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28. Defibrillators and ICD Systems

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Defibrillation is the definitive treatment for the life-threatening cardiac arrhythmias, ventricular fibrillation, and pulseless ventricular tachycardia. Defibrillation consists of delivering a therapeutic dose of electrical energy to the affected heart with a device called a defibrillator. Defibrillators can be external, transvenous, or implanted, depending on the type of device used or needed. Some external units, known as automated external defibrillators (AEDs), automate the diagnosis of treatable rhythms, meaning that lay responders or bystanders are able to use them successfully with little, or in some cases no, training at all except safety precautions also covered in this chapter (Sects. 28.1–28.5). An implantable cardioverter-defibrillator (ICD), described in Sect. 28.6, is a small, battery-powered electrical impulse generator which is implanted in patients who are at risk of sudden cardiac death due to ventricular fibrillation and ventricular tachycardia. The device is programmed to detect cardiac arrhythmia and correct it by delivering a jolt of electricity.

Variable impulse generation or conduction can cause arrhythmias, with the result that the coordination of the myocardial fibers is impaired, suspended or even plunged into chaos (fibrillation). Ventricular fibrillation is uncoordinated myocardial fibrillation with no ejection from the ventricles, being characterized on an electrocardiogram (ECG) by irregular and disorganized depolarizations with high frequency. Pulseless ventricular tachycardia is characterized by a regular and rapid sequence of broad QRS complexes, and as with ventricular fibrillation, there is no ejection. Both types of rhythm are life-threatening conditions of the cardiovascular system and are thus indications for defibrillation. Defibrillation is understood as meaning a brief, phasic pulse of energy which is intended to bring about simultaneous depolarization of all the myocardial fibers, which means that, after approximately 5 s of administering an electrical pulse, no ventricular fibrillation or ventricular tachycardia can be detected any longer in the ECG. The objective of this measure is to terminate tachycardic ventricular and supraventricular arrhythmias so that, following a refractory period (no excitation is possible in this phase) which generally lasts between 200 and 500 ms, the sinus nodes once more assume the pacemaker function as the primary center of excitation.

Defibrillators are electrotherapeutic high-voltage devices which are used within the course of resuscitation and to terminate tachycardic ventricular and supraventricular arrhythmias (Fig. 28.1).

Fig. 28.1 ECG documentation of a defibrillation

Ventricular fibrillation (HF ≈ 300/min)　　　Defibrillation　　　Normal sinus rhythm
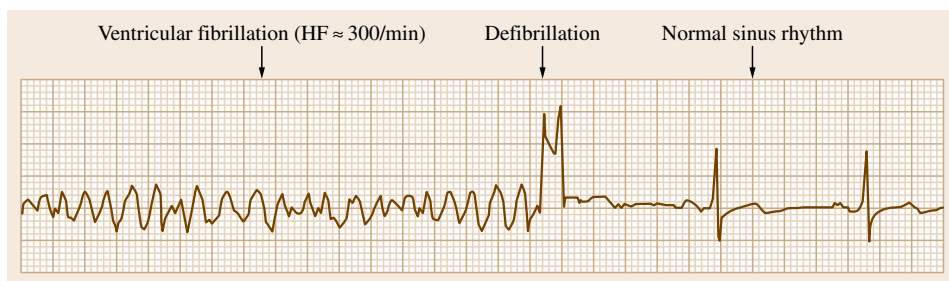
28.1 Defibrillator Technology

28.1.1 Physical Principles

The portable defibrillator is a direct-current (DC) voltage system which is usually not dependent on mains electricity (Fig. 28.2) and which is essentially composed of the following system components:

- The energy supply via mains connection or rechargeable batteries
- A capacitor as an energy store (capacity = n pulses at 360 J)
- A charging circuit for the capacitor (duration of charging, i.e., when the maximum energy is reached, is on average 10^{-8} s, considerably less in some manufacturers' models), and a discharge circuit which delivers the current pulse at different, preselectable energy levels (e.g., 2–360 J).

The DC pulse stimulation ranges between 3 and 8 ms at current of 10–27 A (internally) and 22–60 A (externally).

Automatic safety discharge should occur when no shock is triggered (after ≈ 10 s), when the defibrillator shock is triggered, and when a new energy level is preselected, as well as in the event of technical malfunction.

The energy (E) which can be stored in the capacitor can be determined from the capacity (C) and the available voltage (U) as

$$E = \left(\frac{1}{2}\right) CU^2 , \quad (\mathrm{VA} = \mathrm{W}) .$$

Waveform of the Energy Shock

The terms waveform and curve technology are understood as referring to the time-based sequence of energy output. The shape of the wave dictates firstly how much energy is supplied to the patient and secondly over what period this energy is administered. The optimum amount of energy for the defibrillator pulse is the amount of energy which causes least myocardial damage. A distinction is made between mono-, bi-, and triphasic defibrillation shock configurations (Fig. 28.3). Whereas, in the case of the monophasic waveform, the current only flows in one direction and the polarity does not change, with the biphasic waveform the current is delivered in one direction, interrupted, and continued in the opposite direction. Here, the polarity changes with every phase. The main forms of the biphasic discharge characteristic are the truncated exponential curve and the square pulse. Today, particularly in the case of implantable and automatic external defibrillators, biphasic shock forms are preferably used, which differ as a result of varied adaptation to the thoracic impedance of the patient (e.g., different pulse output, peak-to-peak voltage, and pulse duration) and are more effective on the first shock administered than monophasic shocks. Biphasic defibrillations are generally more effective and gentler on the heart than monophasic ones and have the advantage that the shock-induced dysfunction of the myocardial cells is less and that defibrillation success can be achieved with lower energy and voltage. The device-dependent amount of energy is 150–200 J for the first defibrillation and 200–360 J for all others, whereas it is always 360 J in the first monophasic defibrillation. In addition, biphasic pulse forms allow devices to be further miniaturized.

Whereas the optimum energy flow in monophasic defibrillation is somewhere in the range from 30 to 40 A s, with biphasic shock it is believed to be in the range from 15 to 20 A s. Defibrillators whose administered shock corresponded to the real transthoracic flow would be preferable. Some of the biphasic defibrillators which are available on the market use very different
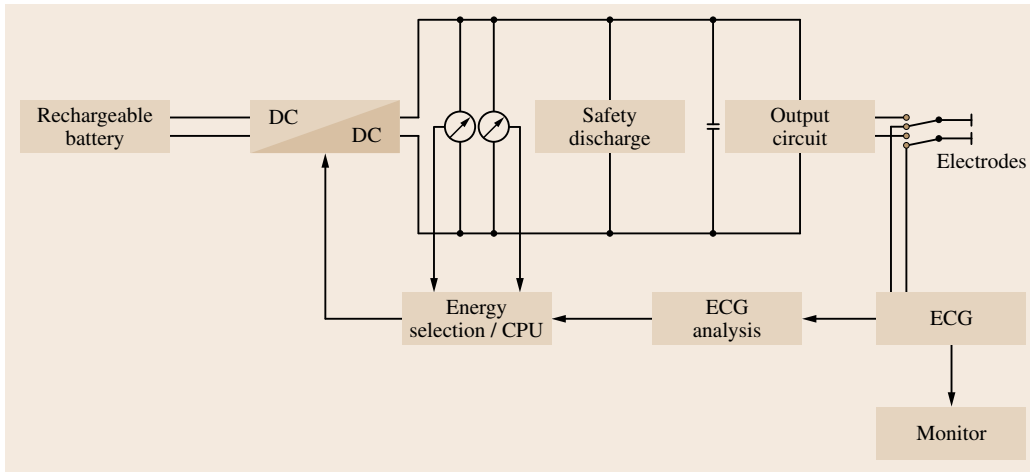
Fig. 28.2 Block diagram of a semiautomated DC defibrillator (after [28.1])

manufacturer-specific pulse forms. There is currently no general consensus about the effectiveness and potential negative effects of the various pulse forms on offer. The operating modes are divided into asynchronous and synchronous operation: whereas the heart's own pulses are taken into account in the synchronous operating mode (so-called sync pulse or QRS triggering), this is not done in the asynchronous operating mode. The latter operating mode should be reserved for *strictly emergency defibrillations*. Only the synchronized operating mode is suitable for cardioversion.

Thoracic Impedance

Thoracic impedance is the resistance in the body which opposes the energy pulse or flow from the defibrillator.

It ranges between 15 and 150 Ω; usually it is 70−80 Ω. The impedance should therefore be taken into consideration when the necessary energy is administered, as the patient's thoracic impedance is crucial to the amount of energy required. Because the impedance varies to a large degree in humans, dynamic adaptation of the waveform of the energy pulse is an important feature. In modern devices, the thoracic impedance is automatically measured and taken into account before defibrillation, meaning that energy can be delivered more accurately. Larger electrodes incidentally reduce the impedance.

Defibrillators can be divided into manual defibrillators, semiautomated and automated external defibrillators (AED), fully automated defibrillators, and defibrillator implants (Fig. 28.4). The criterion for
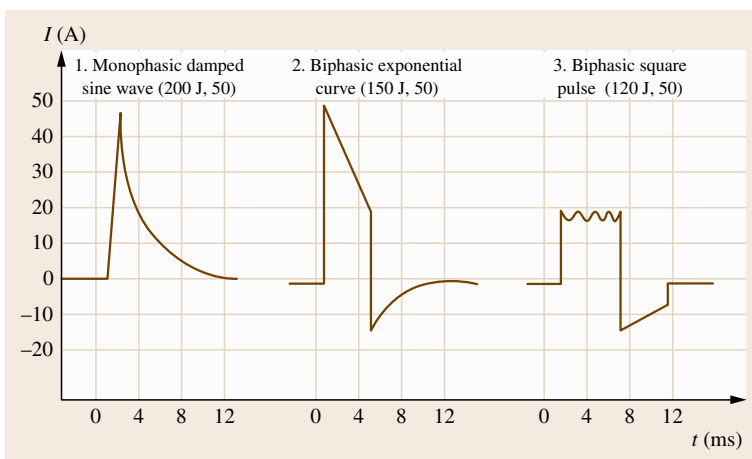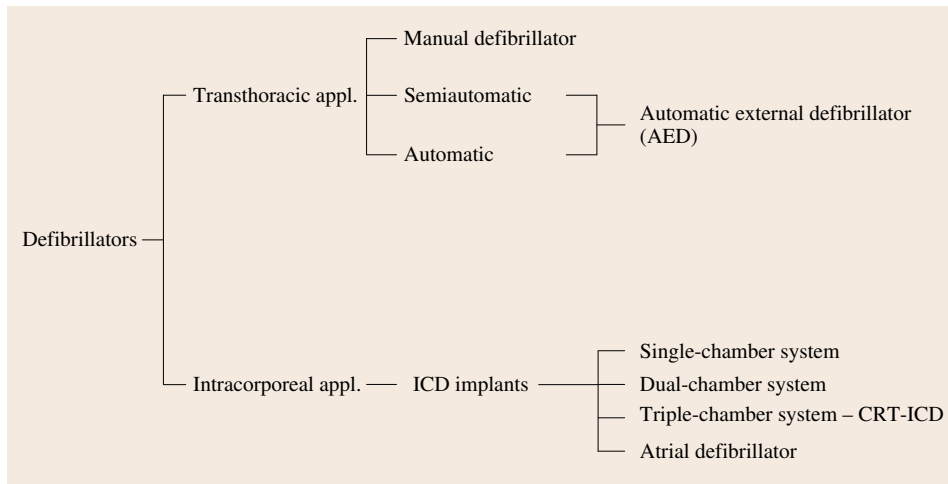

Fig. 28.3 Monophasic and biphasic pulse forms

Fig. 28.4 Overview of types of defibrillator devices

distinguishing between semi- and fully automated defibrillators is that, with the semiautomatic defibrillator, the user is shown a defibrillation recommendation and the administration of the pulse is triggered by the user, whereas this is done automatically with a fully automated defibrillator. The electrodes used are so-called paddles, adhesive electrodes or internal paddles.

28.1.2 System Properties

In addition to the conventional manual defibrillators, there are also semiautomated and automated systems (AED), which perform an automatic ECG analysis via attached electrodes and have an integrated display. Defibrillation without a monitor or display and without rhythm analysis is known as *blind defibrillation*. Modern defibrillators have a *quick look* monitoring device in the paddles. When ventricular fibrillation is detected, in a semiautomated device (Fig. 28.5) the user is given a recommendation to defibrillate.

The expandable functionality, which is usually achieved using pluggable modules, makes the real system properties possible in semiautomated defibrillators and modules: integrated external pacer (transthoracic pacemaker), noninvasive blood pressure, S_pO_2, capnography, arrhythmia detection, and recording component for documentation. Within the scope of quality assurance for a defibrillation which has been performed, complete recording by the device is of particular interest, including ECG recording and 12-channel ECG reports as well as recording of all other relevant data for later evaluation and documentation. The possibility of remote transmission of data, for example, from the ambulance to the hospital's emergency department, will also play a relatively large role in the future.

Form Analysis of Ventricular Fibrillation

To determine the optimum time to deliver the defibrillation pulse when fibrillation characteristics are definitely present, computer-aided form analysis of ECG signals is a promising and innovative new development which is currently still being researched. It involves evaluating the frequency and amplitude characteristics of the surface ECG using so-called fibrillation scoring algorithms. This algorithm is based on linear (e.g., Fourier analysis, wavelet theory) and nonlinear methods (such

Fig. 28.5 Semiautomated defibrillator with paddles (courtesy Schiller)

as an $N(\alpha)$ histogram, which can be used to investigate the degree of randomness in a signal). Further advantages of this technology may be that ineffective energy pulses are avoided and damage to the myocardium is thereby limited, and that information is provided about the quality of the resuscitation performed.

Automated External Defibrillator

AED systems – predominantly using two-phase curve technology – only deliver a defibrillation pulse if there is a life-threatening cardiac arrhythmia present which is recognized as such by the device. The user (or also semiskilled lay helper in the case of *public access defibrillation*) is also guided by means of a control menu. Modern systems additionally offer a voice-controlled user interface. The American Heart Association (AHA) takes the view that up to a third of all deaths resulting from sudden cardiac death could be prevented by widespread AED use. The use of AED systems is classified as an integral part of basic resuscitation measures.

28.2 Therapeutic Intervention

Synchronized defibrillation (Fig. 28.6) is referred to as electrical cardioversion, i. e., the pulse of energy is triggered by the R wave in the ECG.

28.2.1 Defibrillation/Cardioversion

This synchronization is carried out to prevent the pulse being delivered in the vulnerable phase (T wave) and to prevent the risk of ventricular fibrillation being triggered. In contrast, asynchronous cardioversion, which takes place independently of the R wave, is what is known as defibrillation (Fig. 28.7). From a hemodynamic point of view, blood is no longer or is hardly pumped into the circulatory system during ventricular flutter and fibrillation, as the individual muscle fibers do not contract in a coordinated fashion. In the case of atrial flutter and fibrillation, approximately 20–30% less blood is ejected since the filling capacity of the ventricles is not optimized as a result of atrial contraction being stopped. Indications for electrical cardioversion are:

- Atrial flutter and fibrillation
- AV junctional reentrant tachycardia
- WPW (Wolff–Parkinson–White-syndrome) and ventricular tachycardia.

With ventricular fibrillation, defibrillation is the only therapy which can be used that has any prospect of success. Electrical cardioversion is contraindicated in digitalis overdose, hypokalemia, and atrial fibrillation (if there is deficient anticoagulation for at least 2–3 weeks and arrhythmia for longer than 48 h).
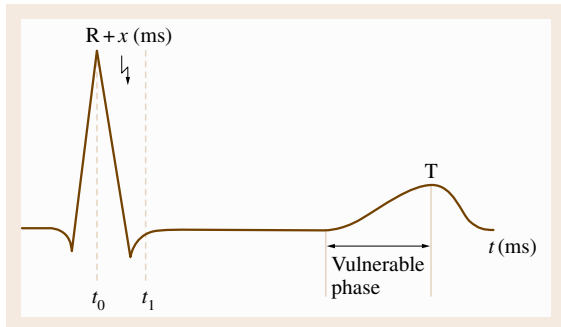
Fig. 28.6 Synchronized defibrillation at the point $R + x$

Fig. 28.7 Method overview for defibrillation/cardioversion

28.2.2 External and Internal Defibrillation

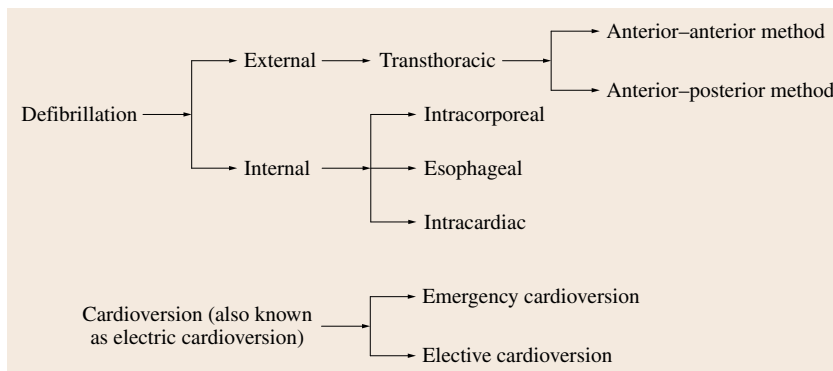External, transthoracic defibrillation is performed by means of electrodes and pulses of energy from $\approx 2\,\text{J}$ up to $360\,\text{J}$. As a guide value which is dependent on the body weight, a pulse strength of $3\,\text{J/kg}$ is recommended for adults and $2\,\text{J/kg}$ for children. In terms of electrode application, a distinction is made between the anterior–anterior method and the anterior–posterior method: whereas in the anterior–anterior method, which is mainly used in emergency situations, both electrodes are placed on the thorax (at the base and apex of the heart), in the anterior–posterior method a large-area electrode is placed below the back. The anterior–posterior method is preferred for electrotherapy in the case of arrhythmias, since the largest proportion of the administered pulse of energy flows directly through the myocardium. For internal, that is to say intracorporeal, defibrillation, sterile internal paddles are used which in the case of an open thorax cover the exposed heart (in this case the pericardium), i. e., the surfaces of the electrodes must be in contact with the myocardium over its entire area. For internal defibrillation the energy pulse is a maximum of $50\,\text{J}$.

Special Applications

Esophagus. An esophageal pulse electrode (cylindrical electrode at the end of a catheter) is placed at the level of the left atrium. The counterelectrode is attached to the thorax. An additional electrode to the cylindrical electrode enables bipolar stimulation and recording of an esophageal ECG signal which is used to synchronize the energy pulse.

Intracardiac. This application is likewise carried out using a catheter. One electrode lies at the apex of the right ventricle, while the second electrode is placed in the superior vena cava.

28.3 Methodological Notes

In principle, all commercially available defibrillators are operated in the same way and are suitable for both internal and external defibrillation. As a rule, a visual and/or acoustic signal is generated when the defibrillator is operational, i. e., when the capacitor is charged. The electrodes, which are provided with gel, are placed firmly on the thorax and pressed on, and the preselected energy dose is triggered. This is usually done directly via a trigger on the handles. Owing to the ERC Guidelines of 2005, the practice of performing defibrillation three times within the space of a minute using mono- and biphasic defibrillators is obsolete. This application model has been replaced by delivery of a single shock at full energy (so-called one-shock strategy); i. e., with a monophasic shock, $360\,\text{J}$ is recommended for delivery of the shock. For the first biphasic shock, at least $150–200\,\text{J}$ is advised for all discharge characteristics. Following each shock, cardiopulmonary resuscitation should be performed for $2\,\text{min}$ before administering the next shock. If further shocks are necessary, with monophasic defibrillators the energy level is kept at $360\,\text{J}$ and with biphasic defibrillators the energy level is in contrast successively increased.

The energy pulse delivered and its amplitude, the form and polarity of the shock, the electrode size and position, and also the homogeneity of the current density in the cardiac muscle (myocardium) are all crucial for efficient defibrillation or cardioversion.

28.3.1 Electrodes and Contact Agents

Correct application of the adhesive electrodes is necessary to achieve faultless ECG recording and ultimately to prevent equipment-related interpretation errors. Despite being more expensive, self-adhesive defibrillation electrodes (so-called pads) are safe and effective and should therefore be preferred over normal plate electrodes (so-called paddles). Another advantage of adhesive electrodes from the viewpoint of the operator is that it is possible to defibrillate from a *safe distance*, without having to lean over the patient. It is also quicker to administer the first pulse of energy using self-adhesive electrodes than it is with paddles. Whereas with paddles a contact gel is needed between the skin surface and the metal plate in order to reduce the skin impedance – and thus improve the electrical contact – and also to prevent burns, this is not necessary with adhesive electrodes. Compared with electrode paste and gels, gel pads are favorable for safe operation because they avoid the risk of arcing and of a short circuit and thus prevent ineffective defibrillation. The Association for the Advancement of Medical Instrumentation (AAMI) recommends a minimum electrode

area of $150 \, \text{cm}^2$, since larger electrodes have a lower impedance or even lead to a decrease in the transmyocardial flow. The diameter of customary electrodes is in the region of $8-12 \, \text{cm}$ for adults and children with body weight $> 10 \, \text{kg}$ and $4.5 \, \text{cm}$ for children with body weight $< 10 \, \text{kg}$.

28.4 Complications

Cardioversion and defibrillation can result in the following serious and minor complications:

- Induced ventricular fibrillation, e.g., as a result of incorrect triggering, which can ultimately lead to asystole (cardiac arrest) (currents $> 10 \, \text{mA}$ flowing through the heart can cause fibrillation in the ventricles).

- Postdefibrillation arrhythmias such as ventricular and supraventricular extrasystoles and ventricular flutter.
- Arterial embolisms.
- Burns and irritation of the skin, for example, due to an insufficient amount of electrode contact paste being used on the electrode surface.

28.5 Technical Safety Aspects

28.5.1 Use

- Avoid direct contact with the electrodes (life-threatening), conductive contact with the patients or other people (safe distance).
- There should be no moisture on the patient's skin (electrical bridge), and the patient should also be positioned such that he is electrically isolated.
- Only perform cardioversion if the ECG is free from artifacts and if reliable ECG monitoring is possible. When too much electrode contact paste is used on the paddles there is the possibility of an electrical bridge forming (risk of short circuit).
- All additional devices which are connected to the patient must be defibrillation proof; otherwise, they must be disconnected from the patient during cardioversion/defibrillation.
- Caution should be exercised with patients with energized implants: the functioning of the implant may be restricted or suspended, and the implant itself may be damaged or may even become unusable.

28.5.2 Device

- Defibrillators belong to class IIb of the German Medical Devices Act (MPG, Medizinprodukte Gesetz).
- Defibrillators must only be used in an explosion-proof atmosphere.
- Devices which are not defibrillator proof must be disconnected from the patient, otherwise
- Equipment should be labeled according to DIN-IEC 601 as defibrillator proof.
- Maximum energy 360 J.
- Trigger buttons only on both paddles (connected in series).
- Protective circuits, which ensure a reduced power setting when the defibrillator is switched off and ensure energy recovery no later than 1 min after defibrillator charging.
- Because of their unforeseeable and frequently changing use, defibrillators should always be connected to mains electricity at their device base locations so that they are operational and ready for use on an ad hoc basis.

28.6 Implantable Cardioverter-Defibrillators

Implantable cardioverter-defibrillators (ICD) are primarily used for reliable detection and treatment of life-threatening cardiac arrhythmias (ventricular tachycardia and fibrillation) which originate in the ventricles and which cannot be treated with medication (Fig. 28.8). The American and European Societies of Cardiology (American College of Cardiology (ACC)/AHA and ESC) also recommend ICD implantation in patients who have survived sudden cardiac death which did not occur as a result of myocardial infarction and also for primary prophylaxis in patients with restricted cardiac pumping function (EF $< 30\%$). When necessary,

Part D | 28.6

Fig. 28.8
Chest x-ray with
implanted ICD
system (courtesy
Medtronic)
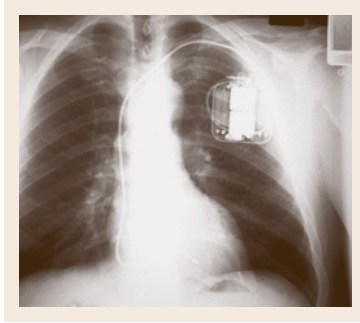
ICD systems can also administer pacemaker pulses
in bradycardic phases. ICD systems can also provide
antitachycardic stimulation, cardioversion, and defibril-
lation.

ICD implantations have increased significantly in
numbers. The following reasons are vital to this devel-
opment:

- A simplified implantation technique reduces the
  rates of mortality resulting from surgery.
- Very low morbidity.
- High level of patient acceptance.
- ICD therapy has considerable advantages over
  medicinal therapy for prevention of sudden cardiac
  death – within the scope of secondary prophylaxis,
  for example, following hemodynamic ventricular
  tachycardia.
- For idiopathic ventricular fibrillation there is cur-
  rently no alternative to ICD therapy.
- A further indication is primary prophylaxis for high-
  risk patients with no symptoms.
- The costs of ICD therapy have decreased consid-
  erably as a result of a reduction in product prices
 alongside increasing product life.

28.6.1 ICD Development

The following chronological events are of particular
significance in ICD development. The first transtho-
racic defibrillation with direct current was carried out
by Lown in 1962. The first model of an implantable
automated defibrillator (*automated implantable cardio-
verter-defibrillator*, AICD) was presented by Mirowski
as early as 1969 and was implanted in a human for
the first time in 1980. This system was used to detect
ventricular flutter and fibrillation using the criteria of
heart rate and/or absence of isoelectric ECG portions.
Detection of arrhythmias was done using myocardial
screw-type electrodes. A programmable ICD system
was used in clinical practice in 1988 and a multipro-
grammable ICD system in 1989. The first dual-chamber
ICD came onto the market in 1997, while an atrial defib-
rillator was implanted as early as 1996. ICD electrodes
placed intra-atrially are a safe and effective method for
terminating atrial fibrillation. The advantages of this
are firstly the low energy output and secondly that the
patient does not require short anesthesia.

A combined atrioventricular defibrillator was first
implanted in 1997. More sophisticated atrioventricular
defibrillators have the advantage that, besides provid-
ing fully automated detection of atrial and ventricular
signals, they also deliver electrical pulses to both ven-
tricles in order to terminate arrhythmias which occur.
So-called implantable CRT defibrillators (CRT-ICD
for short) for cardiac resynchronization therapy (CRT)
have been available since 2001. These devices deliver
a shock to interrupt and therefore stop tachycardia.
The right and left ventricles are also stimulated si-
multaneously so that the cardiac beats are coordinated
(resynchronized, in the true meaning of the word)
(Fig. 28.9).

Fig. 28.9a,b
Implantable
biventricular or
CRT-ICD sys-
tem. (**a**) Position
checking in the
x-ray image.
(**b**) Schematic
electrode posi-
tioning (courtesy
of Biotronik)
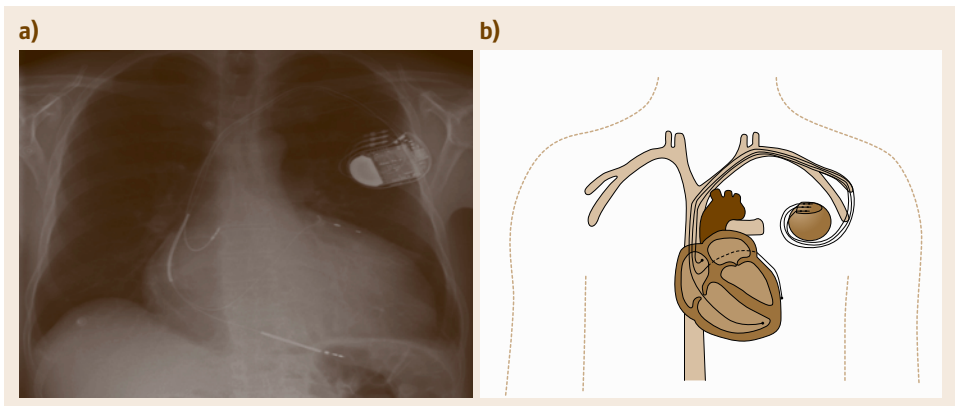
28.6.2 System Technology

Miniaturized construction, more effective defibrillation as a result of low-energy pulses, and improved and updated software enable subpectoral implantation with transvenous electrode insertion under local anesthetic to be standard practice today (Fig. 28.10).

Conventional products have volume $< 40\,\text{cm}^3$ and weight $< 80\,\text{g}$, with average device lifespan of 4–6 years. Today, ICD technology provides fine-tuned, integrated systems:

- Single-chamber ICD (ventricular rate adaptive/rate modulation (VR) system) with the therapeutic possibility of antitachycardic stimulation, cardioversion, and defibrillation. The defibrillator electrode is placed in the right ventricle.
- Dual-chamber ICD (dual rate adaptive/rate modulation (DR) system) with an additional atrial electrode or *single-lead ventricular pacing with atrial tracking-ICD (VDD-ICD)*.
- Triple-chamber ICD (biventricular defibrillator system, CRT-ICD) with the additional possibility of cardiac resynchronization therapy (CRT). The electrode fixed in the right ventricle is supplemented by a further electrode (a so-called coronary sinus electrode) which selectively stimulates the left ventricle (Fig. 28.9a,b).

Just as there is the international pacemaker code (North American Society of Pacing and Electrophys-
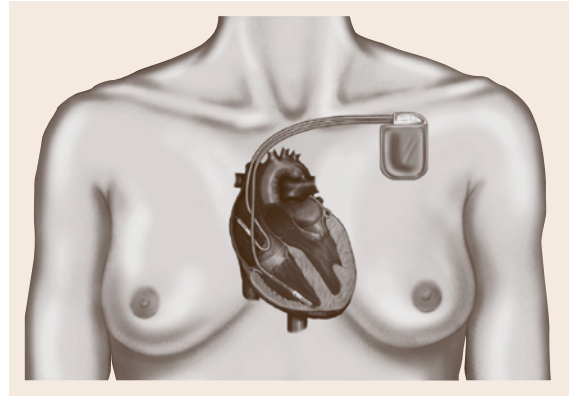

Fig. 28.10 Implantable ICD system (schematic) (courtesy Medtronic)

iology/British Pacing and Electrophysiology Group generic Pacemaker Code (NBG), Chap. 38), there is also a code for ICDs (Table 28.1).

An ICD system consists of a generating unit (or pulse generator) and an electrode. The generating unit includes the housing, the battery (lithium iodide), capacitors, microprocessor, amplifier, magnetic switch, audio transducer for signals, antenna for telemetry, and a connection head for electrodes. The electrode (or probe) consists of an isolated electrode body with a multilumen construction. The conductors for detection, stimulation, and defibrillation are arranged inside the electrode, isolated from one another.

Table 28.1 The NASPE/BPEG defibrillator (NBD) code (after [28.2])

I Shock chamber	II Antitachycardia stimulation chamber	III Tachycardia detection	IV Antibradycardia stimulation chamber
0 = none	0 = none	E = intracardiac EG	0 = none
A = atrium	A = atrium	H = hemodynamics (H includes E)	A = atrium
V = ventricle	V = ventricle		V = ventricle
D = dual (A + V)	D = dual (A + V)		D = dual (A + V)
Short-form code			
ICD-S	ICD with shock capability only		
ICD-B	ICD with bradycardia pacemaker as well as shock		
ICD-T	ICD with tachycardia and bradycardia pacemaker as well as shock		
Additional note: Site of detection and stimulation: Single-chamber system = atrium *or* ventricle, dual-chamber system = atrium *and* ventricle. Reaction to detection: 1. Triggered: synchronous stimulation at available and nonadjustable frequency when there is no cardiac activity. 2. Inhibited: when cardiac activity is present, delivery of a pulse is suppressed. 3. Frequency adaptation: stimulation frequency is adapted to the physical strain at the time. The coding is listed on the ICD housing and in the ICD documentation.			

Depending on the ICD model, the therapy possibilities are:

1. Pacing (pacemaker function in the case of brady-cardic cardiac arrhythmias)
2. Antitachycardic pacing (ATP, the intention is to terminate ventricular tachycardias with overstimulation – a so-called burst with every *n*-th stimulus)
3. Cardioversion (when ATP is unsuccessful, a shock of energy of 15–20 J is automatically administered, and up to 35 J for further shocks)
4. Defibrillation (in the case of ventricular fibrillation, a shock of energy is initiated immediately with an upper limit, depending on the device, of 35–40 J).

Integrated ventricular demand rate-responsive pacing (VVIR) or dual chamber rate-responsive pacing (DDDR) pacemaker circuits (Chap. 38) are standard in modern ICD technology. The operational lifespan of dual-chamber systems is somewhat shorter than that of single-chamber systems. New shock forms, improved electrode systems, and optimized shock delivery are leading to a considerable reduction in the defibrillation threshold (DFT), which today is generally below 15 J. There is also the fact that short and constant charge times prevent the DFT from increasing. Biphasic or sequential defibrillator pulses are currently preferred in clinical use. Studies have confirmed that the pulse of energy required increases with the duration of ventricular fibrillation and with the increase in conduction fronts, and conversely that the sooner the ventricular fibrillation is terminated after it arises, the lower the energy. Comprehensive diagnostic program memories, which in the context of patient aftercare enable validation of the therapeutic intervention, are part of today's standard equipment. Some ICD devices provide the option of telemetry transmission of recorded intracardiac electrograms via an antenna in the head of the ICD implant. The periodic or event-triggered reports are transmitted via mobile telephony to an Internet-based database by means of a mobile patient unit. The attending doctor can then access the transmitted data via the Internet.

28.6.3 Algorithms

Internal ECG signal detection algorithms analyze the amplitude, frequency, and slew rate of the ECG. Errors in the interpretation of tachycardic arrhythmias can lead both to false ICD discharges and to erroneous failure to detect ventricular arrhythmias (so-called undersensing). Detecting ventricular arrhythmias and differentiating them from supraventricular arrhythmias is based on dif-

ferent algorithms for detection and differentiation. The cardiac rhythm frequencies which emerge are classified and assigned to up to six detection zones: a bradycardia zone, a sinus rhythm zone, a fibrillation zone, and one to three tachycardia zones.

ICD algorithms distinguish between supraventricular and ventricular tachycardias on the basis of criteria such as frequency stability, QRS width criterion (if, for example, six out of eight QRS complexes are wider than in the sinus rhythm), sudden-onset rapid heartbeat, the relationship between atrial and ventricular signals, the site of acceleration and AV association, or distinguishes between different variants in the AV relationships by means of detection of a pattern over a period between two RR intervals. Detection criteria can be programmed in the sensing system responsible for detection and re-detection. Furthermore, it is also possible to include atrial events in the detection algorithms. The mode switch algorithm induces an automatic change of operating mode from the DDDR to the dual chamber demand rate-responsive pacing (DDIR) mode to ensure that, after high atrial frequencies have been detected, the triggered mode for ventricular stimulation is actuated in aid of inhibited operation. To increase the sensitivity and specificity of the detection of ventricular tachycardias in ICD therapy, in addition to the electrical criteria it is also a good idea to take into consideration information about the hemodynamic situation, such as the contractility of the left ventricle.

28.6.4 Electrodes

If ICD implantation was still a complex surgical procedure at the beginning of the 1990s, then the development of a transvenous electrode was a considerable simplification. The combination of transvenous electrodes with subcutaneous defibrillation electrodes is a vital step forwards.

The electrically active generating unit housing (*active can*) and/or proximal section of the defibrillation probe is used as the anode, while the section of the electrode in the right ventricle functions as the cathode. A distinction is drawn between two configurations: the single-coil probe from the right ventricle to the ICD housing, and the dual-coil probe with a defibrillation surface between the right ventricle, the superior vena cava, and the ICD housing (triad configuration), which is the most favorable in terms of energy. If the section of the electrode in the right ventricle functions as an anode due to programming, this reversal in polarity likewise results in a reduced energy requirement during defibrillation.

This measure is particularly suitable for patients with a very high defibrillation threshold. The signal detection function and antibradycardic stimulation are performed via the tip of the probe, which is constructed in true bipolar fashion (between the electrode tip and a proximally positioned ring) or in integrated bipolar fashion (between the electrode tip and the distal shock coil).

Modern ICD electrode bodies have a multilumen construction, and a few are coaxial. Silicone is predominantly used (or less often polyurethane) as the insulation for the external layer of the probe and offers a high level of biocompatibility and flexibility but is very sensitive to mechanical stress. Other distinguishing features of transvenous probes are the number of defibrillation probes (one or two) and the number of coils (single or dual). Active or passive fixing of ICD electrodes can be done using fixed screws or extensible screws and using anchors.

Atrial and epimyocardial electrodes and coronary sinus electrodes (CS or superior vena cava (SVC) electrodes) are used as additional pacing/sensing electrodes. The CS electrode has at its distal end an acceleration sensor, which is used to record and differentiate acceleration values in at least two different directions.

A special shock probe is the array electrode (also known as a finger electrode or SQ array), which is implanted subcutaneously. This electrode has up to three shock coils and is used additionally when there is an insufficient defibrillation threshold. The individual coils of the finger electrode are connected in parallel with the right-ventricular shock coil via a Y-connector.

The single-lead VDD-ICD is an electrode system for a dual-chamber ICD. The atrial signals are recorded at this electrode, which is fixed in the apex of the right ventricle, by means of two electrode rings. This electrode thus replaces the otherwise additional atrial electrode. Bipolar and tripolar ECG leads in ICD systems enable reliable ischemia detection, which has considerable advantages over the conventional surface ECG owing to the early detection of ischemias and also their severity and duration.

28.6.5 Complications

The spectrum of ICD complications ranges from harmless complications, such as skin irritations and minor burns on the areas where the electrodes have been applied, to serious complications, such as the emergence of extrasystoles following defibrillation, ventricular tachycardia, ventricular fibrillation (in the case of incorrect triggering) or the occurrence of asystole following electric cardioversion in the case of sick sinus syndrome. ICD-specific complications can be caused on the one hand by the generating unit:

- Pressure-related necroses
- Risk of infection
- Technical errors and malfunctions as a result, for example, of strong external magnetic fields or battery depletion
- Perforation of the generating unit

and on the other hand by the electrodes:

- Electrode dislocation can cause stimulation of muscles
- Inadequate administration of shocks as a result of detection of muscle potential or external sources of interference
- Fractures in the electrodes, defects in the insulation or a rise in the sensitivity threshold can cause electrode malfunction.

One malfunction in the detection function (sensing) is undersensing or oversensing. In the case of undersensing, life-threatening arrhythmias are not detected or are detected too late, whereas with oversensing the shocks administered are inadequate.

28.6.6 Function Checking

Whereas in the early days of ICD device technology it was still necessary for technical reasons to test the functioning of an ICD patient's implant every 2 months, this check is now carried out independently by the device itself. Function checking of the system (ICD query, analysis of stored ECGs, battery status, detection test, etc.) every 3–6 months is sufficient. If there is an indication of incorrect detection (*so-called* over- or undersensing), a chest x-ray is generally performed to identify insulation defects in the probe. Because of the improvement in battery technology, the shelf-life of single-chamber systems should be ≈ 9 years, dual-chamber systems should last ≈ 7 years, and triple-chamber systems ≈ 5 years. The lifespan of the device will therefore be considerably longer than that of previous ICD systems. Replacement of the generating unit is also only necessary at a later point in time. Stored data, such as treatment episodes, electrograms, battery state, and electrode resistance, can be queried via telemetry. For the purpose of function checking, various device parameters are measured intraoperatively during pacemaker and ICD implantations and, if necessary, adjusted (Table 28.2).

Table 28.2 Limit values for intraoperative measurements during implantation of pacemakers and ICD systems (after 28.3)

	Ventricle	Atrium
Signal amplitude	> 5 mV, optimally > 8 mV	> 2 mV, optimally > 3 mV
Impedance (electrode-dependent)	300–1200 Ω	300–1200 Ω
Slew rate	> 0.5 V/s	> 0.3 V/s

Further Reading

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