*17–12 Electrocardiogram (ECG or EKG)

Each time the heart beats, changes in electrical potential occur on its surface that can be detected using *electrodes* (metal contacts), which are attached to the skin. The changes in potential are small, on the order of millivolts (mV), and must be amplified. They are displayed with a chart recorder on paper, or on a monitor (CRT or LCD), Fig. 17–36. An **electrocardiogram** (ECG or EKG) is the record of the potential changes for a given person's heart. An example is shown in Fig. 17–37. We now look at the source of these potential changes and their relation to heart activity.

PHYSICS APPLIED
Electrocardiogram

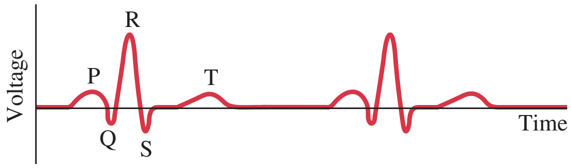


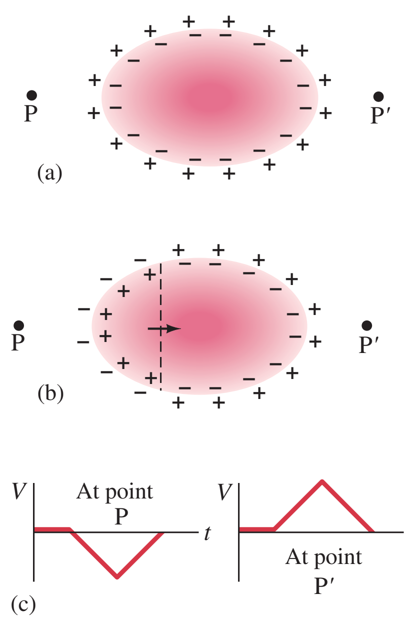
FIGURE 17–37 Typical ECG. Two heart beats are shown.

Both muscle and nerve cells have an electric dipole layer across the cell wall. That is, in the normal situation there is a net positive charge on the exterior surface and a net negative charge on the interior surface, Fig. 17–38a. The amount of charge depends on the size of the cell, but is approximately $10^{-3}\,\mathrm{C/m^2}$ of surface. For a cell whose surface area is $10^{-5}\,\mathrm{m^2}$, the total charge on either surface is thus $\approx 10^{-8}$ C. Just before the contraction of heart muscles, changes occur in the cell wall, so that positive ions on the exterior of the cell are able to pass through the wall and neutralize charge on the inside, or even make the inside surface slightly positive compared to the exterior. This "depolarization" starts at one end of the cell and progresses toward the opposite end, as indicated by the arrow in Fig. 17–38b, until the whole muscle is depolarized; the muscle then repolarizes to its original state (Fig. 17–38a), all in less than a second. Figure 17–38c shows rough graphs of the potential V as a function of time at the two points P and P′ (on either side of this cell) as the depolarization moves across the cell. The path of depolarization within the heart as a whole is more complicated, and produces the complex potential difference as a function of time, Fig. 17–37.

It is standard procedure to divide a typical electrocardiogram into regions corresponding to the various deflections (or "waves"), as shown in Fig. 17–37. Each of the deflections corresponds to the activity of a particular part of the heart beat (Fig. 10–42). The P wave corresponds to contraction of the atria. The QRS group corresponds to contraction of the ventricles as the depolarization follows a very complicated path. The T wave corresponds to recovery (repolarization) of the heart in preparation for the next cycle.

The ECG is a powerful tool in identifying heart defects. For example, the right side of the heart enlarges if the right ventricle must push against an abnormally large load (as when blood vessels become hardened or clogged). This problem is readily observed on an ECG, because the S wave becomes very large (negatively). *Infarcts*, which are dead regions of the heart muscle that result from heart attacks, are also detected on an ECG because they reflect the depolarization wave.

FIGURE 17–38 Heart muscle cell showing (a) charge dipole layer in resting state; (b) depolarization of cell progressing as muscle begins to contract; and (c) potential V at points P and P′ as a function of time.



Summary

The **electric potential** V at any point in space is defined as the electric potential energy per unit charge:

$$V_{\mathrm{a}} = \frac{\mathrm{PE_a}}{q}. \quad \textbf{(17–2a)}$$

The **electric potential difference** between any two points is defined as the work done to move a 1 C electric charge between the two points. Potential difference is measured in volts $(1\,\mathrm{V} = 1\,\mathrm{J/C})$ and is often referred to as **voltage**.

The change in potential energy when a charge q moves through a potential difference V_{ba} is

$$\Delta\mathrm{PE} = qV_{\mathrm{ba}}. \quad \textbf{(17–3)}$$

The potential difference V_{ba} between two points a and b where a uniform electric field E exists is given by

$$V_{\mathrm{ba}} = -Ed, \quad \textbf{(17–4a)}$$

where d is the distance between the two points.

An **equipotential line** or **surface** is all at the same potential, and is perpendicular to the electric field at all points.

The electric potential at a position P due to a single point charge Q, relative to zero potential at infinity, is given by

$$V = \frac{kQ}{r}, \quad \textbf{(17–5)}$$

where r is the distance from Q to position P and $k = 1/4\pi\epsilon_0$.

[*The potential due to an **electric dipole** drops off as $1/r^2$. The **dipole moment** is $p = Q\ell$, where ℓ is the distance between the two equal but opposite charges of magnitude Q.]

A **capacitor** is a device used to store charge (and electric energy), and consists of two nontouching conductors. The two conductors hold equal and opposite charges, of magnitude Q. The ratio of this charge Q to the potential difference V between the conductors is called the **capacitance**, C:

$$C = \frac{Q}{V}, \quad \text{or} \quad Q = CV. \qquad \textbf{(17–7)}$$

The capacitance of a parallel-plate capacitor is proportional to the area A of each plate and inversely proportional to their separation d:

$$C = \epsilon_0 \frac{A}{d}. \qquad \textbf{(17–8)}$$

The space between the two conductors of a capacitor contains a nonconducting material such as air, paper, or plastic. These materials are referred to as **dielectrics**, and the capacitance is proportional to a property of dielectrics called the **dielectric constant**, K (equal to 1 for air).

A charged capacitor stores an amount of electric energy given by

$$\text{PE} = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{Q^2}{C}. \qquad \textbf{(17–10)}$$

This energy can be thought of as stored in the electric field between the plates.

The energy stored in any electric field E has a density

$$\frac{\text{electric PE}}{\text{volume}} = \tfrac{1}{2}\epsilon_0 E^2. \qquad \textbf{(17–11)}$$

Digital electronics converts an analog **signal voltage** into an approximate digital voltage based on a **binary code**: each **bit** has two possibilities, 1 or 0 (also "on" or "off"). The binary number 1101 equals 13. A **byte** is 8 bits and provides $2^8 = 256$ voltage levels. **Sampling rate** is the number of voltage measurements done on the analog signal per second. The **bit depth** is the number of digital voltage levels available at each sampling. CDs are 44.1 kHz, 16-bit.

[*TV and computer monitors traditionally used a **cathode ray tube** (CRT) which accelerates electrons by high voltage, and sweeps them across the screen in a regular way using magnetic coils or electric deflection plates. **LCD flat screens** contain millions of **pixels**, each with a red, green, and blue **subpixel** whose brightness is addressed every $\frac{1}{60}$ s via a **matrix** of horizontal and vertical wires using a **digital** (**binary**) code.]

[*An **electrocardiogram** (ECG or EKG) records the potential changes of each heart beat as the cells depolarize and repolarize.]

Questions

1. If two points are at the same potential, does this mean that no net work is done in moving a test charge from one point to the other? Does this imply that no force must be exerted? Explain.
2. If a negative charge is initially at rest in an electric field, will it move toward a region of higher potential or lower potential? What about a positive charge? How does the potential energy of the charge change in each instance? Explain.
3. State clearly the difference (*a*) between electric potential and electric field, (*b*) between electric potential and electric potential energy.
4. An electron is accelerated from rest by a potential difference of 0.20 V. How much greater would its final speed be if it is accelerated with four times as much voltage? Explain.
5. Is there a point along the line joining two equal positive charges where the electric field is zero? Where the electric potential is zero? Explain.
6. Can a particle ever move from a region of low electric potential to one of high potential and yet have its electric potential energy decrease? Explain.
7. If $V = 0$ at a point in space, must $\vec{\mathbf{E}} = 0$? If $\vec{\mathbf{E}} = 0$ at some point, must $V = 0$ at that point? Explain. Give examples for each.
8. Can two equipotential lines cross? Explain.
9. Draw in a few equipotential lines in Fig. 16–32b and c.
10. When a battery is connected to a capacitor, why do the two plates acquire charges of the same magnitude? Will this be true if the two plates are different sizes or shapes?
11. A conducting sphere carries a charge Q and a second identical conducting sphere is neutral. The two are initially isolated, but then they are placed in contact. (*a*) What can you say about the potential of each when they are in contact? (*b*) Will charge flow from one to the other? If so, how much?
12. The parallel plates of an isolated capacitor carry opposite charges, Q. If the separation of the plates is increased, is a force required to do so? Is the potential difference changed? What happens to the work done in the pulling process?
13. If the electric field $\vec{\mathbf{E}}$ is uniform in a region, what can you infer about the electric potential V? If V is uniform in a region of space, what can you infer about $\vec{\mathbf{E}}$?
14. Is the electric potential energy of two isolated unlike charges positive or negative? What about two like charges? What is the significance of the sign of the potential energy in each case?
15. If the voltage across a fixed capacitor is doubled, the amount of energy it stores (*a*) doubles; (*b*) is halved; (*c*) is quadrupled; (*d*) is unaffected; (*e*) none of these. Explain.
16. How does the energy stored in a capacitor change when a dielectric is inserted if (*a*) the capacitor is isolated so Q does not change; (*b*) the capacitor remains connected to a battery so V does not change? Explain.
17. A dielectric is pulled out from between the plates of a capacitor which remains connected to a battery. What changes occur to (*a*) the capacitance, (*b*) the charge on the plates, (*c*) the potential difference, (*d*) the energy stored in the capacitor, and (*e*) the electric field? Explain your answers.
18. We have seen that the capacitance C depends on the size and position of the two conductors, as well as on the dielectric constant K. What then did we mean when we said that C is a constant in Eq. 17–7?