Section 1 Introductory Chapters

Chapter 1

Basic Electricity, Electrical Concepts, and Circuits

Introduction

Because electricity is at the core of electrodiagnostic (EDX) medicine, and because a strong understanding of this material generates higher-quality and more insightful EDX medicine studies and reports, it behooves practitioners of EDX medicine to possess a strong understanding of a number of electrical concepts (e.g., charge, current, voltage, resistance, and capacitance) pertinent to EDX medicine. This knowledge is mandatory for the proper performance of EDX studies and for a complete understanding of: (1) the instrumentation used in EDX medicine; (2) the generation and propagation of action potentials (APs); (3) the role of myelin to decrease capacitance and increase transmembrane resistance; (4) the EDX manifestations of demyelination; (5) the EDX effects of axon disruption and Wallerian degeneration; (6) the frequently encountered problems in the EMG laboratory (e.g., shock artifact) and how to overcome them; and (7) the proper interpretation of the EDX examination findings, as well as other pertinent issues (see Box 1.1).

Box 1.1 Important electrical concepts and principles

- Electrical circuits (Chapter 1)
  - Series circuits (resistors function as voltage dividers)
    - The importance of proper application of surface recording electrodes
    - The relationship between the recording electrodes and the amplifier
  - Parallel circuits (resistors function as current dividers)
    - Ion channels in membranes
- Instrumentation (Chapter 2)
  - Filters
    - Low-frequency, high-frequency, notch, and bandpass
  - Stimulators
    - Constant current versus constant voltage
  - Amplifiers
    - Monopolar versus differential
    - The importance of proper surface recording electrode position
  - Electrodes
    - Stimulating and recording
- Membrane physiology (see Chapter 3)
  - Resistive and capacitive properties of nerve and muscle membranes
    - The length constant
    - The time constant
  - Resting membrane potential (voltage) of nerve and muscle membranes
  - How action potentials are generated and regenerated (capacitive current)
  - How action potentials are propagated (resistive current)
- Important NCS principles and concepts (Chapters 6–8)
  - Motor NCS
    - The belly-tendon method for motor NCS
  - Sensory NCS
    - Orthodromic versus antidromic recording
    - The ideal interelectrode distance between the surface recording electrodes
    - Peak latency versus onset latency
- Concentric versus monopolar needle recording electrodes (Chapter 13)
- EDX pitfalls and troubleshooting (Chapter 18)
- Electrical safety (Chapter 19)

This chapter includes a number of formulas. It is not necessary to memorize them; it is sufficient to simply understand the relationships between the variables composing them. For board examination preparation, however, it is important to memorize: (1) Ohm's law (V = IR); (2) the formula for calculating the total resistance in a DC circuit in which the resistors are arranged in series with each other and with the voltage source; (3) the formula for calculating the voltage drop across a resistor in series with other resistors; and (4) the power formula (P = VI). These formulas and others, the variables composing them, and the mathematics required to utilize them are detailed in this chapter and the subsequent chapter. This chapter focuses on those electrical principles and concepts pertinent to EDX medicine, including charge, electrostatic force, current, resistance, and voltage. The mathematics provides insight and contributes to a better understanding of EDX instrumentation (discussed in Chapter 2). This chapter was authored for the reader with no significant understanding of electricity. Thus, all of the terms are defined when introduced, the electrical concepts and their relationships are explained in detail, and pertinent everyday examples are provided. Necessary redundancies serve to reiterate important concepts, where needed, and to contribute to the flow of the material being presented, thereby eliminating the need to review a previous section in order to comprehend the information contained in the current section. Although modern EMG machines utilize digital electronics, this chapter and the subsequent one reviews analog and digital electronics.

Electricity

History

Some of the properties of electricity were known to the ancient peoples of the world. For example, as indicated in ancient Egyptian texts dating back as far as the third millennium BC, people were aware of the propagating nature of the shocks received by electricity-generating electric fish (Moller and Kramer, 1991). In the second century, Galen applied a living torpedo fish to the head of a person suffering from a headache (Bonner and DevlescHoward, 1995). In addition, less ancient authors recognized that these shocks propagated along those objects capable of conducting (Bullock, 2005). Regarding *static electricity*, the ancient Mediterranean people were aware that when amber (fossilized plant resin) was rubbed with wool or cat fur, it would subsequently attract lightweight objects, such as small pieces of dust or lint. When the amber is rubbed with fur, the fur transfers electrons to the amber, causing both of these neutral objects to become charged (the fur become positively charged and the amber becomes negatively charged). The lightweight objects attracted to the amber are actually neutral. The negatively charged amber causes them to become polarized (the positive charges in the lightweight particles move closer to the rod, whereas the negative charges move away from the rod). The term *electricity*, which was coined by William Gilbert, a seventeenth-century physician and scientist, is derived from the Greek word for amber, *elektron*. In 1745, the Leyden jar was developed (Bonner and DevlescHoward, 1995). This device could store electricity and, thus, was the precursor to the capacitor. Because it could store electricity, it made it easier to study this phenomenon. Benjamin Franklin invented the lightning rod in 1752, which allowed him to pass the electrical discharges of thunderstorms into a Leyden jar; introduced the concept of positive and negative into electricity; and invented the electrical battery (Bonner and DevlescHoward, 1995).

Electricity, the movement of charged particles through a conductor, is characterized by its charge, current (rate of charge), voltage, and resistance. Consequently, these aspects of electricity are reviewed first, followed by other important concepts and principles pertinent to EDX medicine.

Charge

To understand the principle of charge, we need to understand atomic structure. The universe is composed of two types of matter: dark matter (the majority) and visible matter. Dark matter, as the name implies, is invisible, and its presence is inferred from its effects on visible matter. Visible matter is composed of elements (e.g., copper). Elements, in turn, are composed of atoms. The term *atom* is derived from the Greek word, *atomos*, which indicates *indivisible*, although it subsequently became apparent that atoms consist of subatomic particles – *protons*, *neutrons*, and *electrons* – and, hence, are divisible. The protons and neutrons are centrally located and constitute the nucleus of the atom. Hence, they are also referred to as *nucleons*. These nucleons are held together by the *strong force* (nuclear force) and, except in nuclear reactions, never separate. Protons and neutrons are composed of smaller particles, termed *quarks*; thus, protons and neutrons are not elementary particles. Electrons, like quarks, are elementary particles (i.e., they are not composed of smaller particles and, thus, are indivisible). According to current quantum electrodynamics, electrons are not strictly particles, but rather are both particles and waves. They are located at specific distances from the nucleus (referred to as *shells* or *energy levels*). Neutrons and protons have similar masses, whereas electrons have much smaller masses (the mass of an electron is 1/1836th of the mass of a proton or of a neutron). For this reason, essentially all of the mass of an atom is located within its nucleus. In addition to their mass differences, these subatomic particles also differ in their charge – protons are positively charged, electrons are negatively charged, and neutrons carry no electrical charge (i.e., they are *neutral*). The charge differences of protons and neutrons reflect their elementary particle composition. Thus, protons have a +1 charge because they are composed of 2 up-quarks and 1 down-quark. Because up-quarks carry a +2/3 charge and down-quarks carry a –1/3 charge, protons have a net +1 charge ($2/3 + 2/3 + -1/3 = 4/3 - 1/3 = 1$). Likewise, neutrons are neutral because they are composed of 2 down-quarks and 1 up-quark, which generates a zero charge ($-1/3 + -1/3 + 2/3 = -2/3 + 2/3 = 0$). The magnitude of the positive charge carried by a proton (+1) is equal to the magnitude of the negative charge carried by an electron (–1). The unit of electrical charge is the coulomb (C), where 1 C is equivalent to the charge of 6.24×10^{18} electrons. The quantity of charge possessed by a single electron or a single proton is extremely small and is referred to as an elementary charge unit (ECU); it has a charge value of 1.6022×10^{-19} C. For an electron, this value is negative (i.e., -1.6022×10^{-19} C), whereas for a proton, it is positive ($+1.6022 \times 10^{-19}$ C). Although the sum of positive and negative charges contained within a closed system cannot change (the law of conservation of charge), the charges are able to move throughout the system.

Because atoms contain an equal number of protons and electrons, they have a neutral charge. The *atomic number* of an atom indicates the number of protons it contains (and the number of electrons). The *mass number* of an atom (i.e., its atomic mass) is equal to its weight, which essentially reflects the

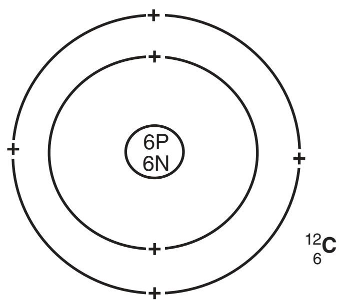

Figure 1.1 The orbital depiction of an atom of carbon and its periodic table symbol, indicating its abbreviation (C), its mass number (12), and its atomic number (6).

number of its protons plus its neutrons. The number of protons dictates the element. For example, if an element has an atomic number of 6, it is carbon. Thus, carbon contains 6 protons. Based on the preceding discussion, it also has 6 electrons (atoms are neutral). Its atomic mass is 12.001; the 12 indicates that it also contains 6 neutrons (because the number to the left of the decimal point indicates the number of protons and neutrons), whereas the digits beyond the decimal point represent the mass of its electrons. In periodic charts, the atomic mass of carbon is often rounded down to 12 (see Figure 1.1).

Some atoms have more than one mass number, because the number of neutrons they contain can vary. These atomic variations are referred to as *isotopes*. For example, in addition to carbon-12 (6 protons and 6 neutrons), carbon-13 (6 protons and 7 neutrons) and carbon-14 (6 protons and 8 neutrons) also exist. Thus, carbon isotopes (e.g., carbon-12, carbon-13, and carbon-14) all contain 6 protons, which is what defines the atom as carbon. Atomic isotopes vary in the number of neutrons they contain.

As stated earlier in the chapter, the electrons are located at various distances (energy levels) from its center, referred to as the 1 shell, 2 shell, 3 shell, 4 shell, 5 shell, 6 shell, and 7 shell. Shells contain subshells, each of which contains up to 2 electrons. The 2-electron per subshell limit reflects the *Pauli exclusion principle*, which states that electrons with the same spin cannot occupy the same subshell. Thus, because electrons can only spin in one of two directions, clockwise or counterclockwise, the maximum number of electrons per subshell is two. So as not to get shells and subshells confused, from this point forward, the shells will be referred to as energy levels. The number of subshells in each energy level varies. Energy level 1 contains only one subshell, termed the *s* subshell, which, by definition, can hold up to two electrons. The second energy level is composed of 4 subshells

(1 *s* subshell and 3 *p* subshells) and, thus, can hold up to 8 electrons (4 × 2 = 8). The third energy level is composed of 9 subshells (1 *s* subshell, 3 *p* subshells, and 5 *d* subshells) and, therefore, can hold up to 18 electrons (9 × 2 = 18). As indicated by the periodic chart, for atoms with an atomic number of 18 or less (i.e., 18 or less electrons), the electrons are distributed within the first 3 energy levels. Except for a few atoms (e.g., copper), atoms containing shells with higher energy levels are not pertinent to this discussion. The atomic number for copper is 29, and its 29 electrons are distributed among 4 energy levels as follows: 2 – 8 – 18 – 1.

Because the negatively charged electrons are attracted to the positively charged nucleus, the innermost shell fills before the shell immediately surrounding it begins to fill. For example, copper, atomic number 29, has 29 electrons and, therefore, as stated above, an electron shell pattern of (2 – 8 – 18 –1). Other important electron shell patterns are sodium (atomic number 11 [2 – 8 – 1]), chlorine (atomic number 17 [2 – 8 – 7]), and potassium (atomic number 19 [2 – 8 – 8 – 1]). These electron shell patterns inform us that copper, sodium, and potassium have a single electron in their outer orbits, whereas chlorine has seven electrons in its outer orbit. The interactions of atoms to form molecules can be predicted by the number of electrons in their outer shell. As demonstrated through quantum mechanics, the electrons do not orbit the nucleus like planets orbit a star. Rather, their location is discontinuous (i.e., first they are at one point in their orbit and then they are at another, noncontiguous point). For this reason, the distribution of electrons around the nucleus is often referred to as an electron cloud. This is analogous to a football (the nucleus) located at the center of the 50-yard line within a stadium consisting of a number of rows of seats (energy levels). In this analogy, the camera flashes occurring during a great play represent the electrons coming in and out of existence at random, discontinuous points within their energy level rather than moving continuously along an orbital path within their energy level.

When an atom gains or loses electrons, it becomes a charged particle (referred to as an *ion*). With electron loss (i.e., the loss of negativity), the atom becomes positively charged, whereas with electron gain (i.e., the acquisition of negativity), it becomes negatively charged. Positively charged ions are referred to as *cations* because they are attracted to the battery cathode (the negative terminal of a battery), whereas negatively charged ions are referred to as *anions* because they are attracted to the battery anode (the positively charged terminal of a battery). This occurs because of a property of electricity that states that *oppositely charged particles attract*. Antimatter also bears charge, with each antiparticle having an equal and opposite charge to its corresponding matter particle (e.g., an anti-electron has a charge of $+1.6022 \times 10^{19}$ coulombs, similar to a proton).

Whenever an object (living or nonliving) has an excess or a deficiency of electrons, that object has a charge. Because the object is not moving, the charge is said to be *static* and is also referred to as an *electrostatic charge*. Electrostatic charge accumulation usually occurs when two objects composed of electrically dissimilar materials are rubbed together so that one object transfers charge (e.g., electrons) to the other. The accumulated electrostatic charge is either positive (electron loss) or negative (electron gain). Objects with an electrostatic charge may attract each other (*attractive* force) or repel each other (*repulsive* force), depending on the similarity or dissimilarity of their charge. An electrostatic attractive force is observed when two objects of opposite charge (one negative and one positive) are brought together. Conversely, an electrostatic repulsive force occurs when two objects of like charge are brought together, such as two negatively charged objects or two positively charged ones. This phenomenon was known to ancient peoples (the frictive contact of amber and cat fur), although the mechanism underlying electrostatic force was not yet understood. In modern times, many of us have rubbed a glass rod with silk (this causes electrons to move from the glass rod to the silk) or caused a balloon to stick to the wall after rubbing it on a shirt. The rubbing process permits electrons to move from one object to the other, thereby *charging* the two objects (the object gaining electrons becomes negatively charged and the object losing electrons becomes positively charged). This is referred to as the *triboelectric effect* (the prefix *tribo-* derives from the Greek word for rub) and represents a type of *contact electrification*. Because the objects accumulate opposite charges, the two objects demonstrate an attractive electrostatic force. However, if two glass rods are rubbed with silk and then brought together, they would repel each other (repulsive electrostatic force) because they would then have the same positive charge. (The frictive force strips the electrons from the glass rod, causing it to have a positive charge. The silk acquires these electrons and, thus, becomes negatively charged.) These attractive and repulsive electrostatic forces are proportional to the product of the charges (q) on the two objects and inversely proportional to the square of the distance (d) between their centers. This mathematical relationship, which resembles the attractive force of gravity (Newton's inverse-square law of universal gravitation), is referred to as Coulomb's inverse-square law, after Charles Augustin de Coulomb, who realized that electrostatic charges manifest in two opposing forms, attractive (objects with opposite charge) and repulsive (objects with like charge). These relationships are expressed by the following formula:

$$F = k_e ql q2/d^2$$

where F is the magnitude of the force of interaction between the two charged objects (in Newtons), q1 and q2 are the magnitudes of the charges of the two objects (in coulombs), d is the distance between the centers of the two charged objects (in meters), and k_e is Coulomb's constant (the dielectric constant), which has a value of 9.0×10^9 Nm^2/C^2 (newton-meters squared per coulombs squared). This formula can be used to calculate the magnitude of an electrostatic force, where positive values indicate repulsive forces and negative values indicate attractive forces. Consequently, and rather amazingly, two separate charges located at some distance from each other have an effect on each other. This phenomenon is referred to as *action at a distance*.

According to the standard model of particle physics, the electrostatic force between two charged objects is expressed through subatomic particles termed *photons*. Photons move at the speed of light, which necessitates that they be massless (for the interested reader, *gauge symmetry* verifies that photons are massless). Because they are massless, they can never move at any speed other than the speed of light. According to quantum theory, photons, like other subatomic particles, are both particles and waves. When a charge moves, it creates ripples within its field (similar to the creation of ripples moving across the top of water by the jiggling of a bobber on the surface of the water). In this analogy, the bobber represents the moving charge and the ripples represent the massless photons. Because photons are massless, it is easy to generate electricity and electrical forces. Indeed, all of the forces in the universe (e.g., gravitation) are manifested through such carriers, although not all carriers are massless.

Electrostatic force is extremely strong. For example, the electrostatic force pushing two electrons apart is 10^{42} times stronger than the gravitational force pulling them together (Hawking, 1988). As another example, the electrical force between a proton and an electron is 10^{36} times greater than the force of gravity (Pollock, 2012). Although electrostatic force is much stronger than gravitational force, the force of gravity dominates throughout the universe because planets generally have no net charge and, therefore, no electrostatic charge.

Electron surpluses and deficiencies underlie the mechanism of static electricity. As previously stated, when two electrically neutral materials are rubbed together, the transfer of electrons from one material to the other one causes the material receiving the electrons to become negatively charged and the material losing the electrons to become positively charged. This relationship also accounts for several common electrical phenomena, such as the electrostatic discharge ("shock") that occurs when an individual with a net charge touches an object capable of conducting that charge or, equally as familiar, the movement of charge through the air (*lightning*) that occurs when the charge difference between a thundercloud and the ground surpasses the insulating ability of the air. In this setting, an electrical potential difference forms within the cloud, with its upper layers becoming positively charged and its lower layers becoming negatively charged. This phenomenon occurs when ice particles and water droplets rub against each other. The buildup of negative charges on the undersurface of the cloud causes the positive charges in the ground to become more superficial and the negative charges in the ground to move deeper into the ground (induction). Lightning occurs between the negatively charged undersurface of the cloud and the positively induced ground. Regarding the flow of electricity between individuals and conducting objects, when the surrounding air is dry (atmospheric humidity conducts electricity and tends to dissipate accumulating charge), insulators can hold a static charge for several minutes. Consequently, in a dry room, an individual wearing hard-soled shoes and walking across a carpeted floor can accumulate a charge difference of several thousand volts (the concept of *voltage* is discussed later in this chapter).

In this scenario, the friction between the carpet and the soles of the shoes generated by walking constitutes the "rubbing" or frictive force. The frictive force permits the exchange of electrons and, therefore, the accumulated charge (electrons accumulate on the body). This charge remains (is stored) on the surface of the body of the person until that person contacts a conductor (including another individual) or until the accumulated charge dissipates into the atmosphere. For example, should your hand approach a metal doorknob, the negative charges would flow from your hand to the doorknob (the electrons are attracted to the positive charges in the doorknob (created by polarization). Regarding lightning, there is a constant charge difference (voltage) between the ionosphere and the surface of the earth. The ionosphere is the ionized (by solar radiation) region of the Earth's upper atmosphere that forms the inner edge of the magnetosphere. The lower atmosphere, which lies between the ionosphere and the surface of the Earth, acts an insulator. Accordingly, when considered together, these three layers (conducting–insulating–conducting) constitute an atmospheric *capacitor*. A capacitor is an electrical element capable of storing electrical charge. This device is discussed in detail later in the chapter. When the insulating layer (the lower atmosphere) breaks down, as it does when the charge difference across it becomes extremely large (the charge difference can reach millions of volts in magnitude), the charged particles pass through the air (lightning). Thus, lightning simply reflects the advancement of electrons through the air, away from the negatively charged object and toward the positively charged one.

Current

Electric current (I) is defined as the *movement* of electric charge with respect to time ($I = Q/t$) across a given area. Thus, current expresses the rate of the flow of charge (charge per unit time). Current (charge) sources include free electrons (metals), ions (ionic solutions, such as the human body), combined electrons and ions (plasma), combined electrons and "holes" (semiconductors), and paired electrons (superconductors, which have near-zero resistance). Holes can be conceptualized as sites of relative positivity created by the displacement of an electron from the material. Thus, as the electrons flow in one direction, the holes flow in the opposite direction. Current was originally defined as the flow of positive charges (typically referred to as *conventional current* and less commonly as *hole current* or *hole flow*) but was later realized to represent the flow of negative charges (*true current*). In some engineering projects, it is easier to think in terms of hole flow than it is to think in terms of electron flow. Electron flow is the focus of this chapter. In subsequent chapters, ion flow (tissue current), which is important to EDX medicine, will be introduced. The principles and concepts of electron flow discussed in this chapter are analogous to those of ion flow.

The flow of charge occurs whenever a conductor is attached to two objects with unequal charges (e.g., electron imbalance). When in motion, charged particles (e.g., electrons) create an electric current. Like with charge, to best understand current, an understanding of atomic structure is again required. As previously discussed, the electrons composing the electron cloud surrounding the nucleus of an atom are located at various distances from the nucleus, termed *energy levels*. The outer energy level of an atom may be entirely filled with electrons or incompletely filled. Atoms that have a completely filled outer energy level neither accept nor donate electrons (i.e., they oppose electron movement) and, accordingly, are termed *inert* atoms. This type of atom is stable. Conversely, atoms with incompletely filled outer shells are less stable and, therefore, to enhance their stability, either gain electrons (to complete their outer energy level) or lose electrons (to eliminate their outer energy level). In exchange for stability, these atoms lose their neutrality and, thus, become ions. The conductivity of a material reflects the degree to which the charged particles composing it are free to move (free charge). The dielectric constant of a material indicates its propensity to conduct.

When substances consist of atoms in which the outer electrons move among the atomic nuclei with relative ease (i.e., atoms that donate or accept electrons), they are referred to as conductors. Conversely, substances composed of atoms with electrons that move among the nuclei with difficulty or not at all (i.e., that are tightly bound) make poor conductors. Because inert substances (substances composed of atoms containing a completely full outer energy shell) do not exhibit electron movement, they make good insulators. When substances are composed of atoms with an outer shell that is half-filled (e.g., silicon and germanium), they are referred to as semiconductors because they have both conducting and insulating properties. They conduct, but not as well as conductors, and they insulate, but not as well as insulators.

In summary, the degree of freedom of the charges composing a material is what distinguishes conductors, semiconductors, and insulators. As discovered by Galvani in the late 18th century, current also flows between dissimilar metals connected through a conductor. Galvani utilized dissimilar metals (i.e., a brass hook attached to an iron railing) to generate the electrical current required in his frog muscle contraction demonstrations (Bonner and DevlescHoward, 1995). For this reason, the production of electricity, especially when it is generated through a chemical action, is termed *galvanism*.

Metals, which contain large numbers of free electrons (free charge), are commonly employed as conductors. Copper, which has one electron is its outer shell (2 – 8 – 18 – 1), has a strong tendency to lose that electron. Consequently, the electrons contained within a copper wire are able to move among the copper nuclei composing that wire. As a result, when a copper wire is attached to a material containing excess electrons, the excess electrons move into the copper wire. However, the entry of electrons into the wire is limited because there is nowhere for the entering electrons to go. However, when a copper wire is connected between two objects, one of which contains excess electrons and the other of which contains a deficiency of electrons, the electrons flow from the electron-rich object to the electron-poor object via the copper atoms composing the wire. As the negatively charged electrons located within the outer energy levels of the copper atoms move toward the electron-poor object, the copper atoms losing their outer electrons become positively charged. This positive charge attracts a nearby electron, which then enters its outer shell, thereby restoring the atom to its neutrally charged state. At this point, the process repeats itself. Thus, the flow of electrons continues from the electron-rich object to the electron-poor object as long as a driving force remains (an electron imbalance between the two objects). Silver and aluminum are two other excellent conductors. The advantage of aluminum over copper is its light weight, which makes it the material of choice for the conducting wire attached to utility poles. Conductors do not have to be solid objects. Regarding liquids, elemental mercury is a good conductor, saltwater is a fair conductor, and distilled water is a poor conductor. In general, gases are poor conductors because the electrons contained in the atoms or molecules composing the gas are extremely far apart. For this reason, most gases make good insulators. Other good insulators include plastic, paper, wood, rubber-like polymers, porcelain, and glass.

When electrically charged particles move through a conductor, there is an electrical current (current equals the flow of charged particles). Examples include electrolysis (the movement of ions through liquid) and metallic conduction (the movement of electrons through a conductor). Although electric current consists of the flow of electrons from negative to positive (*electron current*), as previously stated, early scientists attributed electricity to the flow of positively charged particles, which is now referred to as *conventional current* (or, rarely, as *theoretical current*) and, consequently, is depicted as traveling from the most positive portion of a circuit to its most negative portion (i.e., circuit diagrams with arrows pointing in the positive to negative direction). As stated earlier, this is also referred to as “hole flow,” because the exiting electrons can be envisioned to leave positively charged “holes” in the atom from which they depart. In other words, as the electrons move from negative to positive, the holes are moving in the opposite direction. Although the electrons constituting the current move quite slowly (termed the *drift velocity*, which is measured in millimeters per hour and is proportional to the strength of the electric field), the speed of the electromagnetic waves traveling along the wire is much faster and depends on the dielectric constant of the material through which it is traveling. In a vacuum, the electromagnetic waves travel at the speed of light. Massless particles, termed *photons*, function as the energy carrier for electromagnetic waves (Pollock, 2003).

As stated at the beginning of this chapter, electricity can be characterized in terms of its charge (Q), current (Q/t), voltage (V), and resistance (R). The unit of charge is the coulomb, symbolized as an uppercase C. It is defined as being equivalent to the charge on 6.24×10^{18} electrons. Current is defined as the flow of charge (electrons, ions, or any charged object) per unit of time (Q/t). The standard unit of electrical current is the *ampere*, which is defined as 1 coulomb per second and is symbolized by an uppercase A. Thus, 1 ampere of current is equivalent to 1 coulomb of charge passing a given point in 1 second. Current is typically expressed in milliamperes (mA, where 1 milliampere equals one one-thousandth of an ampere). Examples of approximate current magnitudes include: power lines (1,000 A), household electricity (150 A), a 100-watt light bulb (1 A), cell phones (0.2 A or 200 mA for the iPhone 6), watches (1 microampere), and cell membranes (1 picoampere per receptor; a picoampere is one-trillionth of an ampere). The important relationships for current are:

Current = charge/time ($I = Q/t$)
Ampere = 1 coulomb/second

Voltage

As previously stated, electron current passes through a copper wire when the wire is connected between one material with an electron surplus and another material with an electron deficit (i.e., there is an electron difference, or gradient, between the two materials). Thus, when a conductor is interposed between the two objects, the electrons flow down their concentration gradient (i.e., from the material with the greater number of electrons to the one with the lesser number). These two objects, which are separated in space, also have different charges (i.e., a charge gradient). The size of the charge difference between the two points (i.e., the electron gradient) represents the driving force that pushes the electrons through the copper wire. This driving force is referred to as an *electromotive force* (EMF) and its magnitude is expressed in volts (symbolized by an uppercase V). The EMF is inversely proportional to the distance between the two charges. One volt is the EMF (attractive or repellant) between 1 coulomb of charge located 1 meter from 1 coulomb of unlike [attractive] or like [repellant] charge). It requires 1 joule of energy to separate 1 coulomb of positive charge from 1 coulomb of negative charge by 1 meter (1 volt = 1 joule/1 coulomb). Thus, voltage quantifies the charge imbalance between two distinct sites and is a reflection of the energy per charge; its units are volts (joules per coulomb). For example, a 1.5-volt battery imparts 1.5 joules of energy to each coulomb of electrons exiting the terminal of the battery (e.g., a flashlight battery). In addition, as the electrons travel through the circuitry of the flashlight, some of the energy is lost (e.g., some of the electrical energy is transformed into heat energy) and some of the energy is utilized for the purpose of the circuit (e.g., to power the lightbulb).

In EDX medicine, voltage is commonly expressed in much smaller units – microvolts (μV) and millivolts (mV). In addition, because the units of EMF are termed volts, EMF is often simply referred to as voltage. Finally, because the EMF represents a charge difference, it is also referred to as a *potential difference* because the two separated charges have the *potential* to flow should the opportunity arise (i.e., should a conductor be placed between them). Consequently, voltage is an electrical form of potential energy. Because voltage is defined as the difference in energy per charge between *two separate sites* within a circuit, it can never exist at a single point. When voltage is reported (or measured), it is only meaningful when the two separate sites are specified. Often, for convenience, a reference point is assigned within a circuit and its voltage is declared to be zero (the circuit ground). Then we can report voltages at other points in the circuit as a number, and it is implied that the measurement is made with respect to the zero point or circuit ground. When current (charge/time) is multiplied by voltage (energy/charge), the product is power (energy/time), which is expressed in watts (W). Thus, electric power is the rate at which a system delivers, generates, or consumes electrical energy ($P = IV$, expressed in watts).

Charge differences (EMF) between two points not connected by a conductor underlie electrostatic electricity (partially discussed above). Because there is no conductor, there is no flow, and consequently, the charges do not move (they are electrostatic). Again, they have the potential to move should a conductor be placed between them. These potential differences can be created at one site and then transported elsewhere to do work.

Batteries, which convert chemical energy into electrical energy to maintain an essentially fixed voltage across its terminals, serve as transportable voltage sources. Devices that convert nonelectrical energy into electrical energy, such as batteries (convert chemical energy into electrical energy), are sometimes referred to as EMF sources. Batteries were originally referred to as galvanic cells, after Luigi Galvani. When a conductor (e.g., a conducting wire) is placed between the terminals of a battery, electrons flow from the negatively charged cathode to the positively charged anode until the electron imbalance no longer exists. The electron flow can be directed through a load (e.g., a lamp) to do work (e.g., illuminate a room). The voltage drop across the bulb reflects the