on Soft Computing and Intelligent Systems*; General Chair, *7th International Symposium in Computational Medical and Health Technology* and several other international conferences. He served as Guest Editor in *Pattern Recognition Letters*, Elsevier; *Journal of Multimedia User Interface*, Springer; *Journal of Healthcare Engineering,* Hindawi; *International Journal of Innovative Computing, Information and Control*. He is a Member of OSA, ACM, IEEE Computer Society, IAPR, IEEE RAS, IEEE SMC, etc. He is the Founder Secretary of *IEEE Computer Society Bangladesh Chapter* and *Bangladesh Association of Pattern Recognition*; Executive Committee Member of *Bangladesh Electronics Society* (BES). He volunteers some societies in Bangladesh (e.g., Executive Committee Member of BAPA, the largest environmental group) and Japan. More: http://ahadVisionLab.com.

Chapter 1
The Basics of Healthcare IoT: Data Acquisition, Medical Devices, Instrumentations and Measurements

A. S. M. Shamsul Arefin, K. M. Talha Nahiyan and Mamun Rabbani

Abstract Numerous IoT based systems are in deployment in the healthcare industry in order to monitor and diagnose the current state and to facilitate the wellbeing of a patient in an autonomous way. Increasing global populations in need of care, abundance of low cost powerful smart devices, enormous progress of communication technologies and emergence of robust data analytics have influenced the upsurge of IoT based healthcare systems. However, the reliability and durability of biosignals sensors and devices play vital roles towards establishing an ideal IoT healthcare system. Biosignals that originate due to the alterations of cell membrane potentials, carry important underlying physiological information. Any variations in them from the normal patterns can help diagnose abnormalities in the human body. Hence, to acquire these biosignals special bio-compatible electrodes, amplifiers, safety and isolation circuitry and measurement techniques are required due to their characteristic features like low amplitude, bandwidth and susceptibility to noise. Furthermore, to ensure ubiquitous and reliable data availability, acquired data signals need to be digitized, filtered and processed for the extraction of underlying events and features. All the relevant things are discussed in this chapter in a view to relate their significance in healthcare IoT services and applications. Overall, the chapter provides the fundamental information regarding the most important physiological data for the development of a ubiquitous IoT healthcare system that can ensure more accurate diagnosis, real-time evidence based treatment, lower hospital visits, and optimal utilization of resources.

Keywords Healthcare · IoT · Action potential · Bio-electrodes · Signal processing · Smart devices

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1.1 Introduction

Human body is capable of generating electrical signals due to various physiological activities and these signals can propagate through the whole body by virtue of human body being a volume conductor. These electrical signals originate from a cellular level mainly due to the inversion of potential in the cell membrane. Depending on the source of origin, primarily they are known as Electrocardiogram (ECG) in the heart, Electromyogram (EMG) in the muscles, Electroencephalogram (EEG) in the brain, and Electrooculogram (EOG) in the eye. The generation and propagation of these bioelectrical signals due to various stimuli govern multiple processes in the human body. Hence, the origin and characteristics of major bioelectrical signals need to be examined thoroughly. Furthermore, they can be acquired using electrodes that need to be compatible with biological tissues. Most of the signals are usually low in amplitude and it becomes extremely difficult to display them without any amplification. Consequently, high noise cancellation amplifiers are required to ensure high precision for the low amplitude signals. Apart from general noise cancellation consideration, specific filtering is required for a particular biosignal as each suffers from different types of artifacts. Moreover, the amplifiers need to be attuned with devices such as isolation circuits, analogue to digital (A-D) converters, conditioning and display devices. Overall, these things accumulate in detecting the underlying physiological events that are of utmost importance for an ideal healthcare system. Meanwhile, the emergences of artificial intelligence and data analytics, an aging global population, combined with the increasing connectivity potential of medical devices, i.e., Internet of things (IoT), have created a major opening for biomedical engineers to track and allocate appropriate and timely resources to the relevant patients.

Henceforth, this chapter focuses on the basic building blocks of the healthcare IoT with a view of forging a relationship between bioelectrical signals, medical devices and IoT. The chapter starts with the introduction to the biosignals and their origins. After that, measurements and instrumentations of the major bioelectrical signals are discussed. Subsequently, the data acquisition techniques, challenges and trends are illustrated. Eventually, some services and devices that are pertinent to healthcare IoT are enumerated. Finally, the chapter comes to its end integrating the core concepts leading to the development of a robust and smart IoT healthcare system.

1.2 Biosignals

Cell is the smallest unit in a living human body. Different types of cells vary in terms of their anatomy and physiology and tend to perform diverse tasks. Cells performing similar tasks make up a tissue. However, all cells have one thing in common and that is the cells maintain a potential difference throughout the cell membrane. On the contrary, some special cells like nerve cells, muscle cells and gland cells are excitable. The electrochemical stimulus produced inside these cells are conducted along the cell membrane when they are stimulated. These electrical activities are known as *biosignals* or *bioelectrical signals*. The following subsections explain the origin and the basic characteristics of these biosignals.

1.2.1 Cell Membrane and the Origin of Biosignals

The human body cell is encircled by a semi permeable membrane with thickness of about 7.5–10.0 nm [1]. Cell membrane is a mosaic structure of phospholipid bilayer with more than 50 different kinds of embedded proteins in the fluid matrix. Despite lipids making the base of the membrane, proteins govern most of the functionality of the membrane. The cell membrane is a dynamic structure and is bound together by hydrophobic interactions. Even though this structure is permeable to non-polar molecules, lipid bilayer makes it impermeable to water molecules and ions [2].

Integral proteins play vital roles to transfer ions and polar molecules. Some of the integral proteins are ion or polar molecule selective, i.e., they permit the passage of particular ions. These channels are passive in nature and do not require activation of energy to transport ions as they act according to the specific ion concentration gradient [3]. On the contrary, some proteins functions as pumps. They need to be activated via energy to transport specific ions against a concentration and/or voltage gradient across membrane [2]. The orientation of the ion channels and ion pumps thus determines the electrical properties of a cell by maintaining a difference in ion concentrations between the inside and outside of a cell. Hence, a membrane potential exists in the resting state of a cell and this is the primary originating factor of the biosignals. The significance of membrane potential is so high that this plays a vital role in the beginning of the creation of a life. On the instant of fertilization, only one sperm cell from millions merges with the egg cell. This triggers the ion channels of the egg cell and results in a change of membrane potential to deny the access of other sperm cells [1].

1.2.2 Resting Membrane Potential

The resting potential discussed in the previous subsection is the resultant phenomena due to the variation in ionic concentrations of Na, K, Cl and other relevant ions between inside and outside of the cell. This potential for a particular ion can be measured using the Nernst Equation [4]. Equation (1.1) shows how resting potential can be calculated for K^+ ion.

$$\mathrm{E_k} = \mathrm{v_i} - \mathrm{v_o} = \frac{k\mathrm{T}}{\mathrm{q}} \ln \frac{[\mathrm{K}^+]_\mathrm{o}}{[\mathrm{K}^+]_\mathrm{i}} \tag{1.1}$$

where, E_K is the resting potential for K^+, v_i is the potential inside the cell, v_o is the potential outside of the cell, *k* is the Boltzmann's constant, T is the absolute temperature in degrees Kelvin, $[K^+]_o$ and $[K^+]_i$ are extracellular and intracellular concentrations of ion, and q is the magnitude of the electric charge.

Considering Na^+ and Cl^-, the overall resting potential can be estimated using Goldmann–Hodgkin–Katz equation [5] as in Eq. (1.2).

$$V_m = \frac{kT}{q} \ln\left(\frac{P_K[K^+]_o + P_{Na}[Na^+]_o + P_{Cl}[Cl^-]_i}{P_K[K^+]_i + P_{Na}[Na^+]_i + P_{Cl}[Cl^-]_o}\right) \tag{1.2}$$

where, V_m is the transmembrane equilibrium potential, P_x is the membrane permeability coefficient for particular X ion. The resting membrane potential is in the range of −40 to −90 mV with respect to extracellular medium with a typical value of about −70 mV.

1.2.3 Action Potential

Excitable cells in the body, like neurons can alter the resting potential when they are properly stimulated. This results in a transient and overwhelming influx and efflux of ions which is known as *Action Potential*. Due to this phenomenon, the cell seems like a source of electrical activity that generates a current which is propagated through the human body volume conductor [3].

Action potential emanates due to the rapid incoming of Na^+ ions through the Na channels while the K channels are off. This initiates a *depolarization* of the resting potential and with enough influx of Na^+ ions, there is typically an overshoot of about +40 mV. At this point, the K channels are open and due to the efflux of more positive K^+ ions, the cell tends to repolarize to its resting potential. Due to a relatively prolonged opening period of K channels, sometimes there is a hyper polarizing phase in some cells [6]. A typical action potential is illustrated in Fig. 1.1 indicating the significant phases. Most cells cannot respond to any other internal or external stimuli to generate another action potential just after it has produced one. This period is usually known as the *Refractory Period* of an excitable cell.

1.2.4 Major Biosignals

As discussed in the previous sections, action potential is the source of electric activity through which biosignals are realized. Depending on the origin of the generation, there are four major biosignals that are of utmost importance in the context of this chapter, namely ECG, EMG, EEG and EOG. The well defined biosignal that demonstrates the generation and propagation of action potentials in the cells of the heart

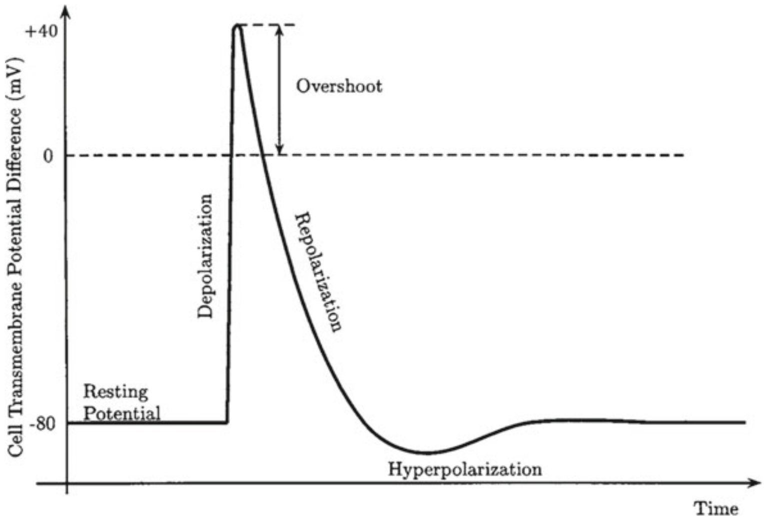

Fig. 1.1 A typical action potential schematic of a neuron [6]

is known as ECG [3]. ECG represents the synchronous contraction and relaxation rhythm of the heart that demonstrates the electric phenomena behind the pumping in and out of the blood through the heart to the whole body [7]. EMG characterizes the electrical activities of muscle tissues in terms of single motor unit potential on the body surface [8]. Additionally, EMG demonstrates electrical signal output for a particular muscular activity like contraction, relaxation etc. [9]. Furthermore, EEG epitomizes the generation and propagation of action potentials by a huge number of neurons via axon and dendrites in the brain due to internal or external stimuli [10]. EEG is one of the prominent non invasive brain mapping technique to understand the neurophysiology and neuro monitoring due to different physical and mental activities. Last but not the least, EOG embodies the electrical activity involved due to the eyeball movements in the brain cavity that alter the potentials in the conductive parts of the brain [9]. Hence, these bioelectrical signals are of great importance in monitoring, diagnosing and treating disorders with proper recording of the data and interpreting them efficiently. However, there are other electromechanical biosignals in the human body which are unfortunately out of scope of this chapter. Table 1.1 lists some of the typical characteristic features of these major biosignals [3, 7, 9].

The following sections deal with the measurement, instrumentation and acquisition related issues of the biosignals and how they relate to the healthcare IoT systems.

Table 1.1 Typical features of major bioelectrical signals

Biosignals	Typical amplitude (mV)	Typical bandwidth (Hz)	Typical applications
ECG	1–5	0.05–100	Cardiac monitoring, diagnosis of cardiac anomalies etc.
EMG	1–10	20–2000	Determination of functionality of muscles, diagnosis of muscular disorders, measurement of muscle properties etc.
EEG	0.001–0.01	0.5–40	Neuro electrophysiology, diagnosis of neuro disorders, brain mapping etc.
EOG	0.01–0.1	0–10	Mapping of states of sleep, positioning of the eye, reflex studies of the eye and face etc.

1.3 Instrumentation and Measurement of Biosignals

The biosignals discussed in the previous section can be recognized in the form of electric signals. Various bio-activities of the body are associated with specific type of biosignals. For example, the spontaneous activity of the cardiac muscles generates an ECG. A deviation from the general pattern of the signal usually represents some anomaly in the generating organ or tissue.

As all the primary biosignals can be realized in electrical form, these signals can be acquired and studied by electronic equipments and interfaces. However, there are challenges associated in this process. In this section we will go through the instrumentation and measurement of biosignals by overcoming the following main challenges:

(a) Biosignals propagate in the biological tissues as ions while any signal propagating in an electronic circuit is due to flow of electrons.
(b) Most of the biosignals are of very low amplitude, hence they need significant amplification.
(c) The frequencies of biosignals are quite low, which makes them prone to noise corruption.

1.3.1 Bio-electrodes

In any biological tissue, biosignal is generated and propagated considering ions as charge carriers. To acquire biosignals, these ionic signals should be obtained and converted into electric signals. Bio-electrodes are the interface between biological tissue medium and electronic circuit medium. Bio-electrodes act as a transducer consisting of electrical conductors in contact with the ionic solution of the body. The relation between electrodes and ionic solution can affect the acquisition of the biosignal. When biosignals are generated on the cell membrane of biological tissues, they give rise to ionic currents [11]. These ionic currents generate an electric field around them. When an electrolyte is placed on the extracellular region, an ionic current is generated in the electrolyte due to this electric field.

When an electrode made of conductor is placed in an electrolyte, a redox reaction takes place which transfers the charge from the electrolyte to the electrode. A redox reaction can be represented by the following equations:

$$C \rightleftharpoons C^{n+} + ne^- \tag{1.3}$$

$$A^{m+} \rightleftharpoons A + me^- \tag{1.4}$$

Here n is the valence of the cation material C and m is the valence of the anion material A. Current passing between electrode and electrolyte follow either one of the two equations. When currents flow from the electrodes towards the electrolytes, Eq. (1.3) dominates, which is the case in stimulating any tissue externally. On the contrary, when current flows from the electrolyte to the electrode, Eq. (1.4) dominates, which is the case of recording any biosignal. These reactions continue to occur even when there is no current crossing the electrode-electrolyte interface. The rate of oxidation is eventually equal to the rate of reduction resulting in no charge transfer across the interface.

When an electrode comes in contact with an electrolyte of the same metal, it changes the local concentration of ions near the metal surface. Hence, the charge neutrality in the region near the electrode-electrolyte interface is changed and the region gains a potential that is different from the rest of the electrolyte. This potential difference between the electrode-electrolyte interface is known as *Half-cell Potential.* Half-cell potentials vary with the materials of the electrode and the ions present in the electrolyte. These potentials are measured with reference to a standard hydrogen electrode, hence, the half-cell potential of hydrogen electrode is considered to be zero [12]. Some values of half-cell potentials with respect to hydrogen electrode are given in Table 1.2. The half-cell potential generated at the electrode-electrolyte interface can be measured using the Nernst equation as in Eq. (1.1). However, the Nernst equation gives the value of half-cell potential only under the condition that no current flows through the interface. When currents flow through the interface of the electrode and electrolyte, a change in potential occurs. This change in voltage is known as *Over-voltage*. As current flows through the interface, it changes the charge distribution of the solution in contact with the electrode. This effect is known as *Polarization* [11].

Electrodes with high level of polarization allow current to pass between the electrode and electrolyte by changing the local charge distribution of the solution near

Table 1.2 Half-cell potential for some common materials used in bio-electrodes [12]

Materials with their corresponding redox reaction	Half-cell potential (in V)
$Al \rightarrow Al^{3+} + 3e^-$	−1.706
$Ni \rightarrow Ni^{2+} + 2e^-$	−0.230
$H_2 \rightarrow 2H^+ + 2e^-$	0.000 (considered as reference)
$Ag + Cl^- \rightarrow AgCl + e^-$	+0.233
$Ag \rightarrow Ag^+ + e^-$	+0.799
$Au \rightarrow Au^+ + e^-$	+1.680

the electrode. Although no actual current passes through the electrode-electrolyte interface, a charge distribution, different from the charge distribution of the biological tissue, prevails in the region near the interface. Such distribution causes problem when there is movement and low frequency signals are involved. When the electrode changes position with respect to the electrolyte, the localized charge distribution changes and as a result a voltage change is recorded in the electrode. This voltage change poses itself as *Motion artifact* and reduces the performance of electrodes. Electrodes made from noble metals like Platinum are often highly polarizable and hence avoided in biomedical measurement.

As movement is quite prevalent during biomedical measurement, non-polarizable electrodes are preferred mostly in measurement. The silver-silver chloride (Ag-AgCl) electrode has characteristic features that are quite close to non-polarizable electrode, hence, it is used in most biomedical applications [13]. The electrode is made up of Ag metal coated with a layer of AgCl. When exposed to light, some of the AgCl is reduced to metallic Ag, creating a matrix of Ag surrounded by AgCl. As this surface of AgCl is stable and the electrode does not show any polarization, motion artifact is reduced along with frequency dependency of electrode impedance. Also due to the non-polarizable behavior, these electrodes are less prone to noise compared to the polarizable counterpart.

1.3.1.1 Electrical Characteristics of Bio-electrodes

Bio-electrodes generally show a non-linear electrical characteristic which is a function of the current density at their surfaces. When operated under low voltage and currents, electrodes can be represented by a model consisting of linear components. Under ideal conditions, bio-electrodes can be represented by the model as shown in Fig. 1.2.

Here, the source E_{hc} represents the half-cell potential associated with the electrode-electrolyte interface. Due to electrostatic effect, ions from the solution get adsorbed onto the surface of the electrodes. As a result, charges of opposite polarity get acquired in the electrode near the interface. This creates a capacitive structure in the electrode-electrolyte interface, which is represented by the capacitor,

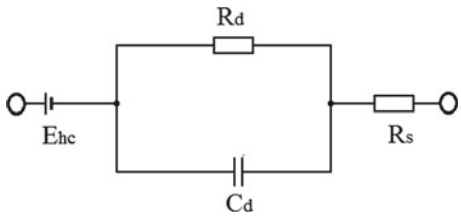

Fig. 1.2 Equivalent circuit for bio-potential electrode

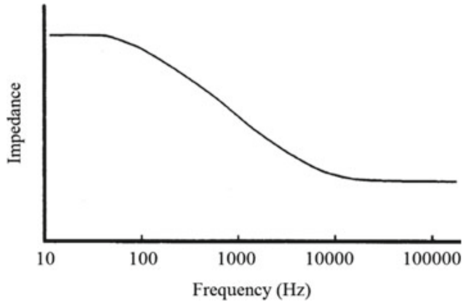

Fig. 1.3 Frequency characteristics of bio-electrodes

C_d. Although the capacitive structure does not allow current to pass, some faradic current passes through as a result of redox reaction occurring at the interface. These reactions show a current flow, which in effect tends to shunt the capacitive structure. Hence, the current flow is represented by a resistor R_d, which is in parallel to C_d. The series resistance R_s is the combination of lead and electrolyte resistances. At low frequencies, the electrode impedance is dominated by the series combination of R_s and R_d, whereas during high frequencies, C_d bypasses R_d and the effective resistance is reduced to $R_{s.}$ This frequency response of bio-electrodes is shown in Fig. 1.3 [12].

1.3.1.2 Bio-electrodes Used in Biomedical Applications

In biomedical applications, various sorts of electrodes are utilized to acquire biosignals. The electrodes can be categorized based on their regions of placement [14].

Body Surface Electrode These electrodes are placed on the surface of the body with a coupling fluid serving as electrolyte at the interface. The acquired signals are usually of low amplitude and corrupted with noise. The main advantage of these electrodes is the non-invasive nature which minimizes patient discomfort and maintains the skin surface integrity. These electrodes are usually used for short term diagnostic recording of biopotentials.

Intracavity and Intratissue Electrodes These electrodes are placed inside the tissue or organ invasively. They do not need any coupling fluid as the body fluids play the part of interfacing electrodes with tissues. These electrodes can record localized body potentials, hence, the signal acquired is of moderate amplitude and nearly artifact-free. These electrodes can be in the form of needle electrodes which can penetrate the skin and tissues and reach the spot of interest, or in the form of electrodes which are surgically placed in a cavity in the body.

Microelectrodes These electrodes are miniatures in dimensions and used to record the response and electrical activity from cellular level. These electrodes are small enough to pass through the cell membrane into the cytosol. As they are small and robust, they are widely used in neurophysiological studies. However, these electrodes suffer from high source impedance and are difficult to fabricate.

1.3.2 Bio-amplifiers

Biosignals typically range from 1 μV to 100 mV accompanied by high source impedance and high-level interference and noise. Hence, these signals are required to be amplified and made compatible with devices such as displays, recorders or converters while rejecting the superimposed noise and interference signal. Amplifiers with such specifications are known as Bio-amplifiers [15]. The basic requirements for bio-amplifiers are

- The origin of biosignal should not be altered by the measuring circuitry.
- The measured biosignal should be undistorted.
- The circuitry should be able to distinguish between biosignal and interference.
- The circuitry should provide an isolation to the patient from unwanted electrical hazard.
- The circuitry should have a safety mechanism to protect itself from high voltages from input end resulting from defibrillators and other electrosurgical equipment.

A typical biosignal has five components: (1) the expected biosignal, (2) unexpected biosignals, (3) interference signal from power line, (4) interference signal generated from the interface of the tissue and electrode, and (5) noise signals. A bio-amplifier usually contains three input electrodes. Two of the electrodes provide with the biosignal to be measured while the third one acts as the reference point of the circuitry. The desired biosignal is presented in a differential form between the two input terminals and is referred to as *differential signal.*

The line frequency interference, unexpected biosignals and noise signals show small amplitudes and nearly the same phase between the two input electrodes. These signals are labeled as *common mode signals*. Due to the differential effect, any signal represented as a common mode signal at the inputs get cancelled out. This characteristic of a bio-amplifier is known as *Common Mode Rejection Ratio (CMRR)* and is an important parameter for analyzing the performance of a bio-amplifier. The amplification factor of an amplifier to a differential signal is known as *Differential gain*. The amplification factor of an amplifier to a common mode signal is known as *Common mode gain.* CMRR is defined as the ratio of the differential gain to common mode gain.

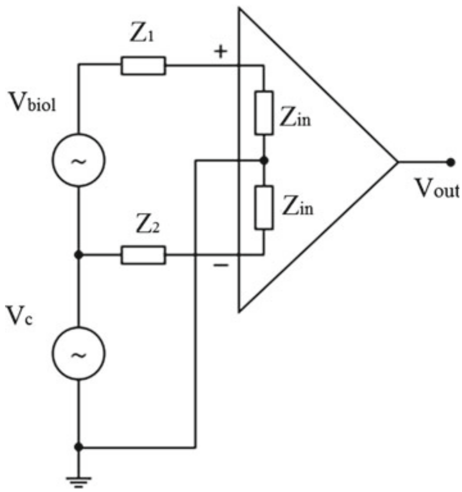

Fig. 1.4 General configuration of bio-amplifier

The general configuration of a bio-amplifier is shown in Fig. 1.4. The biosignal present at the two inputs is shown as V_{biol} while the common mode signal is shown as V_c. The input impedances of the amplifier are Z_1 and Z_2. For ideal amplifiers, the input impedances are equal, so $Z_1 = Z_2$. In ideal cases, the common mode gain is zero, which means that the amplifier would not let any common mode signal to pass into the output. As CMRR is the ratio of differential gain to common mode gain, it is infinite in the case of ideal amplifiers. Hence, the output is the amplified version of the differential input. If the differential gain of the amplifier is G_D, the output of the amplifier is $V_{out} = G_D V_{biol}$.

In practical cases, the common mode signal is not completely rejected, hence, the common mode gain in finite giving rise to a finite CMRR. This gives rise to an interference term due to finite CMRR which can be quantified as $\left(\frac{G_D V_C}{CMRR}\right)$. This interference term is additive to the output signal. In reality, the input impedances Z_1 and Z_2 are usually unequal. Hence, any common signal at the two inputs manifest as two different signals at the two differential inputs. This gives rise to a differential signal which is amplified and added to the output. If the internal impedance of the amplifier is taken as Z_{in}, then the output due to unequal input impedance can be shown as $\left[G_D V_C\left(1 - \frac{Z_{in}}{Z_{in}+Z_1-Z_2}\right)\right]$. Therefore, the output of a bio-amplifier considering all practical scenario can be expressed as

$$V_{out} = G_D V_{biol} + \frac{G_D V_C}{CMRR} + G_D V_C\left(1 - \frac{Z_{in}}{Z_{in} + Z_1 - Z_2}\right) \tag{1.5}$$

As there is always an interference term present at the output, practical bio-amplifiers require a minimum CMRR of 100 dB to maintain the best possible signal-to-noise ratio. To ensure optimum signal quality, the gain of bio-amplifiers should be in the range of 50,000.

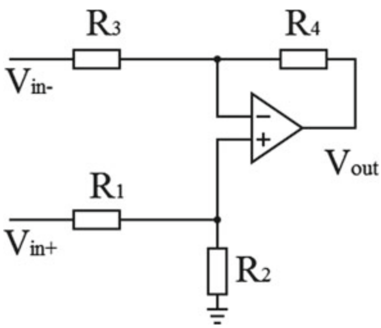

Fig. 1.5 A differential amplifier

Bio-amplifiers require differential input, high input impedances and high CMRR. In practical cases, bio-amplifiers are realized using Operational Amplifier (Op-Amp) based active circuits. Two of the most commonly used bio-amplifiers are the Differential Amplifier and Instrumentation Amplifier configuration [16].

1.3.2.1 Differential Amplifier

One of the simplest forms of bio-amplifier is the Differential Amplifier. The circuit configuration of a differential amplifier is shown in Fig. 1.5.

The two differential inputs are denoted as V_{in+} and V_{in-}. If the gain of the amplifier is denoted by G_D the output of the amplifier is expressed by $V_{out} = G_D(V_{in+} - V_{in-})$. The gain G_D is set by $\frac{R_4}{R_3} = \frac{R_2}{R_1}$. To make the ratio of the resistances equal, a variable resistance is used at the point of R_2.

Although differential amplifier is the simplest form of bio-amplifier, this configuration does not provide high input impedance. The CMRR of the circuit is dependent on the ratio $\frac{R_4}{R_3} = \frac{R_2}{R_1}$, so a slight mismatch in the ratio gives a significant decrease in CMRR. Moreover, as the gain is also dependent on the ratio of the resistances, a fixed CMRR gives a fixed gain, which is troublesome for most biosignal measurements.

1.3.2.2 Instrumentation Amplifier

A robust bio-amplifier used in most biosignal acquisition is the instrumentation amplifier. The circuit diagram is shown in Fig. 1.6.

This amplifier addresses the problems of the differential amplifier configuration. The inputs are fed into the circuit through an R-C filter which eliminates the noise. The Op-Amps 1 and 2 provide the high input impedances which can be considered equal. The final output is taken from Op-Amp 3. The input-output relation can be expressed as

$$V_{out} = \left(1 + \frac{2R_2}{R_1}\right)\left(\frac{R_4}{R_3}\right)(V_{in+} - V_{in-}) \tag{1.6}$$