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The Perioperative Management of Implantable Pacemakers and Cardioverter-Defibrillators

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Keywords

- Pacemaker • Implantable cardioverter-defibrillator
- Cardiovascular implantable electronic device (CIED)
- Electromagnetic interference

Key points

- In addition to delivering high-voltage therapy, all modern transvenous implantable cardioverter-defibrillators (ICDs) can also perform all the sophisticated, advanced functions of a pacemaker (PM) (ie, all ICDs also have antibradyarrhythmia capability).
- Before elective surgery, ensuring that the patient's cardiovascular implantable electronic device (CIED) is functioning properly remains paramount, especially for surgery that is likely to result in hemodynamic embarrassment or whenever electromagnetic interference (ie, the use of monopolar electrosurgery) is likely. In any situation wherein a preoperative device evaluation cannot take place (ie, emergency surgery), practitioners must be prepared for perioperative device malfunction or outright failure. This preparation often includes the placement of transcutaneous pacing/defibrillation pads.

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- Electrical instruments, principally monopolar electrosurgery, but also those used by anesthesiologists (eg, nerve stimulators, radiofrequency scanning devices), can create electromagnetic interference and adversely affect the function of a CIED. If intraoperative electromagnetic interference is anticipated, ICD high-voltage therapy (antitachycardia pacing and shock) should be disabled and external defibrillation pads applied. Reprogramming to an asynchronous pacing mode should also be considered for any pacing-dependent patient.
- Except under exigent circumstances, magnet behavior should be confirmed whenever magnet use is planned. A magnet never alters the pacing mode of an ICD. It is sometimes possible to disable a CIED's magnet response through programming. Especially for an ICD, it might be difficult to determine that a CIED's magnet mode is disabled.
- Perioperative practitioners must be alert to incorrectly displayed electrocardiographic signals and rates resulting from electromagnetic interference.

INTRODUCTION: NATURE OF THE PROBLEM

In the United States, more than 3 million people have an implantable pacemaker (PM) or cardioverter-defibrillator (ICD) [1], and more than 500,000 PMs and ICDs are now implanted each year [2–5]. Initially developed to manage symptomatic bradyarrhythmias and sustained ventricular tachyarrhythmias, these cardiovascular implantable electronic devices (CIEDs) and their indications for use have evolved considerably, including treatment for heart failure [6]. Moreover, patients receiving these devices are older and have increasing medical comorbidities [3]. Although the incidence of patients with a CIED undergoing surgery is currently unknown, this number is likely substantial because these devices are so prevalent and more than 80 million surgical procedures are performed annually in the United States [7,8]. Also, some published reports suggest that the number of potentially eligible patients not receiving ICD therapy is sizable, but that a higher proportion of eligible patients might receive devices going forward [9,10]. Consequently, clinicians involved in perioperative care should expect to encounter and manage these patients with increasing frequency. Thus, anesthesiologists, just like general cardiologists, must become proficient in certain basic aspects of CIED therapy [6].

Unfortunately, the broad functionality of modern CIEDs has increased their complexity. As a result, safe, efficient, and cost-effective perioperative care of patients with CIED has become confounded by economic, personnel, and procedural challenges. The sophistication of these devices, the abundance of complex issues surrounding effective perioperative management of the patient with CIED, and changing patient conditions has increased the difficulty of providing this care. At least 2 reports suggest an association between these devices and increased perioperative morbidity and mortality [11,12]. Particular challenges include manufacturer-specific proprietary features, lack of standardization among device manufacturers, and an array of published literature that is often outdated and sometimes incorrect. Furthermore, in the operating or procedure

room, electrical equipment emitting virtually uncontrolled radiofrequency signals (especially monopolar electrosurgical devices) can affect CIED function and place patients at increased risk of adverse events. Moreover, the presence of a CIED complicates operative scheduling and might introduce operative delays [13].

In response to these challenges, the Heart Rhythm Society (HRS) [14], American Society of Anesthesiologists (ASA) [15], and others [16,17] have published recommendations to guide clinicians in the perioperative management of patients with these devices. These recommendations delineate that, preoperatively, these patients must be identified before arrival at the surgical facility, because proper CIED function must be verified and a comprehensive plan ("perioperative prescription") for managing the CIED must be established that accounts for the patient, the anticipated procedure, and the individual characteristics of the patient's CIED [18]. Although in many instances this management plan can be created by accessing the patient's records and without performing a de novo device interrogation, CIED records sometimes are not readily available to the operative care team on the day of the procedure. In addition, even when a de novo device interrogation is not required, immediate preoperative reprogramming might be needed to mitigate the risks of electromagnetic interference (EMI) arising from the use of radiofrequency instruments, primarily monopolar electrosurgery (electrosurgical unit [ESU]). Although allied health professionals such as manufacturer representatives are frequently engaged to prescribe or independently deliver such care, this practice should be avoided [14]. Moreover, appropriately trained, licensed, and privileged practitioners (typically cardiologists or specially trained advance practice providers) are often not available and are not well incentivized to perform this service on a timely basis, particularly if they do not routinely provide perioperative care. In this situation, routine placement of a magnet over a CIED, presumably to change the pacing mode of a PM or suspend the antitachycardia therapies of an ICD, has been used. However, blind application of a magnet to a CIED during surgery can lead to adverse outcomes [19] and is no longer considered acceptable except under exigent circumstances [14].

Although anesthesiologists and surgeons are not expected to become CIED management experts, any practitioner involved in the perioperative care of patients with CIED should be familiar with the key published practice recommendations and expert consensus statements on this topic. Furthermore, they should understand indications for CIED implantation, along with the basic functions, operations, and limitations of these devices. Finally, they should have enough troubleshooting knowledge to know when expert consultation is warranted.

This review provides the perioperative clinician with a comprehensive understanding of the considerations involved in the safe and effective perioperative management of the patient with a CIED.

The perioperative management of the patient with CIED can be divided into 3 distinct periods: preoperative, intraoperative, and postoperative.

PREOPERATIVE EVALUATION AND MANAGEMENT

Preoperatively, information about the CIED system, patient, and procedure must be obtained (Box 1). The CIED team, anesthesiologist, and proceduralist should review this information and create an appropriate perioperative CIED management plan (see Box 1).

The cardiovascular implantable electronic devices system

CIED systems classically consist of a pulse generator and 1 to 3 leads (Fig. 1). The pulse generator is typically implanted underneath the clavicle (most often on the left side) in a subcutaneous pectoral pocket and the leads are almost always routed directly into the endocardium (heart) transvenously via the superior vena cava. Transvenous leads pace and sense in their respective locations and may be placed into the right atrium, right ventricle (RV), or coronary sinus (CS). The number of leads inserted is determined by the indications for implantation and specific CIED functionality required. An atrial lead is placed for sinus node dysfunction as well as atrial monitoring. RV leads can be used to circumvent atrioventricular (AV) block as well as monitor RV rhythm. Patients in the United States with sinoatrial node disease but without AV block at the time of implant generally still receive an RV lead because of the concern that AV block might develop later [20]. A CS lead is used to pace the left ventricle for cardiac resynchronization therapy (CRT); the position of the CS lead is best determined by lateral (rather than pulmonary artery) chest radiograph (CXR) (Fig. 2). The RV lead of a transvenous ICD contains 1 or 2 shock coils for high-voltage defibrillation therapy. The presence of shock coils can be used to easily distinguish a high-voltage capable device (ICD) from a PM via CXR (Fig. 3), although an ICD's high-voltage therapy might be programmed off at any given time. Of note, in addition to delivering anti-tachyarrhythmia therapy (including anti-tachycardia pacing [ATP] and shocks), all modern transvenous ICDs can perform all the sophisticated functions of a PM (ie, also have anti-bradyarrhythmia capability).

Transvenous leads can be either unipolar or bipolar. With a bipolar lead, the cathode and anode are both present on the lead itself (near the distal end), whereas with a unipolar lead, the cathode is present on the lead and the pulse generator functions as the anode (Fig. 4). Thus, the distance between the cathode and anode is decreased with a bipolar lead, reducing susceptibility to EMI during sensing. PMs (but usually not ICDs) with bipolar leads can be programmed to the unipolar mode for pacing and/or sensing. Sometimes, a PM automatically switches from a bipolar to unipolar pacing and sensing configuration if a lead fault is detected.

Newer CIED systems include a subcutaneous ICD (S-ICD) and leadless PM. The S-ICD (Fig. 5), which gained US Food and Drug Administration (FDA) approval in 2012, has 2 main components, a pulse generator and subcutaneously tunneled single-coil electrode that allows the device to sense malignant cardiac rhythms and deliver a shock when indicted. Because the electrode is implanted under the skin rather than in the heart, the potential for both acute

Box 1: Perioperative evaluation and management

Perioperative evaluation and management

1. CIED system
   a. Identify the presence of a CIED
   b. Determine (a) the CIED type (ie, PM, ICD, CRT), (b) generator manufacturer, (c) indication for implantation, (d) battery status, (e) current programming (including magnet response)
   c. Ensure proper CIED function, especially for surgery that is likely to result in hemodynamic embarrassment or whenever EMI (ie, which most commonly stems from the use of monopolar electrosurgery) is likely. (Proper function may often be established by querying the patient's medical record to determine when the CIED was last interrogated, and by accessing that interrogation report. CIEDs should be evaluated every 3–12 months, with shorter intervals recommended for patients with more complicated devices [ie, CRT systems] or medical conditions, or devices under alert notification).
2. Patient
   a. Determine the patient's underlying rate and rhythm, and whether the patient is pacing dependent.
   b. Evaluate the patient for and optimize coexisting disease or diseases.

Procedure

1. Determine whether intraoperative EMI is anticipated
2. If EMI is anticipated, (a) disable antitachycardia therapy if an ICD; (b) consider asynchronous pacing for the pacing-dependent patient.

(Note: Magnet application might be acceptable for some PMs (provide asynchronous pacing) or ICDs [disable antitachycardia therapy]. Asynchronous pacing from an ICD requires reprogramming.)

3. Consider additional programming changes, including
   a. Increasing the lower rate limit (ie, pacing rate) to optimize oxygen delivery (especially for major surgery)
   b. Programming to off (when present) pacing features that can mimic pacing system malfunction. These features include
      i. Minute ventilation rate response
      ii. Sleep rate (note that CIED clocks will not automatically adjust for travel or daylight savings time)
      iii. Hysteresis rate (pacing onset can be delayed by an intrinsic event)
      iv. Rate drop (high rate pacing, typically 100 bpm after a sudden drop in intrinsic rate is observed, which can be triggered by EMI)
      v. Right ventricular pacing avoidance algorithms that might
         1. Allow prolonged AV delay (to 450 milliseconds)
            a. Biotronik Vp suppression mode
            b. St Jude Medical ventricular intrinsic preference

2. Allow dropped QRS events
   a. Boston Scientific RYTHMIQ
   b. Medtronic managed ventricular pacing
   c. Sorin AAI-SafeR

Intraoperative management

1. Monitor cardiac rhythm/peripheral pulse with pulse oximeter plethysmogram or arterial waveform
2. Disable the artifact filter on the ECG monitor, although some advisories offer caution when doing so, because the painting of noncapturing artifacts might confuse perioperative personnel
3. Whenever feasible, avoid use of monopolar electrosurgery (ESU)
4. Position the ESU dispersive electrode to divert electricity away from the generator-heart circuit, even if the pad must be placed on the distal forearm and the wire covered with sterile drape
5. If the ESU causes ventricular oversensing, pacing quiescence, or inappropriate tachycardia, limit the effect by suspending the use of monopolar electrocautery, reprogramming the cardiac generator, or placing a magnet over the PM (not indicated for ICD)

Postoperative management

1. Any CIED that underwent preoperative or intraoperative reprogramming should be reinterrogated and have its parameters restored or optimized for perioperative recovery. Postoperative CIED interrogation should always be prompted by intraoperative hemodynamic instability or any concern for inappropriate CIED function.
2. The ICD patient must remain in a fully monitored setting (postanesthesia care unit or intensive care unit) until antitachycardia therapy is restored.

Adapted from Crossley GH, Poole JE, Rozner MA, et al. The Heart Rhythm Society (HRS)/American Society of Anesthesiologists (ASA) Expert Consensus Statement on the Perioperative Management of Patients with Implantable Defibrillators, Pacemakers and Arrhythmia Monitors: Facilities and Patient Management this document was developed as a joint project with the American Society of Anesthesiologists (ASA), and in collaboration with the American Heart Association (AHA), and the Society of Thoracic Surgeons (STS). Heart Rhythm 2011;8:1114–54.

(ie, pneumothorax, lead dislodgement, perforation, and endocarditis) and long-term (ie, lead failure, infection) complications are reduced or entirely avoided. The downside of this option is limited functionality; the high-voltage output is fixed at 80 J (ie, is nonprogrammable), and the system does not provide sophisticated antitachycardia or antibradycardia pacing nor can it offer treatment for heart failure (ie, CRT). It may also not be the best option for patients with recurrent monomorphic ventricular tachycardia (VT) because this rhythm can often be terminated with ATP, a feature that is available in all transvenous ICDs but which is not available in current S-ICD models [21]. Another emerging technology is the Leadless PM (Fig. 6), which provides

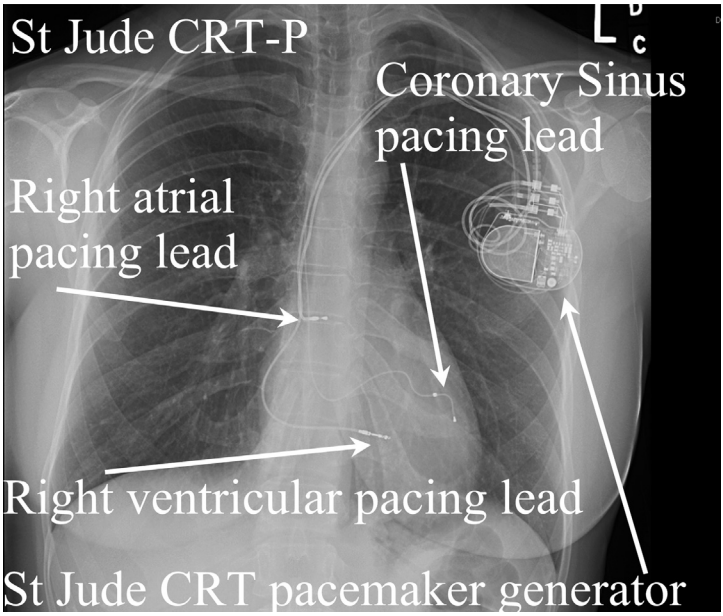


Fig. 1. A cardiac resynchronization pacemaker (CRT-P). The presence of a lead in the CS vein typically identifies a system as CRT. The absence of any shock coil defines this system as CRT-P (as opposed to CRT-D, which would be a cardiac resynchronization system with defibrillation capability).

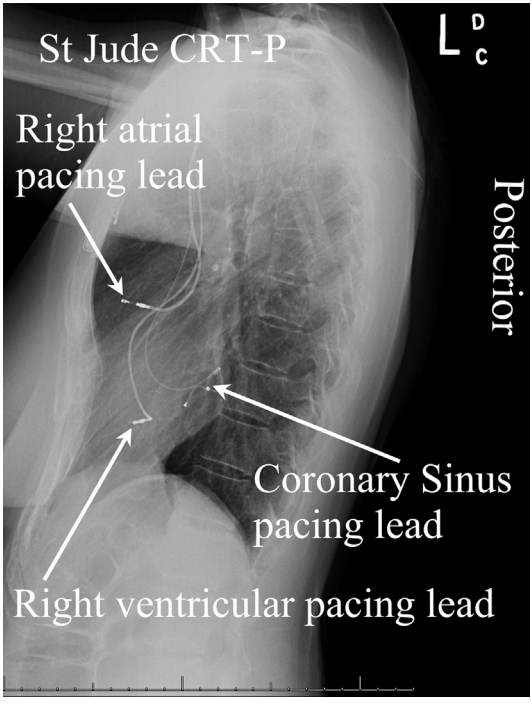


Fig. 2. A lateral CXR demonstrating the posterior position of the CS lead.

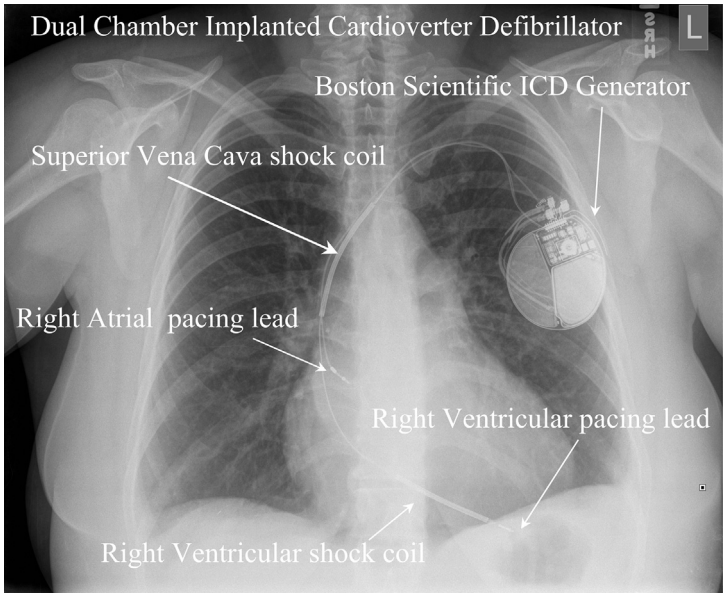


Fig. 3. A dual-chamber ICD system is shown. The presence of a shock coil in the RV (this device has an additional shock coil in the superior vena cava) identifies this CIED as a high-energy capable system, although without knowledge of the actual programming high-energy delivery cannot be assured. In most patients, the presence of an additional shock coil in the superior vena cava lowers the defibrillation threshold.

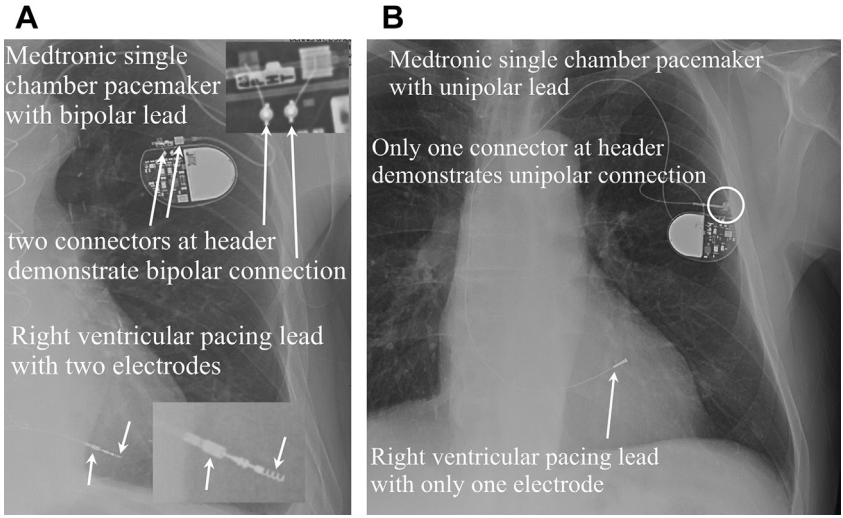


Fig. 4. (*A*) A single-chamber PM with a dedicated unipolar pacing/sensing lead is shown. The radiograph depiction clearly shows only one connector at the generator header. In a unipolar system, the generator always serves as the anode. (*B*) A single-chamber PM with a dedicated bipolar pacing/sensing lead is shown. For the lead in the RV, the downward arrow points to the cathode at the lead tip (which in this case is an active fixation screw). The upward arrow identifies the ring or anode electrode. At the top of the figure, 2 connectors can be seen at the generator header. Note that any bipolar lead can also be configured in unipolar mode, and for some advanced and newer generators, the selection of lead tip or ring as cathode is programmable.

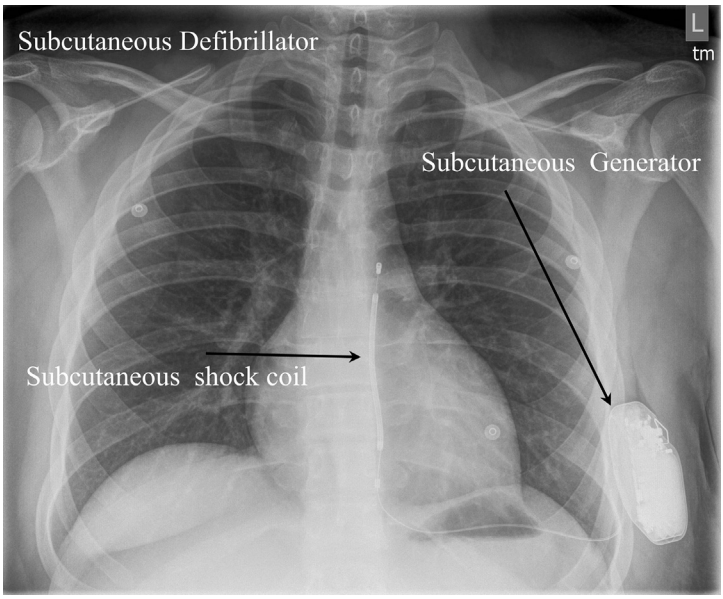


Fig. 5. A subcutaneous ICD (Boston Scientific, Marlborough, MA) is shown. In this case, the lead was tunneled at the level of the diaphragm. The longitudinal position of the shock coil is typical. The S-ICD has no ATP and very limited antibradycardia pacing (it paces for approximately 30 seconds after delivering a shock).

single-chamber RV pacing, is about one-tenth the size of a traditional PM, and is implanted through a catheter. Two versions (Nanostim [St. Jude Medical, Syl Mar, CA] and Micra [Medtronic Inc, Minneapolis, MN]) have a CE mark, and one (Medtronic Micra) has received FDA approval (April, 2016) and will thus become widely available in the United States in the near future. Perioperative clinicians who depend on magnet application to a CIED in the setting of EMI must understand that the magnet behavior of both the S-ICD and the Leadless PM is different from their traditional counterparts (see later discussion on magnet behavior).

A third minimally invasive nontherapeutic CIED is the implantable loop recorder (Fig. 7), a subcutaneous single-lead electrocardiogram (ECG) monitoring device used for diagnostic purposes only.

Understanding CIED nomenclature is necessary when caring for patients with these devices. The Pacemaking Code of the North American Society of Pacing and Electrophysiology and the British Pacing and Electrophysiology Group (NBG) provides a generic understanding of the antibradycardia programming of any CIED [22] (Table 1). The code has 5 positions: position I describes the chamber(s) paced; position II describes the chamber(s) sensed; position III describes how the CIED responds to a sensed event; position IV uses an "R" to denote the presence of rate modulation; and position V

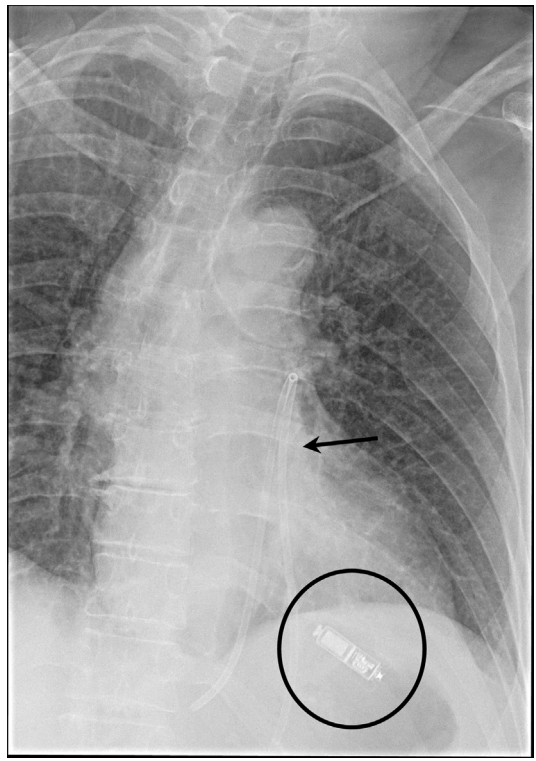


Fig. 6. A leadless PM (Medtronic) is shown (*circle*). The development of a pericardial effusion during PM implantation necessitated insertion of a pericardial drain (*arrow*). As noted in the text, currently all leadless PMs pace only in the VVI mode; thus they cannot provide AV synchrony or optimal hemodynamics. The Medtronic leadless PM has no magnet response. The St Jude leadless PM (not shown) responds to magnet placement with asynchronous (VOO) pacing, although not at constant rate (see text).

describes the presence or absence of multisite pacing (ie, biventricular pacing or CRT). Although not used as often as the NBG Code, transvenous ICDs have a 4-place generic NBD code [23] (Table 2) to indicate lead placement and device function. Position I indicates the chamber(s) shocked; position II indicates the chamber(s) in which ATP is administered; position III identifies the detection method (electrogram signals or hemodynamic sensor; not currently available in the United States); and position IV indicates the chamber(s) delivering antibradycardia pacing [22]. (Many PMs and ICDs now have antiatrial tachycardia, which includes ATP and low-energy cardioversion.) Because all transvenous ICDs can perform pacing for bradycardia, the most comprehensive description includes the first 3 characters of the NBD, followed by a dash, then the 5-character PM NBG [24].

Although traditional CIED systems are generally extremely reliable, system malfunction is not as rare as might be expected [25], and unfortunately, the first

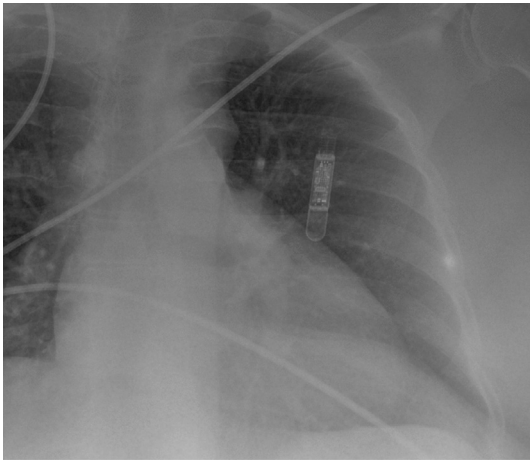


Fig. 7. An implanted loop recorder (in this case, a Medtronic LINQ) is shown in a typical subcutaneous implant position. Note the absence of leads.

indication of system failure can be death [26]. Maisel and colleagues [27] evaluated an FDA database to determine the general failure rate of these devices and found that over the 12-year study period (1990–2002), per 1000 implants, 4.6 PMs and 20.7 ICDs were explanted for issues other than battery depletion. During this time, 2.25 million PMs and 415,780 ICDs were implanted, and 30 PM and 31 ICD patients died as a direct result of device malfunction. In a subsequent analysis, Laskey and colleagues [28] reviewed FDA records from 2003 to 2007 for transvenous ICD explantations (459,000 transvenous ICDs and 256,000 CRT-Ds) and found 10,593 (2.3%) transvenous-ICD and 1925 (0.8%) CRT-D failures.

Table 1
The revised North American Society for Pacing and Electrophysiology/British Pacing and Electrophysiology Group generic code for antibradycardia, adaptive rate, and multisite pacing

Position I	Position II	Position III	Position IV	Position V
Pacing Chamber(s)	Sensing Chamber(s)	Response(s) to Sensing	Programmability	Multisite Pacing
O = None	*O* = None	*O* = None	*O* = None	*O* = None
A = Atrium	*A* = Atrium	*I* = Inhibited	*R* = Rate modulation	*A* = Atrium
V = Ventricle	*V* = Ventricle	*T* = Triggered		*V* = Ventricle
D = Dual (A + V)	*D* = Dual (A + V)	*D* = Dual (T + I)		*D* = Dual (A + V)

Adapted from Bernstein AD, Daubert JC, Fletcher RD, et al. The revised NASPE/BPEG generic code for antibradycardia, adaptive-rate, and multisite pacing. North American Society of Pacing and Electrophysiology/British Pacing and Electrophysiology Group. Pacing Clin Electrophysiol 2002;25:260–4; with permission.

Table 2
North American Society for Pacing and Electrophysiology/British Pacing and Electrophysiology Group defibrillator code

Position I	Position II	Position III	Position IV
Shock Chambers(s)	ATP Chamber(s)	Tachycardia Detection	Antibradycardia Pacing Chamber(s)
O = None	*O* = None	*E* = Electrogram	*O* = None
A = Atrium	*A* = Atrium	*H* = Hemodynamic	*A* = Atrium
V = Ventricle	*V* = Ventricle		*V* = Ventricle
D = Dual (A + V)	*D* = Dual (A + V)		*D* = Dual (A + V)

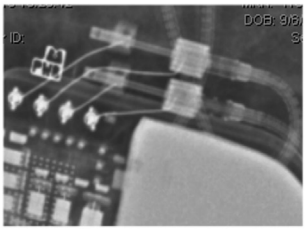
From Bernstein AD, Camm AJ, Fisher JD, et al. North American Society of Pacing and Electrophysiology policy statement. The NASPE/BPEG defibrillator code. Pacing Clin Electrophysiol 1993;16:1776–80.

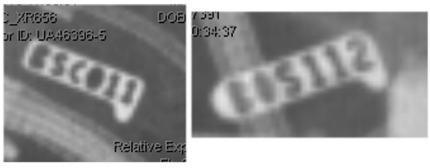
Malfunction stems from issues with the pulse generator or leads, or from external issues such as EMI–the most common cause during the perioperative period. Even when a properly functioning device is perceived to be malfunctioning (termed "pseudomalfunction"), harm to the patient and/or device can ensue; these events occur with some regularity in the hospital [29–31]. Although not well studied, for patients undergoing surgery, the presence of a CIED may be a risk factor for increased morbidity or mortality [11,12].

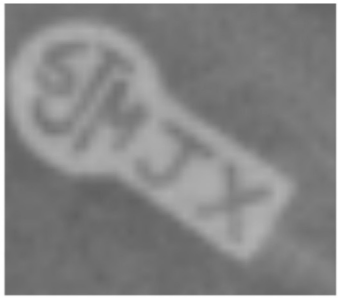
Thus, before elective surgery, a key step is ensuring that the patient's CIED is functioning properly, especially for surgery that is likely to result in hemodynamic embarrassment or whenever EMI (ie, which most commonly stems from the use of monopolar electrosurgery) is likely. Although there are no data conclusively showing the need for a comprehensive preoperative CIED evaluation, anecdotal evidence and case reports suggest that forgoing this step can result in adverse outcomes, including patient harm [19]. In any situation wherein a preoperative device evaluation cannot take place (see emergency surgery in later discussion), clinicians should be adequately prepared for perioperative device malfunction or failure that might occur [19].

Proper device function may often be established by querying the patient's medical record to determine when the CIED was last interrogated, and by accessing that interrogation report. The interrogation report should provide detailed information regarding the device type (ie, PM, ICD, CRT), the indication for its implantation, battery status, the current programming (including the magnet response), whether the patient is pacing dependent, and an overall assessment of whether the device was functioning properly at the time of the evaluation; often, a history of arrhythmias can be obtained. Typically, CIEDs should be evaluated every 3 to 12 months, with shorter intervals recommended for patients with more complicated devices (ie, CRT systems) or medical conditions, or devices under alert notification [14].

For instances in which previous records are not available or it is not otherwise possible to obtain information about the device, as previously noted, a CXR may be used to identify the device type, the device manufacturer (Fig. 8), and information about lead configuration. Additional steps that might







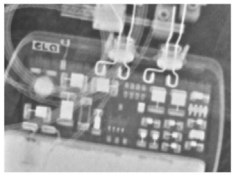


Fig. 8. Radiograph logos (*clockwise from upper left*): Biotronik (US Headquarters; Lake Oswego, OR), Medtronic, St Jude Medical, ELA 9 (which was purchased by Sorin [US Headquarters; Arvada, CO] and subsequently merged with Livanova [US Headquarters; Arvada, CO]), and Boston Scientific (''BSC'' logo is most recent).

provide information about the device include reviewing the implant card that patients with CIED are instructed to carry with them at all times and calling the device manufacturer. Table 3 lists o device manufacturers and their phone numbers.

The patient

After confirming appropriate device function, the next step in preparing the patient with CIED for surgery is determining the patient's underlying rate

Table 3
Pulse generator company phone numbers

Biotronik	800-547-0394	Medtronic	800-505-4636
Boston Scientific	800-227-3422	St Jude Cardiac Rhythm Management	800-722-3774
ELA Medical Became (Sorin) Now LIVANOVA	877-663-7674		

and rhythm, and whether the patient is pacing dependent, because EMI-induced pacing inhibition (Fig. 9) may result in severe bradycardia or asystole in such patients. In general, pacing dependence implies the lack of spontaneous ventricular activity when the CIED is temporarily programmed to the VVI (single-chamber ventricular) or DDI (dual chamber pacing and sensing, but inhibited mode only) mode (or AAI for single-chamber atrial devices) at the lowest programmable rate (Fig. 10). Pacing dependency might alternatively be established by reviewing the patient's history or by examining the surface ECG. Patients with a history of AV node ablation or prior placement of a temporary pacing lead should be assumed to be pacing dependent. If a CIED was implanted for a symptomatic bradyarrhythmia or syncope, the patient might also be pacing dependent. On the ECG, pacing dependence

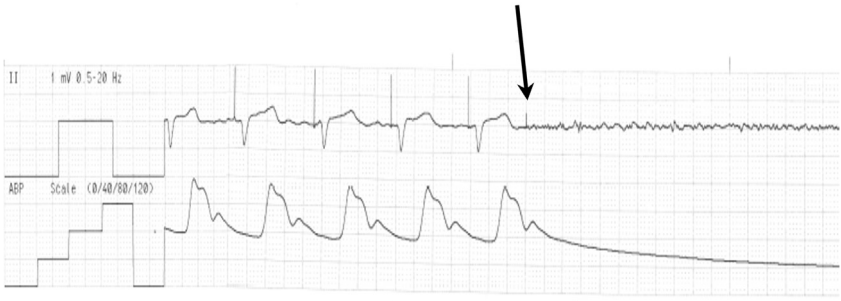


Fig. 9. Pacing inhibition from EMI leading to asystole in a pacing-dependent patient with third-degree heart block. A patient with persistent atrial fibrillation and a VVI PM set to 70 bpm was undergoing right total hip arthroplasty where monopolar electrosurgery was being conducted to a dispersive electrode on his upper back, allowing EMI to cause ventricular oversensing and pacing inhibition. (The preferred location for the dispersive electrode in this case would have been the thigh, ipsilateral to the surgical site.) The upper trace is ECG lead II, and the lower trace is the invasive arterial blood pressure. Pacing artifacts were being ''painted'' by the monitor electronics. Of note, the black downward arrow shows an inappropriately painted artifact caused by the monopolar electrosurgery interfering with the monitor pacing artifact detection, which explains the presumed ''noncapture.'' Pacing resumed immediately upon cessation of monopolar ESU.

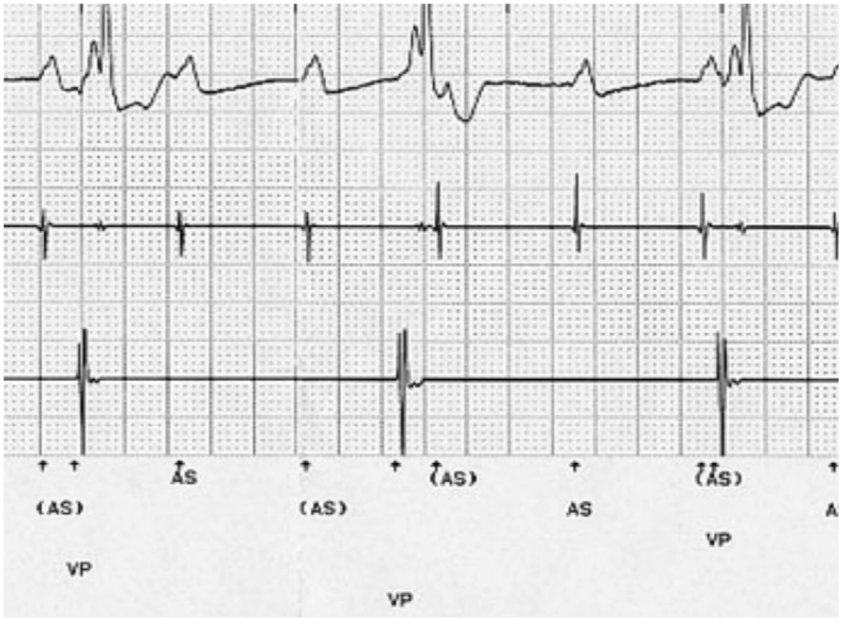


Fig. 10. Pacing dependence demonstrated during interrogation of underlying rhythm. This patient with a Boston Scientific PM was temporarily programmed to DDI at 40 bpm. He has an underlying sinus rhythm at 100 bpm and no conduction to the ventricles, rendering the designation of absolutely pacing dependent. The top trace is lead 2; the middle trace is the intracardiac signal from the atrial lead, and the bottom trace is the intracardiac signal from the right ventricular lead. The PM also provides its interpretation of the signals. ''AS'' means atrial sense (native atrial events are occurring at 600 milliseconds showing the sinus rhythm with rate 100 bpm). ''VP'' means ventricular pace. Note that no atrial event results in a conducted ventricular event (which would be labeled ''VS.'') This PM marks any atrial event preceded by an atrial event without an intervening ventricular event ''(AS).''

should be assumed if every complex is paced, except for patients with a CRT device, because the goal of CRT programming is to force 100% biventricular pacing.

In general, the presence of a conventional CIED (ie, PM or ICD) does not necessitate special preoperative laboratory tests (that is, CXR, cardiac stress test, or echocardiogram). However, consideration should be given to obtaining a CXR in patients with suspected CIED malfunction, abandoned hardware, or leads on alert. Also, in the patient with a CRT device, documenting the position of the CS lead with a CXR before surgery might be useful, especially if central venous cannulation is planned, because spontaneous CS lead dislodgement can occur [32].

As for any surgical patient, proper management of the patient with CIED scheduled for an elective procedure always includes evaluation and optimization of coexisting disease. Although, as a general principle, the decision for

preoperative testing should be based on non-CIED factors, such as the presence of medical comorbidities and stability of underlying disease, certain CIED-related conditions might prompt testing. For example, patients with an ICD or CRT device often have concomitant cardiomyopathy, heart failure, or other coexisting cardiovascular disease–conditions that might trigger a more extensive workup.

The procedure

Mitigating the effects of intraoperative EMI is the principal procedural concern. Thus, a key step to preoperative management is determining whether intraoperative EMI is anticipated so that appropriate precautions may be taken. In the operating room, ESU use is the most frequent cause of EMI, and monopolar electrosurgery is much more likely to cause EMI than bipolar electrosurgery [33]. In addition, the coagulation (high-voltage) mode causes more EMI than the nonblended cutting (low-voltage) mode [34]. The risk is greatest when the ESU will be used near the CIED pulse generator or leads and is typically considered significant when surgery is performed superior to the umbilicus [14,33]. Other important but less common sources of EMI [35–37] during the perioperative period include nerve stimulators for nerve blocks or peripheral nerve stimulation [38–40], transcutaneous electrical nerve stimulation [41–43], radiofrequency scanners used to find retained surgical instruments [44,45], lithotripsy, and other radiofrequency ablation machines or bone saws that cause vibration [46,47]. The ASA Practice Advisory states that all ICDs should have antitachycardia therapy disabled whenever monopolar ESU use is planned [15], whereas the HRS Expert Consensus Statement says ICD deactivation might not be needed when monopolar ESU will only be applied inferior to the patient's umbilicus [14]. Both the ASA and the HRS documents agree that consideration should be given to reprogramming any CIED to an asynchronous pacing mode for a pacing-dependent patient undergoing a procedure likely to cause EMI, and both statements caution that magnet application to an ICD cannot be used to accomplish this goal [14,15] (see later discussion on intraoperative management).

Additional considerations

In addition to suspending antitachycardia therapy and programming the CIED to an asynchronous pacing mode, before surgery additional changes to the device are sometimes warranted, including programming minute ventilation rate response (and possibly other pacing features that can mimic pacing system malfunction) to off when present, and changing the lower rate limit (ie, pacing rate) to optimize oxygen delivery (especially for major surgery).

INTRAOPERATIVE MANAGEMENT

No specific monitoring or anesthesia technique is required for the patient with CIED; however, the presence of a CIED does create specific intraoperative considerations.

Monitoring

Although standard ASA monitors (including continuous ECG, pulse oximetry, and capnography) are always required, every case in which the patient has a CIED also must include direct detection of mechanical systoles, because both EMI and the nerve stimulators used to monitor neuromuscular block can interfere with QRS complex display as well as detection and display of PM artifacts [34,37]. Most ECG monitors require reconfiguration of high-frequency filtering to demonstrate pacing pulses; however, ECG monitors can misinterpret pacing pulses as QRS complexes and display a nonzero heart rate for an asystolic patient [17]. Mechanical systoles are best evaluated by pulse oximetry plethysmography or invasive arterial pressure waveform display, and at least one these monitoring modalities is recommended for these cases by both that ASA and HRS advisories [14,15]. Inappropriate "painting" of pulse oximetry "systoles" can also occur; such false systoles reportedly led to a delay in the diagnosis of a cardiac arrest [48] (see Fig. 9).

Anesthetic agents

Drugs that suppress underlying rhythms, such as high-potency opiates [49] or dexmedetomidine [50], might render a pacing nondependent patient pacing dependent [51], thus reducing any margin of safety for pacing system failure. Anesthetic gases, such as isoflurane, sevoflurane, and desflurane, might prolong QT intervals, whereas halothane appears to reduce this interval [52–56].

Electromagnetic interference

As previously mentioned, during a surgical procedure, the function of a CIED may be impaired by EMI, and monopolar electrosurgery (ESU) use is the most prevalent source of intraoperative EMI. The risk of EMI from bipolar ESU is minimal. CIEDs with a unipolar electrode sensing configuration are more prone to EMI than those with a bipolar sensing configuration. Coagulation ESU will likely cause more problems than nonblended "cutting" ESU [33,34].

Several potential adverse consequences of EMI are possible; however, the 2 most common issues are (1) pacing inhibition and (2) delivery of inappropriate high-voltage therapy (ie, shocks or ATP). All CIEDs interpret electrical signals delivered through the electrodes as P or R waves. Pacing inhibition can occur when the CIED senses electrical activity (ie, electrosurgery "noise," myopotentials, T waves) that it should ignore but instead interprets as an intrinsic rhythm. Consequently, sometimes pacing inhibition in a pacing-dependent patient can result in profound bradycardia or asystole (see Fig. 9). If electrical activity is misinterpreted by an ICD as a tachyarrhythmia, inappropriate shocks or ATP might be triggered (Fig. 11), with the potential for serious consequences. The delivery of high-voltage therapy appears to release troponin [57], and even low-voltage ATP appears to injure the myocardium [58]. Both ATP and shock, whether appropriately delivered to treat a malignant ventricular arrhythmia or inappropriately delivered (ie, because of atrial fibrillation, another supraventricular rhythm, or EMI), have been associated with increased mortality [58]. In-hospital EMI appears to be responsible for more

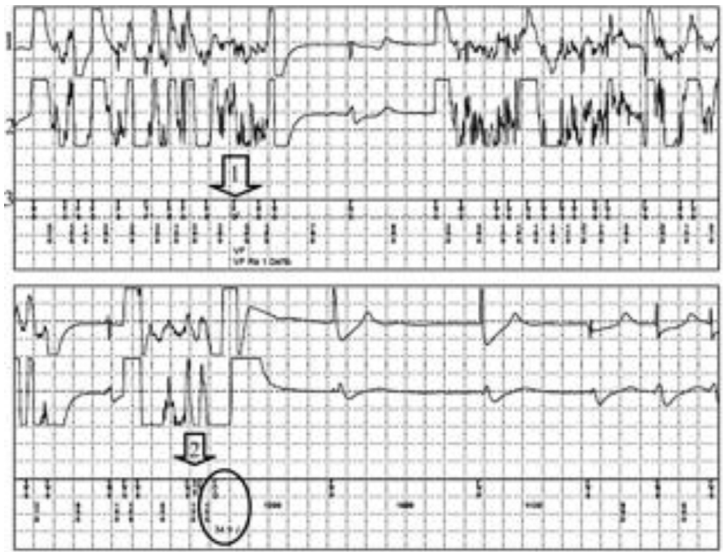


Fig. 11. Intraoperative EMI from monopolar electrosurgery leading to an inappropriate ICD shock. The electrogram demonstrates that a short burst of monopolar electrosurgery at an inopportune time caused the ICD to misdiagnose EMI as a malignant rhythm and deliver a 34.9-J shock. Trace ''1'' (*top panel*) reports the RV signal from the RV tip to ring electrodes. Trace ''2'' reports the RV signal collected using the RV ring electrode and the ICD ''can.'' Trace ''3'' reports the ICD interpretation (marker channel) of the events (see legend below). At downward arrow ''1,'' the ICD determined the aberrant signal persisted long enough to declare a ventricular fibrillation event ''FD'' and charge the capacitor in preparation for shock. ATP while charging was not delivered owing to several short RR intervals preceding charge initiation (this ICD will not deliver ATP while charging when any RR interval in the 8 proceeding RR intervals before the VF detection is <240 milliseconds). ''CE'' downward arrow ''2'' marks the end of capacitor charging and the start of VF reconfirm. Then, a very brief EMI event caused the 34.9-J charge delivery (''CD''). Because the EMI (''VF'') stopped, the ICD classified this shock as successful termination of VF. The lack of EMI right after VF was declared too short to abort this event given the patient's native heart rate of about 80 bpm. CE, charge end; CD, charge delivered-cardioversion/defibrillation pulse; FD, VF detection; FS, VF sense; TS, VT sense; VP, ventricular pace; VS, ventricular sense.

than 4% of inappropriate shock therapy [59], which occurs in 20% to 40% of patients with ICDs [60,61].

Other adverse effects of EMI include (1) oversensing on the atrial lead, which, in a dual chamber pacing mode, can lead to right ventricular pacing at the upper tracking rate; (2) pacing at the upper sensor rate if the device has an active minute ventilation sensor, possibly leading to iatrogenic patient injury [29]; (3) ''power on reset'' wherein the device reverts to safety parameters, which include aggressive settings for ICD high-energy delivery and single-chamber pacing between 60 and 72.5 bpm regardless of the previous setting [14]; and (4) outright failure with no output. Because of the rare but catastrophic risk of outright failure, St Jude Medical has warned that

pacing-dependent patients with legacy devices should undergo placement of temporary pacing backup in the setting of monopolar ESU use [62].

When intraoperative EMI is anticipated, specific actions are required to mitigate the associated risks. For an ICD, anti-tachyarrhythmia therapy should be disabled whenever EMI is likely or, even in the absence of anticipated EMI, if movement from a shock might create a hazard to the patient (ie, intraocular surgery) or procedural personnel (ie, hand surgery using a scalpel). During any period in which the ICD's anti-tachyarrhythmia therapy is disabled, ECG monitoring and the ability to deliver external cardioversion or defibrillation must be present. The ASA states that all ICDs should have anti-tachyarrhythmia therapy disabled whenever monopolar ESU use is planned, whereas the HRS states that ICD deactivation might not be needed for monopolar ESU application inferior to the umbilicus. Both the ASA and the HRS documents agree that consideration should be given to reprogramming a CIED to an asynchronous pacing mode for the pacing-dependent patient undergoing a procedure likely to cause EMI, and both statements caution that magnet application to an ICD does not accomplish this goal.

Caution must be observed with the use of invasive nerve stimulators when performing nerve blocks, because these devices can create EMI leading to ventricular oversensing (and therefore, pacing inhibition) as well [38,40].

Application of a surface nerve stimulator for neuromuscular monitoring within the CIED sensing axis can also inhibit pacing by producing pacing inhibition [63]. Transcutaneous nerve stimulators have also been implicated in the delivery of inappropriate high-energy therapy from an ICD [64]. Special testing is required in the setting of permanent nerve stimulator placement into any patient with a CIED, which is beyond the scope of this document [43].

The use of radiofrequency scanning (RFS) for retained instruments might also create EMI issues in patients with CIED [44,45]. CIED reprogramming before RFS might be indicated, and failure to alert anesthesiology personnel to initiation of RFS can result in asystole [44]. Whether operating room personnel with a CIED are at risk remains to be seen [65].

Finally, procedural personnel should be aware of mechanical issues that can cause a CIED to "detect" exercise, leading to an increase in pacing rates for rate responsive devices. Skin preparation in chest, head and neck, and upper extremity cases can produce vibratory effects that will induce increases in the "sensor indicated rate," a parameter internal to the CIED but which denotes the current lower pacing limit in an active rate response situation. External pressure on the CIED case [66,67] as well as bone saws applied to a site distal to the chest have caused pacing-driven tachycardias [47,68] to the upper sensor rate and confused perioperative personnel regarding the reason for the tachycardia.

Magnets

The decision whether to reprogram a CIED with a programming machine or to use a magnet instead depends on the type of CIED (PM or ICD), how it is

programmed, the patient's underlying rhythm, the likelihood of EMI, the proximity of the CIED to the surgical field, and the planned patient positioning during surgery (eg, appropriate magnet application can be difficult or impossible in a patient who is in the prone or lateral position).

If magnet application is planned, the PM or ICD's magnet response should be known. For most transvenous PMs, magnet application will initiate asynchronous pacing at a fixed rate (85–100 bpm) as well as a fixed AV delay (as short as 100 milliseconds), which varies by manufacturer (and sometimes model) and which might not be appropriate for a given patient. For most transvenous ICDs, magnet application will suspend anti-tachyarrhythmia detection and/or therapy. However, some transvenous CIEDs can be programmed to respond differently to a magnet or have no response at all. Also, as previously stated, a magnet will never change the pacing mode of an ICD (ie, pacing inhibition may still occur). Moreover, if the sterile surgical field will include the CIED, then magnet application is usually not an option and the device will require reprogramming. Because CIED technology continues to evolve, expectations about magnet use will need to change. For example, magnet application to a Medtronic Micra leadless PM has no effect (by design) and is not programmable. Magnet application to a St Jude Nanostim leadless PM initiates VOO pacing at the 100/min for 8 cycles, 90/min assuming battery status normal, 65/min if battery status is "elective replacement indicated," assuming that the magnet sensor is programmed "ON."

Because of the aforementioned considerations, significant controversy exists regarding the appropriateness of using a magnet to achieve asynchronous pacing (PM) or temporarily suspend anti-tachyarrhythmia therapy (ICD). Although in many centers intraoperative magnet use is standard practice, and this approach is often advocated, magnet application may be unreliable, and several investigators have specifically warned against substituting the blind use of a magnet for individualized care. In a published series describing cases from 3 institutions, inadequate preoperative assessment of CIED function coupled with erroneous assumptions about the effects of magnet application contributed to or caused inappropriate ICD therapy, premature CIED battery depletion, and patient injury [19]. The investigators concluded that practitioners should exercise caution when applying magnets to CIEDs for surgery. Moreover, the practice of blindly placing a magnet over an ICD (ie, using a magnet and forgoing appropriate preoperative CIED evaluation) is discouraged by both the ASA and HRS.

Electrosurgical unit dispersive electrode placement

The dispersive electrode of the ESU should be placed such that the presumed current path from the ESU hand tool to the dispersive electrode (often incorrectly called "ground pad") does not cross the pulse generator or leads [33]. No data have been published regarding the safety of a whole-body dispersive electrode. The "harmonic scalpel," an ultrasonic cutting device, has been

championed to prevent EMI while providing the surgeon with the ability to both cut and coagulate tissue. There are several case reports demonstrating successful surgery without EMI issues in these patients [69–71].

Additional considerations

Although many recommendations exist for external defibrillator pad placement to protect the ICD, one should remember that the patient, not the ICD, is being treated, and the anterior-posterior position remains favored. At some centers, the defibrillator pad is placed on the back, but not the front, of the ICD in the patient undergoing a procedure wherein the anterior pad would interfere with the procedure; thus, should an emergency arise, the anterior pad can be placed quickly and without significant repositioning of the patient.

POSTOPERATIVE MANAGEMENT

Many patients require postoperative CIED interrogation or reprogramming. In particular, any CIED that underwent preoperative or intraoperative reprogramming should be reinterrogated and have its parameters restored or optimized for perioperative recovery. Postoperative CIED interrogation should always be prompted by intraoperative hemodynamic instability or any concern for inappropriate CIED function. In many cases, rate enhancements may need to be reinitiated, and optimum heart rate and pacing parameters should be determined and ensured. The ICD patient must remain in a fully monitored setting (postanesthesia care unit or intensive care unit) until antitachycardia therapy is restored.

SUMMARY

The presence of an implantable PM or ICD (collectively, CIED) often complicates perioperative care and might even increase perioperative risk. These devices are being encountered in surgical patients with increasing frequency. Considerations in the proper care of the patient with CIED for surgery include (1) establishing communication with the patient's CIED physician, service, or other CIED expert to ensure appropriate CIED function; (2) acquiring knowledge about the CIED and how it is programmed to understand its intended function; (3) informing the patient's CIED physician, service, or other CIED expert of the upcoming surgical procedure and developing an appropriate perioperative CIED management plan; (4) enacting the perioperative management plan, which might include disabling an ICD's antitachycardia therapy, and asynchronous pacing for the pacing-dependent patient. All perioperative personnel must be made aware of the CIED, especially if electrical equipment (commonly monopolar electrosurgery) will be used that could interfere with CIED function. Whenever a preoperative device evaluation cannot take place or appropriate preoperative and/or intraoperative precautions cannot be enacted, clinicians should understand that device malfunction or failure might occur.

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