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Problems with Implantable Cardiac Device Therapy

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Implantable cardioverter-defibrillators (ICDs) are known to improve survival in patients who have left ventricular dysfunction. Nevertheless, ICD implantation is associated with numerous problems at implant and during follow-up. At implant, acute surgical complications, including pneumothorax, vascular perforation, hematoma, and acute lead dislodgement, occur in approximately 2% to 4% of patients. The diagnosis and management of these problems is usually straightforward. More difficult problems at implant include the management of patients who have elevated energy requirements to terminate ventricular fibrillation (VF) or of those who have postoperative device infections. Long-term issues in ICD patients include the occurrence of inappropriate or frequent appropriate shocks. Finally, ICD generators and leads are more prone to failures than are pacing systems alone. The management of patients potentially dependent on ''recalled'' devices to deliver life-saving therapy is a particularly complex issue involving competing risks. The purpose of this article is to review the diagnosis and management of these more troublesome ICD problems.

Defibrillation threshold

Due to the need for ICD reliability to terminate life-threatening arrhythmias, it is common practice to induce VF to ensure appropriate sensing, detection, and defibrillation during ICD implantation. The success of defibrillation depends on the relationship between the spatial and temporal characteristics of the electrical field of the ICD shock (distribution of potential gradients) and the VF (critical regions or wave fronts). After an ICD shock, according to the critical mass hypothesis, the entire myocardium must be depolarized to establish a critical spatial electrical gradient to terminate VF. Thus, failure of an ICD to defibrillate maybe due failure to achieve this gradient due to inadequate shock waveform, shock vector, or delivered energy [1].

Successful defibrillation is probabilistic in nature, likely due to the spatial and temporal heterogeneities of ventricular myocardium during VF. Defibrillation threshold (DFT) is commonly defined as the minimum shock energy required to terminate VF. Although the term *threshold* is used, clinically, there is no single energy level above which defibrillation is always successful or an energy level below which it always fails. Instead, any given level of energy has a probability of defibrillating the heart [1]. DFT testing is commonly performed with a step-down protocol, which consists of reducing in a step-down fashion the delivered energy with each VF induction until a shock fails to defibrillate. The lowest delivered energy shock that successfully defibrillated VF is termed the DFT. This energy will, on average, achieve a 70% success rate of defibrillation (DFT_{70}), whereas twice the DFT energy will obtain a 98% successful defibrillation [2]. Due to the complexity of DFT protocols, a common practice is to perform two VF inductions with defibrillation energy 10 J below the maximum

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device delivery output, thereby establishing at least a 10-J defibrillation safety margin. Thus, successful defibrillation is achieved in 96% when ICD is programmed at maximum delivery output [2].

A practical alternative to potentially avoid VF induction during DFT testing is to use the upper limit of vulnerability (ULV) test. The ULV is defined as the lowest energy shock that does not induce VF when delivered during the vulnerable phase of ventricular repolarization. The ULV hypothesis of defibrillation links the ULV to the minimum shock strength that defibrillates VF reliably. The ULV has been shown to be a surrogate for DFT. A shock delivered at the ULV plus 5 J has been shown to consistently defibrillate VF [3], reaching a near DFT_{100}. Thus, a 5-J vulnerability safety margin between the ULV and the maximum device delivery shock has been suggested as an acceptable end point during ICD testing [4]. Some clinicians have not accepted inductionless ICD testing because the ULV lacks the confirmation of appropriate VF sensing by the device and occasional large discrepancies exist between the ULV and DFT in individual patients.

DFT testing is considered overall safe and rarely associated with serious complications such as myocardial stunning, cerebral hypoperfusion, intractable VF, pulseless electrical activity, and death. Predictors of high morbidity and mortality during DFT testing include multiple VF inductions, advanced heart failure, and severe left ventricular dysfunction [5–7]. Although no clinical data are published, the authors believe that patients who have severe pulmonary hypertension may carry a high morbidity and mortality during DFT testing.

Successful defibrillation requirements for VF can vary on a daily basis. Several conditions are known to affect DFT, such as electrolyte and acid-base disturbances, hypoxemia, heart failure, sympathetic tone, and drugs (Box 1) [5,7]. Therefore, DFT testing should be performed in stable and ideal conditions. Reversible causes and predictors of high DFT (see Box 1), if present, should be addressed before testing. The intraoperative mortality and morbidity rates during a transvenous ICD implantation have been estimated to be 0.1% and 1.2%, respectively [6,8]. DFT testing is overall contraindicated in the setting of high-risk features such as hemodynamic instability and left atrial or ventricular thrombus (Box 2) [5,7].

High DFT refers to the clinical scenario in which the ICD is unable to consistently defibrillate with an adequate safety margin. The medical literature usually refers to high DFT when the defibrillation safety margin is less than 10 J. The reported prevalence of high DFT has ranged from 5% to 10% [5,7]. One prospective study [7], however, did not find a higher mortality at 6-month follow-up in patients who had high DFT (>18 J).

Several causes of high DFT (see Box 1) are considered reversible and should be treated before

Box 1. Causes and predictors of high defibrillation threshold

Causes of high defibrillation threshold

- Intrinsic myocardial process
  - Electrolyte or acid-base disturbance
  - Hypoxemia
  - Heart failure
- Inadequate vector of shock
  - Poor shock lead placement
  - Shunting current between coils
- High shock voltage impedance
  - Pneumothorax/chronic obstructive pulmonary disease[a]
  - Defective connection or loose setscrew
- Suboptimal shock waveform
  - Excessively long pulse duration reinitiates VF
  - Excessively short duration truncates energy delivery
  - Inadequate second phase reinitiates VF
  - Waveform mismatch with time constant of membrane electrical response
- Drugs
  - Antiarrhythmics: amiodarone, mexiletine
  - Cocaine or illicit drug use
  - Other: fentanyl, isoflurane, halothane, sildenafil[a], venlafaxine
- Other
  - Inactive epicardial patches[a]

Predictors of high defibrillation threshold

- Amiodarone use
- Heart failure class III/IV
- Severe left ventricular dysfunction and dilatation
- Body size
- Prolonged DFT testing
- History of cocaine use

[a] Controversial or limited data.

Box 2. Contraindications for defibrillation threshold testing

Left atrial or ventricular thrombus
Severe coronary artery stenosis
Absence of anesthesia
Recent stroke or transient ischemic event
Atrial fibrillation without adequate anticoagulation[a]
Hemodynamic instability
Critical aortic stenosis[a]
Severe pulmonary hypertension[a]

[a] Relative contraindication.

testing. Known predictors of high DFT include (1) amiodarone therapy, (2) New York Heart Association class III/IV heart failure, (3) severe left ventricular systolic dysfunction or dilatation, (4) nonischemic cardiomyopathy or no previous history of bypass surgery, (5) device upgrade or replacement, (6) older age, (7) body size, and (8) prolonged device implantation time [6,7,9]. Right-sided and abdominal implants have not been shown to be independent predictors of high DFT; however, they have a higher average DFT compared with left-sided implants [9]. The Optimal Pharmacological Therapy in Cardioverter Defibrillator Patients trial [10], a randomized controlled study, corroborated that amiodarone significantly increased the DFT ($+1.29 \pm 4.39$ J) compared with small a decrease of the DFT with β-blocker agents (-1.64 ± 3.54 J on β-blockers and -0.87 ± 3.78 J on sotalol). All patients on amiodarone, however, achieved an appropriate defibrillation safety margin and experienced no effect on outcome. In addition, this trial clarified that carvedilol and other β-blockers do not increase DFT as previously reported [5].

Current ICDs with proper lead implantation can reliably defibrillate most patients successfully. Due to advances in lead technology and defibrillators, appropriate defibrillation safety margins are usually obtained without the need to modify the ICD system. In addition, no difference in long-term mortality has been demonstrated in patients who have high DFT (<10-J safety margin) and who require ICD modification [9]. Moreover, some devices may still result in effective defibrillation despite an inadequate safety margin at implant due to the probabilistic nature of DFT [2]. Therefore, recent debate has arisen questioning the true need for ICD testing [8,9].

The authors strongly believe that it is important to perform ICD testing during implantation or generator replacement, particularly in patients who have clear predictors of high DFT (see Box 1). Besides, the medicolegal implications of failure to defibrillate or unexplained death in patients who have ICD is important. Patients who have high DFTs could be identified with minimal ICD testing involving one or two VF inductions. Advances in technology and the understanding of VF and defibrillation have led to different interventions that can address the problem of high DFTs (see Box 2). The potential advantages of lowering DFT are (1) a further decrease in size of devices, (2) an increase of device longevity, and (3) shorter charge and shock delivery times.

Approach to high defibrillation thresholds

Invasive and noninvasive interventions can be made to improve defibrillation energy requirements. All interventions are intended to optimize shock configuration or vector, with subsequent improvement in defibrillation outcome. Invasive interventions are performed during ICD implantation and obviously carry a higher morbidity, whereas the noninvasive interventions can be performed in patients at implantation or during follow-up. Fig. 1 describes a suggested algorithm to approach high DFTs based on current clinical evidence for new ICD implants and chronic devices.

When high DFT and high shock impedance are noted during implantation, it is important that pneumothorax and a defective connection or a loose setscrew of the shocking coil always be excluded [5]. Invasive interventions include (1) the repositioning of right ventricular lead in an apical-septal location; (2) the use of a high-output device; (3) the addition of coils (superior vena cava [SVC], subclavian, axillary, azygous vein, and coronary sinus) and subcutaneous (SQ) arrays; and (4) alternative right ventricular coil locations such as right ventricular outflow tract.

One of the best initial interventions to lower DFTs is to reposition the right ventricular lead to a more apical-septal position, particularly if a basal position was achieved initially [5]. The most easy and straightforward approach to high DFTs is to replace the standard energy output device with a high-output energy device (maximum energy stored of 35–40 J). Even though

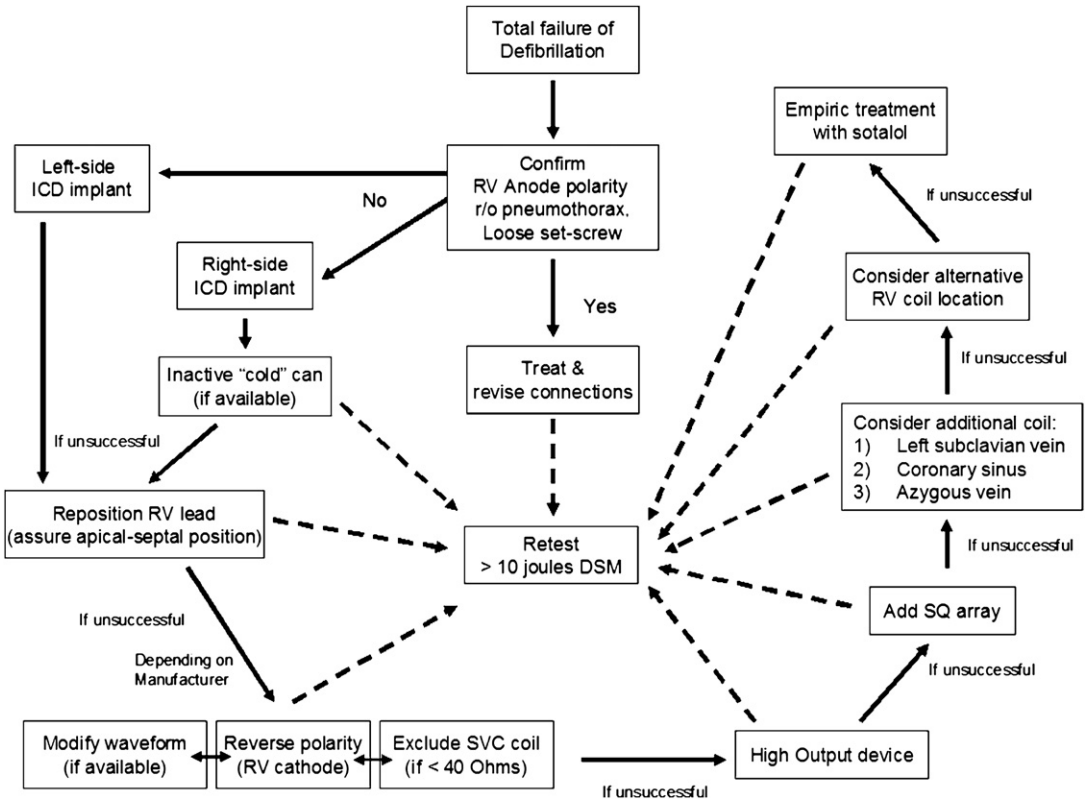

Fig. 1. Approach to high defibrillation threshold. DSM, defibrillation safety margin; RV, right ventricle; SQ, subcutaneous array; SVC, superior vena cava. (*Adapted from* Mainigi SK, Callans DJ. How to manage the patient with a high defibrillation threshold. Heart Rhythm 2006;3:45; with permission.)

a high-output device as a first option is not unreasonable, the use of a high-output device alone does not achieve an adequate safety margin in 48% of cases [9]. In addition, these devices are more expensive. Thus, the authors believe that this should not be the first option unless there is a circumstance that forces the surgeon to finish the case in a prompt manner.

The addition of coils is intended to improve the defibrillation vector, with subsequent reduction in DFTs. The SVC coils and SQ arrays have proved to lower DFTs, with few complications [11,12]. The SVC coil appears to significantly reduce defibrillation requirements, lower the percentage of high DFTs, lower shock impedance, and increase peak current, regardless of position of the SVC coil [11]. Moreover, the SQ arrays further decrease mean DFT by 4 J compared with SVC coils [12]. Other coils have limited data, such as inferior vena cava, left subclavian, brachiocephalic and azygous vein, and coronary sinus [5]. Epicardial patches appear to have lower DFTs than transvenous systems; however, these are frequently associated with lead failure, constrictive pericarditis, and patch crinkling [13].

Noninvasive interventions include (1) reverse shock polarity, (2) waveform tilt and pulse width optimization, (3) electronic exclusion of SVC, (4) "cold can" or exclusion of can, and (5) drugs known to decrease DFTs. It is unfortunate that some approaches are manufacturer specific and not always available.

Anodal right ventricular polarity decreases DFT by 15% and up to 31% in patients who have a DFT greater than 15 J [1,5]. Over the past few years, most ICD manufacturers have changed and adopted right ventricular coil anode polarity based on clinical data. Even though anodal right ventricular polarity has better defibrillation outcome, occasionally reverse polarity (cathode right ventricular polarity) may help to lower DFT and reach an acceptable safety margin. This recommendation, however, is based solely on sporadic cases.

The presence of an SVC coil (right ventricular dual-coil leads) or an SQ array makes it possible to exclude the can as part of the cathode to limit the delivered shock between anodal right ventricular coil and cathodal SVC coil, or so-called ''cold can.'' This methodology can improve DFTs, particularly in patients who have right-sided implants. This feature, however, is only available from specific ICD manufacturers.

Occasionally, electronic exclusion of SVC may be helpful to reach an appropriate defibrillation safety margin, especially when shock impedance is below 40 Ω [5]. Exclusion of the SVC can be performed by some manufacturers by way of software.

Shock optimization is performed by modifying the percentage-voltage delivered (tilt-based waveform) or the pulse width (fixed-duration waveform) in each phase of the biphasic shock. This feature is limited to a few ICD manufacturers. Most studies concur that shorter 42/42% and 50/50% tilt waveforms decrease DFTs by 15% to 25% compared with 65/65% tilt waveforms; however, other studies have not found similar results. Fixed-duration waveforms based on high-voltage impedance appear to reduce DFT by 20% to 30% versus tilt-based waveforms [1].

Finally, an important step to improve DFTs is the discontinuation of medications known to increase DFTs (see Box 1) or the addition of drugs such as sotalol that may improve DFT [10], or both. Sotalol may have a modest effect, decreasing DFT by 1 to 1.5 J in the overall ICD population. It is surprising that even though class III antiarrhythmics (except amiodarone) have been used to decrease DFTs, there have been no randomized controlled trials to assess their effectiveness in achieving appropriate safety margins in patients who have high DFTs.

The understanding of VF and the new ICD technology has decreased the energy requirements and improved the outcome of defibrillation during VF. A few patients, however, still require high-energy shocks to restore normal cardiac rhythm. By combining all these interventions, most centers can achieve an acceptable safety margin in most patients (85%) who have high DFTs [5].

Appropriate implantable cardioverter-defibrillator shocks and electrical storm

The incidence of appropriate ICD shocks is approximately 5% per year for primary prevention devices [14] and approximately 20% to 60% per year for secondary prevention devices [15,16]. ICD therapies are frequent in patients who have advanced heart failure, reaching a 20% to 40% incidence at 6 months after implant [17]. The incidence of appropriate shocks in secondary prevention patients is reduced post implant by prophylactic use of amiodarone combined with a β-blocker, with a trend toward reduction by sotalol [15]. Each ICD shock measurably reduces patient quality of life, with the cumulative effect becoming clinically significant after five or more shocks received [18]. When the frequency of ICD therapies becomes problematic, aggressive antitachycardia pacing, antiarrhythmic drug therapy (typically amiodarone or sotalol), or radiofrequency ablation are therapeutic options.

The long-term temporal patterns of ventricular arrhythmias in ICD patients are nonrandom and clustered in more than 80% of patients who have recurrent arrhythmias. The recurrence pattern can be described by a Weibull distribution [19]. The time between consecutive arrhythmic episodes is less than 1 hour for 78% of events and less than 91 hours for 94% of events [19]. After ICD therapies, patients may experience long periods of quiescence, making decisions about the necessity and efficacy of new therapies difficult. The statistical methodology in clinical trials should take into consideration the nonrandom pattern of arrhythmia recurrences [16].

Electrical storm is arbitrarily defined as two or more or three or more appropriate ICD therapies (shock or antitachycardia pacing) delivered within a 24-hour period. This pattern occurs in 10% to 20% of ICD patients. The recurrent arrhythmia is usually monomorphic ventricular tachycardia (VT), and hundreds of shocks can be delivered during a ''storm.'' The causes of electrical storm are numerous (Box 3), but in approximately two thirds of cases, no clear etiology can be identified [20,21]. Approximately one third of cases are attributed to acute ischemia, decompensated heart failure, or metabolic disturbances [20,21]. Predictors of electrical storm include monomorphic VT as the indication for ICD implant, left ventricular ejection fraction less than 25%, chronic renal failure, QRS greater than 120 milliseconds, digoxin use, coronary artery disease, and absence of β-blocker therapy [20–23].

Electrical storm with multiple ICD shocks should be considered a medical emergency. The first goal is to suppress the arrhythmia to prevent further shock deliveries. Treatment should

Box 3. Etiologies of electrical storm

Unknown
Decompensated heart failure
Acute ischemia
Metabolic disturbances
Drug proarrhythmia
Thyrotoxicosis
Fever with dilated cardiomyopathy or Brugada syndrome
Post cardiac surgery
ICD induced from left ventricular or T-wave pacing

commence simultaneously with a search for the etiology of the electrical storm. ICD therapies can be inhibited by application of a magnet to the device in the case of nonsustained arrhythmias triggering shocks or for recurrent hemodynamically tolerated arrhythmias. Drug therapy with intravenous β-blockers is the best management for electrical storm occurring in the setting of acute ischemia or in the days following myocardial infarction [24]. Otherwise, intravenous antiarrhythmic therapy (typically amiodarone) is the most frequently applied treatment (Box 4) [20,21]. No new therapy is required in a significant percentage of patients, perhaps reflecting the sporadic and self-limiting clustering of events [20,21]. Other common therapies include treatment of heart failure, revascularization, ICD reprogramming, and correction of metabolic derangements. Refractory cases occasionally require emergent radiofrequency ablation to eliminate the responsible arrhythmia.

Box 4. Treatment of electrical storm

Antiarrhythmic drug therapy (amiodarone) (48%–91%)
No specific therapy (29%)
ICD reprogramming (23%)
Heart failure treatment (16%)
Revascularization (3%–11%)
Ablation (7%)
Hyperthyroid treatment (3%)

Data from Brigadeau F, Kouakam C, Klug D, et al. Clinical predictors and prognostic significance of electrical storm in patients with implantable cardioverter defibrillators. Eur Heart J 2006;27:700–7; and Verma A, Kilicaslan F, Marrouche NF, et al. Prevalence, predictors, and mortality significance of the causative arrhythmia in patients with electrical storm. J Cardiovasc Electrophysiol 2004; 15:1265–70.

Although death during an episode of electrical storm is rare, some studies have demonstrated increased mortality in the months following the storm. In the Antiarrhythmics Versus Implantable Defibrillators trial, electrical storm was an independent predictor of mortality, with a relative risk of death of 5.4 in the first 3 months after the storm [22]. Fifty percent of deaths were nonsudden cardiac deaths. Thus, electrical storm may be an indicator of a mechanically failing heart. Because of the increased mortality, the care of the patient after electrical storm should include aggressive revascularization and optimal treatment of heart failure. In addition, the repeated painful shocks can result in a "posttraumatic" type of syndrome with anxiety and depression [18].

Inappropriate implantable cardioverter-defibrillator therapy

The term *inappropriate ICD therapy* is used when ICD therapy is delivered in the absence of ventricular tachyarrhythmia. The incidence remains high even with modern devices, affecting 10% to 20% of ICD recipients [14]. Inappropriately delivered therapy may cause severe psychologic distress, decrease quality of life, impede on the cost-effectiveness, and may be proarrhythmic [25]. Although mechanisms are diverse, the two main causes for inappropriate ICD therapy are oversensing and inappropriate classification of rapid supraventricular tachycardia (SVT) (Box 5). In broader terms, inappropriate ICD therapy may also include withholding ICD therapy in the presence of ventricular arrhythmia.

Implantable cardioverter-defibrillator sensing

Heart rate has proved to be a sensitive parameter to detect VT or VF and it remains the primary parameter of rhythm classification even in modern devices. Appropriate rate sensing is therefore a key feature and one of the main pillars of normal ICD function. Recorded signals undergo filtering and augmentation (gain) to minimize signals that fall into nonphysiologic range

Box 5. Causes of inappropriate therapy

Oversensing
QRS
T wave
P wave
Myopotential
Electromagnetic interference

Algorithm-specific events
Frequent nonsustained VT
Frequent ventricular premature complex
Ventricular premature complex/ oversensing during confirmation before ICD shock
Combined counter use in VT/VF zone

Mechanical complication
Lead fracture
Loose setscrew
Chatter between leads
Header problem

Supraventricular tachycardia
Atrial fibrillation
Sinus tachycardia
Atrial flutter

and to enhance signals of interest. Increasing the use of true bipolar leads instead of integrated bipolar leads allows more specific sampling of the myocardial signals. Further complexity and difficulty of sensing in ICDs results from the fact that ICDs have to recognize and treat brady- and tachyarrhythmias. For example, differentiation between asystole and VF requires special sensing algorithm that allows beat-to-beat adjustment of gain or sensitivity to appropriately sense R waves during fine VF but without sensing other parts of the EKG, such as the P wave or T wave. The drawback of increased sensitivity or gain is that signals from noncardiac or nonarrhythmic sources may be augmented and inappropriately sensed as if they were cardiac signals. A particularly vulnerable period is during bradycardia or following a pacing stimulus, when sensitivity of the ICD is maximized (Fig. 2). Programming options for the correction of oversensing in general are limited to decreasing sensitivity, but at a price of possible undersensing during VF. Defibrillation testing is therefore prudent following any modification of sensing parameters.

Oversensing of intracardiac signals

P waves, R waves, and T waves may be spuriously sensed and cause double counting of each cardiac cycle, which may lead to acceleration of the counter to a tachycardia zone. Recorded electrograms show ventricular-sensed events that correspond to the timing of the oversensed signal, such as a second R-wave component, P wave, or T wave. The timing of the sensed ventricular events shows beat-to-beat alternating cycle length (see Fig. 2). P-wave oversensing is commonly a result of ICD lead dislodgement to the tricuspid annulus as seen in twiddler's syndrome. R-wave oversensing is uncommon in modern devices and requires an alteration of ventricular blanking period or lead repositioning. Oversensing of T waves is more frequently seen in hypertrophic cardiomyopathy, short and long QT syndrome, and Brugada syndrome (see Fig. 2) [26–28]. Another common cause is a temporary or permanent decline in R-wave amplitude (<5 mV) that triggers autoadjustment in sensitivity. Increased sensitivity in turn may be sufficient to sense the T wave. Device-specific filtering may also contribute to differences in T-wave sensing. Initial management of T-wave oversensing is often noninvasive. Decreasing ventricular sensitivity may be sufficient, but lead repositioning is required in select cases. In some devices, a programmable option allows modification of the timing and slopes of sensitivity adjustment after sensed events and may be sufficient to allow noninvasive correction.

Oversensing of extracardiac signals

Myopotential oversensing is a result of sensing skeletal muscle signals, commonly from the diaphragm. Skeletal muscle activity is characterized by a continuous high-frequency signal that usually overlaps several cardiac cycles. The high-frequency signals are sensed as rapid ventricular events and therefore inhibit pacing and may induce ICD therapy (see Fig. 2). Diaphragmatic oversensing is more commonly seen in the ventricular sensing channel in integrated bipolar leads in the right ventricular apex and in devices that use automatic gain adjustment for sensing. Clinical evaluation shows unchanged lead parameters, and noise may be reproduced with special maneuvers. Diaphragmatic oversensing might be corrected by manually adjusting sensitivity without impairing the detection of VF. In some extreme cases, it may be required to reposition the lead higher on the right ventricular septum or to insert

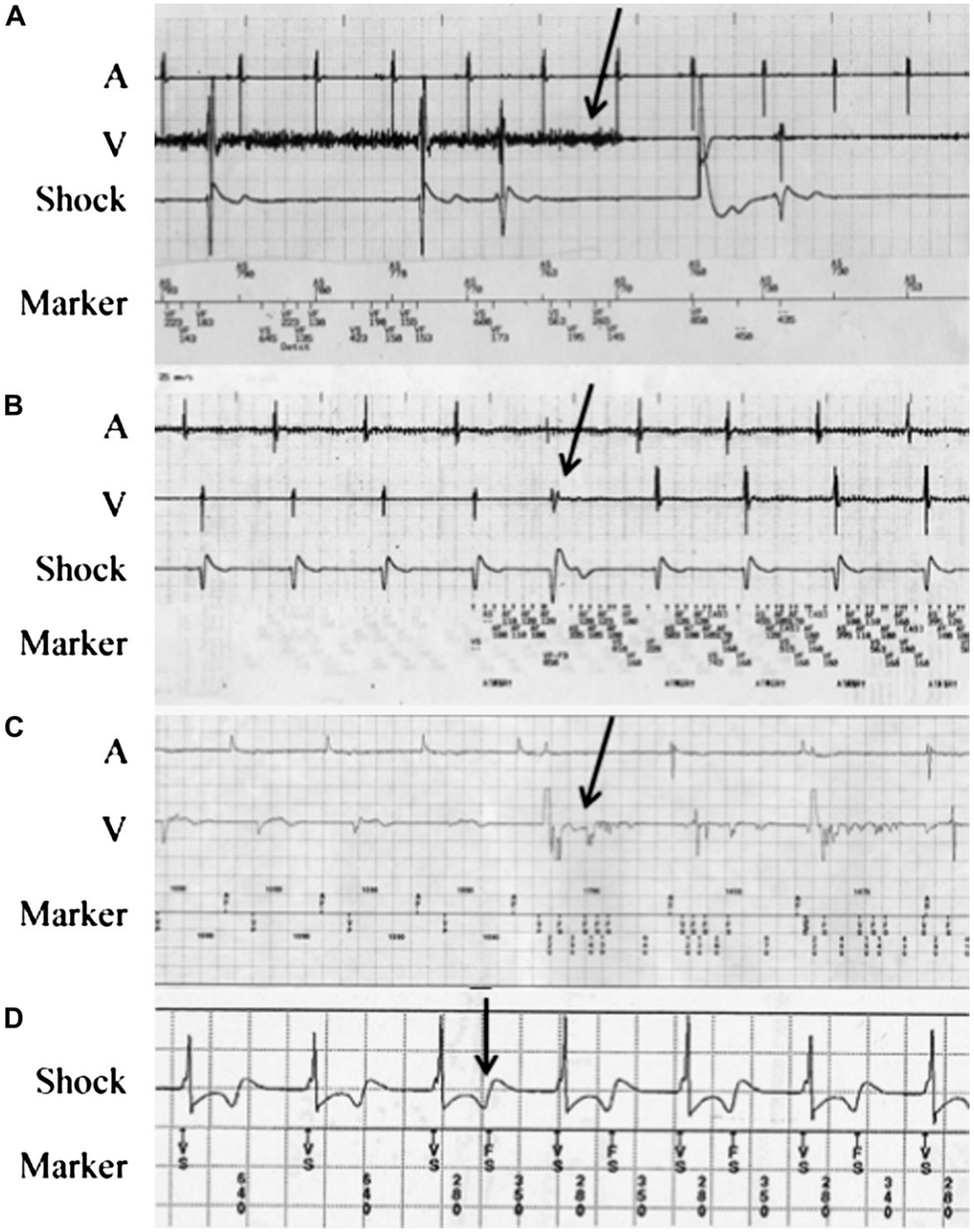

Fig. 2. (*A*) Oversensing of diaphragmatic signals in a pacemaker-dependent patient. High-frequency signals (noise) are noted on V that disappear when the patient stops straining (*arrow*). VF is detected and there is inhibition of ventricular pacing. (*B*) Electromagnetic interference during transcutaneous electrical nerve stimulation. Initially, noise is only present on the atrial lead. Atrial oversensing results in spurious detection of atrial fibrillation. Ventricular pacing at fall-back rate is initiated. There is postpacing automatic gain adjustment, which results in ventricular oversensing (*arrow*). Inappropriate ICD shock was delivered later (not shown). (*C*) Noise on ventricular lead due to lead fracture. Patient presented with ICD storm due to oversensing as a result of ventricular lead fracture. High frequency, nonphysiologic signals are pointed out (*arrow*). (*D*) T-wave oversensing. Arrow points to a sensed event that falls into VT zone and corresponds to oversensing T wave. A, atrial sensing channel; Shock, far-field electrogram from the ICD coil; V, ventricular sensing channel.

a separate dedicated sensing lead to prevent oversensing.

Increasing the use of electronics that emit electromagnetic signals pose challenges in ICD detection. Environmental electromagnetic interference (EMI) may be detected by ICDs and trigger therapy. EMI is a high frequency signal present in all leads, often with highest amplitude in far-field electrograms. Careful clinical correlation is required to identify the exact sources. In general, properly grounded common household appliances carry no substantial risk for EMI. Commonly encountered nonmedical and medical sources include electrocautery, MRI, lithotripsy, transcutaneous nerve stimulation, radiofrequency ablation, gasoline combustion engines, welding equipment, electronic article surveillance systems, and cellular phones. The general approach is avoidance and shielding from the source. If EMI cannot be avoided, especially during hospital care, inhibition of tachycardia detection with magnet application or temporary programming is required to avoid inappropriate ICD shocks. Special attention should be paid to pacemaker-dependent patients to assure appropriate pacing and monitoring because magnet application does not affect pacing mode in ICDs.

Mechanical complications of the ICD system may compromise the integrity of the sensing circuit. Thus, lead fracture and header or setscrew problems may present as intermittent noise. There usually are fluctuations in the lead impedance, and special maneuvers may reproduce the clinical findings. The solution is revision of the failed component.

Inappropriate classification of supraventricular tachycardia

Overlap between the rate of VT detection and supraventricular arrhythmia results in inappropriate therapy unless discriminators are applied to withhold therapy during SVT. Differentiation between SVT and VT remains a challenging task. Special algorithms are used in an attempt to distinguish typical features of arrhythmias and are applied to withhold inappropriate therapy without significantly compromising identification of VT.

In single-chamber ICDs, sudden onset, interval stability, and electrogram morphology are common primary discriminators. Applications and limitations of these discriminators are summarized in Table 1. In general, the combined use of discriminators is needed to improve specificity (ie, reject therapy for SVT) [29,30] but may impede on the sensitivity to detect VT (ie, VT may be misclassified as SVT). An arrhythmia duration timer may be used as a safety feature, which mandates ICD therapy regardless of the classification of the arrhythmia after the timer is expired, but it erodes on specificity [30].

Dual-chamber algorithms use atrial sensing information to assess atrioventricular relationship and are used in combination with single-chamber discriminators. Adequate atrial sensing is of key importance. Atrial undersensing, for example, may accelerate therapy delivery by producing V>A count. Despite the increasingly sophisticated detection algorithms, specificity of dual-chamber detection remains suboptimal [31,32]. For example, a recent multicenter study compared

Table 1
Single-chamber detection enhancement parameters

Detection enhancement parameter	General use of parameter	Common reasons for incorrect arrhythmia classification
Sudden onset	Reject gradual-onset tachycardia (SR)	Nonsudden onset of ST due to VPC VT may appear "sudden onset" if starts during ST
Stability	Reject irregular tachycardia (AF) as opposed to regular monomorphic VT	Regularized conduction in AF Frequent VPC
ECG morphology	Reject tachycardia if morphology is unchanged from SR	Aberrant conduction/BBB during SVT Minimal change in morphology during VT Processing errors of the signals

Abbreviations: AF, atrial fibrillation; BBB, bundle branch block; SR, sinus rhythm; ST, sinus tachycardia; VPC, ventricular premature complex.

single- and dual-chamber detection algorithms. SVT occurred commonly (in 34% of all patients) within 6 months after ICD implantation. Using single-chamber discriminators, 40% of the SVT episodes were classified inappropriately. Dual-chamber discriminators, on the other hand, significantly reduced the rate of inappropriate detection to 31% and reduced ICD shocks by half [33]. Other studies, including a meta-analysis, also confirmed a small but significant difference in favor of dual-chamber detection to reduce inappropriate ICD shocks [34].

Significant differences exist in detection algorithms between different models, and it is imperative to understand device-specific properties in detection algorithms to maximize specificity and maintain high sensitivity for VT therapy [30,33,35]. Additional strategies to reduce inappropriate shocks include increasing VT/VF detection time, increasing VT/VF detection rate, and the liberal use of antitachycardia pacings (ATPs), even for rapid VT [35]. Application of full energy shocks may terminate SVT and may help to minimize the number of shocks.

Undersensing

Suboptimal sensing may occur with a decline in R wave, such as following lead dislodgement, fracture, development of new bundle branch block, or ICD shock; with progression of heart disease; or because of electrolyte disturbances. Defibrillation testing should be considered when there is significant change in R-wave amplitude, when sensing parameters are modified, or when there is clinical suspicion for undersensing. Tachycardia detection may also fail when the tachycardia rate is less than the programmed detection rate or when the device therapy is inadvertently programmed off.

The identification and treatment of device infections

Currently, over 100,000 new ICDs are implanted in the United States per year [36]. In light of the expanded recommendations for ICD implantation, this number has significantly increased, as has the complication rate [37]. The files collected by the National Hospital Discharge Survey revealed that between 1996 and 2003, the rates of hospitalization for infections of implantable antiarrhythmic systems increased faster than the rates of system implants [38]. The estimated rate of infection after implantation of permanent endocardial leads is between 1% and 2%, although the variability described in the literature is 0.13% to 12.6% [39,40]. Device infection carries significant public health consequences and is responsible for significant increases in morbidity, mortality, and financial cost. Reported mortality can range from 31% to 66% when the device is not removed and is 18% when the combined approach of device removal and antibiotic therapy is employed [41,42]. The combined average cost of medical and surgical treatment of an infected defibrillator may reach $57,000 [39].

Diagnosis

Correct diagnosis of device infection may prove difficult, even to an experienced clinician. An ICD infection is manifest by pocket cellulitis, erosion or fistula, wound dehiscence, abscess, persistent bacteremia, or endocarditis. The infection may involve the skin, the generator, the defibrillator pocket, or the leads as they track the tissue and enter the venous system. The most common signs and symptoms of device infection are shown in Table 2 [43]. Fever is an unreliable symptom and is reported in less than half of patients who have device infections. Most symptoms are nonspecific. Erythema, pain, and swelling at the device site are the most common signs. Leukocytosis and positive blood cultures occur in a minority of patients [43].

One must recognize less serious but common signs of infection such as local irritation around the incision site and superficial stitch abscess that are not considered device infections and that respond to local measures alone [44]. The average time to device infection from implant is approximately 1 year but may be manifest at almost any time after device surgery [43].

Blood cultures have the highest yield when the patient is febrile or directly after lead extraction and should be obtained before administration of antibiotics. Swab culture of the pocket or purulent exudate expressed from the fistula may facilitate identification of the organism; however, it has been shown that pocket tissue cultures are more effective than pocket swab cultures for the isolation of the pathogens in cardiac device infections [37,45]. Incubation and culture of explanted leads and devices appears to provide the highest yield of all [46]. Despite the need for a high index of suspicion for ICD infections, routine pocket cultures of asymptomatic patients should be

Table 2
Clinical presentation of patients who have permanent pacemaker or implantable cardioverter-defibrillator infection

Clinical presentation	n (%)
Systemic symptoms	
Fever (>38°C)	82 (43)
Chills	73 (39)
Malaise	79 (42)
Anorexia	32 (17)
Nausea	16 (8)
Sweating	34 (18)
Hypotension (systolic blood pressure <90 mm Hg)	18 (10)
Murmur on examination	66 (35)
Symptomatic heart failure	52 (28)
Local findings at generator site	
Erythema	128 (68)
Pain	93 (49)
Swelling	127 (67)
Warmth	71 (38)
Tenderness	86 (46)
Drainage	95 (50)
Purulent drainage	65 (34)
Skin ulceration	59 (31)
Generator/lead erosion	48 (25)
Intraoperative purulence at generator pocket	151 (80)
Laboratory abnormalities	
Leukocytosis (WBC $>10 \times 10^9$/L),	82 (43)
Anemia (HCT <38% in men; <35% in women)	94 (50)
High ERS (>22 mm/h in men; >29 mm/h in women)	47 (25)
Positive blood culture	76 (40)

Abbreviations: ESR, erythrocyte sedimentation rate; HCT, hematocrit; WBC, white blood cell count.

From Sohail MR, Uslan DZ, Khan AH, et al. Management and outcome of permanent pacemaker and implantable cardioverter-defibrillator infections. J Am Coll Cardiol 2007;49:1853; with permission.

discouraged [45]. Positive cultures by pocket swab or tissue cultures are not uncommon in the absence of clinical signs and symptoms of infection, due to contamination or chronic innocuous colonization. This situation does not appear to require therapy [45]. Patients who have positive blood cultures or negative blood cultures after antibiotics should have a transesophageal echocardiogram to assess for device-related endocarditis [43].

Approximately two thirds of device infections are caused by *Staphylococcus* species (Fig. 3). Methicillin-resistant *Staphylococcus aureus* occurs in 4% of infections, gram-negative organisms occur in 9%, and fungal infections are rare (2%) [43]. The most common source of the infection appears to be local contamination from the skin at the time of implant or generator change [47].

Risk factors

A number of studies examined and found multiple risk factors associated with development of ICD or permanent pacemaker infection (Table 3). In a retrospective multicenter study that evaluated 6319 patients who had permanent pacemaker and ICD implant, early repeat intervention for hematoma or lead dislodgement was the leading risk factor for infection, associated with an odds ratio of 15.0 [48]. Although repeated intervention for lead dislodgment or hematoma might seem essential in some cases, the risk of infection must be weighted against the absolute necessity of the revision procedure. Secondary procedures such as pulse generator replacements are well established to be a risk factor for infection. The rate of infectious complications is increased in patients who undergo multiple implantations of devices in their lifetime. In a retrospective analysis, the infection rate in young patients who had undergone a median of two pacemaker implantations was 5.5% [49].

The absence of antibiotic prophylaxis at the time of procedure is another risk factor for developing device infection. A meta-analysis showed a possible benefit conferred by systemic antibiotic administered before the procedures [50]. The antibiotics used in these trials included penicillin or cephalosporins. Classen and colleagues [51] showed that the risk of infection is best reduced when antibiotics are administered 2 hours before the initial incision.

Patients in whom a temporary pacing system is present at the time of implantation of the permanent antiarrhythmic systems are more than twice as likely to develop device-related infections [48]. Fever within 24 hours before implantation of the permanent system also increases the risk of postprocedure infection [48]. Renal insufficiency impairs cellular and humoral immunity and is a contributing factor in device infection. Patients who have renal insufficiency are nearly five times more likely to develop device infection than those who have preserved renal function [52].

Treatment

The management of ICD infection can be a challenge for the electrophysiologist and the infection disease specialist. Extraction of the

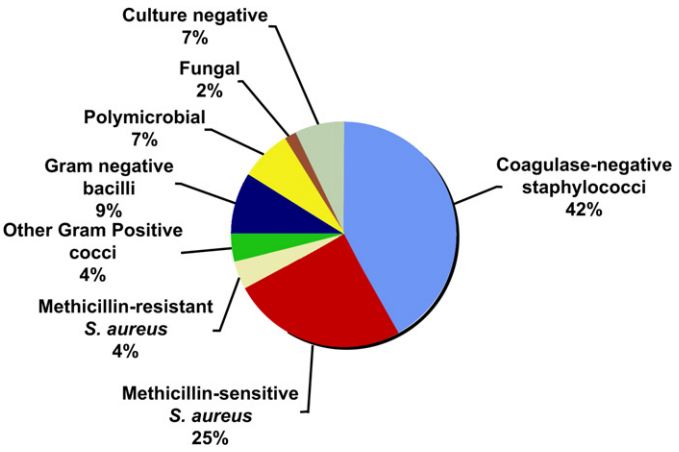

Fig. 3. Microbiology of pacemaker/ICD infections (n = 189). (*From* Sohail MR, Uslan DZ, Khan AH, et al. Management and outcome of permanent pacemaker and implantable cardioverter-defibrillator infections. J Am Coll Cardiol 2007;49:1853; with permission.)

generator and leads is mandatory in cases of sepsis or endocarditis involving any intravascular part of the pacing system (class I indication) [53]. In the case of localized pocket infection, erosion, or chronic draining sinus, multiple studies have shown high rates of relapsing infection (even after prolonged medical therapy) when the entire system is not removed. In a case series of 123 patients who had an infected device, only 1 of 117 (0.86%) patients who underwent removal of the entire system had infection relapse. In contrast, 3 of 6 (50%) patients who did not have complete hardware removal suffered relapse [37]. Complete device extraction is therefore recommended when infection of any part of the system is diagnosed; however, if the diagnosis is not certain, one can wait and reassess the pocket until the infection becomes more apparent and then proceed with lead extraction.

Based on a retrospective analysis and review of the published literature, Sohail and colleagues [43] proposed guidelines for the management of cardiac device infections (Fig. 4). These guidelines include complete extraction of all hardware after infection is identified regardless of the clinical presentation and complete debridement of the infected scar tissue. Blood cultures should be repeated in all patients after device extraction. Patients who have positive blood cultures and patients who have complicated infection should be treated for at least 4 weeks with antibiotics even if transesophageal echocardiography is negative for vegetations or other evidence of infection. Adequate debridement and control of infection should be achieved at all sites before reimplantation of a new device at a remote anatomic location. Implanting devices submuscularly does not appear to prevent infection. It is extremely important before initiation of treatment to plan the course of the treatment. For example, if the patient is pacer dependent, provision for extended temporary pacing may be needed. Also, an alternative location for new implant must be identified [44]. Every implanter needs to keep in mind that the best method to treat device infection is to prevent it.

Table 3
Predictors of device infections

Risk factor	Odds ratio
Fever within 24 h before system implantation [48]	4.8
Early reintervention [48]	55.3
Antibiotic prophylaxis [48]	0.4
Renal insufficiency (creatinine $\geq$1.5) [52]	4.6
Generator change [52]	2.2

Lead extraction

Progressive growth of fibrous tissue around the electrode tip and the defibrillator coils and along the entire length of the lead body create a major barrier to the removal of leads [53]. Guidelines for lead extraction have been previously published [53,54]. In experienced hands, lead extraction

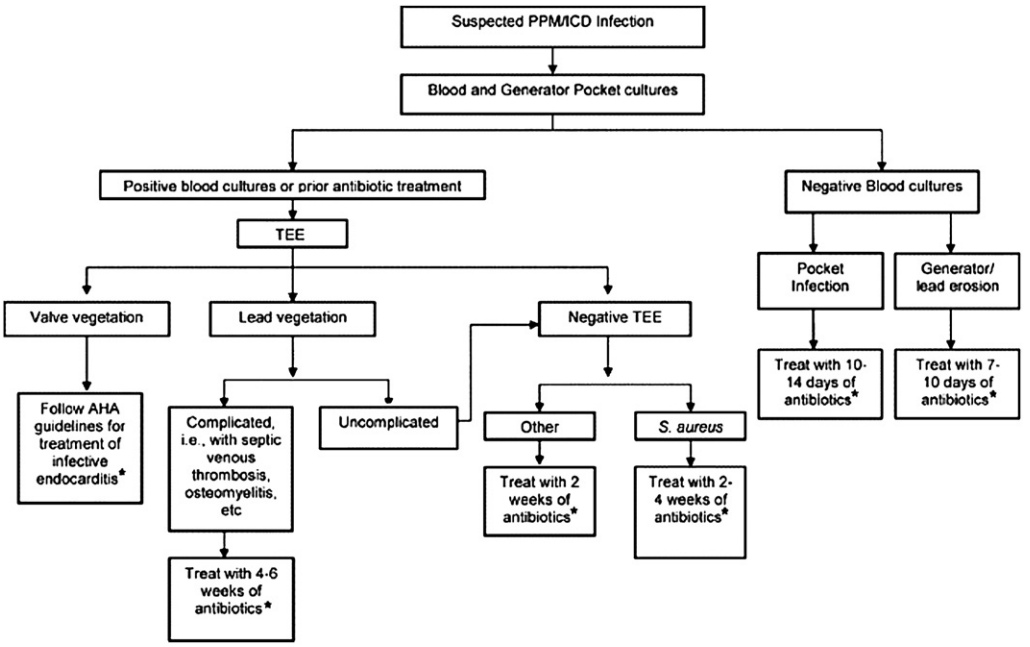

Fig. 4. Algorithm of cardiac device infection management. *Duration of antibiotics should be counted from the day of device explantation. AHA, American Heart Association; PPM, permanent pacemaker; TEE, transesophageal echocardiography. (*From* Sohail MR, Uslan DZ, Khan AH, et al. Management and outcome of permanent pacemaker and implantable cardioverter-defibrillator infections. J Am Coll Cardiol 2007;49:1857; with permission.)

can be a very successful procedure, with a success rate between 90% and 94% [55,56]. Nevertheless, the procedure can carry a significant rate of major complications (1%–5%) [55,56]. Potential lethal complications requiring extensive surgical procedures include tearing of the SVC/subclavian vein or the heart wall leading to tamponade, arterial tears causing arteriovenous fistula or dissecting hematoma, and tearing into the thoracic cavity causing a hemothorax. The mortality rate associated with laser lead extractions has been reported as high as 0.8% [55,56].

Prevention

Useful methods to prevent device infection are listed in Box 6. The infection rate for each implanting laboratory should be monitored, annually evaluated, and held under 0.5% [44]. Adherence to surgical conditions such as careful skin preparation and sterile operating room conditions is crucial in prevention of infections. The highest risk of infection is associated with generator changes and reimplants; therefore, some practitioners prefer to debride the device capsule to facilitate increased blood flow and migration of inflammatory cells.

Implantable cardioverter-defibrillator generator and lead failure

Over their 20 years of evolution, ICD generators have undergone a fourfold to fivefold reduction in size along with incredible increases in function and complexity. Implanted ICDs and leads must endure a hostile physiologic environment and are subject to physical stresses imposed by the body. ICD generators and leads may fail due to design flaws, manufacturing problems, implant techniques, mechanical stress, or aging and fatigue of materials [36,57,58].

Implantable cardioverter-defibrillator generator failure

A recent study suggests that the reliability of ICD generators has decreased over recent years concomitant with an exponential rise in device implants [36]. As with any manufactured device, all ICD generators are subject to a random failure rate, but when failures are systematic due to

Box 6. Useful methods to prevent device infection

Perform chlorhexidine skin scrubs up to 24 hours pre procedure
Administer antibiotics 2 hours before the first incision
Observe strict sterile techniques and sterile operating room conditions
Perform careful chlorhexidine skin preparation
Limit duration of pocket exposure
Perform antibiotic flush of pocket
Redose antibiotics for long procedure

design or manufacturing problems, the device may be subject to a safety advisory issued by the manufacturer or imposed by the Food and Drug Administration (FDA). Between 1990 and 2000, 18 safety alerts involving more than 114,000 ICDs were issued by the FDA [36,58]. In 2005, four major ICD manufacturers issued alerts involving more than 200,000 devices. There were several deaths directly attributed to ICD failures. With expanded indications for ICD implants, the absolute number of ICD and lead failures is certain to grow.

Recognizing implantable cardioverter-defibrillator generator failure

ICD failure modes that result in loss of pacing may produce symptoms of bradycardia or syncope. Sudden death may occur from loss of pacing in pacemaker-dependent patients or from failure to treat ventricular tachyarrhythmias. Current ICD generators have patient alert capabilities (audible tone or vibratory alert) that may be activated by failure modes resulting from battery depletion, abnormal lead impedances, or prolonged capacitor charge times. A unique symptom of one manufacturer's failure mode is warmth at the device site due to heat generated by a sudden battery short-circuit. Most device failures are detected by device interrogation at follow-up. Remote monitoring capabilities of some devices allow for daily device follow-up, enabling rapid recognition of some failure modes. Nevertheless, some failure modes result in loss of critical functions only at the time of their activation and cannot be recognized in advance.

Management of device failure and safety alerts

Management of a failed device is straightforward: replace the device. A critical but overlooked part of device replacement is the reporting of a device failure (known or suspected) to the manufacturer and the FDA (www.fda.gov/medwatch). The FDA compiles, analyzes, and posts these reports in the Manufacturer and User Device Experience database, which is accessible to the public (www.fda.gov/cdrh/maude.html). Because the reporting of device failures is voluntary at the provider level, it is essential that health care professionals report all malfunctions to form the most complete picture of device behavior.

The more difficult problem is the management of a patient who has a device under safety alert but who has not experienced problems. Safety advisories are issued to physicians who are following such patients. It then falls to the physician to inform each patient regarding the advisory. The authors' policy is to notify each patient in writing and to have the patient come to the clinic for device follow-up, to answer questions, and to make management decisions individually. The patient who has an ICD under advisory faces the competing risks of harm from device failure and the risks of surgical replacement (primarily infection from lead extraction leading to complications or death). The decision to replace a device or to continue monitoring the patient is complex, and physician practice is nonuniform [59–61]. Guidelines from scientific agencies are based on expert opinion alone [62]. These guidelines suggest that device replacement should be considered when failure could result in serious harm and when the patient is pacemaker dependent, has a secondary prevention ICD indication, or has received an appropriate therapy from the device. Clinical data suggest, however, that widespread categorical replacement of devices under advisory may be misguided [59,60]. Gould and Krahn [60] found that major complications including death were more common in patients undergoing elective "recalled" device replacement (43/533 replacements [8.1%]) compared with no adverse events directly attributable to device failures in 2382 patients.

In the absence of controlled clinical data to direct decisions regarding replacement of devices under advisory, a decision analysis model has been developed [61]. This form of analysis simulates a two-armed clinical trial. Using a hypothetic cohort of patients who have ICDs under advisory

for failure, half of the patients have device replacement and the other half continue to be monitored. The primary outcome variable is average survival for each strategy. According to the model, the most important considerations for device replacement are (1) estimated advisory failure rate, (2) procedural mortality rate for device replacement, (3) degree of pacemaker dependency, and (4) remaining generator life (Fig. 5). Patient age, indication for ICD (primary or secondary prevention), and frequency of follow-up had much less influence on the decision-making process. According to this model, to favor routine device replacement for highly pacemaker-dependent patients, the device failure rate should exceed 3 in 10,000 for the lowest procedural mortality rates (0.1% death per procedure) and more than 3 in 100 for the highest procedural mortality rates (1.0% death per procedure). For non–pacemaker-dependent patients, ICD failure rates should exceed 1 to 3 in 100 to favor routine replacement over the range of procedural mortality rates. Of interest, remaining device life favors replacement only when less than 10% of service life remains. These findings suggest that ongoing monitoring of "recalled" devices is likely to be the preferred strategy in most cases.

Implantable cardioverter-defibrillator lead failure

ICD leads have always been the "weakest link" in the ICD system, with failure rates far exceeding those of ICD generators. The failure rate for ICD leads may be 15% at 5 years and 40% at 8 years [57]. The reasons for the high failure rates are many, including the complex physical stresses placed on the leads by cardiac motion, subclavian "crush" due to implant technique, the complex construction compared with pacemaker leads, the high voltage stresses (up to 800 V) imposed on the leads, chemical reactions between insulation materials and metallic components, and attempts to downsize the lead diameters. Most lead problems result from insulation failure [57]. Lead failure appears to be more likely in women, younger patients, coaxial lead designs, multiple lead implants, and with the subclavian implant technique [57]. Despite the high failure rate for ICD leads in general, only one lead model has been subjected to an FDA safety alert, perhaps acknowledging the low expectations for the performance of these devices. Like ICD generators, ICD leads should be considered to have a finite service life.

Recognizing implantable cardioverter-defibrillator lead failures

One third of ICD lead failures are recognized by electrical noise producing inappropriate therapies from the device [57]. Syncope or presysncope may result from inhibition of pacing or loss of ventricular capture. Activation of patient alerts due to abnormal lead impedances may occur.

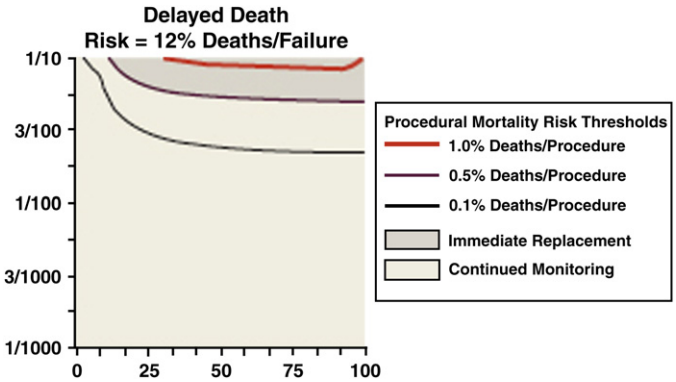

Fig. 5. Three-way threshold analysis graph identifying combinations of values for which device replacement or continued observation is the preferred strategy. This graph represents the case of a primary prevention ICD generator under safety advisory. The estimated risk of patient death is 12%/y if the device fails. The three lines in the graph represent different procedural mortality rates for device replacement of 0.1%, 0.5%, and 1.0% per procedure. By finding the position on the graph using coordinates of device failure rate and remaining generator life, the decision to replace the device is favored for a given procedural mortality rate when the point falls above the procedural mortality rate line; monitoring is favored when the point falls below the line. (*From* Amin MS, Matchar DB, Wood MA, et al. Management of recalled pacemakers and implantable cardioverter-defibrillators: a decision analysis model. JAMA 2006;296:417; with permission.)

Most failures (65%), however, are diagnosed at follow-up from the review of stored electrograms, the recording of nonphysiologically short R–R intervals, or abnormal lead impedance trends [57]. Noise on the ICD lead must be differentiated from intermittent exposure to EMI. Occasionally, the electrical noise may be reproduced by motion of the ipsilateral arm, body movement, or palpation of the lead.

Management of implantable cardioverter-defibrillator lead failure

Management of a known ICD lead failure is simple in theory (ie, provide a new lead) but often difficult in practice. Difficulties attend the decision to extract the failed lead or, more simply, to add a new lead. A small retrospective study suggests that both strategies carry equal risks, but the high likelihood of future lead malfunction favors extraction in younger patients [63]. Thrombosis of the venous system may complicate lead replacement by requiring lead extraction to restore vascular access or by requiring movement of the ICD system to the contralateral side. Extraction of ICD leads carries a major complication rate (including death) of 1% to 3% [56]. There are no randomized studies for these treatment strategies, and the decisions must be individualized for each patient.

As with ICD generator advisories, there is no consensus on the optimal management strategy. Although the incidence of ICD lead failures may greatly exceed that of generator failure, the risks of lead replacement or extraction are significant. For ICD leads under advisory, it is likely that continued monitoring will be favored in most cases. In these cases, increased surveillance including the use of home monitoring is warranted.

Summary

ICD technology has advanced greatly since its initial development a quarter of a century ago. Although improvements in technology have solved many problems associated with ICD therapy, others problems remain. Some new clinical syndromes have even resulted from these technical advances, such as inappropriate shocks. Despite their unquestioned benefits, with the increasing use of ICDs, especially in primary prevention patients who have an anticipation of long life spans spent with an ICD, we can expect continued problems with ICD systems and must remain vigilant.

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