Circulation

AHA SCIENTIFIC STATEMENT

Periprocedural Management and Multidisciplinary Care Pathways for Patients With Cardiac Implantable Electronic Devices: A Scientific Statement From the American Heart Association

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ABSTRACT: The rapid technological advancements in cardiac implantable electronic devices such as pacemakers, implantable cardioverter defibrillators, and loop recorders, coupled with a rise in the number of patients with these devices, necessitate an updated clinical framework for periprocedural management. The introduction of leadless pacemakers, subcutaneous and extravascular defibrillators, and novel device communication protocols underscores the imperative for clinical updates. This scientific statement provides an inclusive framework for the periprocedural management of patients with these devices, encompassing the planning phase, procedure, and subsequent care coordinated with the primary device managing clinic. Expert contributions from anesthesiologists, cardiac electrophysiologists, and cardiac nurses are consolidated to appraise current evidence, offer patient and health system management strategies, and highlight key areas for future research. The statement, pertinent to a wide range of health care professionals, underscores the importance of quality care pathways for patient safety, optimal device function, and minimization of hemodynamic disturbances or arrhythmias during procedures. Our primary objective is to deliver quality care to the expanding patient cohort with cardiac implanted electronic devices, offering direction in the era of evolving technologies and laying a foundation for sustained education and practice enhancement.

Key Words: AHA Scientific Statements ■ critical pathways ■ defibrillators, implantable ■ delivery of health care ■ pacemaker, artificial ■ patient safety ■ perioperative care

Since the prior consensus statement on the perioperative management of cardiac implantable electronic devices (CIEDs),[1] technology has advanced rapidly. Concurrently, there has been an increase in the number of patients implanted with these devices and an expanded variety of procedures that may affect device function.

The rapid evolution in the field, including the advent of leadless pacemakers, subcutaneous and extravascular implantable cardioverter defibrillators (ICDs), and novel device communication protocols, necessitates recurring updates to clinical guidance on the periprocedural management of CIEDs. Equally important is the development of multidisciplinary care pathways to establish best practices for managing devices in patients undergoing procedures. The goal of such pathways is to ensure patient safety and appropriate device function during the periprocedural period and provide proper training for all those who may encounter a patient with a CIED.

Recognizing the urgent need for an updated clinical resource, we have assembled a writing group comprising experts in anesthesiology, cardiac electrophysiology, and cardiac nursing. In this scientific statement,

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we critically appraise the current evidence and offer management strategies at both the patient and health system levels. Moreover, we identify essential areas for future research that may allow further improvements in the periprocedural management of patients with CIEDs.

This scientific statement is not exclusive to a particular group of practitioners. Instead, it is a vital resource for a broad population of health care professionals, including surgeons, anesthesiologists, referring physicians, nurses, advanced practice clinicians, and cardiologists managing patients with CIEDs throughout the periprocedural cycle (Figure 1). We have endeavored to present our guidance in an accessible manner, ensuring its utility for all individuals engaged in the care of patients with CIEDs.

Understanding and managing CIEDs are of utmost importance because interference with device function during procedures may result in severe hemodynamic consequences or arrhythmias. Therefore, the meticulous planning of any invasive procedure in patients with these devices begins before the procedure and continues through the patient's recovery and follow-up by the CIED care center.

Our overarching aim is to facilitate the delivery of quality care to this growing patient population. Through this scientific statement, we aspire to not only provide timely guidance to health care professionals navigating the challenges posed by technological advancements in CIEDs but also establish a framework for ongoing education and practice improvement in the area.

PREPROCEDURAL MANAGEMENT

The initial step to periprocedural evaluation and management of CIEDs is patient preprocedural screening. This process involves a systematic approach to identify aspects of an individual's medical history that may influence the safety and efficacy of a particular procedure with respect to the implanted device (Figure 2).[1] Involvement of the cardiology clinic primarily managing the device, or CIED care center, in the planning of the procedure improves patient safety and continuity of care. Like many aspects of operative care, careful planning for CIED management may begin immediately after the decision to proceed with an operative procedure.[2]

Essential elements of patient screening for perioperative CIED management include the following:

- Presence of a CIED and its location (right/left infraclavicular, abdominal, and midaxillary region);

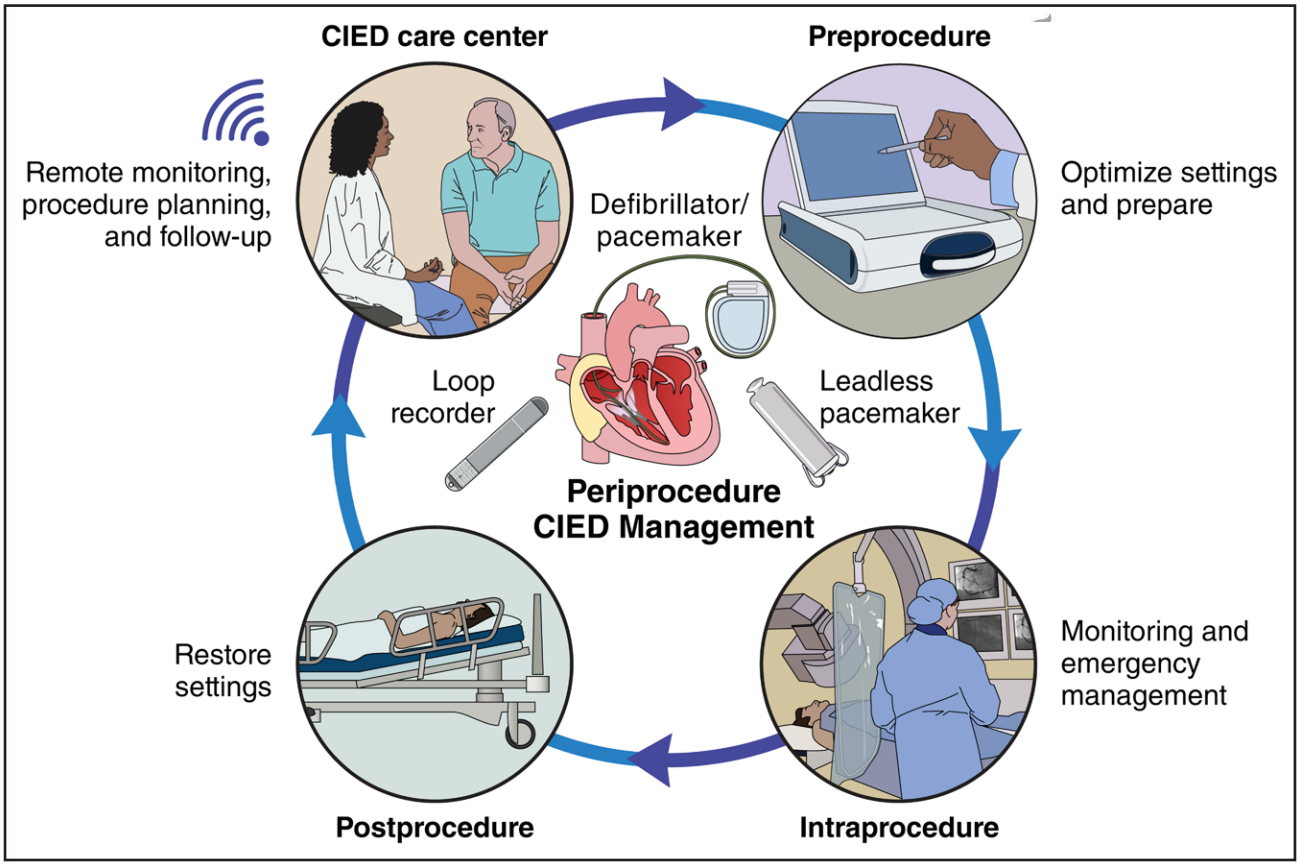

Figure 1. Central Illustration: The cycle of periprocedural management of cardiac implantable electronic devices.
Periprocedural management of CIEDs begins with the development of a procedural plan at the CIED care center (cardiology clinic with and without remote monitoring; **top left**), which is communicated to the surgical/procedural team and implemented before the procedure (**top right**). The device and patient are monitored during the procedure (**bottom right**); settings are restored; and events are noted postprocedurally (**bottom left**) and communicated back to the CIED center. CIED indicates cardiac implantable electronic devices.

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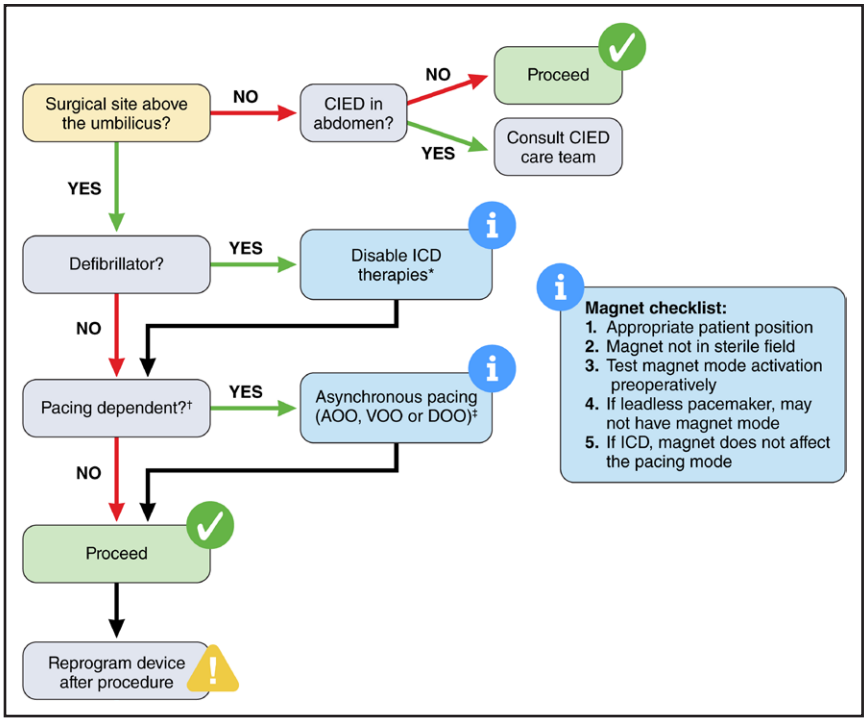

Figure 2. Decision pathway for intraprocedural CIED management. Decision pathway for CIED planning during medical procedures including surgical site, considerations for the presence of a defibrillator, pacemaker dependence, and requirements for magnet application. All devices with programming changes are usually reverted to preprocedural settings, and defibrillator therapies are re-enabled after the procedure. CIED indicates cardiac implantable electronic devices; ICD, implantable cardioverter defibrillator. *May use a magnet or reprogram the device, depending on pacing dependency, patient positioning, or recommendations from the CIED team. †Pacemaker dependency may be increased under sedation. In nondependent patients, the underlying rhythm/rate may still be inadequate for the operative procedure. ‡Reprogramming is required for defibrillators because the magnet does not affect the pacing mode. AOO, VOO, and DOO are asynchronous pacing of the atrium, ventricle, and both atrium and ventricle, respectively.

- Type of device (transvenous or leadless pacemaker; transvenous, subcutaneous, or extravascular defibrillator; cardiac resynchronization device; or implantable cardiac monitor);
- Indication (sick sinus syndrome, atrioventricular block, primary or secondary prevention of sudden cardiac death, ventricular tachycardia, or ventricular fibrillation) and pertinent arrhythmic history (eg, sinus node dysfunction, tachy-brady syndrome, supraventricular tachycardia, atrial fibrillation or ventricular tachycardia, and cause of cardiomyopathy);
- Physical examination (jugular venous pressure, pulmonary auscultation, lower extremity edema, and condition of CIED pocket if applicable);
- Sources of electromagnetic interference (EMI; eg, nerve stimulators, cochlear implants, programmable hydrocephalus shunts, left ventricular assist devices, and cardiac contractility management devices);
- Assessment of new cardiac arrhythmia events recorded by device; and
- Assessment of extracardiac conditions that may affect intraprocedural safety, including chronic or acute kidney dysfunction, hepatic failure, acute or subacute neural impairment, pulmonary insufficiency, and impediments to vascular access.

Specific device type can be identified from several sources: the patient's device card, recent device interrogation or remote monitoring transmission performed by the physician who is managing the patient's CIED, review of the electronic health record, and examination of the device on chest x-ray film (Figure 3). Understanding device features, including battery longevity, programmed pacing mode, magnet response, noise response, magnetic resonance imaging (MRI) conditional compatibility, and advisory status, will assist in optimal perioperative planning.

Specific elements of the device interrogation during procedural planning include the following:

- Cardiac rhythm status, including underlying rhythm, baseline heart rate, and dependency on pacing support;
- Battery life, threshold, impedances, sensing parameters, and history of prior arrhythmias;
- Whether the device is MRI conditional and at what magnet strength; and
- Testing and confirmation of magnet response.

Anticipated Procedure and Surgical Site

Understanding the details and characteristics of the proposed operative procedure along with specific CIED features is vital, particularly in patients who may be pacemaker dependent. Unipolar cautery[1] is the principal source of EMI; true bipolar cautery, frequently used by ocular and plastic surgeons, is safe and has no adverse effects. Oversensing of EMI may result in failure of appropriate pacing output or false detection of arrhythmias. These effects and common sources of EMI are reviewed in Table 1. Procedures and use of electrosurgery below the level of the umbilicus are associated with lower risk of EMI than procedures above the umbilicus and closer to the CIED in the absence of an abdominal pulse

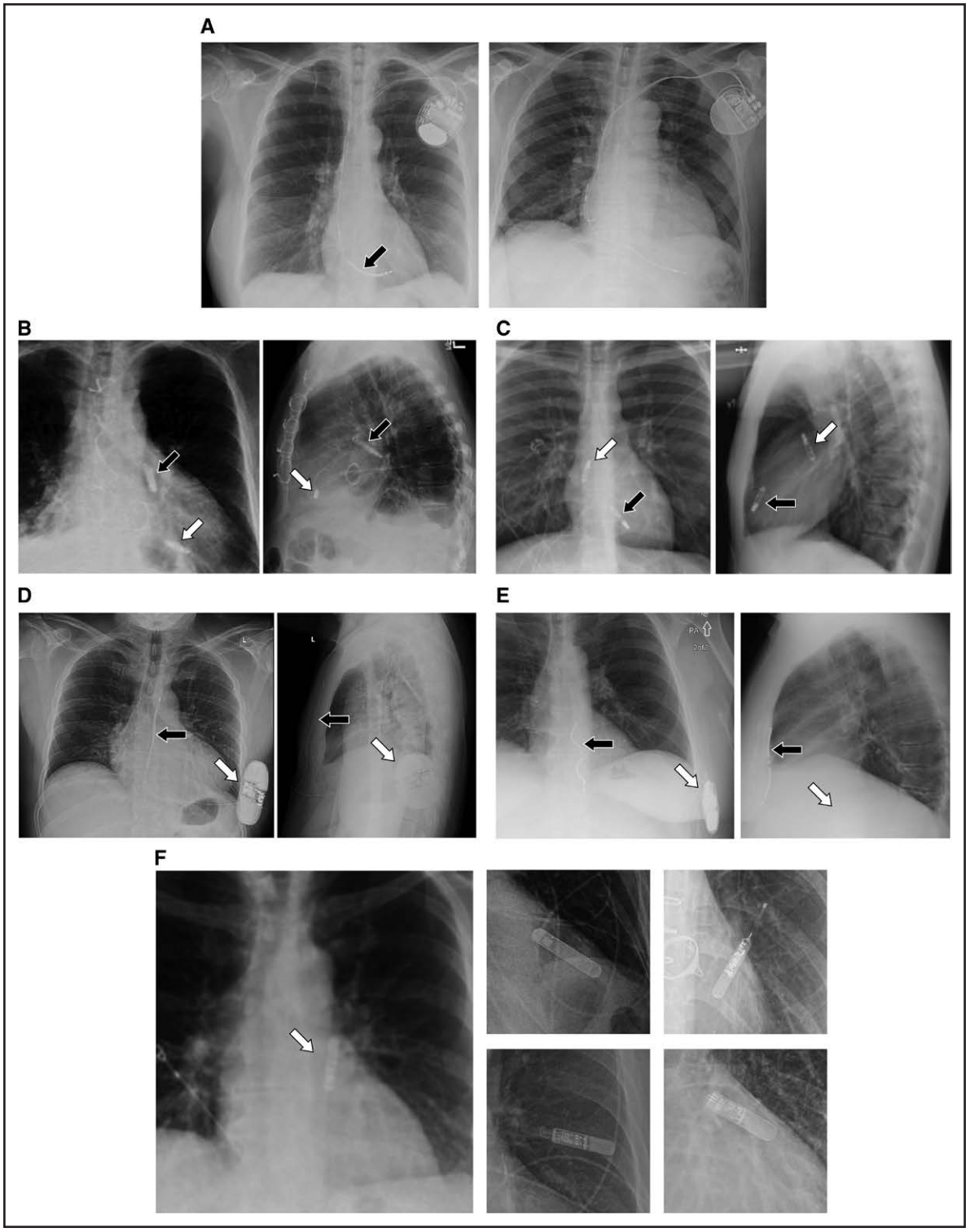

Figure 3. Radiographic appearance of cardiac implantable electronic devices.
A, Side-by-side comparison of the chest x-ray film appearance of a dual-chamber implantable cardioverter defibrillator (ICD; **left**) and dual-chamber permanent pacemaker (**right**). The coil on the ICD lead (black arrow) is the hallmark of a defibrillator and helps distinguish it from a pacemaker. **B**, Anteroposterior (**left**) and lateral (**right**) chest x-ray film with Medtronic Micra AV ventricular implant (white arrow). Also shown are the atrial appendage clip (black arrow) and mitral valve replacement (white asterisk). **C**, Anteroposterior (**left**) and lateral (**right**) chest x-ray film with Aveir DR atrial implant (white arrow) and Aveir DR ventricular implant (black arrow). **D**, Anteroposterior (**left**) and lateral (**right**) chest x-ray film with Boston Scientific subcutaneous ICD generator (white arrow) and subcutaneous coil (black arrow). **E**, Anteroposterior (**left**) and lateral (**right**) chest x-ray film with Medtronic Aurora extravascular ICD generator (white arrow) and substernal coil (black arrow). **F**, Anteroposterior chest x-ray film (**left**) with loop recorder implant (white arrow). **Right**, **clockwise**: Medtronic Linq II, Biotronik Biomonitor 3, Abbott Confirm Rx, and Boston Scientific Lux-DX.

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Table 1. Effects and Common Sources of EMI

EMI source	Effect
General risks	Oversensing of electrosurgery energy[3] Initiation of noise-reversion mode (asynchronous pacing) Initiation of electrical reset mode Permanent damage to or failure of the CIED pulse generator Damage to the lead-myocardial interface causing an increase of pacing thresholds
Bipolar electrosurgery	Does not cause EMI unless it is applied directly to a CIED[4]
Monopolar electrosurgery	Electrosurgery applied below the umbilicus is unlikely to cause EMI as long as the return pad is also below the umbilicus.[5] Most common problem incurred during surgical procedures: Pacemakers: oversensing of electromagnetic interference and device inhibition, which may lead to inappropriately high heart rates due to tracking ICD: false detection of tachyarrhythmia and inappropriate therapy Device reset occurs infrequently with electrosurgery. Pulse generator damage from electrosurgery can occur but is uncommon.[6]
Procedures	
Electrical cardioversion	May result in reset of the CIED, device programming changes, premature battery depletion, or premature lead failure.[7,8]
Radiofrequency ablation	Interactions similar to those of monopolar electrosurgery but greater risk profile with prolonged exposure to current and risk to leads[9]
Therapeutic radiation	Most likely source of EMI to result in CIED reset and can cause oversensing, change pacing thresholds, change lead impedances, or prematurely deplete battery; exposure to neutron contamination and increased absorbed dose due to the proximity of the radiation field warrant enhanced monitoring[10]
Electroconvulsive therapy	Unlikely to cause EMI during the stimulus[11] More commonly, extreme sinus tachycardia may occur with seizure, prompting a need to review ICD tachycardia therapy zones.
Interventional pulmonology procedures	Laser procedure appears to be safe with little risk of EMI. Endobronchial electrocautery may result in CIED interference and theoretical risk of thermal injury at the lead-myocardium interface.[12] Endoscopic argon plasma coagulation uses monopolar circuitry and high voltage and is more likely to result in EMI.[13] Electromagnetic navigational bronchoscopy is unlikely to cause EMI.[14]
Gastrointestinal procedures	Gastrointestinal procedures that use electrosurgery (eg, biliary sphincterotomy, polypectomy, hemostasis, ablation of lesions, or endoscopic surgery) may result in EMI.[15–17] Procedures that use argon plasma coagulation are more likely to result in EMI.[13]
Transcutaneous electrical nerve stimulation units	May rarely result in EMI, influenced by the nerve stimulator position in the chest and current intensity, and may be assessed for interference before use[18]
Lithotripsy	Possible risk of reset; use magnet in the case of inhibition[19]
Left ventricular assist devices	A common cause of EMI that can result in CIED reset, inappropriate shocks, inhibition of pacing, magnet mode, or premature battery depletion[20]
Cardiac contractility management	This device is often present over the right chest and may be present in patients with ICD on the contralateral side. Pulses from this device are applied through multiple leads to the right ventricle periodically over the course of the day. The device (OPTIMIZER, Impulse Dynamics) is rechargeable.[21]
Risk mitigation strategies	
Keep the current path away from CIED by placing return electrode on the contralateral lower limb to diminish adverse interactions with the CIED	
Use bipolar electrosurgery whenever possible	
Minimize the length of monopolar electrosurgery bursts to ≤5 s	
Avoid whole-body return electrodes	
Low battery increases the risk of electrical current intrusion	

CIED indicates cardiovascular implantable electronic device; EMI, electromagnetic interference; and ICD, implantable cardioverter defibrillator.

generator.[1] If the CIED generator is located in the abdomen, the electrophysiology care team may be consulted about the use of cautery, and reprogramming may be needed for procedures. Furthermore, careful placement of the grounding pad far away from the CIED will help to eliminate EMI.

Defibrillator Therapies

For procedures above the umbilicus, defibrillators may be inhibited preoperatively to avoid inappropriate shocks due to EMI. Continuous application of a magnet to a defibrillator inhibits arrhythmia detection and therapy but does not affect pacing functions. Therefore, oversensing of EMI may still result in inhibition of pacing during magnet application. Removal of the magnet restores arrhythmia detection to its original settings. If it is difficult to maintain stable magnet application because of patient positioning or extent of procedural sterile field, reprogramming may be necessary. Some magnet responses are programmable, and the setting and magnet response may be checked routinely before the proposed procedure.[22] It is critical that there is a designated workflow to ensure that ICD therapies are re-enabled before the patient is discharged from a monitored setting.

Pacing Dependency

A CIED interrogation within 3 months may be reviewed to assess the most recent device activity. The burden of atrial or ventricular pacing, or both atrial and ventricular pacing, may be documented on interrogation and can assist in determining pacing dependency. A 12-lead ECG can be performed to determine whether intrinsic conduction (ie, underlying rhythm) or pacing (atrial, ventricular, or both) is present. Pacing dependency may change according to the programmed pacemaker mode, depth of anesthesia, changes in autonomic activity, and administration of other pharmacological agents.[2] In addition, patients who are not pacing dependent may have an underlying rhythm that is inadequate for the hemodynamic demands of the procedure. If the patient has sinus node dysfunction with a stable rhythm and is not pacemaker dependent, careful observation may be used. Magnet application to some pacemakers, although not all, causes pacing at a proprietary rate, with variability between leadless and transvenous devices (Table 2).[23] Some leadless devices may not have a magnet response, or it may be difficult to activate, which is discussed further in the Leadless Devices section. Programmed asynchronous pacing for those patients who are pacemaker dependent may be recommended according to hospital preoperative workflow.

Additional Screening

Physical examination plays an important part of the screening process for periprocedural management in patients with CIEDs. Active or ongoing heart failure symptoms, including orthopnea and paroxysmal nocturnal dyspnea, noted during the periprocedural period necessitate assessment of atrial or ventricular arrhythmias in patients with CIEDs and optimization of cardiac status before the procedure. A high burden of atrial or ventricular arrhythmias noted on device interrogation or recent ICD therapy such as antitachycardia pacing or shocks may warrant further medical evaluation before periprocedural management unless there is an urgent or emergency indication for operative care.[24]

TRANSVENOUS DEVICES

Device Identification

It is essential to identify the manufacturer of the transvenous device before any procedure. Each device manufacturer may have different functionalities or susceptibilities (Table 2). The patient may carry an identification card with the company and model information. The CIED team may differentiate the manufacturer of the device by evaluating the shape and markings of the device on chest x-ray film or may use available mobile technologies that aid identification.[25] A chest x-ray film or a transvenous pacemaker would show endocardial leads attached to a generator in the right or left pectoral pocket. A chest x-ray film of a transvenous ICD would have a similar appearance except it would include a radiopaque coil on an endocardial lead (Figure 3A). In rare cases, pacemaker or ICD leads may be attached to a generator in the abdomen below the xiphoid process. Otherwise, the device manufacturer's medical records department can be contacted to verify the patient and device registration.

Unipolar Sensing and Pacing

CIED sensing of cardiac activity must occur between 2 electrical references. In most cases, this occurs between closely spaced electrodes in the heart (bipolar configuration). However, in some cases, a transvenous device may be programmed to use an electrode in the heart and the device generator (unipolar configuration). Transvenous devices with unipolar sensing are more susceptible to EMI, resulting in greater potential for oversensing.[1]

Lead Dislodgement and Vascular Instrumentation

The introduction of surgical instruments or guide wires can cause potential lead or leadless pacemaker dislodgement, leading to loss of pacing or inappropriate shocks in patients with defibrillator. Avoiding central line access on the ipsilateral side of a CIED may reduce the risk of vascular stenosis and infection.[26] Recently implanted leads and leadless devices may be at higher risk for dislodgment. Furthermore, when a central venous catheter is placed from the upper body in patients with an ICD, especially those with dual-coil ICD leads, there is a risk of inducing ventricular arrhythmias or oversensing due to guide wire interference. High-voltage shorting, arising from guide wire contact with coils, can cause issues with the ICD circuitry.[27]

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Table 2. Magnet Response and Special Considerations by Device Type

Device type	Magnet response	Special considerations
Transvenous pacemaker/ CRT-P	Asynchronous pacing (VOO/DOO)*	Abbott: can be programmed to "off" Biotronik: nominal is 10 asynchronous beats followed by prior settings, also programmable to VOO/DOO or AAI/VVI/DDD pacing[23] Boston Scientific: can be programmed to "off"
Leadless pacemaker	Abbott AVEIR: VOO/DOO Medtronic Micra VR and AV: None	AVEIR: Because of the location within the heart, magnet response may be more difficult to achieve compared with traditional transvenous systems and may be tested before the patients enters the procedural suite. Micra VR/AV: There is no magnet response mode.
Transvenous ICD/CRT-D	Tachycardia detection and therapy inhibited, no change to pacing function	Biotronik: After 8 h of continuous magnet application, tachycardia detection and therapy are automatically re-enabled. No audible tone when magnet is applied, unlike all other manufacturers[23]
Subcutaneous ICD	Tachycardia detection and therapy inhibited	Boston Scientific: No bradycardia pacing through the subcutaneous system with magnet application; emergency bradycardia pacing not possible
Extravascular ICD	Tachycardia detection and therapy inhibited	Medtronic: No bradycardia pacing through the subcutaneous system with magnet application; emergency bradycardia pacing possible
ILR	Some models use magnet application to communicate with applications	Negligible risk to the patient during surgery from EMI

CRT-D indicates cardiac resynchronization therapy–defibrillator; CRT-P, cardiac resynchronization therapy–pacemaker; EMI, electromagnetic interference; ICD, implantable cardioverter defibrillator; and ILR, implantable loop recorder.

VOO is single-chamber asynchronous ventricular pacing; DOO is dual-chamber asynchronous atrial and ventricular pacing; AAI is single chamber atrial demand pacing; VVI is single chamber ventricular demand pacing; and DDD is dual-chamber atrial and ventricular sensing and pacing.

*The rate of asynchronous pacing in magnet mode is manufacturer and battery life specific. If magnet application is planned for a procedure, the magnet response may be tested preoperatively to ensure that the desired response is achieved.

Existing lead complications or venous stenosis can significantly influence the surgical procedure, necessitating caution. Specifically, venous stenosis from transvenous leads can complicate future attempts at venous access, making procedures like catheter placements or even surgeries in the area challenging.

CIED Pockets

When surgical procedures are performed, the proximity to the CIED pocket may require caution. Surgical intervention near the device pocket can lead to device malfunction, device damage, potential infection, or lead dislodgement. Direct surgical interventions or passing a needle through the pocket significantly heightens the risk for infections. Consultation with the CIED team may be done if surgical interventions near the device are unavoidable. EMI may cause the pulse generator to reset to a backup mode, necessitating reprogramming or, on some devices, causing a permanent alteration requiring pulse generator replacement. EMI damage to a CIED is rare[28] unless the energy is applied very near the pulse generator.[29] However, a CIED with low battery voltage (at or near the elective replacement indicator) is considerably more susceptible to electrical current intrusion because the protection circuitry depends on current from the battery.[30]

Management of CIEDs During Radiofrequency Catheter Ablation

Radiofrequency catheter ablation is one of the most common procedures performed in patients with CIEDs with a significant risk of EMI and interaction with transvenous leads. Sensing, impedance, and threshold testing may be checked after electrophysiology study to ensure that there have been no significant changes due to ablation or manipulation of intracardiac leads. Loop recorders usually are not reprogrammed during ablation, but it may be noted that the patient was undergoing a cardiac procedure that may lead to recorded arrhythmias, artifact, or noise.

Conduction System Pacing

Transvenous pacing leads that have been implanted within the conduction system will usually have a narrower ventricular-paced QRS complex compared with traditional right ventricular pacing or biventricular pacing. Compared with traditional lead positions, leads in the His bundle or left bundle-branch position may exhibit different thresholds or sensing parameters. Specifically, His bundle pacing sites may have a higher risk of elevated pacing thresholds or microdislodgement compared with right ventricular apical or left bundle-branch pacing sites.[31]

LEADLESS DEVICES

Device Identification

Since the prior consensus statement, leadless pacing devices have been developed and approved by the US Food and Drug Administration for treatment of bradycardia management.[32–36] Unlike a transvenous device, a

leadless pacemaker is entirely contained within the heart and may not be seen or palpated by physical examination. Thus, a careful history may be required to identify that the patient has a leadless pacemaker. Currently, there are 2 leadless pacemaker systems that are commercially available in the United States. It is important to identify the company and specific type of leadless pacemaker that the patient has for the purposes of device interrogation and important differences in behavior such as magnet response. If the device type cannot be identified on patient interview, a chest x-ray film may provide the characteristic markings, number of devices implanted, and their corresponding locations (Figure 3B). One leadless device in the right atrium and another leadless device in the right ventricle would suggest that it is a dual-chamber leadless pacemaker (Figure 3C). Multiple devices may be seen in the ventricle in the setting of battery depletion of 1 device because removal is not always required.

As with transvenous pacemaker systems, leadless devices are usually interrogated before the planned procedure for the purpose of determining pacing burden, battery life, ventricular sensing amplitude, capture threshold, and device impedance. The device may be reprogrammed if the leadless pacemaker will be exposed to EMI such as cautery, which may result in inappropriate sensing of noncardiac signals and failure to appropriately pace. After completion of the procedure, a thorough assessment of the device is usually performed again to ensure that there are no changes.

Ventricular Leadless Pacing

Ventricular leadless pacing devices provide ventricular pacing with or without rate response (VOO, VVI, or VVIR). Some ventricular leadless pacing devices with accelerometers may also provide atrioventricular synchrony through atrial mechanical sensing (VDD). Unlike transvenous pacing devices, leadless pacemakers can also be programmed "off." The management principles of leadless pacemakers in the perioperative space are similar to the principles applied to traditional transvenous systems.[1] Within 3 months of the planned procedure, an interrogation may be performed to assess pacing burden, battery life, ventricular sensing amplitude, capture threshold, and device impedance.

An important consideration in the perioperative plan of a patient with a leadless pacemaker is that the magnet response can be either absent or difficult to activate because of device position or body habitus. Of the currently available devices, the Abbott AVEIR VR and DR have a magnet response,[36,37] and the Medtronic Micra VR and AV do not (Table 2).[33] Therefore, if a patient is pacemaker dependent and a procedure will involve EMI above the umbilicus, programming the device in asynchronous ventricular pacing mode (VOO) would avoid any sensing of noise. If electrocautery is to be used, the current path between the surgical site and grounding path should be kept at a distance away from the CIED and electrodes.[1] When the magnet modes of the Abbot series leadless pacemaker are activated, they will pace asynchronously (VOO mode) at a rate of 100 bpm for 5 seconds, followed by a fixed rate determined by the battery voltage (Table 2). When the magnet is removed and the device no longer detects the magnet, it will return to its previous settings. However, the authors note that experience in activating the magnet mode, even if available, on leadless devices may be limited by patient body habitus and can be tested before the patient enters the operating room.

Similarly, the mechanism of rate response is different between manufacturers, which may be activated to differing extents, depending on the nature of the procedure. The Micra series pacemakers increase the rate according to activation of an accelerometer, whereas the Abbott series pacemakers increase the rate according to the temperature of the blood returning to the heart from the body.

Ventricular leadless pacemakers with accelerometers may additionally provide atrioventricular synchrony by sensing the mechanical contraction of the atrium using an accelerometer. The currently available model with this technology is the Medtronic Micra AV.[34,38] In addition to the pacing modes listed above, this device allows dual-chamber sensing with ventricular pacing only (VDD and VDI modes).

Atrial and Dual-Chamber Leadless Pacing

The Abbott AVEIR DR device is the only available dual-chamber leadless pacemaker system[36] that involves 2 separate leadless devices, 1 implanted in the atrium and another implanted in the right ventricle. The 2 devices communicate locally to allow dual-chamber pacing and sensing. The AVEIR DR has a magnet response such that when a magnet is placed over the device, the device will pace asynchronously in the DOO mode at rates based on battery longevity (Table 2). If there is a single leadless pacemaker in the atrium alone, the device will convert to the AOO mode with magnet application. Thus, just as with the AVEIR VR device, the 2 options for reprogramming when EMI is anticipated are magnet application and device reprogramming to an asynchronous pacing mode (AOO or DOO).

SUBCUTANEOUS AND EXTRAVASCULAR ICDs

Subcutaneous ICDs (S-ICDs; Boston Scientific)[39,40] and extravascular ICDs (EV-ICDs; Medtronic)[41] are CIEDs implanted outside of the vascular system that provide defibrillation without the vascular and endocardial complications of transvenous ICDs. Both devices are composed of a pulse generator implanted in the extrathoracic space along the left midaxillary line and a single lead with a shock coil and sensing electrodes tunneled to the

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midline. The S-ICD shock coil is placed superficial to the sternum (Figure 3D); the EV-ICD shock coil is placed deep to the sternum (Figure 3E).

Unlike the transvenous ICD, the S-ICD and EV-ICD use widely spaced electrode recordings generated between the pulse generator and the sensing electrodes or between sensing electrodes on the lead, rendering the systems more susceptible to EMI compared with transvenous bipolar sensing configurations.[42] Neither the S-ICD or the EV-ICD provides long-term bradycardia pacing; however, both devices provide temporary pacing after defibrillation "postshock pacing." The EV-ICD additionally can provide antitachycardia pacing for ventricular arrhythmias and temporary "pause prevention" pacing at 40 bpm for pauses >5 seconds (programmable up to 15 seconds).

During procedural preparation, attempts should be made to avoid inclusion of the pulse generator and defibrillator electrode in the path of the electrocautery to the grounding pad. To inhibit EMI-induced shocks or pacing, a magnet can be placed over the pulse generator, or the defibrillators may be programmed "off" (Table 2). For the EV-ICD, pause prevention pacing functionality is not affected by the application of a magnet. A clinical study involving the S-ICD has shown best magnet response with direct placement with ring-shaped magnet.[43] Devices that combine leadless pacemakers that communicate with an S-ICD are currently under investigation in the United States.

LOOP RECORDERS

Implantable loop recorders (ILRs) and implantable cardiac monitors are continuous cardiac monitors implanted subcutaneously in the left upper chest.[44,45] ILRs may be palpated along the chest and identified on chest x-ray film (Figure 3F). If the ILR insertion site is within the area of the planned surgical incision, ILR removal may be considered. Equipment used during the procedure (electrocautery, defibrillation, radiofrequency ablation, lithotripsy, nerve stimulators) can cause inappropriate episode storage or inhibition of episode storage. Preprocedural data retrieval may be necessary to avoid data loss of symptomatic preprocedural events. Postprocedural data retrieval may include artifacts, so accurate reporting of procedural date/time is essential to avoid errant device data analysis. MRIs pose minimal risk in patients with ILRs but may produce artifacts on the images around the area of the ILR.[46,47]

EMERGENCY USE OF MAGNETS

In the periprocedural period, there may be an increased risk of scenarios that lead to unwanted ICD therapy aside from EMI such as supraventricular tachycardia, sinus tachycardia, atrial fibrillation, atrial flutter, oversensing secondary to lead fracture, T-wave oversensing, or presence of mechanical circulatory support devices.[48] In the absence of hemodynamic instability and malignant ventricular arrhythmia, a magnet can be used to cease unwanted tachytherapies from an ICD as a bridge to further treatment and device reprogramming. A magnet can be applied to a pacemaker to temporarily increase the heart rate through asynchronous pacing if the magnet response rate is greater than the current intrinsic heart rate. However, asynchronous ventricular pacing may be detrimental in some clinical cases.

It is important to note that magnet mode may be disabled in some devices; thus, it is important to test the response to magnet application before the procedure. Not all devices produce an audible tone to ensure activation. Furthermore, magnet behavior may become unpredictable when battery voltage falls below end-of-life values.[49] An additional consideration is the magnet mode timeout, which reverts back to original programming after a set time period (Table 2).[23]

MEDICAL CENTER WORKFLOWS FOR REPROGRAMMING

Procedure Planning Workflow

Periprocedural CIED management starts as soon as a patient with a CIED is scheduled to undergo a procedure (Figure 4). Adequate planning requires input from a multidisciplinary team, including but not limited to surgical, anesthesia, and CIED teams under the supervision of an electrophysiologist. In most cases, the information required for safe and effective decision-making is often available in the patient's records. If this information is not readily available, every effort should be undertaken to retrieve documentation about the patient's CIED and cardiac history. In the absence of prior records, chest x-ray film and direct communication with device company representatives may provide information on the type of device implanted and any prior issues affecting the CIED. In some cases, a dedicated outpatient evaluation by the CIED team may be required to facilitate decision-making.

For patient safety and appropriate care, planning of the surgical procedure may be shared with the CIED care team. Once information is known about the nature of the procedure, including possible sources of EMI, and the anatomical location of the procedure, the CIED team can provide recommendations for programming changes to take place on the day of the procedure. In some cases, modifications to the procedure itself may be required to avoid potential risks to the patient with a CIED. In the absence of recommendations from the CIED team before the planned procedure, consultation with a local, available CIED team may be pursued, a process typically handled by the anesthesiology service or a preprocedural consultant responsible for risk stratification.

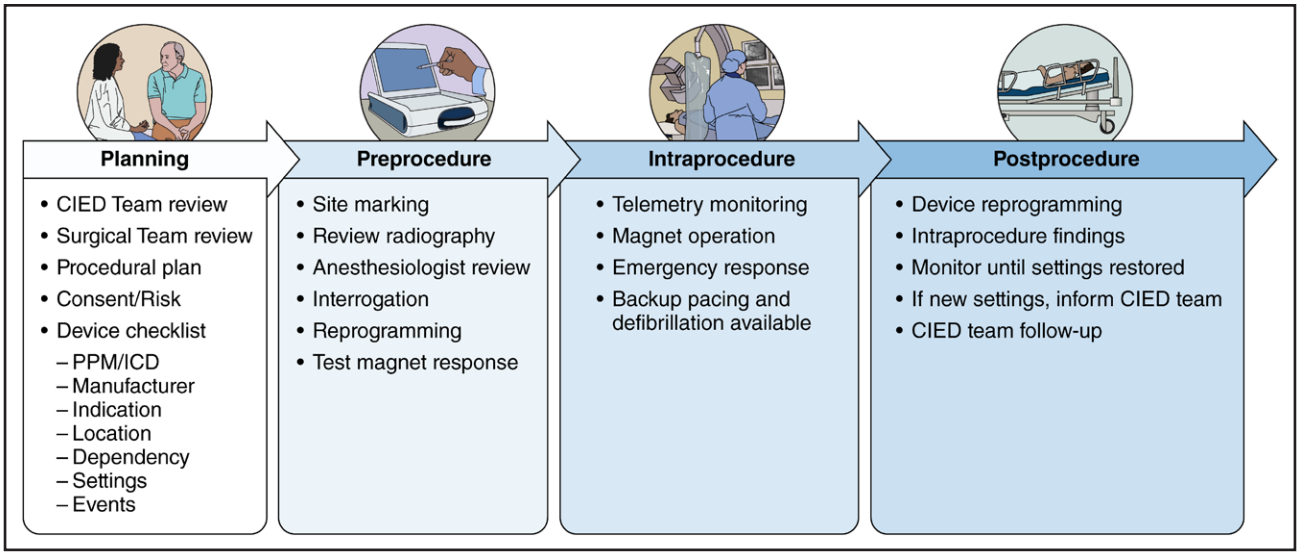

Figure 4. Proposed workflow and interdisciplinary care of cardiac implantable electronic devices.
Medical center workflow for a patient with a CIED from periprocedural phases from advance outpatient procedure planning, preprocedural preparation, intraprocedural monitoring and emergency response, and postprocedural return to outpatient CIED follow-up. CIED indicates cardiac implantable electronic device; ICD, implantable cardioverter defibrillator; and PPM, permanent pacemaker.

Preprocedural Workflow

On the patient's arrival for the planned procedure, recommendations made by the CIED team may be reviewed with consideration for any possible interval changes (eg, ventricular pacing percentage or changes in the underlying cardiac rhythm). For patient safety, plans should be made for rapid detection and treatment of ventricular arrhythmias in the instance of temporary deactivation of ICD therapies or alteration of pacing settings such as immediate availability of an external defibrillator or external transcutaneous pacing device. If a magnet is planned to be used during the procedure, the response to magnet application (or magnet mode) may be tested in a monitored environment before the procedure. If programming changes are performed, they may be completed under the direct supervision of a physician or health care professionals with experience in periprocedural CIED management. Although industry-employed allied professionals may assist with logistical support and technical aspects, they should not be primarily responsible for any perioperative recommendations.[50]

Intraprocedural Workflow

Continuous telemetry monitoring is usually placed on all patients with CIEDs for the duration of the procedure.[51] Because of the possibility of electrical interference with telemetry recordings, plethysmography or arterial blood pressure monitoring may be used. Storage of telemetry strips for expert review after the procedure may be helpful if concerns arise about possible device malfunction or arrhythmia detection. Of note, cardiac pacing spikes seen on cardiac telemetry systems are added to the tracing by an algorithm, which may not be identified/displayed if the pacing output is low. Therefore, this is often not a reliable means of monitoring pacing output.

If magnet use is anticipated during the procedure, the magnet will need to be continuously applied directly to the CIED without contamination of the sterile field. The device will return to its prior settings as soon as the magnet is no longer detected. While ICD therapies are deactivated, external defibrillation pads are used in case of ventricular arrhythmias or need for pacing.

Postprocedural Workflow

In the final step of the medical center workflow (Figure 4), it is critically important to ensure that the device is returned to its prior settings after the procedure because patient deaths have been reported after failure to reactivate ICD therapies after elective procedures.[52] Once a magnet is removed from the CIED, it will return to its previous settings. If reprogramming is required to reinstate tachyarrhythmia detection and therapies, continuous monitoring until the time that the device therapy is re-enabled is useful.[51] All reprogramming documentation is usually placed in the electronic health record.

In the event of major intraprocedural events (eg, cardiac arrest, ICD therapy delivery, external defibrillation, or suspected device reset), the device can be interrogated postprocedurally. In the absence of any major procedural events, the patient can return to routine device follow-up.

Magnetic Resonance Imaging

It is noteworthy that improvements in CIED structure, electronics, and programmed algorithms and changes

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in the protocol design of MRI studies over the past decade have created a relatively safe environment for performing MRI in patients with CIEDs.[1] Institution-specific protocols improve safety of MRI studies and MRI-based procedures in patients with CIEDs, with the understanding that most (but not all) contemporary devices are considered MRI conditional; that is, they have US Food and Drug Administration labeling for performance under MRI conditions provided that certain prespecified conditions are met, including periprocedural monitoring and programming when indicated.[53] MRI-conditional labeling must apply to the entire system, and abandoned leads or parts that are not MRI conditional would render the whole system not MRI conditional.

Best Practices in Medical Center Workflows

Multiple different strategies and workflows may be used for successful periprocedural management of CIEDs. There have been published data from large, academic medical centers with examples of effective models of CIED management with anesthesia-based teams, although such systems may be institution specific in order to best meet the needs of each facility.[54–56] Furthermore, quality assurance and improvement initiatives are useful for the purposes of monitoring outcomes, continuously assessing quality issues, and providing optimal device management as new CIED technologies become available.[56]

CONCLUSIONS

The overarching principle for optimal perioperative management of the patient with a CIED focuses on patient-centered care that includes appropriate periprocedural assessment of the patient and the device, as well as effective and timely communication with the procedural team. Periprocedural management of a patient with a CIED includes patient-specific factors such as pacemaker dependency and CIED location; device-specific factors such as device type, settings, and function; and procedure-specific factors including surgical approach, electrocautery, and anesthesia. Incorporating these factors informs appropriate programming and management of the patient during the perioperative period.

Considerations for Clinical Practice

- Pacemaker-dependent patients: Electrocautery can cause EMI, which leads to oversensing of nonphysiological signals and inhibition of pacing, particularly when surgery is performed above the umbilicus, except for patients with CIED generators in the abdomen, which may require reprogramming because of proximity to the generator. To prevent this, the pacemaker may be programmed to an asynchronous mode (DOO, AOO, or VOO), or a magnet can be placed over the device during the procedure, assuming that a stable magnet position can be maintained and the pulse generator is not located within the sterile surgical field. It can be noted that application of a magnet to an ICD has no effect on the pacing function.
- Patients with ICDs: To prevent inappropriate therapies from a defibrillator due to EMI, tachyarrhythmia detection should be programmed "off." If a programmer is not available, one may place a magnet over the pulse generator during the procedure. It is essential to re-enable detection of tachyarrhythmias before discharge from a monitored setting.
- Magnet response in leadless pacemakers: It may be noted that, unlike transvenous pacemakers, the Micra leadless pacemaker does not have a programmed response to a magnet. Therefore, if a patient is pacemaker dependent and a procedure will involve EMI above the umbilicus, the device may be programmed in a VOO asynchronous pacing mode before the use of electrocautery. Although some leadless pacemakers do have an asynchronous magnet response, the magnet mode may be limited by patient body habitus, and testing before entering the operating room may be considered. If this positioning cannot be consistently maintained, the device can be reprogrammed to an asynchronous mode before the use of electrocautery.
- Emergency magnet use: In addition to the magnet mode programming described previously, magnets may be useful in certain emergency scenarios, including avoiding inappropriate shocks due to hemodynamically stable rhythms, EMI, or ICD lead fracture or increasing the heart rate to the pacemaker magnet response rate before a device programmer is available.
- Communication with the CIED team: Before the procedure, notifying the device team about the upcoming procedure may facilitate generation of a periprocedural plan for the CIED. Postprocedural communication with the device team about any device changes or reprogramming would ensure patient safety and safe continuity of care.

ONGOING RESEARCH AND FUTURE DIRECTIONS

There is limited research related to establishing optimal workflows for perioperative management of patients with CIEDs. Although remote programming may be an option in the future, it is not currently available with most devices. Like other areas of medicine, team-based care is essential. This involves an integrated care model and multidisciplinary team that includes various specialties

(cardiology, anesthesia, surgery, and electrophysiology) and various team members (nurses, advanced practice clinicians, and physicians) with the patient at the center of the framework. We anticipate that the field will continue to establish a framework for ongoing education and practice improvement, including involvement of the patient in helping to establish a patient-centered approach to workflow and development of guidelines in this area.

ARTICLE INFORMATION

The American Heart Association makes every effort to avoid any actual or potential conflicts of interest that may arise as a result of an outside relationship or a personal, professional, or business interest of a member of the writing panel. Specifically, all members of the writing group are required to complete and submit a Disclosure Questionnaire showing all such relationships that might be perceived as real or potential conflicts of interest.

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This table represents the relationships of writing group members that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all members of the writing group are required to complete and submit. A relationship is considered to be "significant" if (a) the person receives $5000 or more during any 12-month period, or 5% or more of the person's gross income; or (b) the person owns 5% or more of the voting stock or share of the entity, or owns $5000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

†Significant.

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*Modest.

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