Biopotentials and Electrophysiology Measurement

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74.1 Introduction

This chapter reviews the origins, principles, and designs of instrumentation used in biopotential measurements, in particular for the electrocardiogram (ECG), the electroencephalogram (EEG), the electromyogram (EMG), and the electrooculogram (EOG). These biopotentials represent the activity of the respective organs: the heart, brain, muscle, and eyes. The biopotentials are acquired with the help of specialized electrodes that interface to the organ or the body and transduce low-noise, artifact-free signals. The basic design of a biopotential amplifier consists of an instrumentation amplifier. The amplifier should possess several characteristics, including high amplification, input impedance, and the ability to reject electrical interference, all of which are needed for the measurement of these biopotentials. Ancillary useful circuits are filters for attenuating electric interference, electrical isolation, and defibrillation shock protection. Practical considerations in biopotential measurement involve electrode placement and skin preparation, shielding from interference, and other good measurement practices.

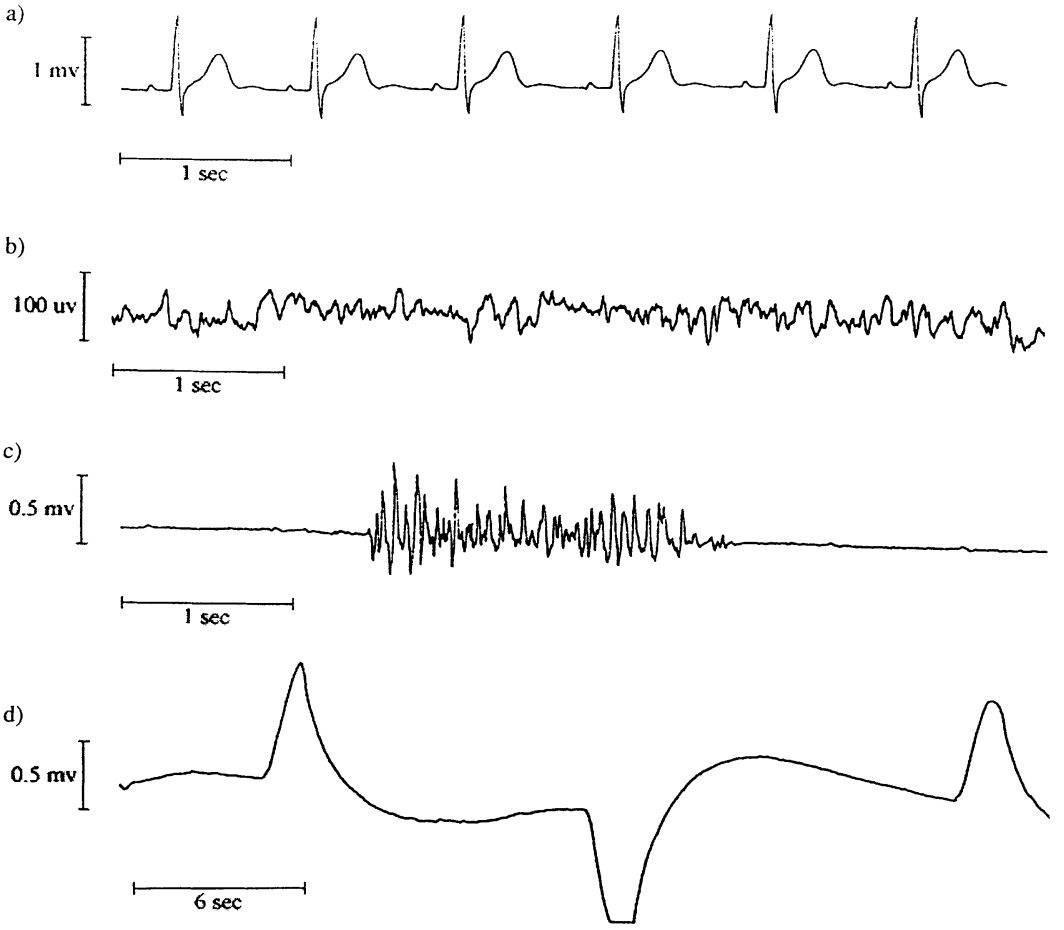


FIGURE 74.1 Sample waveforms: (a) ECG, normal sinus rhythm; (b) EEG, normal patient with open eyes; (c) EMG, flexion of biceps muscles; (d) EOG, movement of eyes from left to right.

74.2 The Origins of Biopotentials

Many organs in the human body, such as the heart, brain, muscles, and eyes, manifest their function through electric activity [1]. The heart, for example, produces a signal called the electrocardiogram or ECG (Figure 74.1a). The brain produces a signal called an electroencephalogram or EEG (Figure 74.1b). The activity of muscles, such as contraction and relaxation, produces an electromyogram or EMG (Figure 74.1c). Eye movement results in a signal called an electrooculogram or EOG (Figure 74.1d), and the retina within the eyes produces the electroretinogram or ERG. Measurements of these and other electric signals from the body can provide vital clues as to normal or pathological functions of the organs. For example, abnormal heart beats or arrhythmias can be readily diagnosed from an ECG. Neurologists interpret EEG signals to identify epileptic seizure events. EMG signals can be helpful in assessing muscle function as well as neuromuscular disorders. EOG signals are used in the diagnosis of disorders of eye movement and balance disorders.

The origins of these biopotentials can be traced to the electric activity at the cellular level [2]. The electric potential across a cell membrane is the result of different ionic concentrations that exist inside and outside the cell. The electrochemical concentration gradient across a semipermeable membrane results in the Nernst potential. The cell membrane separates high concentrations of potassium ion and low concentrations of sodium ions (along with other ions such as calcium in less significant proportions)

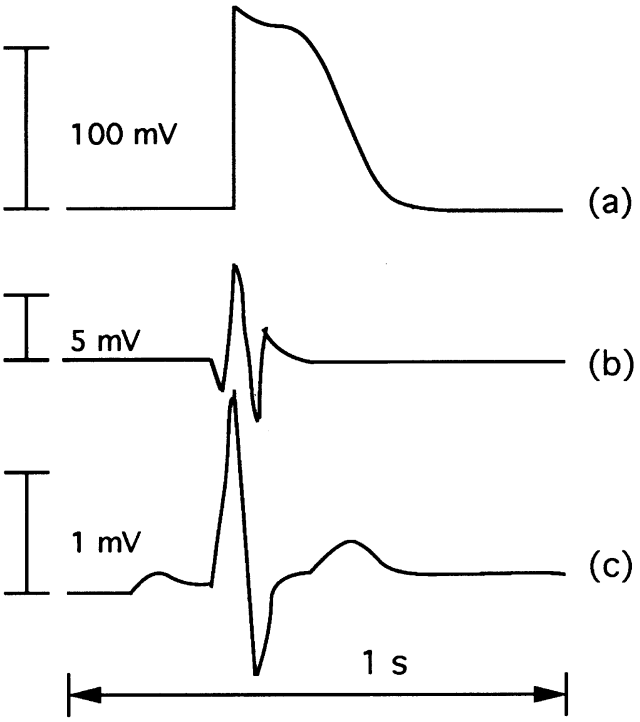


FIGURE 74.2 Schematic showing origins of biopotentials: (a) an action potential from a heart cell (recorded using a microelectrode); (b) the electrogram from the heart surface (recorded using an endocardial catheter); and (c) the ECG signal at the chest (recorded using surface electrodes).

inside a cell and just the opposite outside a cell. This difference in ionic concentration across the cell membrane produces the resting potential [3]. Some of the cells in the body are excitable and produce what is called an action potential, which results from a rapid flux of ions across the cell membrane in response to an electric stimulation or transient change in the electric gradient of the cell [4]. The electric excitation of cells generates currents in the surrounding volume conductor manifesting itself as potentials on the body.

Figure 74.2 illustrates the continuum of electrophysiological signals from the (a) heart cells, (b) myocardium (the heart muscle), and (c) the body surface. Each cell in the heart produces a characteristic action potential [4]. The activity of cells in the sinoatrial node of the heart produces an excitation that propagates from the atria to the ventricles through well-defined pathways and eventually throughout the heart; this electric excitation produces a synchronous contraction of the heart muscle [5]. The associated biopotential is the ECG. Electric excitation of a neuron produces an action potential that travels down its dendrites and axon [4]; activity of a massive number of neurons and their interactions within the cortical mantle results in the EEG signal [6]. Excitation of neurons transmitted via a nerve to a neuromuscular junction produces stimulation of muscle fibers. Constitutive elements of muscle fibers are the single motor units, and their electric activity is called a single motor unit potential [7]. The electric activity of large numbers of single motor unit potentials from groups of muscle fibers manifests on the body surface as the EMG. Contraction and relaxation of muscles is accompanied by proportionate EMG signals. The retina of the eye is a multilayered and rather regularly structured organ containing cells called rods and cones, cells that sense light and color. Motion of the eyeballs inside the conductive contents of the skull alters the electric potentials. Placing the electrode in the vicinity of the eyes (on either side of the eyes on the temples or above and below the eyes) picks up the potentials associated with eye movements called EOGs. Thus, it is clear that biopotentials at the cellular level play an integral role in the function of various vital organs.

TABLE 74.1 Biopotentials, Specifications, and Applications

Source	Amplitude (mV)	Bandwidth (Hz)	Sensor (Electrodes)	Measurement Error Source	Selected Applications
ECG	1–5	0.05–100	Ag–AgCl disposable	Motion artifact, 50/60 Hz powerline interference	Diagnosis of ischemia, arrhythmia, conduction defects
EEG	0.001–0.01	0.5–40	Gold-plated or Ag–AgCl reusable	Thermal (Johnson) RF noise, 50/60 Hz	Sleep studies, seizure detection, cortical mapping
EMG	1–10	20–2000	Ag or carbon, stainless steel, needle	50/60 Hz, RF	Muscle function, neuromuscular disease, prosthesis
EOG	0.01–0.1	dc–10	Ag–AgCl	Skin potential motion	Eye position, sleep state, vestibulo-ocular reflex

74.3 Biopotentials

Biopotentials from organs are diverse. Table 74.1 lists some of these biopotentials, their representative clinical applications, and their key measurement indices and associated sensors. Note that all acquisitions are made with the aid of specialized electrodes in which actual design may be customized for specific needs. The most noteworthy features of biopotentials are [1,8]

- Small amplitudes (10 μV to 10 mV),
- Low frequency range of signals (dc to several hundred hertz)

The most noteworthy problems of such acquisitions are

- Presence of biological interference (from skin, electrodes, motion, etc.),
- Noise from environmental sources (power line, radio frequency, electromagnetic, etc.).

These signal acquisition challenges and problems for each of the biopotentials are considered in greater detail below.

ECG

ECG signals are acquired by placing electrodes directly on the torso, arms, and legs (Figure 74.3a). The activity on the body surface is known to reflect the activity of the heart muscle underneath and in its proximity. A clinically accepted lead system has been devised and is called the 12-lead system [9, 10]. It comprises a combination of electrodes taking measurements from different regions designated limb leads, the precordial leads, and the chest leads. Limb leads derive signals from electrodes on the limbs, and are designated as leads I, II, and III. Precordial leads are designated aVR, aVL, and aVF, and are derived by combining signals from the limb leads. The remaining six leads, V1, V2, … V6, are chest leads. Together, ECGs from these various leads help define the nature of the activity on a specific part of the heart muscle: for example, ischemia (impaired oxygen supply to the muscle) or infarction (damage to the muscle) on the left side of the chest may be noticeable in lead III.

The ECG signals at the surface of the body are small in amplitude, which make the measurements susceptible to artifacts [11], generated by the relative motion of the electrode and the skin as well as by the activity of the nearby muscles. An important consideration in good ECG signal acquisition is the use of high-quality electrodes [12]. Electrodes made out of silver coated with silver chloride or of sintered Ag–AgCl material, are recommended. An electrolytic gel is used to enhance conduction between the skin and the electrode metal. Artifacts at the electrode–skin contact as well as electromagnetic interference from all sources must be minimized [13]. Since ECG instruments are often used in critical-care environments, they must be electrically isolated for safety [14] and protected from the high voltages generated by defibrillators [15].

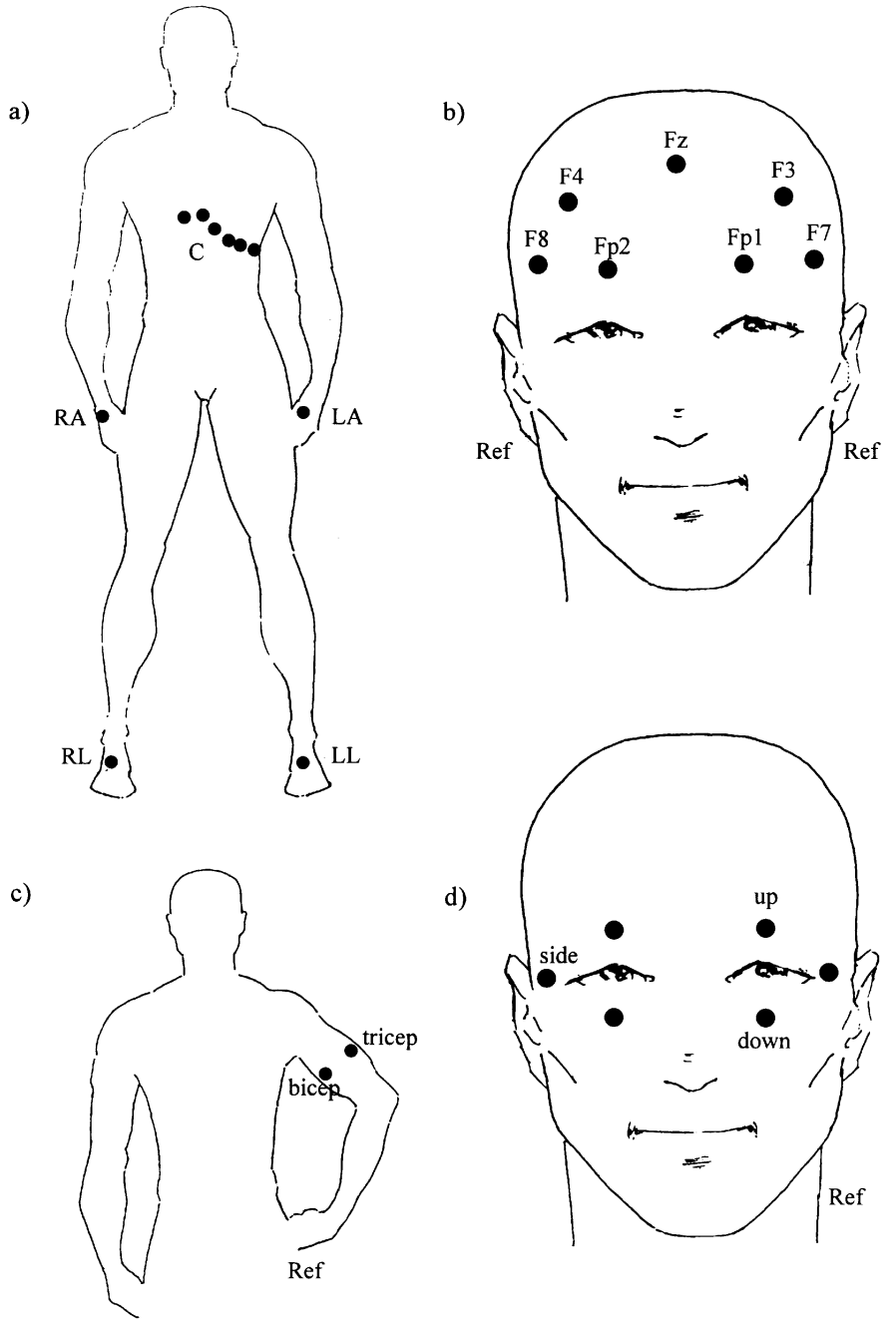


FIGURE 74.3 Schematics showing how biopotential signals are recorded from the human body. (a) ECG: 12-lead ECG is recorded using right arm (RA), left arm (LA), left leg (LL), right leg reference (RL), and six chest (C) electrodes. (b) EEG: selected electrode locations from the standard 10-20 EEG lead system with ears used as reference. (c) EMG: recording electrodes on the biceps and triceps with an independent reference. (d) EOG: electrodes above or below (up–down) and the sides of the eyes along with an independent reference.

ECG biopotential amplifiers find use in many monitoring instruments, pacemakers, and defibrillators [16]. ECG signal acquisition is also useful in many clinical applications including diagnosis of arrhythmias, ischemia, or heart failure.

EEG

EEG signals are characterized by their extremely small amplitudes (in the microvolt range). Gold-plated electrodes are placed very securely on the scalp to make a very low resistance contact. A clinically accepted lead system [17], which includes several electrodes placed uniformly around the head, is called the 10-20 lead system (Figure 74.3b). This comprehensive lead system allows localization of diagnostic features, such as seizure spikes, in the vicinity of the electrode [18].

EEG signals are difficult to interpret since they represent the comprehensive activity of billions of neurons transmitted via the brain tissues, fluids, and scalp [18]. Nevertheless, certain features can be interpreted. In the waveform itself, it is possible to see interictal seizure spikes or a full seizure (such as petit mal and grand mal epilepsy) [18]. Analysis of the frequency spectrum of the EEG can reveal changes in the signal power at different frequencies being produced during various stages of sleep, as a result of anesthetic effects, and sometimes as a result of brain injury [17].

Practical problems and challenges associated with EEG signal recordings arise from physiological, environmental, and electronic noise sources. Physiological sources of interference are motion artifact, muscle noise, eye motion or blink artifact, and sometimes even heartbeat signals. Electrical interference arises from the usual sources: 60 Hz power lines, radio frequencies (RF), and electrically or magnetically induced interference. Moreover, the electronic components in the amplifier also contribute noise. Good design and measuring techniques can mitigate the effects of such noise and interference.

EMG

Muscle fibers generate electric activity whenever muscles are active [19]. EMG signals are recorded by placing electrodes close to the muscle group (Figure 74.3c). For example, a pair of electrodes placed on the biceps and another pair placed on the triceps can capture the EMG signals generated when these muscles contract. EMG signals recorded in this manner have been shown to give a rough indication of the force generated by the muscle group [8]. Electrodes used for such applications should be small, securely attached and should provide recordings free of artifacts. Either silver–silver chloride or gold-plated electrodes perform quite well, although inexpensive stainless steel electrodes may also suffice.

Since the frequency range of EMG signals is higher than that of ECG and EEG signals, and since the signals are of comparable or larger amplitudes, the problem of motion artifact and other interference is relatively less severe. Filtering can reduce the artifact and interference: for example, setting the bandwidth to above 20 Hz can greatly reduce the skin potentials and motion artifacts.

Recording activity directly from the muscle fibers themselves can be clinically valuable in identifying neuromuscular disorders [19]. Therefore, invasive electrodes are needed to access the muscle fibers or the neuromuscular junction. Fine-needle electrodes or thin stainless steel wires are inserted or implanted to obtain local recording from the fibers or neuromuscular junctions [7].

EOG

Electric potentials are generated as a result of movement of the eyeballs within the conductive environment of the skull. The generation of EOG signals can be understood by envisaging dipoles (indicating separated positive and negative potential sources) located in the eyeballs. Electrodes placed on either side of the eyes or above and below them pick up the potentials generated by the motion of the eyeball (Figure 74.3d). This potential varies approximately in proportion to the movement of the eyeballs, and hence EOG is sometimes used to study eye positions or disorders of eye movement and balance (a reflex called vestibulo-ocular reflex affects the nystagmus of the eye). Similarly, saccades inherent in eye motion as well as blinking of the eyelids can produce changes in the EOG signal.

This signal is small (10 to 100 μV) and has low frequencies (dc to 10 Hz) [8]. Hence, an amplifier with a high gain and good low frequency response and dc stability is desirable. Additionally, the electrode–gel combination should be such that it produces low levels of junction potential, motion artifacts, and drift in the dc signal [20]. Practical problems associated with dc drift, motion artifacts, and securing

electrodes in the vicinity of the eyes make their long-term use problematic. Nevertheless, EOG signals can be useful clinically in acute studies of human disorders, and therefore careful acquisition of the signal followed by appropriate analysis is used to interpret the EOG potentials.

Other biopotential recording techniques follow similar principles of measurements. The electrode design should be specifically adapted to the source of the signal. A thorough effort is required to minimize the noise and interference by improving electrode design and placement and optimizing the amplifier circuit. Good electrode attachment along with selective filtering at the amplifier can help obtain relatively noise-free recording. The design principles and practical considerations are described below.

74.4 The Principles of Biopotential Measurements

The unifying principles of biopotential recordings involve

- Electrode design and its attachment suited to the application;
- Amplifier circuit design for suitable amplification of the signal and rejection of noise and interference;
- Good measurement practices to mitigate artifacts, noise, and interference.

74.5 Electrodes for Biopotential Recordings

Electrodes for biopotential recordings are designed to obtain the signal of interest selectively while reducing the potential to pick up artifact. The design should be pragmatic to reduce cost and allow for good manufacturing and reliable long-term use. These practical considerations determine whether high-quality but reusable electrodes made of silver or gold or cheaper disposable electrodes are used [20].

Silver–Silver Chloride Electrodes

The classic, high-quality electrode design consists of a highly conductive metal, silver, interfaced to its salt, silver chloride, and connected via an electrolytic gel to the human body [21]. Silver–silver chloride–based electrode design is known to produce the lowest and most stable junction potentials [1, 20]. Junction potentials are the result of the dissimilar electrolytic interfaces, and are a serious source of electrode-based motion artifacts. Therefore, additionally, an electrolytic gel typically based on sodium or potassium chloride is applied to the electrode. A gel concentration in the order of 0.1 *M* (molar concentration) results in a good conductivity and low junction potential without causing skin irritation.

Reusable silver–silver chloride electrodes (Figure 74.4a) are made of silver disks coated electrolytically by silver chloride [1], or, alternatively, particles of silver and silver chloride are sintered together to form the metallic structure of the electrode. The gel is typically soaked into a foam pad or is applied directly in a pocket produced by the electrode housing. The electrode is secured to the skin by means of nonallergenic adhesive tape. The electrode is connected to the external instrumentation typically via a snap-on connector. Such electrodes are well suited for acute studies or basic research investigations.

Disposable electrodes are made similarly, although the use of silver may be minimized (for example, the snap-on button itself may be silver coated and chlorided). To allow for a secure attachment, a large foam pad attaches the electrode body with adhesive coating on one side (Figure 74.4b). Such electrodes are particularly suited for ambulatory or long term use.

Gold Electrodes

Gold-plated electrodes (Figure 74.4c), which have the advantages of high conductivity and inertness desirable in reusable electrodes, are commonly used in EEG recordings [1]. Small reusable electrodes are designed so that they can be securely attached to the scalp. The electrode body is also shaped to make a recessed space for electrolytic gel, which can be applied through a hole in the electrode body [18]. The electrodes are attached in hair-free areas by use of a strong adhesive such as colloidon or securely attached with elastic bandages or wire mesh. Similar electrodes may also be used for recording EMG, especially

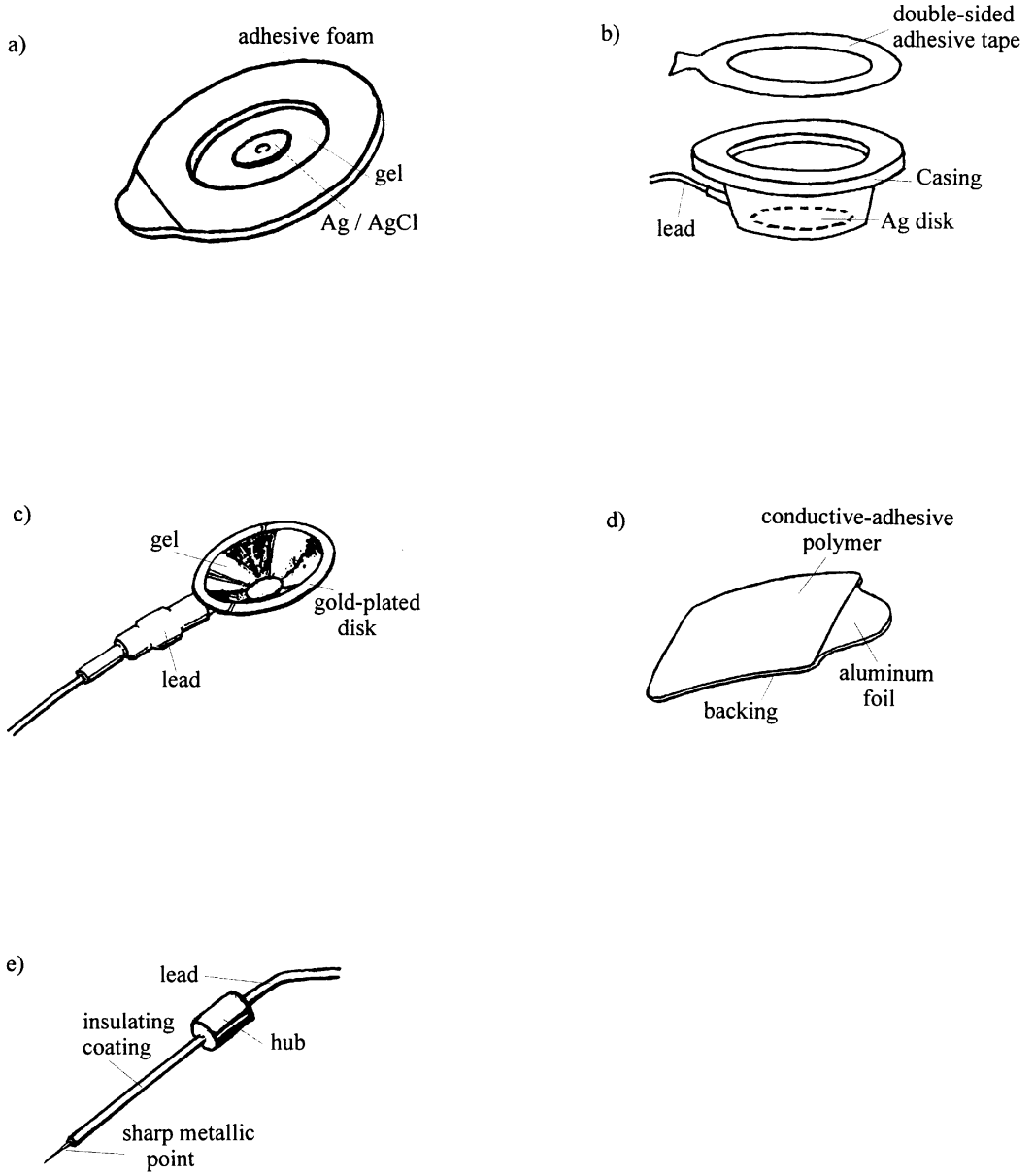


FIGURE 74.4 Examples of electrodes used in biopotential recordings: (a) disposable Ag–AgCl electrode, (b) reusable Ag–AgCl disk electrode, (c) gold disk electrode, (d) disposable conductive polymer electrode, and (e) needle electrode.

when a great deal of motion is expected. Disadvantages of using gold electrodes over silver–silver chloride electrodes include greater expense, higher junction potentials, and greater susceptibility to motion artifacts [20]. On the other hand, gold electrodes maintain low impedance, are inert and reusable, and are good for short-term recordings as long as a highly conductive gel is applied and they are attached securely.

Conductive Polymer Electrodes

It is often convenient to construct an electrode out of a material that is simultaneously conductive and adhesive [20]. Certain polymeric materials have adhesive properties and by attaching monovalent metal ions can be made conductive. The polymer is attached to a metallic backing made of silver or aluminum

foil, which allows electric contact to external instrumentation (Figure 74.4d). This electrode does not need additional adhesive or electrolytic gel and hence can be immediately and conveniently used. The conductive polymeric electrode performs adequately as long as its relatively higher resistivity (over metallic electrodes) and greater likelihood of generating artifacts are acceptable. The higher resistivity of the polymer makes these electrodes unsuitable for low-noise measurement. The polymer does not attach as effectively to the skin as does the conventional adhesive on disposable ECG electrodes built with a foam base and, furthermore, the potentials generated at the electrode–skin interface are more readily disturbed by motion. Nevertheless, when the signal level is high and when restricting the subject movement minimizes artifact, the polymeric electrode offers a relatively inexpensive solution to biopotential recording.

Metal or Carbon Electrodes

Although other metals such as stainless steel or brass electrodes [21] are used rather infrequently now because high-quality noble metal electrodes or low-cost carbon or polymeric electrodes are so readily available, historically these metallic electrodes were used in laboratory or clinical settings because of their sturdy construction and reusability. Electrode gel is applied to the metal electrode which is fastened to the body by means of a rubber band. These electrodes have the potential for producing very high levels of artifact and are bulky and awkward to use, but do offer the advantage of being reusable and tend to be inexpensive. Carbon or carbon-impregnated polymer electrodes are also used occasionally (although they are mainly used as electrical stimulation electrodes) [20]. These electrodes have a much higher resistivity and are noisier and more susceptible to artifacts, but they are inexpensive, flexible, and reusable and are thus chosen for applications such as electric stimulation or impedance plethysmography. For these applications, gel is usually not applied and the electrodes are used in "dry" form for easy attachment and removal.

Needle Electrodes

Needle electrodes (Figure 74.4e) comprise a small class of invasive electrodes, used when it is absolutely essential to record from the organ itself. The most common application is in recording from muscles or muscle fibers [8]. A metallic, typically steel, wire is delivered via a needle inserted at the site of the muscle fiber. The wire is hooked and hence fastens to the muscle fiber, even as the needle is removed. Small signals such as motor unit potentials can be recorded in this manner [7]. For research applications, similar needle or wire electrodes are sometimes connected directly to the heart muscle. Since such electrodes are noninvasive, their use is limited to only highly specialized and supervised clinical or research applications.

74.6 The Biopotential Amplifier

Biopotentials exhibit small amplitudes and low frequencies [22]. Moreover, biopotential measurements are corrupted by environmental and biological sources of interference. Therefore, the essential, although not exhaustive, design considerations include proper amplification and bandwidth, high input impedance, low noise, and stability against temperature and voltage fluctuations. The key design component of all biopotential amplifiers is the instrumentation amplifier [21]. However, each biopotential acquisition instrument has a somewhat differing set of characteristics, necessitating some specialization in the design of the instrumentation amplifier. Table 74.2 summarizes the circuit specialization needed in various biopotential amplifiers, with the ECG amplifier used as the basic design.

The Instrumentation Amplifier

The instrumentation amplifier is a circuit configuration that potentially combines the best features desirable for biopotential measurements [8], namely, high differential gain, low common mode gain,

TABLE 74.2 Distinguishing Features and Design Consideration for Biopotentials

Biopotential	Distinguishing Feature	Exclusive Amplifier Design Consideration	Additional Features Desired
ECG[a]	1 mV signal, 0.05–100 Hz BW[b]	Moderate gain, BW, noise, CMRR, input *R*	Electrical safety, isolation, defibrillation protection
EEG	Very small signal (microvolts)	High gain, very low noise, filtering	Safety, isolation, low electrode–skin resistance
EMG	Higher BW	Gain and BW of op amps	Postacquisition data processing
EOG	Lower frequencies, small signal	dc and low drift	Electrode–skin junction potential, artifact reduction

[a] The ECG signal acquisition is considered as the standard against which the other acquisitions are compared.
[b] BW = bandwidth.

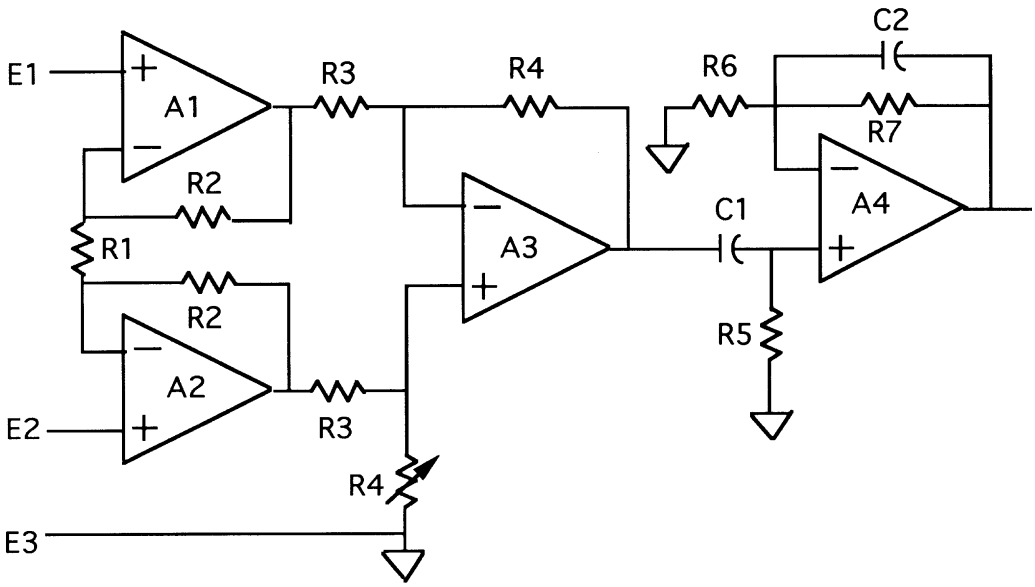


FIGURE 74.5 The instrumentation amplifier. This amplifier has a very high input impedance, high CMRR, and a differential gain set by the resistors in the two amplifier stages. The gain of the first stage (amplifiers A1 and A2) is $1 + 2R2/R1$, the second stage (amplifier A3) is $R4/R3$, and the third stage (amplifier A4) is $1 + R7/R6$. The lower corner frequency is $1/(2\pi R5C1)$ and the upper corner frequency is $1/(2\pi R7C2)$. The variable resistor *R* is adjusted to maximize the CMRR. Electrodes E1 and E2 are the recording electrodes while E3 is the reference or the ground electrode.

high common mode rejection ratio (CMRR), and high input resistance [23]. Figure 74.5 shows the design of the basic instrumentation amplifier. The basic circuit design principles have been described elsewhere [23,25]. The instrumentation amplifier is constructed from operational amplifiers, or op amps, which have many of the desirable features listed above [24]. The front end of the amplifier has two op amps, which consists of two noninverting amplifiers that have been coupled together by a common resistor *R*1. The gain of the first stage is $(1 + 2R2/R1)$. The second stage is a conventional differential amplifier with gain of $-(R4/R3)$. This design results in the desired differential gain distributed over two stages of the amplifier. It also achieves a very high input resistance as a result of the noninverting amplifier front end. It exhibits a very high CMRR as a result of the differential first stage followed by a second-stage differential amplifier. The CMRR is enhanced by adjusting one of the matching resistors and by selecting high CMRR op amps. This instrumentation amplifier is a key design component universal to many biosensor interfaces and almost all biopotential instruments [22].

The ECG Amplifier

The ECG amplifier can readily be designed using the instrumentation amplifier as the principal building block. Active filters with a lower corner frequency of 0.05 Hz and an upper corner frequency of 100 Hz are also typically added [8].

ECG amplifiers are needed in many applications, such as monitoring in cardiac intensive-care units, where safety and protection are of paramount importance. Because the possibility of a direct or low-resistance access to the heart via catheters or intravenous lines exists in such settings, very small electric leakage currents can be fatal. Consequently, leakage from the amplifier is required to be below the safety standard limit of 10 μA [14]. Additionally, safety of the patient is achieved by providing electrical isolation from the power line and the earth ground, which prevents passage of leakage current from the instrument to the patient under normal conditions or under reasonable failure conditions. Electrical isolation is achieved by using transformer or optical coupling components [9], although it is important to remember that any such design should preserve the bandwidth and linearity of the amplifier. ECG amplifiers are also likely to be operated in circumstances where defibrillators might be used; thus, the amplifier circuit must be protected against the high defibrillation voltages and must be augmented by circuit components such as current-limiting resistors, voltage-limiting diodes, and spark gaps [15].

The EEG Amplifier

The distinguishing feature of an EEG amplifier is that it must amplify very small signals [8]. The amplifier gain must be suitably enhanced to deal with microvolt or lower levels of signals. Furthermore, all components of the amplifier must have a very low thermal noise and in particular low electronic (voltage and current) noise at the front end of the amplifier. EEG amplifiers used in clinical applications again must be electrically isolated and protected against high defibrillation voltages, similar to the ECG amplifier.

The EMG Amplifier

EMG amplifiers are often used in the investigation of muscle performance, neuromuscular diseases, and in building certain powered or smart prostheses. In such applications, slightly enhanced amplifier bandwidth suffices. In addition, postprocessing circuits are almost always needed. For example, a rectified and integrated EMG signal has been shown to give a rough indication of the muscle activity, approximately related to the force being generated at the location of the EMG electrode [8].

The EOG Amplifier

The EOG signal is small in amplitude and consists of very low frequencies. Therefore, an EOG amplifier must not only have a high gain, but also a very good low frequency, or even dc, response. This frequency response also makes the amplifier potentially susceptible to shifts in the junction potential at the skin–electrode interface and to drift in the electronic circuit characteristics. In addition to using good electrodes (Ag–AgCl) and gel (high conductivity), some type of active dc or drift cancellation or correction circuit design may be necessary.

74.7 Circuit Enhancements

The basic biopotential amplifier described above, along with the specific design considerations for each biopotential, can yield a signal acquisition of acceptable quality in most laboratory settings. In practice, however, further enhancements are always necessary to achieve acceptable clinical performance in novel applications. These enhancements include circuits for reducing electric interference, filtering noise, reduction of artifacts, electrical isolation of the amplifier, and electrical protection of the circuit against defibrillation shocks [9].

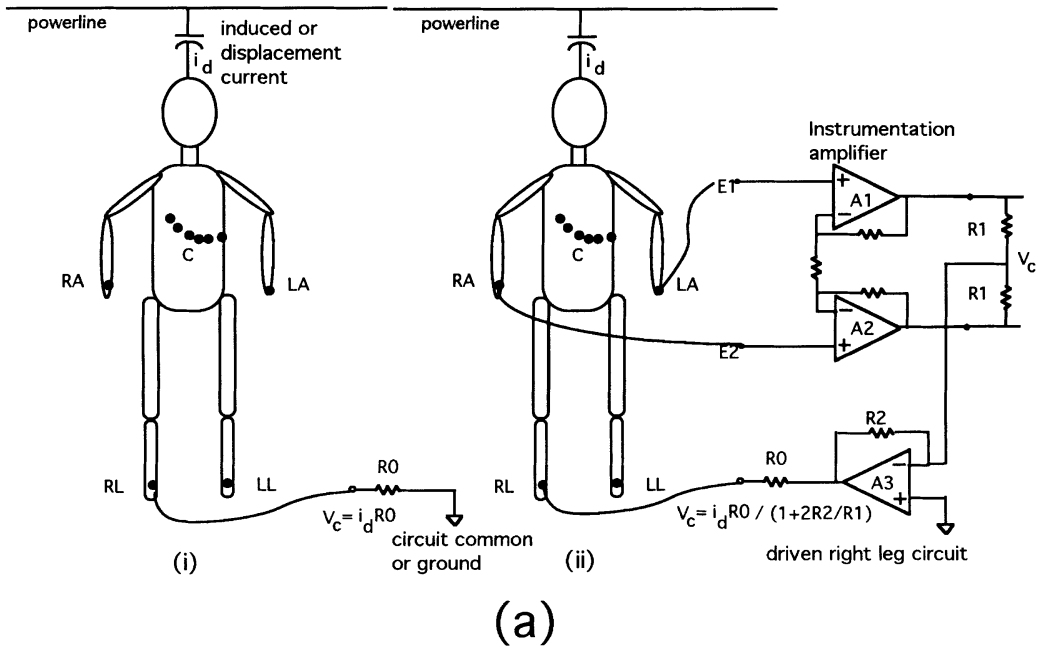
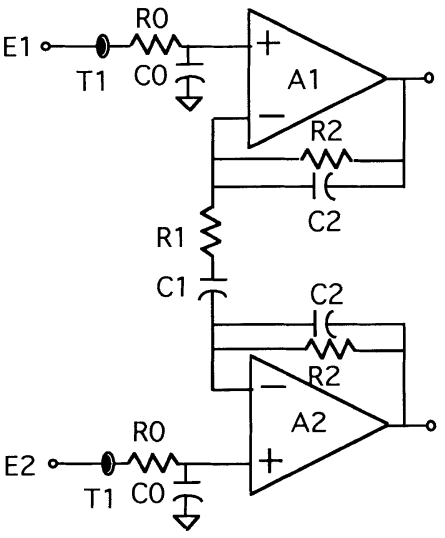


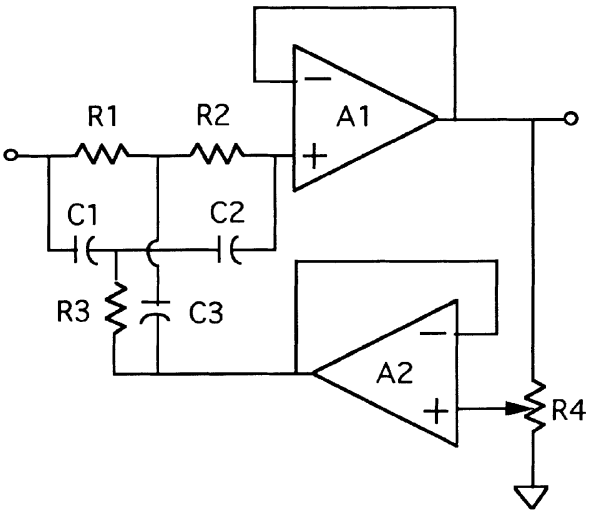
FIGURE 74.6 Circuit enhancements for biopotential measurements. (a) The schematic on the left shows electric interference induced by the displacement current i_d from the power line. This current flows into the ground electrode lead generating common-mode voltage V_c. The driven right leg circuit on the right uses negative feedback into the right leg electrode to reduce the effective common-mode voltage. (b) Amplifier front end filters — T1: RF choke; *R*0 and *C*0: RF filter; *R*1 and *C*1: high-pass filter; *R*2 and *C*2: low-pass filter. (c) Notch filter for power line interference (50 or 60 Hz): twin T notch filter in which notch frequency is governed by *R*1, *R*2, *R*3, *C*1, *C*2, and *C*3, and notch tuning by *R*4. (d) Baseline restoration circuit: the high-pass filter capacitor *C*1 is discharged by field effect transistor F when activated manually or automatically by a baseline restoration pulse. (e) Electrical isolation: transformer coupled using the transformer T (top) or optical using the diode D and the photodetector P (bottom). Note that the isolator separates circuit common on the amplifier side from the Earth ground on the output side. (f) Electrical protection circuit: resistance *R* limits the current, reverse-biased diodes D limit the input voltage, and the spark gap S protects against defibrillation pulse-related breakdown of the isolation transformer T.

Electrical Interference Reduction

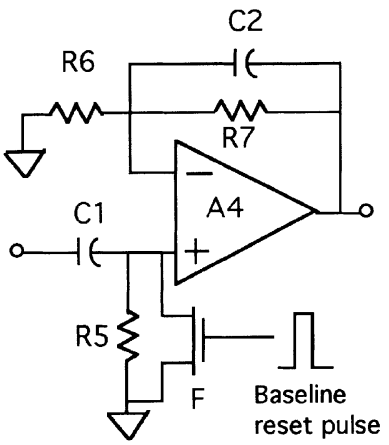
Environmental electric interference is always present, especially in urban hospital environments. It is desirable to eliminate interference before it enters the amplifier, for example, by proper shielding of the subject, leads, and the instrument and by grounding the subject and the instrument. Sources of interference include induced signals from power lines and electric wiring; RF from transmitters, electric motors, and other appliances; magnetically induced currents in lead wires; and so on [13]. Interference induced on the body common to the biopotential sensing electrodes is called the common mode interference (as distinguished from the biopotential that is differential to the sensing electrodes). If the induced current is i_d and the resistance to ground is *R*0, then the common mode interference potential is $V_c = i_d R0$. The common mode interference is principally rejected by a differential or instrumentation amplifier with a high CMRR. Further improvement is possible by use of the "driven right leg circuit." The right leg lead, by standard convention, is used as the ground or the circuit reference. The driven right leg circuit employs the clever idea of negative feedback of the common mode signal into this lead. The common mode signal is sensed from the first stage of the instrumentation amplifier, amplified and



(b)



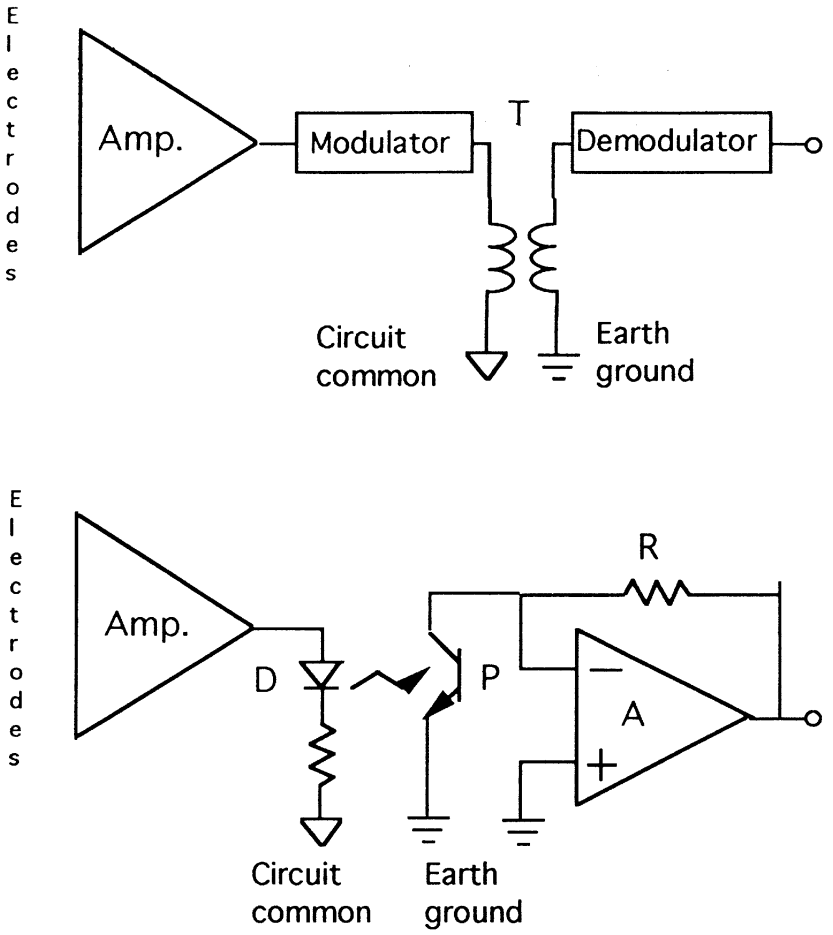
(c)



(d)

FIGURE 74.6 (continued)

inverted, and fed back into the right leg lead (Figure 74.6a). At this stage the common mode signal is reduced to $(i_d R0)/(1 + 2R2/R1)$. Thus, the common mode interference is greatly reduced at its source. The driven right leg circuit along with a high CMRR of the amplifier and filtering permit very high quality biopotential measurements.



(e)

FIGURE 74.6 (continued)

Filtering

After following the precautions described above, filtering at the front end of the amplifier and limiting the bandwidth of the biopotential amplifier can further help to reduce the interference (Figure 74.6b). Small inductors or ferrite beads in the lead wires help to block very high frequency electromagnetic interference. Small capacitors between each electrode lead and ground filter the RF interference. Bandwidth limitation can be imposed at each stage of the amplifier. Because dc potentials arising at the electrode–skin interface must be blocked well before the biopotential is amplified greatly (otherwise, the amplifier could saturate), use of high-pass filtering in the early stages of amplification is recommended. Low-pass filtering at several stages of amplification is recommended to attenuate residual RF interference as well as muscle signal interference. Power line interference at 50 or 60 Hz and their harmonics clearly poses the biggest problem in biopotential measurement [11,13]. Sometimes it may be desirable to provide

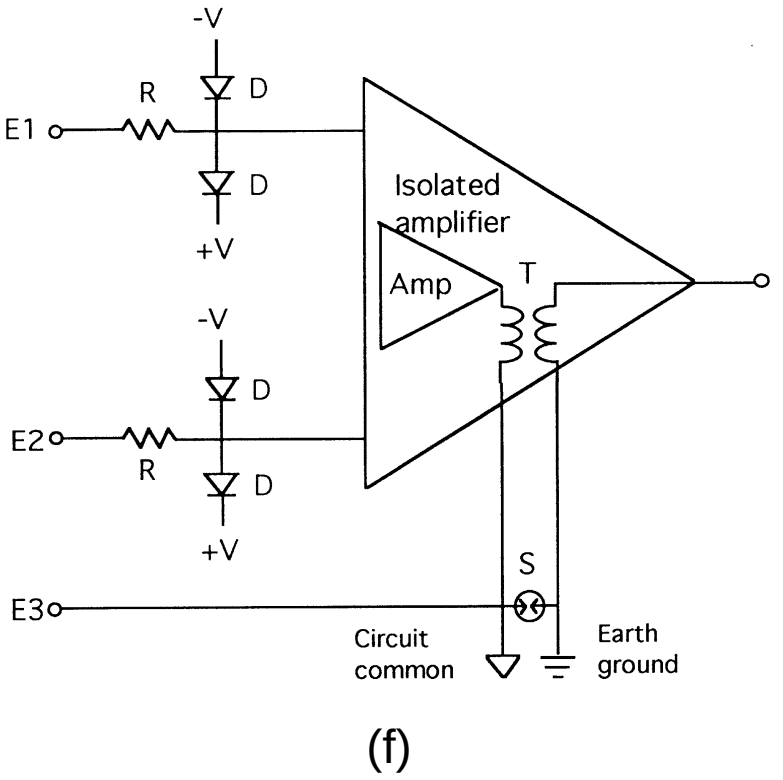


FIGURE 74.6 (continued)

a 50 or 60 Hz notch filter to remove the power line interference (Figure 74.6c), an option that is often available with low-level signal (EEG, EOG) measuring instruments. The risk of a distorted biopotential signal arises when a notch filter is used and this may affect diagnosis. Filtering should, therefore, be used selectively.

Artifact Reduction

One principal source of artifact is the potential arising at the electrode–skin interface [11]. Slow changes in the baseline can arise due to changes in the junction potential at this interface and, in some instances, can cause a temporary saturation of the amplifier [9]. This event is detected manually or automatically (by quickly discharging the high-pass capacitor in the amplifier to restore the baseline; Figure 74.6d). Movement of the subject or disturbance of the electrode can produce motion artifacts [11], which can be reduced by filtering the signal, but as suggested above, such filtering, typically high pass, can severely distort the biopotential being measured. Alternatively, computerized processing may be necessary to identify an artifact and delete it from display and processing. Of note, a biopotential source could be the desired one in one case, but an unwanted artifact in another case. For example, EOG signal resulting from blinking of eyes can produce a rather significant artifact in EEG recordings. Similarly, EMG signals become unwanted artifacts in all other non-EMG biopotential measurements. ECG monitoring must especially account for EMG artifact for high-fidelity recording. Another example is the pacemaker pulse. Since a pacemaker pulse can be detected and amplified as a short (about 2 ms) pulse preceding a QRS complex, it can be mistakenly interpreted as a heartbeat by some circuits for automatically determining heart rate. Special circuits must be designed to identify and delete this artifact [9].

Electrical Isolation

Electrical isolation limits the possibility of the passage of any leakage current from the instrument in use to the patient [22]. Conversely, patient safety must be ensured by electrical isolation to reduce the prospect of leakage of current from any other sensor or instrument attached to the patient to the Earth ground of the instrument being tested [8]. Passage of leakage current through the patient could be harmful or even fatal if this current were to leak to the heart via a catheter or intravenous line. Electrical isolation can be done electrically by inserting a transformer in the signal path or optically by introducing an optical coupler (Figure 74.6e). Since the primary and the secondary of the transformer remain electrically isolated, no direct path to ground can exist. One problem with this approach is that the transformer is inherently an ac high-frequency device. Therefore, a suitable solution is to modulate the biopotential signal using a high-frequency carrier preferred by the transformer. An alternative solution is to use optical isolation. The electric signal from the amplifier is first converted to light by a light-emitting diode (LED). This optical signal is modulated in proportion to the electric signal, and transmitted to the detector. A photodetector (photodiode or a phototransistor) then picks up the light, converts it into an electric signal, which is then demodulated to recover the original signal. The optical signal is typically pulse code modulated to circumvent the inherent nonlinearity of the LED–phototransistor combination.

Defibrillation Protection

Biopotential-measuring instruments can encounter very high voltages, such as those from electric defibrillators, that can damage the instrument [9]. For example, electric shocks in the order of 1500 to 5000 V may be produced by an external defibrillator [1]. Other high-voltage sources are electrocautery (used in surgery) and power lines (inadvertent short circuits in the instrument). Therefore, the front end of the biopotential instrument must be designed to withstand these high voltages (Figure 74.6f). Use of resistors in the input leads can limit the current in the lead and the instrument. Protection against high voltages is achieved by the use of diodes or Zener diodes. These components conduct at 0.7 V (diode conduction voltage) or 10 to 15 V (depending on the Zener diode breakdown voltage), thus protecting the sensitive amplifier components. Since it is more likely that protection against higher voltages will be needed, low-pressure gas discharge tubes such as neon lamps are also used. They break down at voltages on the order of 100 V, providing an alternative path to ground for the high voltages. As a final line of protection, the isolation components (optical isolator or transformer) must be protected by a spark gap that activates at several thousand volts. The spark gap ensures that the defibrillation pulse does not breach the isolation.

74.8 Measurement Practices

Biopotential measurements are made feasible, first of all, by good amplifier designs. High-quality biopotential measurements require use of good electrodes and their proper application on the patient, along with good laboratory or clinical practices. These practices are summarized below.

Electrode Use

Various electrodes best suited for each biopotential measurement were described earlier. First, different electrodes by virtue of their design offer distinguishing features: more secure (use of strong but less-irritant adhesives), more conductive (use of noble metals such as silver and gold), less prone to artifact (use of low-junction-potential materials such as Ag–AgCl). Electrode gel can be of considerable importance in maintaining a high-quality interface between the electrode metal and the skin. High conductivity gels, in general, help reduce the junction potentials along with the resistance (they tend, however, to be allergenic or irritating and hence a practical compromise in terms of electrolyte concentration must be found) [20]. Movement of the electrode with respect to the electrode gel and the skin is a potential source of artifact (Figure 74.7a). Such movements can change the electrode junction to skin potentials, producing

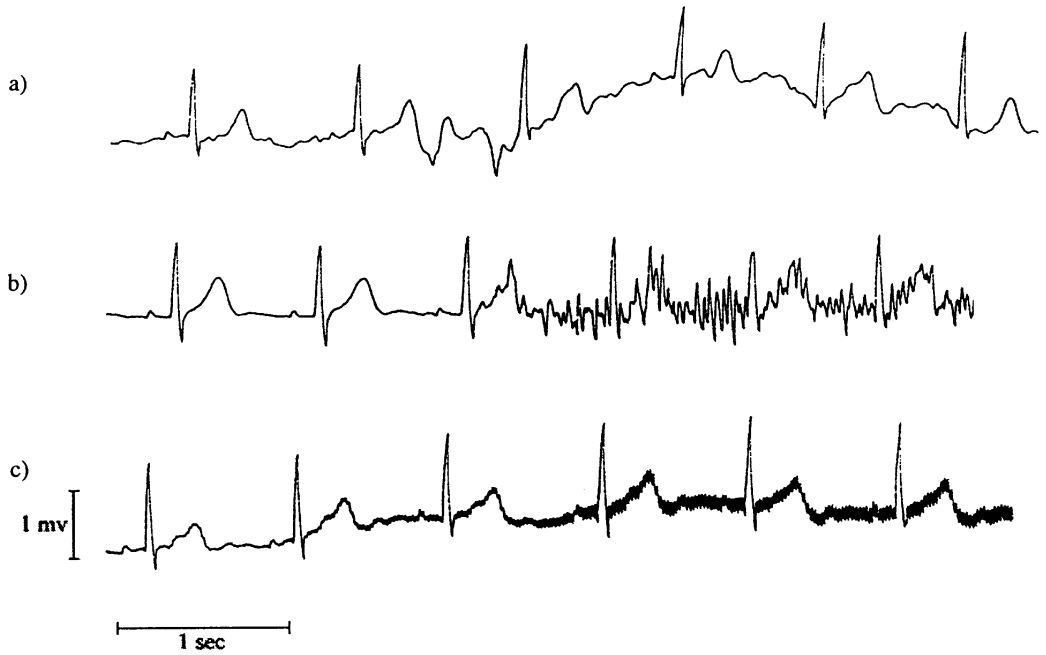


FIGURE 74.7 Examples of electric interference in biopotential recordings: (a) ECG signal with baseline changes and motion artifacts, (b) muscle signal interference, (c) electromagnetic interference (60 Hz power line and RF).

motion artifacts [21]. Placement above bony structures where there is less muscle mass can reduce unwanted motion artifact and EMG interference (Figure 74.7b). Electrodes must be securely attached, for example, with stress loops secured away from the electrode site, so that motion artifact can be reduced. In certain instances, the electrodes may be essentially glued to skin, as in the case of EEG measurements.

Skin Preparation

The potentials existing at the skin surface, attributable to potentials at the membranes of cells in the epidermal layers of the skin, can result in a large dc potential (which can be a significant problem in EOG measurements). Any disturbance of the skin by motion, touching, or deformation can cause this potential to change and result in motion artifacts (Figure 74.7a). Sweat glands in the epidermis can also contribute varying extents of skin resistance and skin potential. Such potentials and artifacts can be reduced by abrading the epidermal skin. A mild abrasion by sandpaper or its equivalent can significantly reduce skin resistance and skin potential and thereby reduce artifact [26]. A less traumatic, but somewhat less effective approach, is to use an alcohol swab or similar skin-cleansing solution to wet and clean the skin surface to remove debris, oils, and damaged or dead epidermal cells. Sometimes, as with EEG measurements where very low signals are recorded and very low noise is permitted, skin resistance must be significantly lowered, perhaps to below 2 kΩ [18]. Obviously, reduced motion or muscle activity while measurement is carried out also helps.

Reduction of Environmental Interference

Electromagnetic interference radiated from the power lines, RF interference from machines, induced magnetic field in the leads, and electric currents induced on to the body are all potential sources of environmental interference (Figure 74.7c). Shielding of the amplifier along with the electrode and the lead, and in certain extreme conditions, shielding of the subject (for example, when taking magnetic field measurements from the body) can greatly help reduce the signals picked up by or induced into the

amplifier. The electrode leads can be shielded or at the very least twisted together to reduce induced electromagnetic interference.

The amplifier circuit should also have extensive filtering of unwanted electromagnetic interference. To eliminate RF interference, filter capacitors should be used in the front end of the amplifier as well as at various stages of the amplifier. Very high frequencies can be blocked by the use of a choke or an inductor at the input leads. The effect of electrostatic interference can be minimized or eliminated by grounding the instrument.

Electric interference in the environment induces current into the body, which is then picked up by the biopotential amplifier as a common-mode voltage [27]. The CMRR property of the amplifier is essential for reduction of the common-mode voltage [24]. Finally, the driven right leg design [27], described earlier, can be optionally used to reduce further the common-mode voltage and the effective interference.

74.9 Conclusions

Biopotential acquisition is a well-developed science, and acceptable engineering design solutions do exist. It is apparent that each biopotential source presents its own distinct challenge in terms of electrode interface, amplifier design, pre- or postprocessing, and practical implementation and usage. ECG signals can be best acquired using Ag–AgCl electrodes, although good experimental/clinical practice is needed to reduce biological and environmental interference. Further circuit protection and isolation are necessary in clinical usage. EEG signals are distinguishable by their very low amplitude, and hence EEG electrodes must be securely attached via a very small electrode–skin resistance and the amplifier must exhibit exceptionally low noise. For EMG acquisition, electrodes are needed that can be attached for long periods of time to the muscle groups under study. The EMG signal inevitably needs postprocessing, such as integration, to derive a measure of muscle activity. EOG signals have small amplitudes and are characterized by dc or low frequencies. Skin–electrode potentials and dc drift of the amplifier are, therefore, important considerations.

These biopotential measurement principles are applicable to a variety of conventional as well as emerging applications. For example, although ECG acquisition is used mainly in cardiac monitors, it is also of interest and importance in implantable pacemakers and defibrillators. EEG acquisition is useful in the detection of seizure spikes and study of sleep patterns and it may also be used to identify cortical dysfunction after trauma or stroke. EMG acquisition is used in diagnosing neuromuscular diseases. Interesting attempts have been made to use EMG for controlling prostheses. EOG has been helpful in diagnosing vestibulo-oclular disorders and also has been studied as a way of operating communication devices (pointing) used by quadriplegics. The measurement and instrumentation principles described in this chapter would be applicable, with some modifications, to these emergent applications.

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