brief high-current pulse from a defibrillator is applied to depolarize all the cells of the heart muscle simultaneously. After all the cells relax together, a normal rhythm usually returns. In the United States, approximately 1000 deaths per year occur in accidents that involve cord-connected appliances.

SUSTAINED MYOCARDIAL CONTRACTION

When the current is high enough, the entire heart muscle contracts. Although the heart stops beating while the current is applied, a normal rhythm ensues when the current is interrupted, just as in defibrillation. Data from ac-defibrillation experiments on animals show that minimal currents for complete myocardial contraction range from 1 to 6 A. No irreversible damage to the heart tissue is known to result from brief applications of these currents (Roy et al., 1980).

BURNS AND PHYSICAL INJURY

Very little is known about the effects of currents in excess of 10 A, particularly for currents of short duration. Resistive heating causes burns, usually on the skin at the entry points, because skin resistance is high. Voltages greater than 240 V can puncture the skin. The brain and other nervous tissue lose all functional excitability when high currents pass through them. Furthermore, excessive currents may stimulate muscular contractions that are strong enough to pull the muscle attachment away from the bone (Lee et al., 1992).

14.2 IMPORTANT SUSCEPTIBILITY PARAMETERS

The physiological effects previously described are for an average 70 kg human and for 60 Hz current applied for 1 to 3 s to moistened hands grasping a No. 8 copper wire. The current needed to produce each effect depends on all these conditions, as explained below. Safety considerations dictate thinking in terms of minimal rather than average values for each condition.

THRESHOLD AND LET-GO VARIABILITY

Figure 14.2 shows the variability of the threshold of perception and the let-go current for men and women (Dalziel, 1973). On this plot of percentile rank versus rms current in milliamperes, the data are close to the straight lines shown, so a Gaussian distribution may be assumed. For men, the mean value for the threshold of perception is 1.1 mA; for women, the estimated mean is 0.7 mA. The minimal threshold of perception is 500 μA. When the current was applied to ECG gel electrodes, the threshold of perception averages only 83 μA with a range of 30 to 200 μA (Tan and Johnson, 1990). Recent data for surface electrical stimulation of skeletal muscle showed that sensory threshold

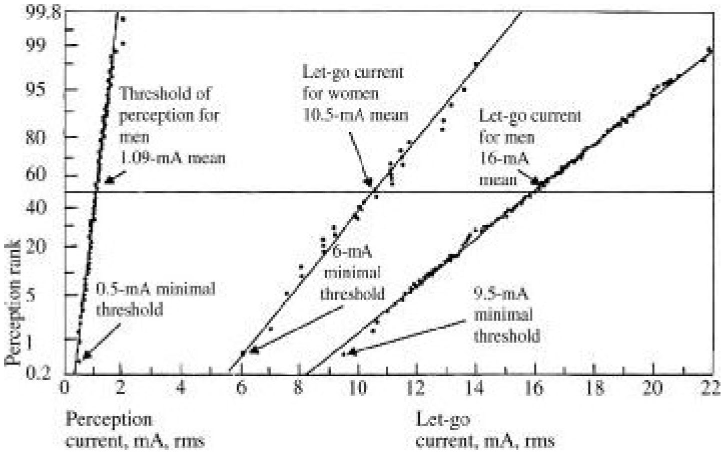

Figure 14.2 Distributions of perception thresholds and let-go currents These data depend on surface area of contact (moistened hand grasping AWG No. 8 copper wire). (Replotted from C. F. Dalziel, "Electric Shock," *Advances in Biomedical Engineering*, edited by J. H. U. Brown and J. F. Dickson III, 1973, 3, 223–248.)

was 43% ($p < 0.001$) lower in women and supramotor threshold was 17% ($p < 0.01$) less for women (Maffiuletti *et al.*, 2008).

Let-go currents also appear to follow Gaussian distributions, with mean let-go currents of 16 mA for men and 10.5 mA for women. The minimal threshold let-go current is 9.5 mA for men and 6 mA for women. Note that the range of variability for let-go current is much greater than the range for threshold-of-perception current.

FREQUENCY

Figure 14.3 shows a plot of let-go current versus frequency of the current. Unfortunately, the minimal let-go currents occur for commercial power-line frequencies of 50 to 60 Hz. For frequencies below 10 Hz, let-go currents rise, probably because the muscles can partially relax during part of each cycle. And at frequencies above several hundred hertz, the let-go currents rise again.

DURATION

To estimate the ventricular fibrillation (VF) risk of electromuscular incapacitation devices (EMDs), it is important to understand the excitation behavior of myocardial cells. Geddes and Baker (1989) presented the cell membrane excitation model by a lumped parallel *RC* circuit that represents the resistance and capacitance of the cell membrane. This model determines the cell excitation thresholds that exceed about 20 mV for varying rectangular pulse durations d by assigning the rheobase currents I_r (for very long pulse durations) and cell

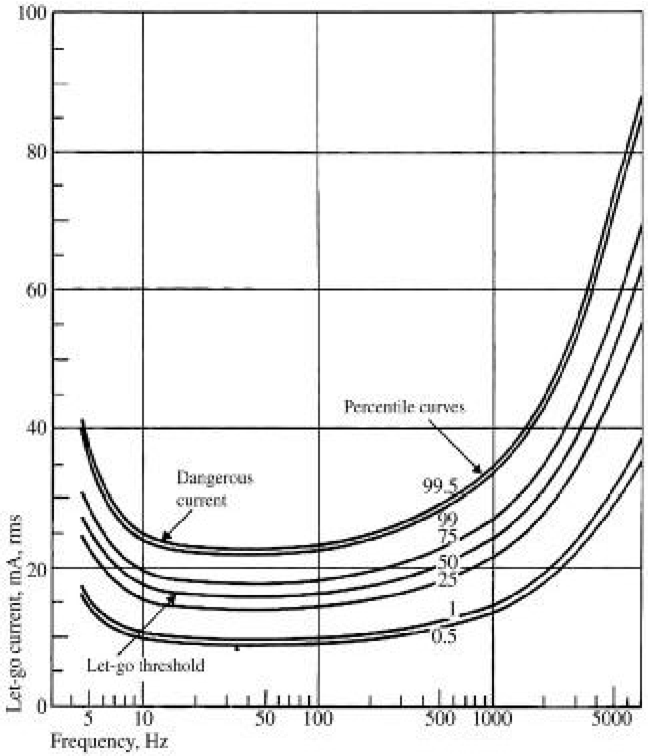

Figure 14.3 Let-go current versus frequency Percentile values indicate variability of let-go current among individuals. Let-go currents for women are about two-thirds the values for men. (Reproduced, with permission, from C. F. Dalziel, "Electric Shock," *Advances in Biomedical Engineering*, edited by J. H. U. Brown and J. F. Dickson III, 1973, 3, 223–248.)

membrane time constant $\tau = RC$. Figure 14.4 shows that for short durations the stimulation current threshold I_d is inversely related to the pulse duration d by the well-known strength–duration equation

$$I_d = \frac{I_\mathrm{r}}{1 - e^{-d/\tau}} \tag{14.1}$$

EXAMPLE 14.1 A cardiac pacemaker company wants to minimize pacing duration d while keeping current at 3 times I_r. Assume cardiac membrane $\tau = 2\,\mathrm{ms}$, and calculate d.

ANSWER Use (14.1): $0.33 = 1 - e^{-d/0.002}, 0.67 = e^{-d/0.002}, \ln 0.67 = -d/0.002 = -0.4, d = 0.8\,\mathrm{ms}$.

A single electric stimulus pulse can induce VF if it is delivered during the vulnerable period of cardiac repolarization that corresponds to the T wave on

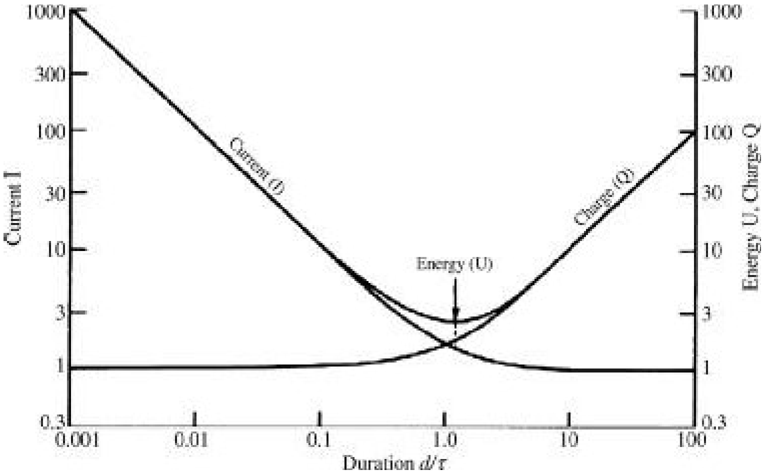

Figure 14.4 Normalized analytical strength–duration curve for current *I*, charge *Q*, and energy *U*. The *x* axis shows the normalized duration of d/τ. (From Geddes, L. A., and L. E. Baker, *Principles of Applied Biomedical Instrumentation*, 3rd ed. New York: John Wiley & Sons, 1989).

the ECG. For large-amplitude electric transients less than 100 μs in duration applied directly to the heart, the stimulation threshold approaches a constant charge transfer density of $3.5\,\mu\text{C}\cdot\text{cm}^{-2}$. For normal hearts, the ratio of the fibrillation stimulation threshold to the single-beat stimulation threshold is 20:1 to 30:1 for electrodes on the heart and 10:1 to 15:1 for chest surface electrodes (Geddes *et al.*, 1986). For 60 Hz current applied to the extremities, the fibrillation threshold increases sharply for shocks that last less than about 1 s, as shown in Figure 14.5. Shocks must last long enough to take place during the vulnerable period that occurs during the T wave in each cardiac cycle (Reilly, 1998). For the 100 μs pulses of electric fences (IEC, 2006) and Tasers, Figure 14.4 shows that much higher currents are required for excitation.

BODY WEIGHT

Several studies using animals of various sizes have shown that the fibrillation threshold increases with body weight. Fibrillating current increases from 50 mA rms for 6 kg dogs to 130 mA rms for 24 kg dogs. These findings deserve more study, because they are used to extrapolate fibrillating currents for humans.

POINTS OF ENTRY

When current is applied at two points on the surface of the body, only a small fraction of the total current flows through the heart, as shown in Figure 14.6(a). These large, externally applied currents are called *macroshocks*.

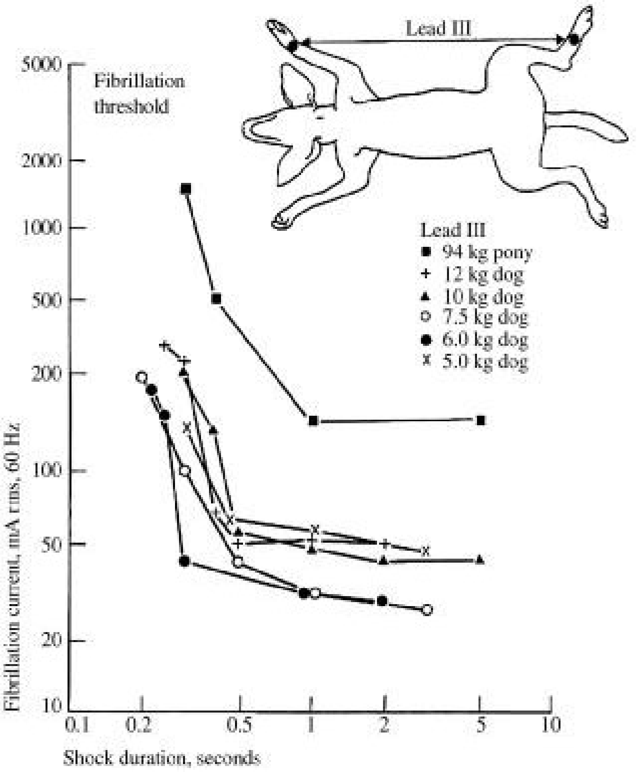

Figure 14.5 Fibrillation current versus shock duration. Thresholds for VF in animals for 60 Hz ac current. Duration of current (0.2 to 5 s) and weight of animal body were varied. (From L. A. Geddes, *IEEE Trans. Biomed. Eng.*, 1973, 20, 465–468. Copyright 1973 by the Institute of Electrical and Electronics Engineers. Reproduced with permission.)

The magnitude of current needed to fibrillate the heart is far greater when the current is applied on the surface of the body than it would be if the current were applied directly to the heart. The importance of the location of the two macroshock entry points is often overlooked. If the two points are both on the same extremity, the risk of fibrillation is small, even for high currents. For dogs, the current needed for fibrillation is greater for ECG lead I (LA–RA) electrodes than for ECG leads II and III (LL–RA and LL–LA) (Geddes, 1973). The protection afforded by the skin resistance (15 kΩ to 1 MΩ for 1 cm^2) is eliminated by many medical procedures that require insertion of conductive devices into natural openings, skin incisions, skin abrasion, or electrode gel.

If the skin resistance is bypassed, less voltage is required to produce sufficient current for each physiological effect.

Patients are particularly vulnerable to electric shock when invasive devices are placed in direct contact with cardiac muscle. If a device provides a conductive path to the heart that is insulated except at the heart, then very

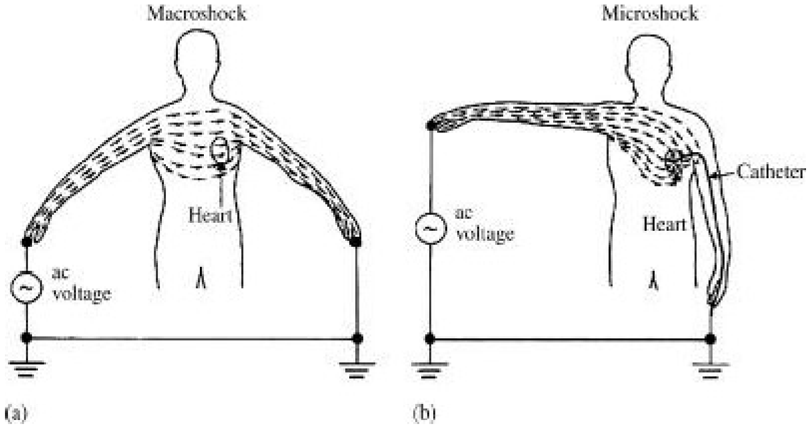

Figure 14.6 Effect of entry points on current distribution (a) *Macroshock:* Externally applied current spreads throughout the body. (b) *Microshock:* All the current applied through an intracardiac catheter flows through the heart. (From F. J. Weibell, "Electrical Safety in the Hospital," *Annals of Biomedical Engineering*, 1974, 2, 126–148.)

small currents called *microshocks* can induce VF. As Figure 14.6(b) shows, all the current flowing through such a conductive device flows through the heart. The current density at the point of contact can be quite high, and fibrillation in dogs can be induced by total currents as low as 20 μA. [See Roy (1980).] Application of 60 Hz ac for 5 s test periods to a ventricular pacing catheter during implantable cardioverter–defibrillator implant testing in 40 patients showed intermittent capture with a minimum current of 20 μA, continuous capture with hemodynamic collapse with a minimum current of 32 μA and VF persisting after ac termination with a minimum current of 49 μA (Figure 14.7) (Swerdlow *et al.*, 1999.) The other connection can be at any point on the body. The widely accepted safety limit to prevent microshocks is 10 μA.

14.3 DISTRIBUTION OF ELECTRIC POWER

Electric power is needed in health-care facilities not only for the operation of medical instruments but also for lighting, maintenance appliances, patient conveniences (such as television, hair curlers, and electric toothbrushes), clocks, nurse call buttons, and an endless list of other electric devices. A first step in providing electrical safety is to control the availability of electric power and the grounds in the patients' environment. This section is concerned with methods for safe distribution of power in health-care facilities. Then, in the sections that follow, we will discuss various macroshock and microshock hazards (Klein, 1996).

A simplified diagram of an electric-power-distribution system is shown in Figure . High voltage (4800 V) enters the building—usually via underground