CHAPTER 13
DEFIBRILLATORS AND CARDIOVERTERS
Excerpted from J. Webster's Medical Instrumentation Textbook

Cardiac fibrillation is a condition wherein the individual myocardial cells contract asynchronously without any pattern relating the contraction of one cell and that of the next. This serious condition reduces the cardiac output to near zero, and it must be corrected as soon as possible to avoid irreversible brain damage to the patient. It is one of the most serious medical emergencies of the cardiac patient. Hence resuscitative measures must be instituted within 5 min or less after the attack.

Electric shock to the heart can be used to reestablish a more normal cardiac rhythm. Electric machines that produce the energy to carry out this function are known as defibrillators. There are four basic types: the ac defibrillator, the capacitive-discharge defibrillator, the capacitive-discharge delay-line defibrillator, and the square-wave defibrillator. We shall examine each of these types.

Defibrillation by electric shock is carried out either by passing current through electrodes placed directly on the heart or transthoracically, by using large-area electrodes placed against the anterior thorax (Tacker and Geddes, 1980; Tacker, 1988). The physician can achieve defibrillation of the heart with lower levels of current in the former case than in the latter, but electrodes can be placed directly on the heart only when the heart is exposed in a surgical procedure. Many defibrillators, however, have provisions for both types of defibrillation. They also incorporate appropriate safety features so that the high voltage used with surface electrodes cannot be applied accidentally when internal electrodes are being used, and so that the lower energy used with internal electrodes cannot be inadvertently connected to the surface electrodes, causing them not to produce effective defibrillation.

CAPACITIVE-DISCHARGE dc DEFIBRILLATORS

A shorter high-amplitude defibrillation pulse can be obtained by using the capacitive-discharge circuit shown in Figure 13.11. In this case, a half-wave rectifier driven by a step-up transformer is used to charge the capacitor C. The voltage to which C is charged is determined by a variable autotransformer in the primary circuit. A series resistance R limits the charging current to protect the circuit components, and an ac voltmeter across the primary is calibrated to indicate the energy stored in the capacitor. The resistor also helps to determine the time necessary to achieve a full charge on the capacitor. Five times the RC time constant for the circuit is required to reach 99% of a full charge. A good rule of thumb is to keep this time under 10 s, which means that the time constant must be less than 2 s. The clinician discharges the capacitor when the electrodes are firmly in place on the body by momentarily changing the switch S from position 1

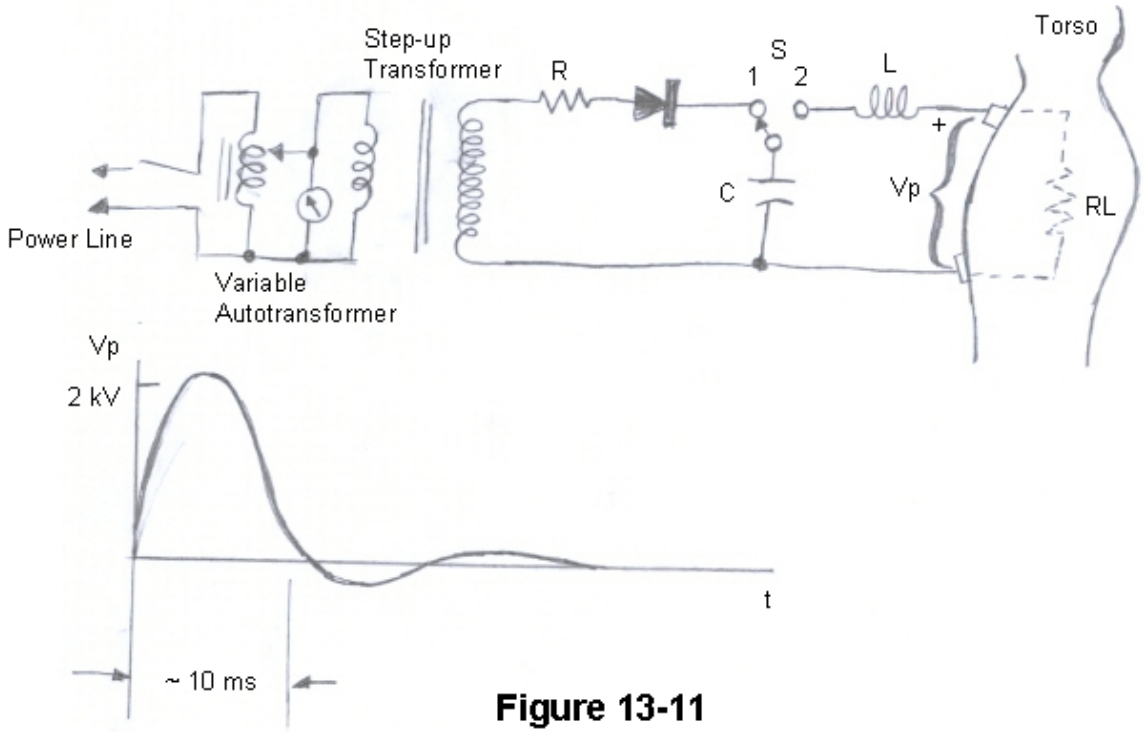

Figure 13-11

to position 2. The capacitor is discharged through the electrodes and the patient's torso, which represent a primarily resistive load, and the inductor

L. The inductor tends to lengthen the pulse, producing a wave shape of the type shown in Figure 13.11. The slightly underdamped case is illustrated here, but overdamping and critical damping can also occur, the latter being most desirable. The situation is determined entirely by the resistance between the electrodes, which can vary from patient to patient. Once the discharge is completed, the switch automatically returns to position 1, and the process can be repeated if necessary.

With a circuit such as this, 50 to 100 J (W x s) is required for defibrillation, using electrodes applied directly to the heart. When external electrodes are used, energies as high as 400 J may be required.

The energy stored in the capacitor is given by the well-known equation

$$E = \frac{Cv^2}{2} \qquad (13.4)$$

where C is the capacitance and v is the voltage to which the capacitor is charged. Capacitors used in defibrillators range from 10 to 50 uF in capacitance. Thus we see that the voltage for a maximal energy of 400 J ranges from 2 to 9 kV, depending on the size of the capacitor. This stored energy is not necessarily the same energy that is delivered to the patient. Losses in the discharge circuit and at the electrodes result in an actual delivered energy that is lower. In one test of 23 commercial defibrillators, the average delivered output to a standard load was only 60% of the indicated energy (Flynn, 1972).

SQUARE-WAVE DEFIBRILLATORS

Geddes (1976) presents a comprehensive review of defibrillators and includes a description of square-wave defibrillators. The capacitor is discharged through the subject by turning on a series silicon-controlled rectifier (SCR). When sufficient energy has been delivered to the subject, a shunt SCR short-circuits the capacitor and terminates the pulse. This eliminates the long discharge tail of the

waveform. The output may be controlled by varying either the voltage on the capacitor or the duration of discharge. This design offers several advantages. (1) It requires less peak current. (2) It requires no inductor. (3) It makes it possible to use physically smaller electrolytic capacitors. And (4) it requires no relay.

DEFIBRILLATOR ELECTRODES

An important aspect of any defibrillator system is the electrodes. It is essential that they maintain excellent contact with the body so that the energy from the defibrillator reaches the heart and is not dissipated at the electrode-skin interface. If energy is dissipated at this interface, it can cause serious burns to the patient, further complicating a critical condition. To maintain good contact, the electrodes must be firmly placed against the patient. Often force-activated switches are contained within the electrode assembly, so that if firm-enough pressure is not applied to the electrodes, the circuit is interrupted and it is not possible to apply the defibrillation pulse.

A second key consideration is that the defibrillator electrodes must be safe to use. They must be sufficiently well insulated so that they do not allow any of the defibrillator output to pass through the hands of the operator. It would be tragic indeed if, in the process of the clinician's defibrillating a patient, her or his own heart were set into fibrillation. It is therefore important to consider the electrical safety of the defibrillator and electrodes.

Three types of electrodes are used for defibrillation. Figure 13.13(a) shows an internal type of electrode. It consists of the metal electrode itself, which is spoon-shaped. The electrode is placed in a well-insulated handle with protecting corrugation between the electrode and hand positions so that body fluids cannot accidentally complete the circuit between the operator's hand and the electrode. A control switch is also often located on the

handle, so that once the electrodes are in place, the operator can push the switcn to initiate the pulse.

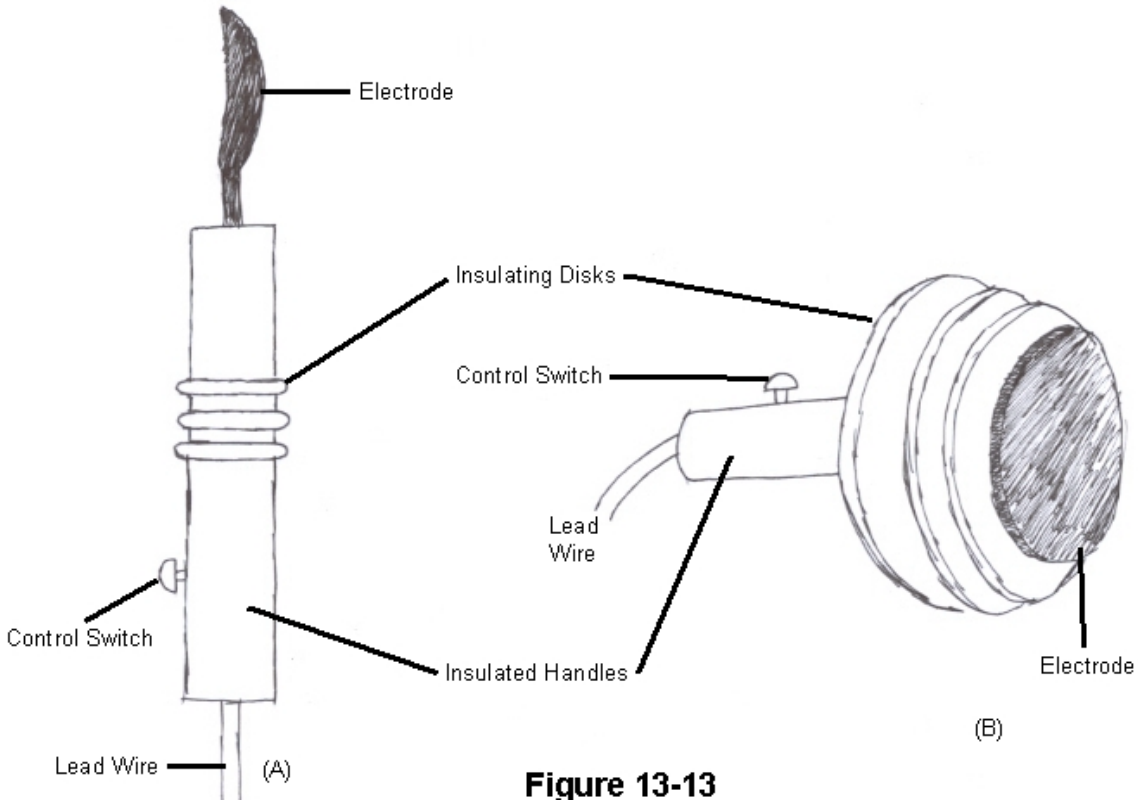

Figure 13-13

Figure 13.13(b) shows the type of electrode used for external defibrillation. It consists of a large metal disk in an insulated housing that is approximately 100 mm in diameter. The rest of the handle is similar to that for the internal electrodes, except that the insulating corrugation between the electrodes and the operator's hands are of greater diameter than the electrodes. The electrodes are sometimes called paddles because of their appearance. In operation, the electrodes (a pair must be used) are liberally coated with electrolyte gel of the type used with ECG-recording electrodes and are pressed firmly against the patient's chest. The operator then initiates the pulse with the control switch on the handle.

Disposable electrodes are also available. One type is like a large pre-

gelled ECG electrode with a 50-square cm pregelled sponge backed by foil and surrounded by foam and pressure-sensitive adhesive to keep it in place. Another type is made from metal foil faced with conductive adhesive polymer so that the entire face is pressure-sensitive.

CARDIOVERTERS

When an operator applies an electric shock of the magnitude of that from a dc defibrillator to the patient's chest during the T wave of the ECG, there is a strong risk of producing ventricular fibrillation in the patient. Because the most frequent use of defibrillation is to terminate ventricular fibrillation, this problem does not occur; there is no T wave. If, on the other hand, the patient suffers from an atrial arrhythmia, such as atrial tachycardia or flutter, which in turn causes the ventricles to contract at an elevated rate, dc defibrillation can be used to help the patient revert to a normal sinus rhythm. In such a case, it is indeed possible accidentally to apply the defibrillator output during a T wave (ventricular repolarization) and cause ventricular fibrillation. To avoid this problem, special defibrillators are constructed that have synchronizing circuitry so that the output occurs immediately following an R wave, well before the T wave occurs.

Figure 13.14 is a block diagram of such a defibrillator, which is known as a cardioverter. Basically, the device is a combination of the cardiac monitor and the defibrillator. ECG electrodes are placed on the patient in the location that provides the highest R wave with respect to the T wave. The signal from these electrodes passes through a switch that is normally closed, connecting the electrodes to an appropriate amplifier. The output of the amplifier is displayed on a cardioscope so that the operator can observe the patient's ECG to see, among other things, whether the cardioversion was successful-or, in extreme cases, whether it produced more serious arrhythmias.

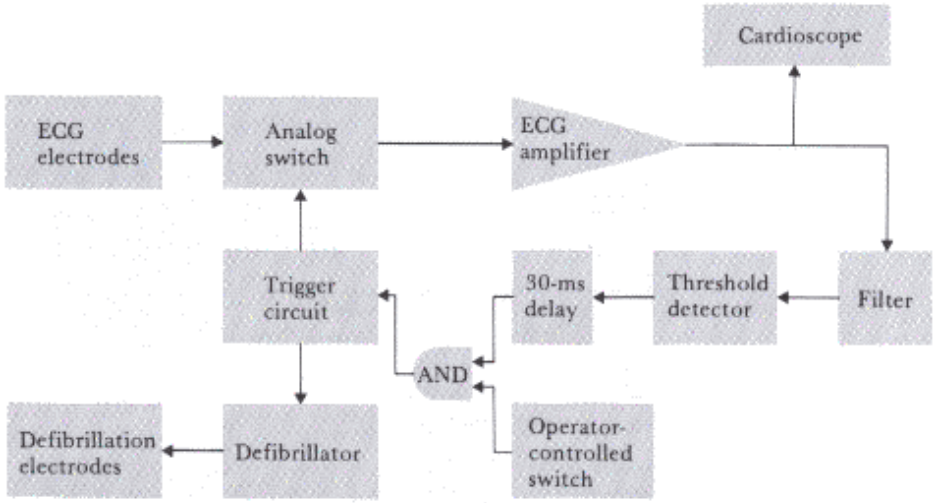

Figure 13.14 **A cardioverter** The defibrillation pulse in this case must be synchronized with the R wave of the ECG so that it is applied to a patient shortly after the occurrence of the R wave.

The output from the amplifier is also filtered and passed through a threshold detector that detects the R wave. This activates a delay circuit that delays the signal by 30 ms and then activates a trigger circuit that opens the switch connecting the ECG electrodes to the amplifier to protect the amplifier from the ensuing defibrillation pulse. At the same time, it closes a switch that discharges the defibrillator capacitor through the defibrillator electrodes to the patient. This R-wave-controlled switch discharges the defibrillator only once after the operator activates the defibrillator switch. Thus when the operator closes the defibrillator switch, it is discharged immediately after the next QRS complex. After the discharge of the defibrillator, the switch connecting the ECG electrodes to the amplifier is again closed, so that the operator can observe the cardiac rhythm on the cardioscope to determine the effectiveness of the therapy.

IMPLANTABLE AUTOMATIC DEFIBRILLATORS

It is well known that electrodes placed directly on the myocardium require less energy to defibrillate the heart than do transthoracic electrodes. It is

also widely accepted that the earlier defibrillation can be achieved, the better it is for the patient. Thus it was inevitable that implantable automatic defibrillators would be developed. These devices, similar in appearance to the implantable pacemaker, consist of a means of sensing cardiac defibrillation or ventricular tachycardia, a power-supply and energy-storage component, and electrodes for delivering a stimulus pulse should it be needed. The need for defibrillation is determined by processing the electric signals picked up by the implanted defibrillation electrodes, In some experimental devices, mechanical signals related to ventricular tachycardia and myocardial fibrillation were used to determine the need for a fibrillation pulse.

Energy storage adequate to provide pulses of from 5 to 30 J is necessary in the implantable defibrillator. This is considerably less than the amount of energy required for both the transthoracic defibrillator and those used on the exposed heart. The electrodes used with the implantable defibrillator are similar to those used with a cardiac pacemaker. They can be located in pericardial tissue, within the myocardium, or in the ventricular lumen. Although the first human implant of an automatic defibrillator occurred in 1980, it was not until eight years later that commercial devices appeared on the market for widespread application. Today, the implantable defibrillator is part of the cardiologist's armamentarium for treating cardiac fibrillation and tachyrhythmias, just as the pacemaker has become a major therapeutic method for treating bradyarrhythmias.