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Biopotential Electrodes

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Biologic systems frequently have electric activity associated with them. This activity can be a constant dc electric field, a constant flux of charge-carrying particles or current, or a time-varying electric field or current associated with some time-dependent biologic or biochemical phenomenon. Bioelectric phenomena are associated with the distribution of ions or charged molecules in a biologic structure and the changes in this distribution resulting from specific processes. These changes can occur as a result of biochemical reactions, or they can emanate from phenomena that alter local anatomy.

One can find bioelectric phenomena associated with just about every organ system in the body. Nevertheless, a large proportion of these signals are associated with phenomena that are at the present time not especially useful in clinical medicine and represent time-invariant, low-level signals that are not easily measured in practice. There are, however, several signals that are of diagnostic significance or that provide a means of electronic assessment to aid in understanding biologic systems. These signals, their usual abbreviations, and the systems they measure are listed in Table 48.1. Of these, the most familiar is the electrocardiogram, a signal derived from the electric activity of the heart. This signal is widely used in diagnosing disturbances in cardiac rhythm, signal conduction through the heart, and damage due to cardiac ischemia and infarction. The electromyogram is used for diagnosing neuromuscular diseases, and the electroencephalogram is important in identifying brain dysfunction and evaluating sleep. The other signals listed in Table 48.1 are currently of lesser diagnostic significance but are, nevertheless, used for studies of the associated organ systems.

Although Table 48.1 and the above discussion are concerned with bioelectric phenomena in animals and these techniques are used primarily in studying mammals, bioelectric signals also arise from plants [1]. These signals are generally steady-state or slowly changing, as opposed to the time-varying signals listed in Table 48.1. An extensive literature exists on the origins of bioelectric signals, and the interested reviewer is referred to the text by Plonsey and Barr for a general overview of this area [2].

48.1 Sensing Bioelectric Signals

The mechanism of electric conductivity in the body involves ions as charge carriers. Thus, picking up bioelectric signals involves interacting with these ionic charge carriers and transducing ionic currents into electric currents required by wires and electronic instrumentation. This transducing function is carried out by electrodes that consist of electrical conductors in contact with the aqueous ionic solutions

TABLE 48.1 Bioelectric Signals Sensed by Biopotential Electrodes and Their Sources

Bioelectric Signal	Abbreviation	Biologic Source
Electrocardiogram	ECG	Heart—as seen from body surface
Cardiac electrogram	—	Heart—as seen from within
Electromyogram	EMG	Muscle
Electroencephalogram	EEG	Brain
Electrooptigram	EOG	Eye dipole field
Electroretinogram	ERG	Eye retina
Action potential	—	Nerve or muscle
Electrogastrogram	EGG	Stomach
Galvanic skin reflex	GSR	Skin

of the body. The interaction between electrons in the electrodes and ions in the body can greatly affect the performance of these sensors and requires that specific considerations be made in their application.

At the interface between an electrode and an ionic solution redox (oxidation-reduction), reactions need to occur for a charge to be transferred between the electrode and the solution. These reactions can be represented in general by the following equations:

$$C \rightleftharpoons C^{n+} + ne^{-} \tag{48.1}$$

$$A^{m-} \rightleftharpoons A + me^{-} \tag{48.2}$$

where n is the valence of cation material C, and m is the valence of anion material, A. For most electrode systems, the cations in solution and the metal of the electrodes are the same, so the atoms C are oxidized when they give up electrons and go into solution as positively charged ions. These ions are reduced when the process occurs in the reverse direction. In the case of the anion reaction, Eq. (48.2), the directions for oxidation and reduction are reversed. For best operation of the electrodes, these two reactions should be reversible, that is, it should be just as easy for them to occur in one direction as the other.

The interaction between a metal in contact with a solution of its ions produces a local change in the concentration of the ions in solution near the metal surface. This causes charge neutrality not to be maintained in this region, causing the electrolyte surrounding the metal to be at a different electrical potential from the rest of the solution. Thus, a potential difference known as the *half-cell potential* is established between the metal and the bulk of the electrolyte. It is found that different characteristic potentials occur for different materials, and some of these potentials are summarized in Table 48.2. These half-cell potentials can be important when using electrodes for low frequency or dc measurements.

The relationship between electric potential and ionic concentrations or, more precisely, ionic activities is frequently considered in electrochemistry. Most commonly two ionic solutions of different activity are separated by an ion-selective semipermeable membrane that allows one type of ion to pass freely through

TABLE 48.2 Half-cell Potentials for Materials and Reactions Encountered in Biopotential Measurement

Metal and Reaction	Half-cell Potential, V
$Al \rightarrow Al^{3+} + 3e^{-}$	–1.706
$Ni \rightarrow Ni^{2+} + 2e^{-}$	–0.230
$H_2 \rightarrow 2H^{+} + 2e^{-}$	0.000 (by definition)
$Ag + Cl^{-} \rightarrow AgCl + e^{-}$	+0.223
$Ag \rightarrow Ag^{+} + e^{-}$	+0.799
$Au \rightarrow Au^{+} + e^{-}$	+1.680

the membrane. It can be shown that an electric potential E will exist between the solutions on either side of the membrane, based upon the relative activity of the permeable ions in each of these solutions. This relationship is known as the Nernst equation

$$E = -\frac{RT}{nF} \ln\left(\frac{a_1}{a_2}\right) \tag{48.3}$$

where a_1 and a_2 are the activities of the ions on either side of the membrane, R is the universal gas constant, T is the absolute temperature, n is the valence of the ions, and F is the Faraday constant. More detail on this relationship can be found in Chapter 49.

When no electric current flows between an electrode and the solution of its ions or across an ion-permeable membrane, the potential observed should be the half-cell potential or the Nernst potential, respectively. If, however, there is a current, these potentials can be altered. The difference between the potential at zero current and the measured potentials while current is passing is known as the *over voltage* and is the result of an alteration in the charge distribution in the solution in contact with the electrodes or the ion-selective membrane. This effect is known as polarization and can result in diminished electrode performance, especially under conditions of motion. There are three basic components to the polarization over potential: the ohmic, the concentration, and the activation over potentials. Of these, the activation over potential is of greatest concern in bioelectric measurements. More details on these over potentials can be found in electrochemistry or biomedical instrumentation texts [4].

Perfectly polarizable electrodes pass a current between the electrode and the electrolytic solution by changing the charge distribution within the solution near the electrode. Thus, no actual current crosses the electrode-electrolyte interface. Nonpolarized electrodes, however, allow the current to pass freely across the electrode-electrolyte interface without changing the charge distribution in the electrolytic solution adjacent to the electrode. Although these types of electrodes can be described theoretically, neither can be fabricated in practice. It is possible, however, to come up with electrode structures that closely approximate their characteristics.

Electrodes made from noble metals such as platinum are often highly polarizable. A charge distribution different from that of the bulk electrolytic solution is found in the solution close to the electrode surface. Such a distribution can create serious limitations when movement is present and the measurement involves low frequency or even dc signals. If the electrode moves with respect to the electrolytic solution, the charge distribution in the solution adjacent to the electrode surface will change, and this will induce a voltage change in the electrode that will appear as motion artifact in the measurement. Thus, for most biomedical measurements, nonpolarizable electrodes are preferred to those that are polarizable.

The silver–silver chloride electrode is one that has characteristics similar to a perfectly nonpolarizable electrode and is practical for use in many biomedical applications. The electrode (Fig. 48.1*a*) consists of a silver base structure that is coated with a layer of the ionic compound silver chloride. Some of the silver chloride when exposed to light is reduced to metallic silver, so a typical silver–silver chloride electrode has finely divided metallic silver within a matrix of silver chloride on its surface. Since the silver chloride is relatively insoluble in aqueous solutions, this surface remains stable. Because there is minimal polarization associated with this electrode, motion artifact is reduced compared to polarizable electrodes such as the platinum electrode. Furthermore, due to the reduction in polarization, there is also a smaller effect of frequency on electrode impedance, especially at low frequencies.

Silver–silver chloride electrodes of this type can be fabricated by starting with a silver base and electrolytically growing the silver chloride layer on its surface [4]. Although an electrode produced in this way can be used for most biomedical measurements, it is not a robust structure, and pieces of the silver chloride film can be chipped away after repeated use of the structure. A structure with greater mechanical stability is the sintered silver–silver chloride electrode in Fig. 48.1*b*. This electrode consists of a silver lead wire surrounded by a sintered cylinder made up of finely divided silver and silver-chloride powder pressed together.

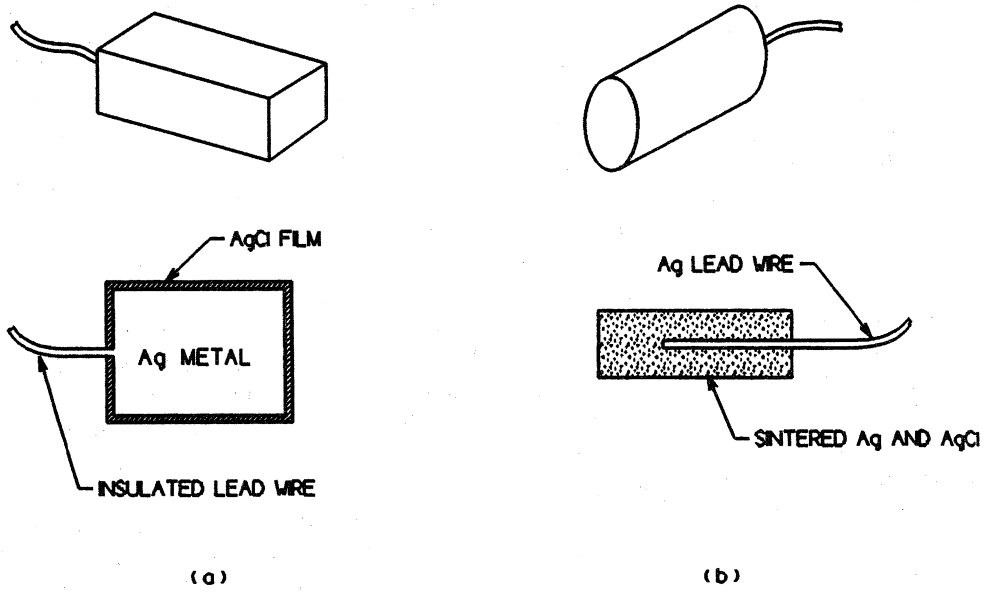

FIGURE 48.1 Silver–silver electrodes for biopotential measurements: (*a*) metallic silver with a silver chloride surface layer and (*b*) sintered electrode structure. The lower views show the electrodes in cross-section.

In addition to its nonpolarizable behavior, the silver–silver chloride electrode exhibits less electrical noise than the equivalent polarizable electrodes. This is especially true at low frequencies, and so silver–silver chloride electrodes are recommended for measurements involving very low voltages for signals that are made up primarily of low frequencies. A more detailed description of silver–silver chloride electrodes and methods to fabricate these devices can be found in Janz and Ives [5] and biomedical instrumentation textbooks [4].

48.2 Electric Characteristics

The electric characteristics of biopotential electrodes are generally nonlinear and a function of the current density at their surface. Thus, having the devices represented by linear models requires that they be operated at low potentials and currents. Under these idealized conditions, electrodes can be represented by an equivalent circuit of the form shown in Fig. 48.2. In this circuit R_d and C_d are components that represent the impedance associated with the electrode-electrolyte interface and polarization at this interface. R_s is the series resistance associated with interfacial effects and the resistance of the electrode materials themselves.

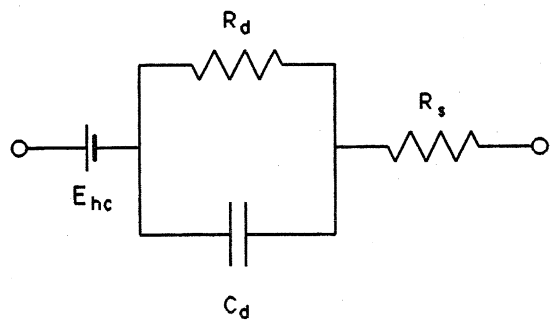

FIGURE 48.2 The equivalent circuit for a biopotential electrode.

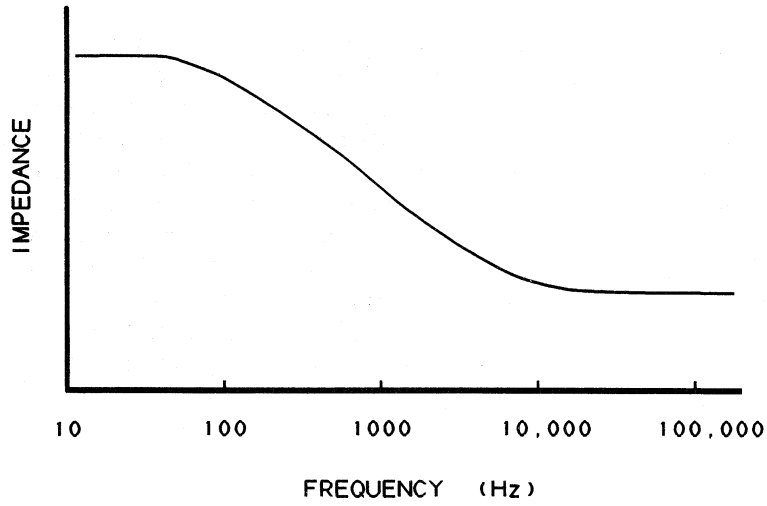

FIGURE 48.3 An example of biopotential electrode impedance as a function of frequency. Characteristic frequencies will be somewhat different for electrode different geometries and materials.

TABLE 48.3 The Effect of Electrode Properties on Electrode Impedance

Property	Change in Property	Changes in Electrode Impedance
Surface area	↑	↓
Polarization	↑	↑ At low frequencies
Surface roughness	↑	↓
Radius of curvature	↑	↓
Surface contamination	↑	↑

The battery E_{hc} represents the half-cell potential described above. It is seen that the impedance of this electrode will be frequency dependent, as illustrated in Fig. 48.3. At low frequencies the impedance is dominated by the series combination of R_s and R_d, whereas at higher frequencies C_d bypasses the effect of R_d so that the impedance is now close to R_s. Thus, by measuring the impedance of an electrode at high and low frequencies, it is possible to determine the component values for the equivalent circuit for that electrode.

The electrical characteristics of electrodes are affected by many physical properties of these electrodes. Table 48.3 lists some of the more common physical properties of electrodes and qualitatively indicates how these can affect electrode impedance.

48.3 Practical Electrodes for Biomedical Measurements

Many different forms of electrodes have been developed for different types of biomedical measurements. To describe each of these would go beyond the constraints of this article, but some of the more commonly used electrodes are presented in this section. The reader is referred to the monograph by Geddes for more details and a wider selection of practical electrodes [6].

Body-Surface Biopotential Electrodes

This category includes electrodes that can be placed on the body surface for recording bioelectric signals. The integrity of the skin is not compromised when these electrodes are applied, and they can be used for short-term diagnostic recording such as taking a clinical electrocardiogram or long-term chronic recording such as occurs in cardiac monitoring.

Metal Plate Electrodes

The basic metal plate electrode consists of a metallic conductor in contact with the skin with a thin layer of an electrolyte gel between the metal and the skin to establish this contact. Examples of metal plate electrodes are seen in Fig. 48.4*a*. Metals commonly used for this type of electrode include German silver (a nickel-silver alloy), silver, gold, and platinum. Sometimes these electrodes are made of a foil of the metal so as to be flexible, and sometimes they are produced in the form of a suction electrode (Fig. 48.4*b*) to make it easier to attach the electrode to the skin to make a measurement and then move it to another point to repeat the measurement. These types of electrodes are used primarily for diagnostic recordings of biopotentials such as the electrocardiogram or the electroencephalogram. Metal disk electrodes with a gold surface in a conical shape such as shown in Fig. 48.4*c* are frequently used for EEG recordings. The apex of the cone is open so that electrolyte gel or paste can be introduced to both make good contact between the electrode and the head and to allow this contact medium to be replaced should it dry out during its use.

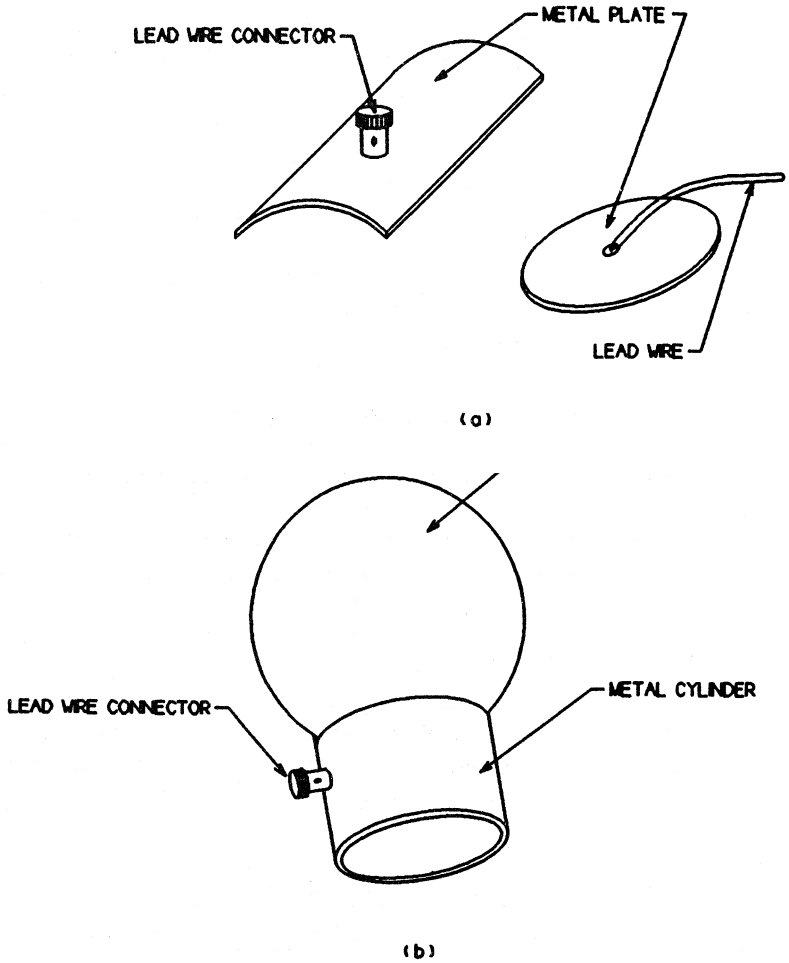

FIGURE 48.4 Examples of different skin electrodes: (*a*) metal plate electrodes, (*b*) suction electrode for ECG, (*c*) metal cup EEG electrode, (*d*) recessed electrode, (*e*) disposable electrode with electrolyte-impregnated sponge (shown in cross-section), (*f*) disposable hydrogel electrode (shown in cross-section), (*g*) thin-film electrode for use with neonates (shown in cross-section), (*h*) carbon-filled elastomer dry electrode.

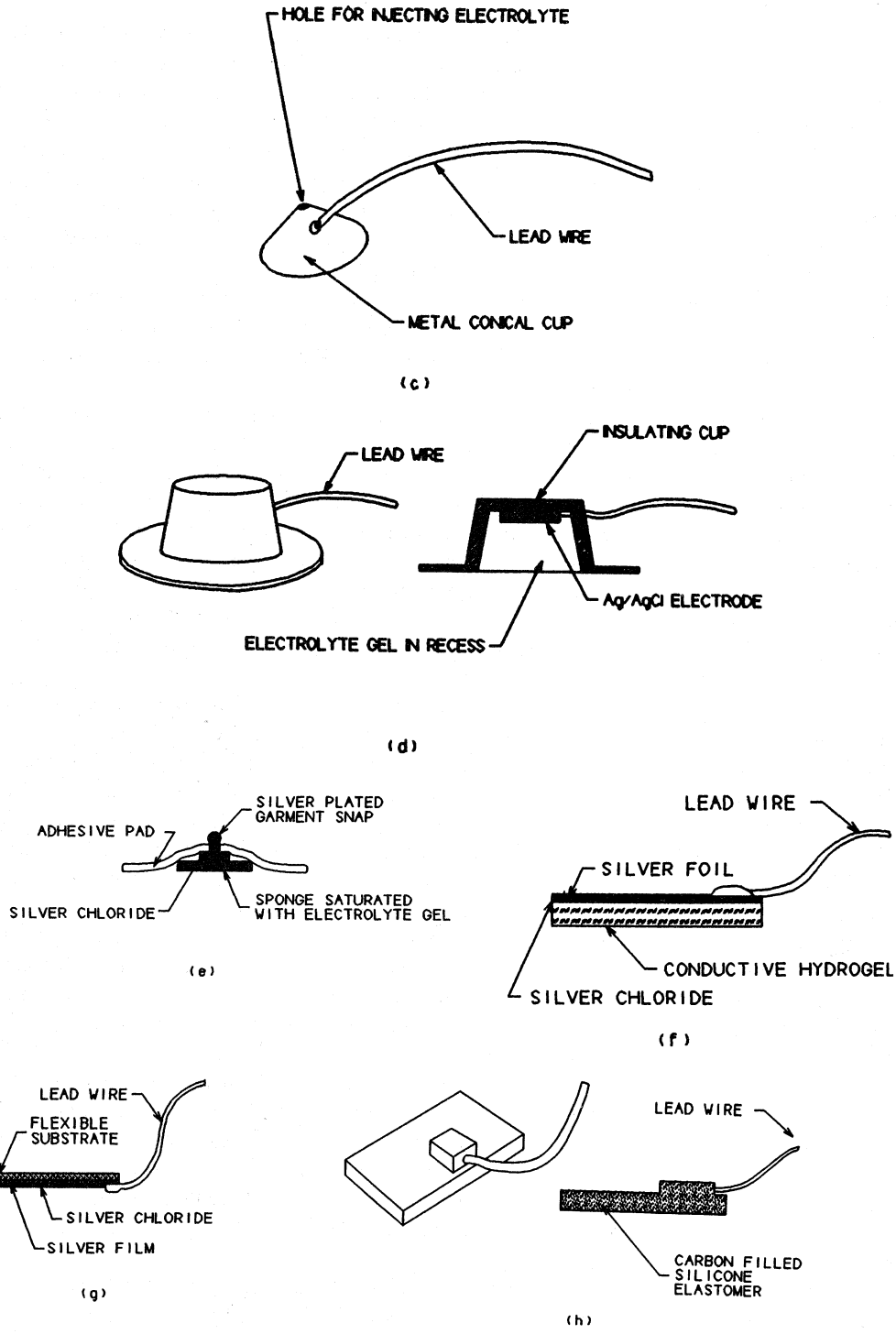

FIGURE 48.4 (continued)

Electrodes for Chronic Patient Monitoring

Long-term monitoring of biopotentials such as the electrocardiogram as performed by cardiac monitors places special constraints on the electrodes used to pick up the signals. These electrodes must have a stable interface between them and the body, and frequently nonpolarizable electrodes are, therefore, the best for this application. Mechanical stability of the interface between the electrode and the skin can help to reduce motion artifact, and so there are various approaches to reduce interfacial motion between the electrode and the coupling electrolyte or the skin. Figure 48.4*d* is an example of one approach to reduce motion artifact by recessing the electrode in a cup of electrolytic fluid or gel. The cup is then securely fastened to the skin surface using a double-sided adhesive ring. Movement of the skin with respect to the electrode may affect the electrolyte near the skin-electrolyte interface, but the electrode-electrolyte interface can be several millimeters away from this location, since it is recessed in the cup. The fluid movement is unlikely to affect the recessed electrode-electrolyte interface as compared to what would happen if the electrode was separated from the skin by just a thin layer of electrolyte.

The advantages of the recessed electrode can be realized in a simpler design that lends itself to mass production through automation. This results in low per-unit cost so that these electrodes can be considered disposable. Figure 48.4*e* illustrates such an electrode in cross section. The electrolyte layer now consists of an open-celled sponge saturated with a thickened (high-viscosity) electrolytic solution. The sponge serves the same function as the recess in the cup electrodes and is coupled directly to a silver–silver chloride electrode. Frequently, the electrode itself is attached to a clothing snap through an insulating-adhesive disk that holds the structure against the skin. This snap serves as the point of connection to a lead wire. Many commercial versions of these electrodes in various sizes are available, including electrodes with a silver–silver chloride interface or ones that use metallic silver as the electrode material.

A recently developed modification of this basic monitoring electrode structure is shown in Fig. 48.4*f*. In this case the metal electrode is a silver foil with a surface coating of silver chloride. The foil gives the electrode increased flexibility to fit more closely over body contours. Instead of using the sponge, a hydrogel film (really a sponge on a microscopic level) saturated with an electrolytic solution and formed from materials that are very sticky is placed over the electrode surface. The opposite surface of the hydrogel layer can be attached directly to the skin, and since it is very sticky, no additional adhesive is needed. The mobility and concentration of ions in the hydrogel layer is generally lower than for the electrolytic solution used in the sponge or the cup. This results in an electrode that has a higher source impedance as compared to these other structures. An important advantage of this structure is its ability to have the electrolyte stick directly on the skin. This greatly reduces interfacial motion between the skin surface and the electrolyte, and hence there is a smaller amount of motion artifact in the signal. This type of hydrogel electrode is, therefore, especially valuable in monitoring patients who move a great deal or during exercise.

Thin-film flexible electrodes such as shown in Fig. 48.4*g* have been used for monitoring neonates. They are basically the same as the metal plate electrodes; only the thickness of the metal in this case is less than a micrometer. These metal films need to be supported on a flexible plastic substrate such as polyester or polyimide. The advantage of using only a thin metal layer for the electrode lies in the fact that these electrodes will then become x-ray transparent. This is especially important in infants where repeated placement and removal of electrodes, so that x-rays may be taken, can cause substantial skin irritation.

Electrodes that do not use artificially applied electrolyte solutions or gels and, therefore, are often referred to as dry electrodes have been used in some monitoring applications. These sensors as illustrated in Fig. 48.4*h* can be placed on the skin and held in position by an elastic band or tape. They are made up of a graphite or metal-filled polymer such as silicone. The conducting particles are ground into a fine powder, and this is added to the silicone elastomer before it cures so to produce a conductive material with physical properties similar to that of the elastomer. When held against the skin surface, these electrodes establish contact with the skin without the need for an electrolytic fluid or gel. In actuality such a layer is formed by sweat under the electrode surface. For this reason these electrodes tend to perform better after they have been left in place for an hour or two so that this layer forms. Some investigators have found that placing a drop of physiologic saline solution on the skin before applying

the electrode accelerates this process. This type of electrode has found wide application in home infant cardiorespiratory monitoring because of the ease with which it can be applied by untrained caregivers.

Intracavitary and Intratissue Electrodes

Electrodes can be placed within the body for biopotential measurements. These electrodes are generally smaller than skin surface electrodes and do not require special electrolytic coupling fluid, since natural body fluids serve this function. There are many different designs for these internal electrodes, and only a few examples are given in the following paragraphs. Basically these electrodes can be classified as needle electrodes, which can be used to penetrate the skin and tissue to reach the point where the measurement is to be made, or they are electrodes that can be placed in a natural cavity or surgically produced cavity in tissue. Figure 48.5 illustrates some of these internal electrodes.

A catheter tip or probe electrode is placed in a naturally occurring cavity in the body such as in the gastrointestinal system. A metal tip or segment on a catheter makes up the electrode. The catheter or, in the case where there is no hollow lumen, probe, is inserted into the cavity so that the metal electrode

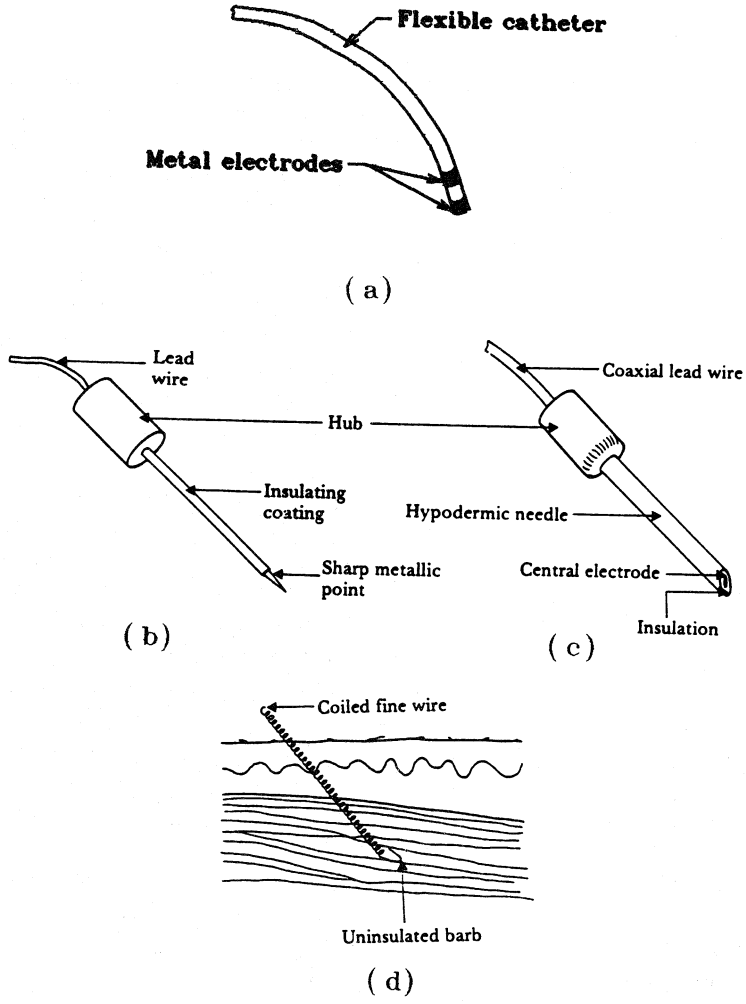

FIGURE 48.5 Examples of different internal electrodes: (*a*) catheter or probe electrode, (*b*) needle electrode, (*c*) coaxial needle electrode, (*d*) coiled wire electrode. (Reprinted with permission from Webster JG (ed). 1992. Medical Instrumentation: Application and Design, Houghton Mifflin, Boston.)

makes contact with the tissue. A lead wire down the lumen of the catheter or down the center of the probe connects the electrode to the external circuitry.

The basic needle electrode shown in Fig. 48.5*b* consists of a solid needle, usually made of stainless steel, with a sharp point. An insulating material coats the shank of the needle up to a millimeter or two of the tip so that the very tip of the needle remains exposed. When this structure is placed in tissue such as skeletal muscle, electrical signals can be picked up by the exposed tip. One can also make needle electrodes by running one or more insulated wires down the lumen of a standard hypodermic needle. The electrode as shown in Fig. 48.5*c* is shielded by the metal of the needle and can be used to pick up very localized signals in tissue.

Fine wires can also be introduced into tissue using a hypodermic needle, which is then withdrawn. This wire can remain in tissue for acute or chronic measurements. Caldwell and Reswick have used fine coiled wire electrodes in skeletal muscle for several years without adverse effects [7].

Microelectrodes

The electrodes described in the previous paragraphs have been applied to studying bioelectric signals at the organism, organ, or tissue level but not at the cellular level. To study the electric behavior of cells, electrodes that are themselves smaller than the cells being studied need to be used. Three types of electrodes have been described for this purpose: etched metal electrodes, micropipette electrodes, and metal-film-coated micropipette electrodes. The metal microelectrode is essentially a subminiature version of the needle electrode described in the previous section (Fig. 48.6*a*). In this case, a strong metal such as tungsten is used. One end of this wire is etched electrolytically to give tip diameters on the order of a few micrometers. The structure is insulated up to its tip, and it can be passed through the membrane of a cell to contact the cytosol. The advantage of these electrodes is that they are both small and robust and

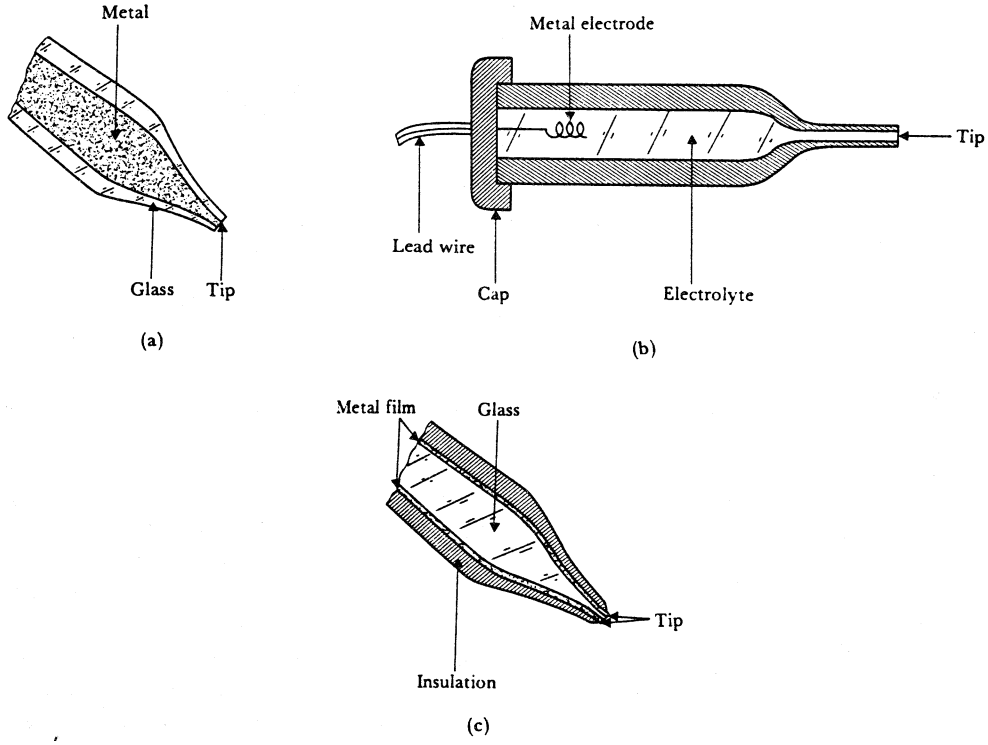

FIGURE 48.6 Microelectrodes: (*a*) metal, (*b*) micropipette, (*c*) thin metal film on micropipette. (Reprinted with permission from Webster JC (ed). 1992. Medical Instrumentation: Application and Design, Houghton Mifflin, Boston.)

can be used for neurophysiologic studies. Their principal disadvantage is the difficulty encountered in their fabrication and their high source impedance.

The second and most frequently used type of microelectrode is the glass micropipette. This structure, as illustrated in Fig. 48.6*b* consists of a fine glass capillary drawn to a very narrow point and filled with an electrolytic solution. The point can be as narrow as a fraction of a micrometer, and the dimensions of this electrode are strongly dependent on the skill of the individual drawing the tip. The electrolytic solution in the lumen serves as the contact between the interior of the cell through which the tip has been impaled and a larger conventional electrode located in the shank of the pipette. These electrodes also suffer from high source impedances and fabrication difficulty.

A combined form of these two types of electrodes can be achieved by depositing a metal film over the outside surface of a glass micropipette as shown in Fig. 48.6*c*. In this case, the strength and smaller dimensions of the micropipette can be used to support films of various metals that are insulated by an additional film up to a point very close to the actual tip of the electrode structure. These electrodes have been manufactured in quantity and made available as commercial products. Since they combine the features of both the metal and the micropipette electrodes, they also suffer from many of the same limitations. They do, however, have the advantage of flexibility due to the capability of being able to make films of different metals on the micropipette surface without having to worry about the strength of the metal, as would be the case if the metal were used alone.

Electrodes Fabricated Using Microelectronic Technology

Modern microelectronic technology can be used to fabricate many different types of electrodes for specific biomedical applications. For example, dry electrodes with high source resistances or microelectrodes with similar characteristics can be improved by incorporating a microelectronic amplifier for impedance conversion right on the electrode itself. In the case of the conventional-sized electrodes, a metal disk 5–10 mm in diameter can have a high input impedance microelectronic amplifier configured as a follower integrated into the back of the electrode so that localized processing of the high source impedance signal can produce one of lower, more practical impedance for signal transmission [8]. Single- and multiple-element electrodes can be made from thin-film or silicon technology. Mastrototaro and colleagues have demonstrated probes for measuring intramyocardial potentials using thin, patterned gold films on polyimide or oxidised molybdenum substrates [9]. When electrodes are made from pieces of micromachined silicon, it is possible to integrate an amplifier directly into the electrode [10]. Multichannel amplifiers or multiplexers can be used with multiple electrodes on the same probe. Electrodes for contact with individual nerve fibers can be fabricated using micromachined holes in a silicon chip that are just big enough to pass a single growing axon. Electrical contacts on the sides of these holes can then be used to pick up electrical activity from these nerves [11]. These examples are just a few of the many possibilities that can be realized using microelectronics and three-dimensional micromachining technology to fabricate specialized electrodes.

48.4 Biomedical Applications

Electrodes can be used to perform a wide variety of measurements of bioelectric signals. An extensive review of this would be beyond the scope of this chapter, but some typical examples of applications are highlighted in Table 48.4. The most popular application for biopotential electrodes is in obtaining the electrocardiogram for diagnostic and patient-monitoring applications. A substantial commercial market exists for various types of electrocardiographic electrodes, and many of the forms described in the previous section are available commercially. Other electrodes for measuring bioelectric potentials for application in diagnostic medicine are indicated in Table 48.4. Research applications of biopotential electrodes are highly varied and specific for individual studies. Although a few examples are given in Table 48.4, the field is far too broad to be completely covered here.

Biopotential electrodes are one of the most common biomedical sensors used in clinical medicine. Although their basic principle of operation is the same for most applications, they take on many forms

TABLE 48.4 Examples of Applications of Biopotential Electrodes

Application	Biopotential	Type of Electrode
Cardiac monitoring	ECG	Ag/AgCl with sponge
		Ag/AgCl with hydrogel
Infant cardiopulmonary monitoring	ECG impedance	Ag/AgCl with sponge
		Ag/AgCl with hydrogel
		Thin-film
		Filled elastomer dry
Sleep encephalography	EEG	Gold cups
		Ag/AgCl cups
		Active electrodes
Diagnostic muscle activity	EMG	Needle
Cardiac electrograms	Electrogram	Intracardiac probe
Implanted telemetry of biopotentials	ECG	Stainless steel wire loops
	EMG	Platinum disks
Eye movement	EOG	Ag/AgCl with hydrogel

and are used in the measurement of many types of bioelectric phenomena. They will continue to play an important role in biomedical instrumentation systems.

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Further Information

Good overviews of biopotential electrodes are found in Geddes LA. 1972. *Electrodes and the Measurement of Bioelectric Events,* New York, Wiley; and Ferris CD. 1974. *Introduction to Bioelectrodes,* New York, Plenum. Even though these references are more than 20 years old, they clearly cover the field, and little has changed since these books were written.

Overviews of biopotential electrodes are found in chapters of two works edited by John Webster. Chapter 5 of his textbook, *Medical Instrumentation: Application and Design,* covers the material of this chapter in more detail, and there is a section on "Bioelectrodes" in his *Encyclopedia on Medical Devices and Instrumentation,* published by Wiley in 1988.

The journals *IEEE Transactions on Biomedical Engineering* and *Medical and Biological Engineering and Computing* are good sources of recent research on biopotential electrodes.