External Defibrillators

79.1 Mechanism of Fibrillation ........................................ 79-1
79.2 Mechanism of Defibrillation ...................................... 79-2
79.3 Clinical Defibrillators .............................................. 79-3
79.4 Electrodes .......................................................... 79-5
79.5 Synchronization ..................................................... 79-6
79.6 Automatic External Defibrillators ............................... 79-6
79.7 Defibrillator Safety ................................................ 79-8

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Defibrillators are devices used to supply a strong electric shock (often referred to as a countershock) to a patient in an effort to convert excessively fast and ineffective heart rhythm disorders to slower rhythms that allow the heart to pump more blood. External defibrillators have been in common use for many decades for emergency treatment of life-threatening cardiac rhythms as well as for elective treatment of less threatening rapid rhythms. Figure 79.1 shows an external defibrillator.

Cardiac arrest occurs in more than 500,000 people annually in the United States, and more than 70% of the out-of-hospitals are due to cardiac arrhythmia treatable with defibrillators. The most serious arrhythmia treated by a defibrillator is ventricular fibrillation. Without rapid treatment using a defibrillator, ventricular fibrillation causes complete loss of cardiac function and death within minutes. Atrial fibrillation and the more organized rhythms of atrial flutter and ventricular tachycardia can be treated on a less emergent basis. Although they do not cause immediate death, their shortening of the interval between contractions can impair filling of the heart chambers and thus decrease cardiac output. Conventionally, treatment of ventricular fibrillation is called defibrillation, whereas treatment of the other tachycardias is called cardioversion.

79.1 Mechanism of Fibrillation

Fibrillation is chaotic electric excitation of the myocardium and results in loss of coordinated mechanical contraction characteristic of normal heart beats. Description of mechanisms leading to, and maintaining, fibrillation and other rhythm disorders are reviewed elsewhere [1] and are beyond the scope of this chapter. In summary, however, these rhythm disorders are commonly held to be a result of reentrant excitation pathways within the heart. The underlying abnormality that leads to the mechanism is the combination of conduction block of cardiac excitation plus rapidly recurring depolarization of the membranes of the cardiac cells. This leads to rapid repetitive propagation of a single excitation wave or of multiple excitatory waves throughout the heart. If the waves are multiple, the rhythm may degrade into total loss of synchronization of cardiac fiber contraction. Without synchronized contraction, the chamber affected will not contract, and this is fatal in the case of ventricular fibrillation. The most common cause of these conditions, and therefore of these rhythm disorders, is cardiac ischemia or infarction as a complication of atherosclerosis. Additional relatively common causes include other cardiac
disorders, drug toxicity, electrolyte imbalances in the blood, hypothermia, and electric shocks (especially from alternating current).

### 79.2 Mechanism of Defibrillation

The corrective measure is to extinguish the rapidly occurring waves of excitation by simultaneously depolarizing most of the cardiac cells with a strong electric shock. The cells then can simultaneously repolarize themselves, and thus they will be back in phase with each other.

Despite years of intensive research, there is still no single theory for the mechanism of defibrillation that explains all the phenomena observed. However, it is generally held that the defibrillating shock must be adequately strong and have adequate duration to affect most of the heart cells. In general, longer duration shocks require less current than shorter duration shocks. This relationship is called the strength-duration relationship and is demonstrated by the curve shown in Fig. 79.2. Shocks of strength and duration above and to the right of the current curve (or above the energy curve) have adequate strength to defibrillate, whereas shocks below and to the left do not. From the exponentially decaying current curve an energy curve can also be determined (also shown in Fig. 79.2), which is high at very short durations due to high current requirements at short durations, but which is also high at longer durations due to additional energy being delivered as the pulse duration is lengthened at nearly constant current. Thus, for most electrical waveforms there is a minimum energy for defibrillation at approximate pulse durations of 3–8 ms. A strength-duration charge curve can also be determined as shown in Fig. 79.2, which demonstrates that the minimum charge for defibrillation occurs at the shortest pulse duration.
tested. Very-short-duration pulses are not used, however, since the high current and voltage required is damaging to the myocardium. It is also important to note that excessively strong or long shocks may cause immediate refibrillation, thus failing to restore the heart function.

In practice, for a shock applied to electrodes on the skin surface of the patient's chest, durations are on the order of 3–10 milliseconds and have an intensity of a few thousand volts and tens of amperes. The energy delivered to the subject by these shocks is selectable by the operator and is on the order of 50–360 joules for most defibrillators. The exact shock intensity required at a given duration of electric pulse depends on several variables, including the intrinsic characteristics of the patient (such as the underlying disease problem or presence of certain drugs and the length of time the arrhythmia has been present), the techniques for electrode application, and the particular rhythm disorder being treated (more organized rhythms require less energy than disorganized rhythms).

79.3 Clinical Defibrillators

Defibrillator design has resulted from medical and physiologic research and advances in hardware technology. It is estimated that for each minute that elapses between onset of ventricular fibrillation and the first shock application, survival to leave hospital decreases by about 10%. The importance of rapid response led to development of portable, battery-operated defibrillators and more recently to automatic external defibrillators (AEDs) that enable emergency responders to defibrillate with minimal training.

All clinical defibrillators used today store energy in capacitors. Desirable capacitor specifications include small size, light weight, and capability to sustain several thousands of volts and many charge-discharge cycles. Energy storage capacitors account for at least one pound and usually several pounds of defibrillator weight. Energy stored by the capacitor is calculated from

\[ W_s = \frac{1}{2} CE^2 \]  

(79.1)
where \( W_s \) = stored energy in joules, \( C \) = capacitance in farads, and \( E \) = voltage applied to the capacitor. Delivered energy is expressed as

\[
W_d = W_s \times \left( \frac{R}{R_i + R} \right) \tag{79.2}
\]

where \( W_d \) = delivered energy, \( W_s \) = stored energy, \( R \) = subject resistance, and \( R_i \) = device resistance.

Figure 79.3 shows a block diagram for defibrillators. Most have a built-in monitor and synchronizer (dashed lines in Fig. 79.3). Built-in monitoring speeds up diagnosis of potentially fatal arrhythmias, especially when the ECG is monitored through the same electrodes that are used to apply the defibrillating shock. The great preponderance of defibrillators for trans-chest defibrillation deliver shocks with either a damped sinusoidal waveform produced by discharge of an RCL circuit or a truncated exponential decay waveform (sometimes called trapezoidal). Basic components of exemplary circuits for damped sine waveform and trapezoidal waveform defibrillators are shown in Figs. 79.4 and 79.5. The shape of the waveforms generated by RCL defibrillators depend on the resistance of the patient as well as the energy storage capacitance and resistance and inductance of the inductor. When discharged into a 50-\( \Omega \) load (to stimulate the patient's resistance), these defibrillators produce either a critically damped sine waveform or a slightly underdamped sine waveform (i.e., having a slight reversal of waveform polarity following the main waveform) into the 50-\( \Omega \) load.

FIGURE 79.4 Resistor-capacitor-inductor defibrillator. The patient is represented by \( R \). (Modified from Feinberg B. 1980. *Handbook Series in Clinical Laboratory Science*, vol 2, Boca Raton, Fla, CRC Press, with permission.)
The exact waveform can be determined by application of Kirkchoff's voltage law to the circuit

\[ L \frac{di}{dt} + (R_i + R) i + \frac{1}{C} \int i \, dt = 0 \]  
\[(79.3)\]

where \( L \) = inductance in H, \( i \) = instantaneous current in amperes, \( t \) = time in seconds, \( R_i \) = device resistance, \( R \) = subject resistance, and \( C \) = capacitance. From this, the second-order differential equation describes the RCL defibrillator.

\[ L \frac{d^2 i}{dt^2} + (R_i + R) \frac{di}{dt} + \frac{1}{C} i = 0 \]  
\[(79.4)\]

Trapezoidal waveform (actually, these are truncated exponential decay waveform) defibrillators are also used clinically. The circuit diagram in Fig. 79.4 is exemplary of one design for producing such a waveform. Delivered energy calculation for this waveform is expressed as

\[ W_d = 0.5 \, I_i^2 \, R \left[ \frac{d}{\log_2 (I_f / I_i)} \right] \left[ 1 - \left( \frac{I_f}{I_i} \right)^2 \right] \]  
\[(79.5)\]

where \( W_d \) = delivered energy, \( I_i \) = initial current in amperes, \( I_f \) = final current, \( R \) = resistance of the patient, and \( d \) = pulse duration in seconds. Both RCL and trapezoidal waveforms defibrillate effectively. Implantable defibrillators now use alternative waveforms such as a biphasic exponential decay waveform, in which the polarity of the electrodes is reversed part way through the shock. Use of the biphasic waveform has reduced the shock intensity required for implantable defibrillators but has not yet been extended to trans-chest use except on an experimental basis.

RCL defibrillators are the most widely available. They store up to about 440 joules and deliver up to about 360 joules into a patient with 50-ohm impedance. Several selectable energy intensities are available, typically from 5–360 J, so that pediatric patients, very small patients, or patients with easily converted arrhythmias can be treated with low-intensity shocks. The pulse duration ranges from 3–6 ms. Because the resistance (\( R \)) varies between patients (25–150 ohms) and is part of the RCL discharge circuit, the duration and damping of the pulse also varies; increasing patient impedance lengthens and damps the pulse. Figure 79.6 shows waveforms from RCL defibrillators with critically damped and with under-damped pulses.

### 79.4 Electrodes

Electrodes for external defibrillation are metal and from 70–100 cm² in surface area. They must be coupled to the skin with an electrically conductive material to achieve low impedance across the electrode-patient interface.
interface. There are two types of electrodes: hand-held (to which a conductive liquid or solid gel is applied) and adhesive, for which an adhesive conducting material holds the electrode in place. Hand-held electrodes are reusable and are pressed against the patient's chest by the operator during shock delivery. Adhesive electrodes are disposable and are applied to the chest before the shock delivery and left in place for reuse if subsequent shocks are needed. Electrodes are usually applied with both electrodes on the anterior chest as shown in Fig. 79.7 or in anterior-to-posterior (front-to-back) position, as shown in Fig. 79.8.

79.5 Synchronization

Most defibrillators for trans-chest use have the feature of synchronization, which is an electronic sensing and triggering mechanism for application of the shock during the QRS complex of the ECG. This is required when treating arrhythmias other than ventricular fibrillation, because inadvertent application of a shock during the T wave of the ECG often produces ventricular fibrillation. Selection by the operator of the synchronized mode of defibrillator operation will cause the defibrillator to automatically sense the QRS complex and apply the shock during the QRS complex. Furthermore, on the ECG display, the timing of the shock on the QRS is graphically displayed so the operator can be certain that the shock will not fall during the T wave (see Fig. 79.9).

79.6 Automatic External Defibrillators

Automatic external defibrillators (AEDs) are defibrillators that automatically or semiautomatically recognize and treat rapid arrhythmias, usually under emergency conditions. Their operation requires less
FIGURE 79.7  Cross-sectional view of the chest showing position for standard anterior wall (precordial) electrode placement. Lines of presumed current flow are shown between the electrodes on the skin surface. (Modified from Tacker WA (ed). 1994. Defibrillation of the Heart: ICDs, AEDs and Manual, St. Louis, Mosby-Year Book, with permission.)

FIGURE 79.8  Cross-sectional view of the chest showing position for front-to-back electrode placement. Lines of presumed current flow are shown between the electrodes on the skin surface. (Modified from Tacker WA (ed). 1994. Defibrillation of the Heart: ICDs, AEDs and Manual, St. Louis, Mosby-Year Book, with permission.)

Training in the use of automated defibrillators is simpler and requires less training than operation of manual defibrillators because the operator need not know which ECG waveforms indicate rhythms requiring a shock. The operator applies adhesive electrodes from the AED to the patient and turns on the AED, which monitors the ECG and determines by built-in signal processing...
whether or not and when to shock the patient. In a completely automatic mode, the AED does not have a manual control as shown in Fig. 79.3 but instead has an automatic control. In semiautomatic mode, the operator must confirm the shock advisory from the AED to deliver the shock. AEDs have substantial potential for improving the chances of survival from cardiac arrest because they enable emergency personnel, who typically reach the patient before paramedics do, to deliver defibrillating shocks. Furthermore, the reduced training requirements make feasible the operation of AEDs in the home by a family member of a patient at high risk of ventricular fibrillation.

79.7 Defibrillator Safety

Defibrillators are potentially dangerous devices because of their high electrical output characteristics. The danger to the patient of unsynchronized shocks has already been presented, as has the synchronization design to prevent inadvertent precipitation of fibrillation by a cardioversion shock applied during the T wave.

There are other safety issues. Improper technique may result in accidental shocking of the operator or other personnel in the vicinity, if someone is in contact with the electric discharge pathway. This may occur if the operator is careless in holding the discharge electrodes or if someone is in contact with the patient or with a metal bed occupied by the subject when the shock is applied. Proper training and technique is necessary to avoid this risk.

Another safety issue is that of producing damage to the patient by application of excessively strong or excessively numerous shocks. Although cardiac damage has been reported after high-intensity and repetitive shocks to experimental animals and human patients, it is generally held that significant cardiac damage is unlikely if proper clinical procedures and guidelines are followed.

Failure of a defibrillator to operate correctly may also be considered a safety issue, since inability of a defibrillator to deliver a shock in the absence of a replacement unit means loss of the opportunity to resuscitate the patient. A recent review of defibrillator failures found that operator errors, inadequate defibrillator care and maintenance, and, to a lesser extent, component failure accounted for the majority of defibrillator failures [7].
References

5. Canadian National Standard CAN/CSA C22.2 No. 601.2.4-M90. 1990. Medical electrical equipment, part 2: Particular requirements for the safety of cardiac defibrillators and cardiac defibrillator/monitors.

Further Information

Detailed presentation of material on defibrillator waveforms, algorithms for ECG analysis, and automatic defibrillation using AED’s, electrodes, design, clinical use, effects of drugs on shock strength required to defibrillate, damage due to defibrillator shocks, and use of defibrillators during open-thorax surgical procedures or trans-esophageal defibrillation are beyond the scope of this chapter. Also, the historical aspects of defibrillation are not presented here. For more information, the reader is referred to the publications at the end of this chapter [1–3]. For detailed description of specific defibrillators with comparisons of features, the reader is referred to articles from Health Devices, a monthly publication of ECRI, 5200 Butler Pike, Plymouth Meeting, Pa USA. For American, Canadian, and European defibrillator standards, the reader is referred to published standards [3–6] and Charbonnier’s discussion of standards [1].