Cardiac Magnetic Resonance in Patients With Cardiac Implantable Electronic Devices

Challenges and Solutions

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Abstract: Until recently, cardiac implantable electronic devices (CIEDs) were an absolute contraindication to magnetic resonance imaging (MRI), due to concerns about their adverse interaction in the MRI environment. The increasing clinical need to perform MRI examinations in these patients was an impetus to the development of MR-Conditional CIEDs. Secure performance of MRI in these patients requires scanning under specified MR conditions as well as operating the device in MR-scanning mode. This requires robust institutional protocols and a well-trained multidisciplinary team of radiologists, cardiologists, device applications specialists, physicists, nurses, and MRI technologists. MRI can also be performed in patients with non-MRI Conditional or "legacy" CIEDs by following safety precautions and continuous monitoring. Cardiac magnetic resonance (CMR) is additionally challenging due to expected susceptibility artifacts generated by the CIEDs, which are either near or in the heart. As the most common indication for CMR in these patients is the evaluation of myocardial scar/fibrosis, acquiring a high-quality late gadolinium enhancement image is of the utmost importance. This sequence is hampered by artifactual high signal due to inadequate myocardial nulling. Several solutions are available to reduce these artifacts, including reducing inhomogeneity, technical adjustments, and use of sequences that are more resilient to artifacts. In this article, we review the precautions for CMR in patients with CIEDs, provide guidelines for secure performance of CMR in these patients, and discuss techniques for obtaining high quality CMR images with minimized artifacts.

Key Words: magnetic resonance imaging, pacemakers, implantable cardiac defibrillators, electronic devices, susceptibility

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Cardiac implantable electronic devices (CIEDs) such as pacemakers, implantable cardiac defibrillators (ICD), and cardiac resynchronization therapy (CRT) devices were an absolute contraindication to magnetic resonance imaging (MRI) until recently. The components of MRI environment such as the static magnetic field, gradient fields, and radiofrequency (RF) coils can all adversely interact with CIEDs (Fig. 1), with some deaths reported in the early literature.[1] The static magnetic field can induce force and torque on ferromagnetic components in devices, resulting in vibration and displacement of the device. More importantly, it can inadvertently activate the magnetically operated reed switch in the pacemaker that programs the device and changes its operating modes. The effects of activation of the reed switch are variable, dependent on the magnetic field strength and orientation of the switch.[2] This can theoretically lead to unpredictable and potentially harmful change of the pacing mode (eg, asynchronous pacing, inhibition of tachycardia therapies). The electromagnetic energy from gradient fields and RF coils can also create electrical interference in the functioning of pacemaker such as sensing, pacing thresholds, and lead impedances, which may result in sensing of signals that are incorrectly considered to be a heartbeat, inappropriate acceleration, inhibition, and battery depletion.[3–5] High-energy electromagnetic interference can result in power-on-reset, which is a backup demand mode wherein pacing is inhibited, and tachyarrhythmia therapy is activated, leading to catastrophic consequences.[6] The device lead may also act as an antenna for transfer of electromagnetic energy, either in the form of heat that results in tissue damage and pain or as electrical current that can induce arrhythmias or interfere with device function.[6] There is also a theoretical risk of cardiac stimulation from the gradient fields, resulting in arrhythmias.[2,6] ICDs have additional issues in the MRI environment, including sensing of electromagnetic noise, changes in battery voltage, inability to communicate, and inappropriate activation or inhibition of therapy.[6]

MRI is an important imaging test and in some clinical scenarios, it may be the only imaging test that can provide crucial information required for accurate diagnosis and therapeutic management. An estimated 2 million patients in the United States have implanted CIEDs.[7,8] Up to 75% of these patients will have an indication for at least one MRI in their lifetime,[9,10] with one-third requiring >MRI scan and 28% requiring an MRI within 4 years of implementation.[11] Neurological disorders were the most common indications for these MRIs (29%), followed by spinal disorders (16%) and cancer (12%).[11] Cardiac magnetic resonance (CMR) is now well established in the evaluation of cardiovascular disorders, providing comprehensive morphologic information, tissue characterization, and accurate quantification of several parameters.[12] CMR is also increasingly indicated in patients with CIEDs for several reasons. One of the more common indications is the evaluation of patients with ventricular tachycardia,[13] who already have an ICD in situ. In these patients, CMR is used to establish the arrhythmogenic substrate (scar or fibrosis),[13] map the scar for guiding catheter ablation by the integration of 3D maps into clinical mapping systems,[14] and provide outcome measures.[15–17] CMR provides complementary information to voltage-mapping techniques that are limited by spatial resolution, prolonged times, and false

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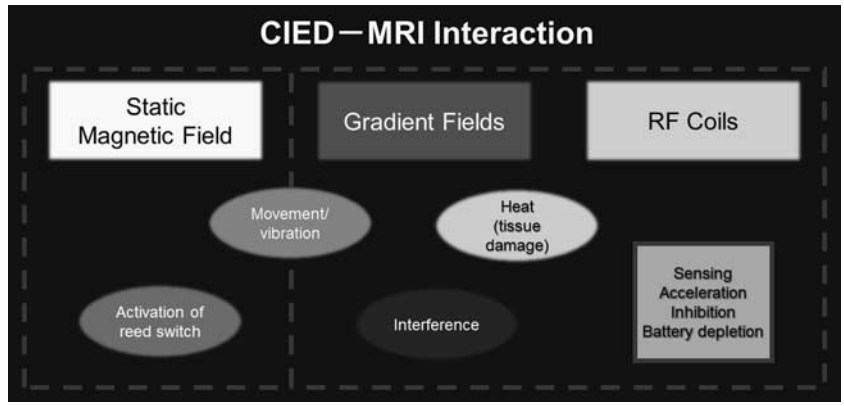

FIGURE 1. Illustration showing the effects of different components of the MRI environment on implanted PM/ICD.

low-voltage measurements.[14] CMR can identify patients who will benefit from an epicardial procedure in patients with previous failed ablation procedures.[15] CMR also provides comprehensive morphologic and functional information in congenital heart disease patients who have CIEDs, particularly for the right ventricle.[18] Significant extracardiac findings can also be incidentally discovered in CMR.[19]

CMR is challenging in these patients due to the proximity of the devices to the heart, which heightens patient safety concerns and image-quality issues. In the first portion of this article, we provide guidelines for securely performing CMR in patients with CIEDs. In the second portion, we review the CMR artifacts associated with CIEDs and provide practical solutions for mitigating those artifacts.

PERFORMING CMR IN PATIENTS WITH CIEDS

CIEDs can be broadly classified as MR-Conditional and non–MR-Conditional, or legacy devices.

MR-Conditional Devices

MR-conditional systems (ie, device, leads, and programming) are those associated with no known hazards in the MRI environment within specified conditions of use.[20] These systems were innovated and developed in response to the increasing clinical need to perform MRI examinations in patients with CIEDs and the improved understanding of device/MRI interactions. Specific device design adaptations for the static magnetic field include reduction of their ferromagnetic component and replacement or modification of the reed switch such as with a solid-state Hall sensor or magnet detector sensor, which are more predictable in the MRI environment. Adaptations to the gradient fields include redesigning of leads such as increased winding turns, which increases the inductance and lead-tip coating, which decreases polarization. The resonant frequency of a lead is circumvented to reduce the antenna effect, which causes conductance of electrical current, inducing rapid capture and stimulation of myocardium with potential for arrhythmias.[2,6] Adaptations for RF coils include circuitry filters and shielding to block or limit the transfer of electromagnetic effects and dedicated programming to reduce the influence of magnetic fields.[2]

The first MR Conditional pacemakers were developed in 2008 and MR Conditional ICDs in 2011.[21] Since then, the list of US Food and Drug Administration (FDA) and *Conformité Européenne* (CE)-approved pacemakers, ICDs, CRT-devices, and leads from different manufacturers has only grown. Most of these MR Conditional devices have been validated in studies of variable designs, which generally evaluated the adverse event rates of these devices and changes in pacing thresholds during the scan and for variable time after the scans (Table 1).[11,22–32] Revo MRI SureScan (Medtronic In., Minneapolis, MN) was the first MR Conditional-pacing system approved by the FDA in 2011. Its MR Conditional status and effectiveness on 1.5-T magnets were tested in a prospective controlled multicenter clinical trial that enrolled 464 patients, from which 258 were randomly selected to undergo nonclinically indicated MRI. The study was powered to detect MRI-related complication-free rate within 1 month following the scan of $>90\%$. No definite immediate complications were recorded in all of the 226 patients undergoing MRI. Of these, 211 patients completed the 1-month follow-up visit with no MRI-related complications identified. Eight observations were deemed either MRI related or unclear, including paresthesia, palpitations, chest pressure, swallowing problems, and atrial arrhythmias. The primary effectiveness endpoint was also met in this study, which was the absence of significant pacing capture thresholds and sensing amplitude changes between baseline and 1-month follow-up on MRI versus control groups.[23] Another single-center prospective nonrandomized study found no MR-related complications or statistically significant difference between sensing/pacing thresholds before and up to one month after 1.5-T MRI in 30 patients receiving Evia pacemakers with Safio S leads.[27] A global multicenter prospective observational study was performed to assess the occurrence of adverse event rates of 1.5-T MRI scanning in patients with SureScan pacing system.[11] This study included 526 patients with 872 clinically indicated scans. Devices implanted less than 6 weeks from the MRI, or the presence of abandoned leads were considered exclusion criteria. The anatomic regions most commonly scanned were the head and neck ($n=457$), followed by abdominal or lumbar region ($n=281$), extremities ($n=118$), and chest ($n=60$). MRI-related adverse events were defined as those caused by interactions between the SureScan pacing and the MRI system or by the programming adjustments required per protocol during or up to 1 month after the MRI. The study was statistically powered to detect an MRI-related adverse event $>2\%$. No MRI-related adverse events were detected. Two patients without prior history of atrial fibrillation (AFib) developed transient AFib during the MRI. There were 2 additional events related to failure-to-capture and threshold

TABLE 1. Summary of a Few Currently Approved Devices and their Related Studies

Device	Manufacturer	FDA	CE	Trial	No. Patients	Adverse Events	Comments
EnRhythm MRI SureScan) and (CapSureFix MRI Model 5086)	Medtronic			Prospective randomized[22,23]	211	None during scan and 1 mo	Only minimal changes in pacing thresholds Similar sensed electrogram amplitudes
EnRhythm MRI SureScan) vs. standard model	Medtronic			Prospective controlled[24]		None	Slightly increased procedural and fluoroscopic implant times, no complications
Revo MRI SureScan	Medtronic	2011					Based on EnRhythm
Ensura MRI SureScan	Medtronic	2013	2010				
Advisa MRI Surescan systems	Medtronic	2013	2010				
Advisa MRI SureScan generator with CapSureFix MRI 5086MRI leads	Medtronic			Randomized multicenter[25]	177	None	Only minimal differences between pacing capture threshold values before and at 1 mo
Accent MRI pacemaker	St. Jude Medical		2011	Multicenter[26]	283 implanted 140 MRI	None up to 1 mo	None up to 1 mo
Assurity MRI	Abbot Laboratories/St. Jude Medical	2017					
Ingenio	Boston Scientific		2012				
Advantio	Boston Scientific		2012				
ImageReady Ingenio MRI	Boston Scientific	2016		The INFINITE-MRI prospective	13	None at 1 mo	
ImageReady MR-conditional pacemakers	Boston Scientific			SAMURAI prospective			
ImageReady MR-conditional ICD/CRT-D	Boston Scientific			ENABLE prospective			
EVIA	Biotronik		2010	Prospective[27]		None at 3 mo	None at 3 30 mo
ProMRI pacemaker systems	Biotronik			Prospective[28]	226, head, lumbar	None at 1 mo	
ProMRI pacemaker systems	Biotronik			Prospective[29]	216, thoracic and cardiac	1 event	
Iforia ProMRI ICD	Biotronik			Prospective[30]	153	None at 1 mo	1 patient
KORA 100	LivaNova/Sorin		2013	Prospective[31]	29	None at 1 mo	None at 1 mo

elevation, which were adequately adjusted on follow-up.[11] Some of the other devices are listed in Table 1.

The MRI operating conditions for some of the commonly used MR Conditional CIEDs are listed in Table 2. The most common conditions involve the magnet field strength, specific absorption rate (SAR), gradient slew rate, and exclusion zones for scanning. While some of the devices can be operated both at 1.5 and 3 T strengths, others are cleared only at 1.5 T. The SAR limit is variable and, for the same device, can vary with the region, generally $\leq$2 to 4 W/kg body weight. The gradient slew rate should generally be $\leq$200 T/m/s. Some devices were initially restricted to specific zones, which precluded CMR. For example, the Revo (Medtronic) was restricted between C1 and T12 and Entovis DR T/SR T (Biotronik) was restricted between the shoulders and iliac crest. However, currently, these devices do not have any zone restriction, and CMR can be securely performed. With some devices, scanning cannot be longer than 30 minutes, and the table mode must be fixed. All Conditional devices should be scanned at normal operating mode as per manufacturer guidelines. Non MR Conditional abandoned leads should also be evaluated before MRI, as per the manufacturer guidelines. However, MR Conditional status and Conditional operating instructions of these devices is an ever-changing field, as new data become available. This highlights the importance of MRI facility staff continually reviewing specific conditional information about implanted devices before scanning patients. A list with devices labeled be MR unsafe after tests on 1.5-T and 3.0-T scanners can be found in Table 3. It is crucial that the current labeling information pertaining to a CIED being considered for MR scanning, including the leads, be reviewed during the screening process. Table 4 lists the websites from the main manufacturers.

Steps for Performing a Secure MRI in Conditional Devices

Secure performance of MRI in patients with CIEDs requires the establishment of robust institutional guidelines and a multidisciplinary team of radiologists, cardiologists, medical physicists, device application specialists, nurses, and MRI-technologists (Fig. 2). The three steps required for secure scanning include assessment of device labeling, secure scanning, and follow-up. A workflow that can be followed for secure performance is illustrated in Figure 3.

Before Scanning

A risk-benefit analysis is required before doing the scan. Although MR-Conditional devices are cleared for scanning under specific conditions, the entire process of scanning these patients is labor intensive and should be resorted to only if the information from CMR has

TABLE 2. Operating Conditions for Some of the Commonly Used MR-Conditional Devices

Device	Manufacturer	PM/ICD	MR System/Field Strength	SAR (W/kg-body)	Gradient Slew Rate (T/m/s)	Scan Coverage Exclusion Zones
Revo MRI	SureScan Medtronic	PM	Horizontal cylindrical bore magnet 1.5 T	Body ≤2	≤200	No exclusion zone (previously C1-T12)
Advisa SR and DR MRI	SureScan Medtronic	PM	Horizontal cylindrical bore magnet 1.5-3 T	Body ≤2	≤200	No exclusion zone
Micra transcatheter pacing system	SureScan Medtronic	PM	Horizontal cylindrical bore magnet 1.5-3 T	Body ≤4	≤200	No exclusion zone
ACCOLADE MRI ESSENTIO MRI	ImageReady Boston Scientific	PM	Closed bore, horizontal magnet 1.5-3 T	Body ≤2-4	≤200	No exclusion zone
Entovis DR-T/SR-T	ProMRI Biotronik	PM	Closed bore, cylindrical magnets 1.5 T	Body ≤2	≤200	No exclusion zone (previously between shoulder blade and iliac crest)
Eluna DR-T/SR-T	ProMRI Biotronik	PM	Closed bore, cylindrical magnets 1.5 T	Body ≤2	≤200	No exclusion zone
Evera MRI SureScan	Medtronic	ICD	Horizontal cylindrical bore magnet 1.5 T	Body ≤2	≤200	No exclusion zone
Iperia ProMRI	Biotronik	ICD	Closed bore, cylindrical magnets 1.5 T	Body ≤2	≤200	No exclusion zone
Emblem MRI S-ICD	Boston Scientific	ICD	Closed bore, horizontal 1.5 T	Body ≤2	≤200	No exclusion zone

The ability to use the MRI scanner in normal operating mode only or first-level controlled operating mode may vary depending on the attached MRI leads and strength of the magnet and should be verified before scanning. ImageReady and Emblem: The use of receive-only coils is not restricted; local transmit coils may be used but should not be placed directly over the pacing system. Patient in supine or prone position only. These parameters have to be assessed directly from current manufacturer instructions.

management implications, and this information cannot be obtained from any other diagnostic study.

A thorough assessment of device labeling and scanning conditions is the most important step before scanning. Device specifications should be ideally established several days before the scan. Information about the CIED can be gleaned from the device ID card or electronic medical record. In our institution, the MR-Conditional status of the device and the specified conditions are verified and documented by the medical physicist. All the components of the CIED, including the generator and leads, should be MR-Conditional. The device should have been implanted for at least 6 weeks. Ideally, there should be no broken or abandoned leads, leads with intermittent electrical contact, epicardial leads, lead adaptors, or extenders. These could be evaluated by assessment of medical records and imaging, particularly chest radiographs.

The patient should also be evaluated and cleared by the cardiologist/electrophysiologist, either through a clinic visit or an online process. Factors to be assessed by the electrophysiologist include the type of device and attached leads; the indication for the device; type of arrhythmia; device (pacemaker) dependence; device usage patterns; measurements; and battery life. The evaluation typically includes verification of appropriate capture thresholds of ≤2.0 V at a pulse width of 0.4 ms, lead impedance of between 200 and 1500 Ω, and lack of diaphragmatic pacing at 5.0 V and 1.0 ms. The location of the implant (right or left pectoral—prepectoral or submuscular) and any position restrictions should also be confirmed.[32,33]

On the basis of the above-mentioned parameters, the cardiologist/electrophysiologist determines the labeling and specifications of the device for MRI and prescribes the safe parameters in the medical record. Broadly, for MR-Conditional pacemakers, MRI can be performed in both pacer-dependent and nondependent individuals, whereas for MR-Conditional ICDs, MRI can be obtained only in pacer nondependent individuals. Additional device-specific requirements pertaining to capture thresholds, lead impedance, diaphragmatic stimulation, and pulse width should be met. Devices with near the end-of-life battery status should also not be imaged.

Scanning

Informed consent is not required for scanning patients with MR-Conditional approved devices. All the personnel involved in scanning should be well versed in the institutional guidelines and should be prepared for managing complications. MR-compatible crash-cart with external defibrillator that has external pacing capability should be readily available. Personnel skilled in advance cardiac life support, including CPR, recognition of arrhythmia, defibrillation, and transcutaneous pacing, should be available.[6] There should be continuous monitoring with visual and verbal contact with the patient, and pulse oximetry or telemetry, as per manufacturer guidelines. Electrophysiology personnel, that is, an individual with expertise in device management and programming, typically a device representative, should be available to set the device to safe scanning mode, inactivate sensing, detect system integrity, and clear the program when necessary. The device-specific programmer should be kept outside the scanner room, that is, outside of zone IV.[6] Back-up pacing and device reprogramming capabilities should be available. Device-specific training is required by most MR-Conditional manufacturer guidelines (eg, SureScan).

Scanning is performed under specified conditions with the device interrogated and reprogrammed to the MR-scanning mode, according to the manufacturer's specifications. The North American Society of Pacing and Electrophysiology (NASPE) and the British pacing and Electrophysiology Group (BPEG) developed the NASPE/BPEG Generic (NBG)

TABLE 3. List of Devices Labeled MR Unsafe

Object Status*	Field Strength (T)	Device Model	Device Type	Manufacturer
Unsafe 1	3.0	Cosmos (283-01)	Pacemaker	Intermedics Inc.
Unsafe 1	3.0	Cosmos II (284-05)	Pacemaker	Intermedics Inc.
Unsafe 1	3.0	Delta TRS Type DDD (0937)	Pacemaker	Cardiac Pacemakers Inc.
Unsafe 1	3.0	GEM DR 7271	Dual-chamber implantable defibrillator	Medtronic Inc.
Unsafe 1	3.0	KAPPA DR706	Dual-chamber implantable defibrillator	Medtronic Inc.
Unsafe 1	3.0	MARQUIS DR 7274	Implantable defibrillator	Medtronic Inc.
Unsafe 1	3.0	MICRO JEWEL II 7223CX	Implantable defibrillator	Medtronic Inc.
Unsafe 1	3.0	Nova Model 281-01	Pacemaker	Intermedics Inc.
Unsafe 1	3.0	Quantum Model 253-19	Pacemaker	Intermedics Inc.
Unsafe 1	3.0	Relay Model 294-03	Pacemaker	Intermedics Inc.
Unsafe 1	3.0	Res-Q ACE Model 101-01	Pacemaker	Intermedics Inc.
Unsafe 1	3.0	SIGMA SDR306	Dual-chamber pacemaker	Medtronic Inc.
Unsafe 1	1.5	S-ICD System	Subcutaneous implantable defibrillator	Boston Scientific
Unsafe 2	3.0	Cosmos II Model 283-03	Pacemaker	Intermedics Inc.
Unsafe 2	3.0	KAPPA DR403	Dual-chamber pacemaker	Medtronic Inc.
Unsafe 2	3.0	Nova II Model 281-05	Pacemaker	Intermedics Inc.
Unsafe 2	3.0	Nova II Model 282-04	Pacemaker	Intermedics Inc.
Unsafe 2	3.0	THERA VDD 8968I	Dual-chamber pacemaker	Medtronic Inc.
Unsafe 2	1.5	Adapta	Pacemaker	Medtronic Inc.
Unsafe 2	1.5	Concerto II	CRT	Medtronic Inc.
Unsafe 2	1.5	Consulta CRT-D	CRT-D	Medtronic Inc.
Unsafe 2	1.5	Consulta CRT-P	CRT-P	Medtronic Inc.
Unsafe 2	1.5	InSync Maximo II	CRT	Medtronic Inc.
Unsafe 2	1.5	Maximo II ICD	Implantable defibrillator	
Unsafe 2	1.5	Protecta CRT-D	CRT-D	Medtronic Inc.
Unsafe 2	1.5	Protecta ICD	Implantable defibrillator	Medtronic Inc.
Unsafe 2	1.5	Protecta XT CRT-D	CRT-D	Medtronic Inc.
Unsafe 2	1.5	Protecta XT ICD	Implantable defibrillator	Medtronic Inc.
Unsafe 2	1.5	Secura ICD	Implantable defibrillator	Medtronic Inc.
Unsafe 2	1.5	Sensia	Pacemaker	Medtronic Inc.
Unsafe 2	1.5	Syncra CRT-P	CRT-P	Medtronic Inc.
Unsafe 2	1.5	Versa	Pacemaker	Medtronic Inc.
Unsafe 2	1.5	Virtuoso ICD	Implantable defibrillator	Medtronic Inc.

*Unsafe 1—The object is considered to pose a potential or realistic risk or hazard to a patient or individual in the MR environment primarily as the result of movement or displacement of the object. Other risks or a different hazard may also exist. Therefore, in general, the presence of this object is considered to be a contraindication for an MR procedure and/or for an individual to enter the MR environment depending on the nature of the object or item.

Unsafe 2—This object displays only minor magnetic field interactions which, in consideration of the in vivo application of this object, are unlikely to pose a hazard or risk in association with movement or displacement. Nevertheless, the presence of this object is considered to be a contraindication for an MR procedure or for an individual in the MR environment. Potential risks of performing an MR procedure in a patient or individual with this object are related to possible induced currents, excessive heating, or other potentially hazardous conditions. Therefore, it is unadvisable to perform an MR procedure in a patient or individual with this object.

CRT indicates cardiac resynchronization therapy; D, defibrillator; P, pacemaker.

Source: www.mrisafety.com

Table courtesy of Dr Frank G. Shellock, PhD, FACR, FACC, FISMRM.

pacemaker code to describe various pacing modes.[34] The NBG code usually consists of three letters (Fig. 4). Letter 1 represents the chamber (s) paced, which can be O-none; A-atrium; V-ventricle; D-dual (atrium+ventricle); letter 2 represents the chamber (s) sensed O-none; A-atrium; V-ventricle; D-dual (atrium+ventricle); and letter 3 is the response to the sensed event—with O-none; T-triggered; I-inhibited, and D: dual (triggered+inhibited). The commonest pacing mode is DDD, in which the atria and ventricles are paced and sensed. Other common pacing modes are AAI and VVI, in which the atria

TABLE 4. Comprehensive Listing of MR-safety Conditions for Pacemakers/ICDs

Manufacturer	Website Safety Information*
Abbott (St. Jude Medical)	http://www.sjm.com/mriready
Biotronik	http://www.biotronikusa.com/manuals/index.cfm
Boston Scientific	http://www.bostonscientific.com/imageready/en-US/home.html
LivaNova (Sorin)	http://www.livanova.sorin.com/products/cardiac-rhythm-management
Medtronic	http://www.medtronic.com/MRI

Disclaimer: Acceptance of pacemakers, ICD, and leads listed under for patients undergoing MR procedures or individuals in the MR environment depend on specific object MR-compatibility (ie, conditional 5 status) and strict compliance with technical requirements, as recommended by manufacturer's guidelines (Sommer). Consult specific and updated safety information about implanted pacemakers, ICD, and leads on the manufacturer's website.

*Circa April 2019.

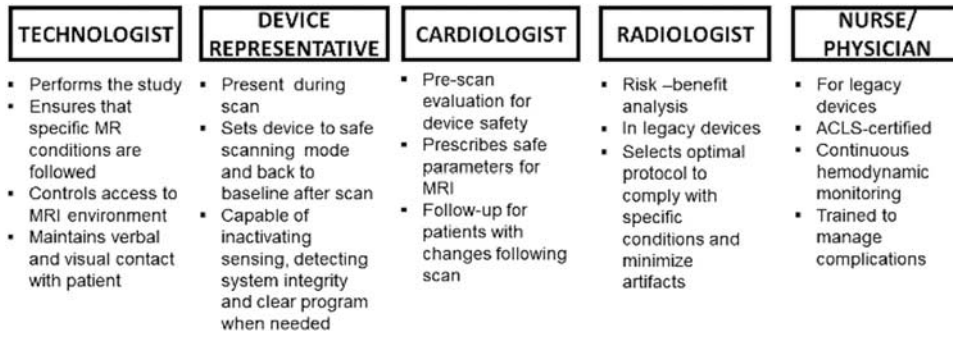

FIGURE 2. Illustration showing the role and contribution of a multidisciplinary team that is required for safely performing MRI in patients with implanted PM/ICDs.

and ventricles are sensed, and these chambers are paced if there is no native atrial or ventricular activity, respectively. The NBG code can be used to describe both single and dual-chamber pacemaker modes. These may be separated by a "/" mark. For example, asynchronous modes: DOO/VOO for dual and single-chamber modes, respectively.[35]

Multiple device variables such as lead impedance, lead threshold, P/R wave amplitude, and battery voltage are recorded for comparison after an MRI scan.[6] For pacemakers in a pacemaker-dependent patient, asynchronous pacing mode (AOO/VOO/DOO) is selected with disabling of magnet response (ie no sensing occurs with the device delivering stimuli at a fixed rate independent of atrial or ventricular activity). In a for pacemakers in a non–pacemaker-dependent patient, nonpacing and sensing, that is, inhibited mode (ODO/OVO) (VVI/DDI) is selected (Fig. 5). For ICDs in a non–pacemaker-dependent patient, in addition to nonpacing and sensing, inhibited mode (ODO/OVO) (VVI/DDI), monitoring and tachyarrhythmia therapies are also deactivated.[36,37] MRI is typically not performed in pacer-dependent patients with ICD; however, if performed, the detection and therapy are turned off, and asynchronous pacing is left. For both PM and ICD, magnet, rate, PVC, noise, ventricular sense, and conducted atrial fibrillation response are deactivated.[36] The initial programming mode is stored in the device.

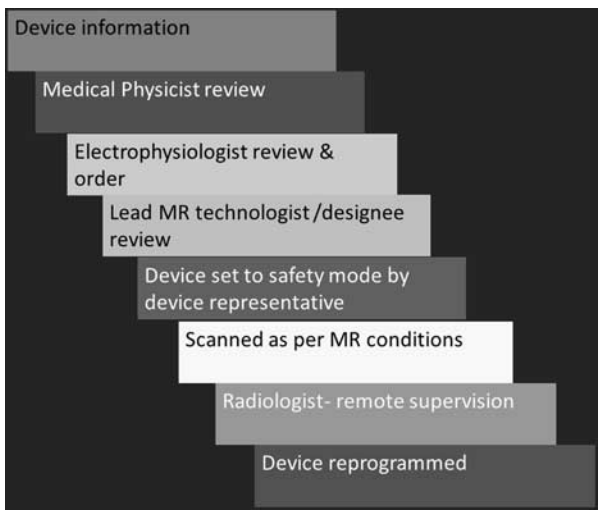

FIGURE 3. An example of workflow for safe performance of CMR in patients with MR-conditional CIED.

The MRI technologist performs the study ensuring that the conditional specifications are followed. The MRI technologist also controls access to the MRI environment. The radiologist/cardiologist need not to be present at the scanner but are notified about the scan and should be readily available to review the images. The CMR protocol should be optimized with only the clinically necessary sequences used, ensuring that the least amount of time is taken. If the main clinical question is to evaluate for myocardial fibrosis/scar, it may be adequate to obtain only those sequences. An imaging protocol to scan these patients should be established with minimal artifacts, and the radiologist should be available for troubleshooting. The image quality should be evaluated before the patient leaves the scanner.[6]

The patient is monitored with electrocardiogram and pulse oximetry throughout the scanning. If the patient develops an arrhythmia or complication during the scan, he/she is removed from the scanner room. All resuscitation that involves the use of defibrillator/monitor and device programming is performed outside the scanner room, that is, outside of zone IV.

After the Scan

Following the scan, the device is again interrogated and evaluated for variables such as lead impedance, threshold, P/R amplitude, and battery voltage, which are then compared with the pre-MRI values.[36] The pacemaker is then reprogrammed to its prescan parameters. If there are no changes in the parameters compared with pre-MRI, follow-up interrogation can be performed at 3-6 months. However, if there are changes, prolonged observation is necessary. Follow-up interrogations are recommended at 1 week, 3 months, and 6 months.[37]

CMR in non-Conditional Devices

MR non-Conditional or legacy PM/ICDs, which are devices that were typically implanted after 2001, were considered

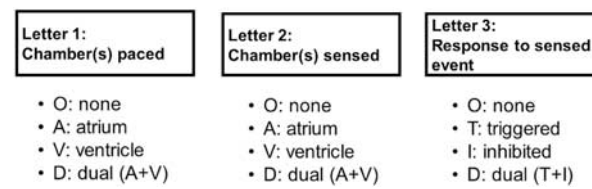

FIGURE 4. Illustration showing the NBG pacemaker code, which consists of three letters, with the first letter representing the chamber (s) paced, the second letter the chamber (s) sensed, and the third letter representing the response to the sensed event.

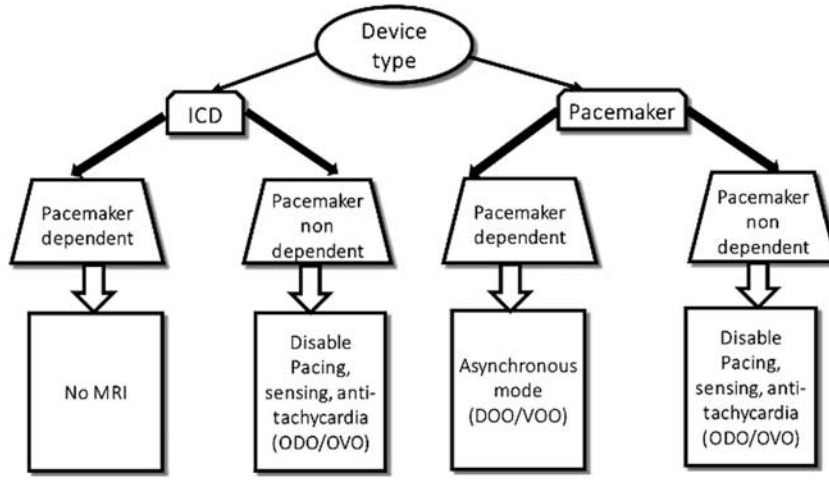

FIGURE 5. Flowchart showing the parameters for operating the cardiac device safely in the MRI environment.

a relative contraindication for MRI. Power-on-reset events (ie reverting the device to factory default settings and commonly resetting to inhibition pacing) can occur in up to 3.5% of these individuals, which can be potentially life-threatening in pacemaker-dependent patients.[38,39] More recently, a prospective study of 555 1.5T MRIs performed in 438 patients (54% pacemakers, 46% ICDs; 12% with biventricular pacing), which included legacy pacemakers implanted after 1998 and ICDs implanted after 2000, showed that MRI could be securely performed across several types of systems and leads, with only minor changes in device variables and programming.[36] The exclusion criteria in this two-center prospective trial were devices implanted less than 6 weeks before the MRI, the presence of abandoned epicardial leads, and pacemaker-dependent ICDs. The devices were interrogated before and after all scans, and a registered nurse with ACLS training was present during the MRI. Three of the 438 patients (0.7%, 95% confidence interval: 0% - 1.5%) experienced acute power-on-reset events. None of these patients had device dysfunction after a follow-up interval ranging between 105 and 463 d. A right ventricular lead required revision in a different patient, 3 months after the MRI, due to low impedance detected on a routine interrogation. Otherwise, no immediate or long-term change in variables was sufficient to elicit lead/system revision or device programming.[36] The MagnaSafe study on 1500 non-MRI Conditional devices (1000 pacemakers, 500 ICDs) showed no deaths, lead failures, loss of capture, or ventricular arrhythmia when MRI was performed with a prespecified protocol, appropriate screening, and post-procedural reprogramming.[40] Only one ICD generator could not be interrogated, and 6 cases of partial electrical reset or atrial fibrillation were noted, but none at 6 months.[40] Another meta-analysis of 5908 MRI studies with non-MR Conditional devices also showed low lead failure and clinical event rates.[41] A small study on 111 patients showed that, with a standardized protocol, CMR could be securely performed in these patients without any major complications.[13] Lead impedances were significantly lower after the procedure.[13]

The performance of CMR in patients with these non-MR Conditional/legacy devices is almost similar to MR Conditional devices, with few additions to the above-mentioned workflow. A risk-benefit analysis and discussion with the referring physician should be conducted and documented in the medical record. CMR should be performed only if there is a clear benefit and there are no alternative imaging tests available. Guidelines and appropriateness criteria for CMR developed by different societies can be used for this purpose. It should also be understood that it may be a safer option to perform CMR in these patients with adequate precautions than the alternative options such as unable to make a diagnosis due to non-availability of other good imaging tests; wrong diagnosis or suboptimal diagnosis due to suboptimal imaging tests for that indication; or extracting the device and lead and replacing it with a MR Conditional. Written informed consent should be obtained from the patients.

The patient should be screened ahead of time by the cardiology/electrophysiology (EP) clinic. In addition to the above-mentioned contraindications for an MR Conditional device, MRI is also contraindicated if the patient is pacer dependent (both for pacemakers and ICDs). The pacemakers and ICDs are programmed to the nonpacing and sensing mode, that is, inhibited (VVI/DDI). Undesired behavior may be programmed off, such as setting of asynchronous mode only, or leaving the synchronous mode and scanning only in the refractory period. MRI is performed on a 1.5 T scanner, in normal operating mode with a gradient slew rate <200 T/m/s. While earlier studies suggested a threshold of <1.5 W/kg, subsequent studies indicated that there is no need to limit SAR below the 2 W/kg normal operating mode threshold. Dorsal patient position is preferred, with avoidance of local transmit coils and locations near the devices. An ACLS-certified physician, physician assistant, or nurse practitioner should be present at the scanner. Throughout the study, the blood pressure, electrocardiogram, and pulse O_2 saturation are monitored, while maintaining verbal and visual contact with the patient. They should be trained to manage complications and have immediate access to the crash cart. After the scan is completed, the device is evaluated and reprogrammed. Until recently, these scans were not FDA-approved or reimbursed by CMS.[6] The Heart Rhythm Society (HRS) with endorsement of other societies such as American College of Cardiology (ACC), American College of Radiology (ACR), and American Heart Association (AHA) have provided recommendations for scanning these devices, particularly the development of a standardized institutional policy and protocols, including the use of checklists.[6]

Devices that have not been approved for scanning over the chest are also considered to be similar to scanning a non Conditional device.

Other Issues

Apart from pacemakers and ICDs, MR Conditional CRT-devices, leadless pacemakers,[42] and subcutaneous ICD[43] can also be scanned under certain conditions. Abandoned leads were traditionally considered an absolute contraindication for MRI due to a higher risk of lead-tip heating than PM-attached leads.[6] However, a recent study of 97 MRIs with 90 abandoned leads showed no clinical or electrical evidence of device dysfunction, pain, or arrhythmia and no evidence of myocardial injury, as measured by paired cardiac troponin.[44] Other studies also showed similar results.[45,46] However, lead orientation in the MR environment and lead composition may interact in an adverse way. Hence, caution is still suggested in scanning such patients. Epicardial leads were also absolute contraindications due to the potential for higher tissue heating in in vitro studies.[6] A small study of 11 MRI scans in pediatric congenital heart disease, which included 9 patients with epicardial lead systems, did not show any adverse effects.[47] Conclusive data are not yet available on the adverse events related to older non-MR Conditional coronary sinus electrodes.[21] A small study showed that MRI scanning is not associated with major adverse events even with batteries close to depletion and recall components.[48] Data from these small observational studies are promising, but further research is needed. Manufacturer and FDA guidelines have not changed yet to reflect what these small observational studies found. Most manufacturers recommend scanning patients only 6 weeks after implementation. There is no theoretical reason on why the complications should be higher when scanned earlier following implantation. The Heart Rhythm Society suggests that it is reasonable to perform MRI more recently than the exempt period for the conditionality of that system, on the basis of risk-benefit analysis.[6] A small study has shown no significant issues in scanning these patients.[49]

Current status of MRI in CIEDs

The use of MRI in CIEDS has now been approved by several clinical societies and regulatory bodies. In the latest European pacing guidelines, performing MRI in MR Conditional devices is a class IIA indication, and, in non MR Conditional devices, it is a Class IIb indication.[50] Specific recommendations are available in different societies such as the Heart Rhythm Society.[6] In the United States, Centers for Medicare and Medicaid Services (CMS) provides reimbursement/coverage for MRI scans in patients with CIEDs, when they are used according to the FDA labeling in an MRI environment (https://www.cms.gov/medicare-coverage-database/details/nca-decision-memo.aspx?NCAId=289&bc=AAAAAAAAACAA&). Even for those devices without FDA labeling, that is, MR-non Conditional/legacy devices, MRI is reimbursed, provided it is performed at ≤ 1.5 T, ≥ 6 weeks after implantation, the device is not pacer dependent, is without fractured, epicardial, or abandoned leads, and there is a checklist implemented by the facility. The checklist includes patient assessment to evaluate the type of device; benefits and harms communicated to the patient; device is interrogated and programmed into MRI scanning mode before scanning; qualified physician, nurse practitioner, or physician assistant directly supervises; and a discharge plan including patient evaluation (https://www.cms.gov/medicare-coverage-database/details/nca-decision-memo.aspx?NCAId=289&bc=AAAAAAAAACAA&). With the secure performance of MRI in non-Conditional devices, some experts feel there may not be a utility for implanting MR Conditional devices, which are more expensive. They can be reserved for specific situations such as a planned MRI, younger patients, at risk for ventricular arrhythmia, congenital heart disease, or lack of capabilities for scanning non-MR Conditional devices.[51]

Despite the above-mentioned advances in knowledge and guidelines, the access for MRI in patients with CIEDs remains poor. A recent Really ProMRI study showed that, in 555 patients with devices, a total of 37 MRI referrals were made, of which 14 were denied and 23 were performed.[52] The rate of scans was higher in pacemaker than in ICD. The event rate was 7/100 patient-years. Many studies were denied despite the presence of MR Conditional systems.[52] Cultural and regulatory changes will be required for more widespread adoption of MR imaging in patients with CIEDs.[52]

CMR IMAGE QUALITY IN PATIENTS WITH CIEDs

The acquisition of a diagnostic-quality CMR scan is as important as the secure performance of the scan. If the image quality is not satisfactory, all the above-mentioned safety measures will be an exercise in futility. Of all the MRI techniques, CMR is the most challenging, due to the presence of CIEDs directly overlying the heart, making it highly vulnerable to artifacts. These artifacts are seen in both Conditional and legacy devices.

Artifacts Expected From CIEDs

Susceptibility variations between the metal in CIEDs and surrounding tissues results in inhomogeneity of the static magnetic field. This, in turn, causes large variations in the resonant frequency (precession rate) across the object and produces a variety of local MRI artifacts. The most apparent artifacts related to CIEDs are large black regions of signal loss near the implant, that is, within a radius of 5-12 cm (Figs. 6 and 7), caused by rapid signal dephasing and loss of coherence induced by magnetic field inhomogeneities. Displacement artifacts occur in the slice selection, and readout directions, including geometric distortion, signal loss, and signal pile-up.[51] The severity of the artifacts is variable, dependent on several factors, including the size, shape, and type of metal, the physical location of the pulse generator,[53] and device orientation in the magnetic field.[54] Artifacts also depend on the field strength, with more prominent artifacts at higher field strengths.[55] Pulse sequence, specific parameters, body size and shape, and dielectric constant of the body also affect the artifacts.[6] Artifacts are more pronounced closer to the metal object due to larger resonant frequency shifts. Leads cause only minor artifacts (Fig. 8, Movie 1, Supplemental Digital Content 1, http://links.lww.com/JTI/A155). ICD and CRT-D systems cause the highest image degradation (Fig. 7) due to their larger size and higher metallic component, whereas PM (Fig. 6) and implantable loop recorders produce less imaging artifact.[56] Pulse generators in the left anterior chest wall produce more artifacts than those on the right anterior chest wall, except in cases of dextrocardia. The subcutaneous ICDs with pulse generators typically located in the left anterior chest wall create the most imaging artifacts due to proximity to the heart and are frequently difficult to completely suppress. Leadless pacemakers are likely to generate more artifacts due to the generators located directly within the right ventricle.[55]

Strategies to Decrease Artifacts

Familiarity with the typical artifacts in CMR with CIEDs allows prompt recognition and initiation of corrective measures (Table 5). As noted above, knowledge of the generator location (eg, right or left side of the chest) has implications for the expected location of artifact. In some instances, the device generator may be mobile, and a slight cranial displacement of the device within its pocket by

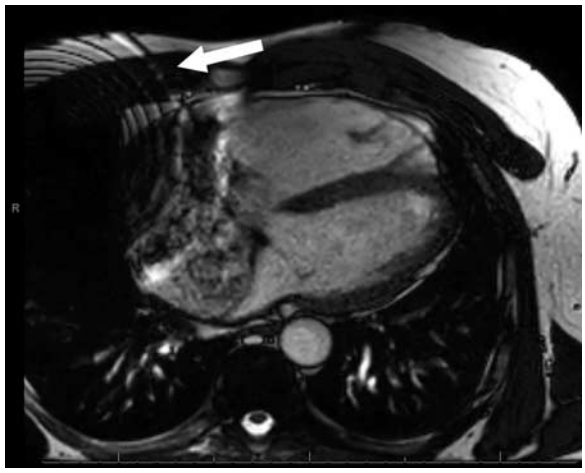

FIGURE 6. Axial balanced-SSFP image (Philips Ingenia 1.5T, TR/TE 2.43/1.2 ms, matrix 192×192, FOV 385 mm, slice thickness 8 mm) in a patient with pacemaker implanted in the right anterior chest wall shows moderate to severe susceptibility artifacts originating from the generator over the right chest (arrow), which involve the right and left atria.

raising the ipsilateral upper extremity and/or taping may improve image quality due to the associated displacement of the related artifact. Improved local shimming with additional/new algorithm higher-order shimming or frequency scout imaging are potential approaches to decreasing artifact as well.

Technical Adjustments

There are several technical adjustments that can be made to minimize artifacts. For example, decreasing the voxel size, using the shortest TE or TR, using the highest bandwidth, using parallel imaging, and using reconstruction algorithms correcting phase errors periodically (e.g PROPELLER—Periodically Rotated Overlapping ParallEL Lines with Enhanced Reconstruction) are some of the adjustments. Parallel imaging is only helpful in minimizing minor susceptibility artifacts on calibration images; otherwise, it worsens artifacts. One study on patients with congenital heart diseases showed that, by modifying basic sequence parameters, image quality improves and artifact size decreases compared to conventional sequences for both cine imaging and black-blood imaging.[18]

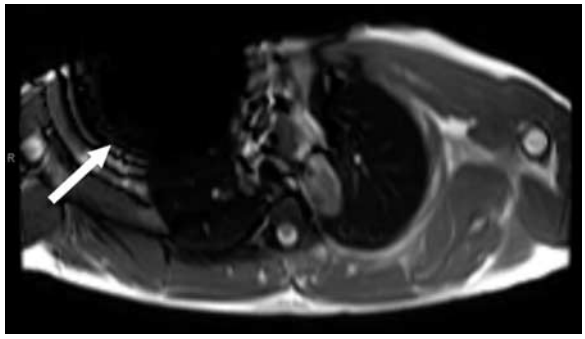

FIGURE 7. Axial b-SSFP image (Philips Ingenia 1.5T, TR/TE 2.09/0.82 ms, matrix 192×96, FOV 400 mm, slice thickness 10 mm) in a patient with ICD implanted in the right anterior chest wall shows extensive susceptibility artifacts originating from the device over the right chest (arrow).

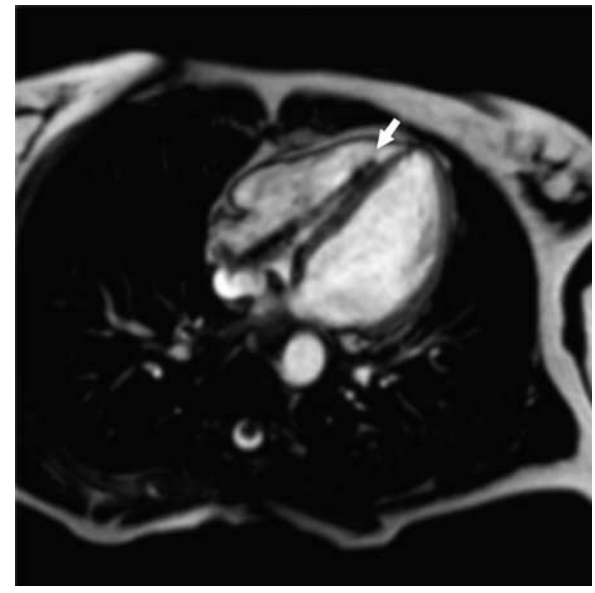

FIGURE 8. Four-chamber cine b-SSFP image (Philips Achieva1.5T, TR/TE 2.43/1.2 ms, matrix 160×124, FOV 320 mm, slice thickness 8 mm) in a patient with a pacemaker (arrow) shows that the presence of lead does not impair diagnostic confidence.

Artifacts for cine steady-state free precession (SSFP) decreased by 1.5 mm, cine gradient-recalled echo (GRE) by 4.6 mm, and TSE images by 1.6 mm.[18]

Appropriate Sequences

Selecting an appropriate sequence with fewer artifacts is another practical approach to address these device-related artifacts. For example, the dephasing effect can be diminished and even almost completely reverted using spin-echo sequences (Fig. 9) instead of using gradient-echo sequence, due to reversal of static field dephasing by the 180° refocusing pulse in a spin-echo sequence. An alternative to using spin-echoes is to use ultrashort TE; hence, imaging is performed immediately after the RF excitation with less time for magnetization vector to become incoherent. However, these sequences are of limited use in CMR.

Morphologic Imaging

For morphologic imaging, static black-blood imaging is performed using Turbo spin-echo (TSE)/Fast Spin echo (FSE) sequence. As described above, the spin-echo sequences have significantly lower artifacts than gradient echo sequences (Fig. 10). Black-blood imaging can be performed with either T1 or T2 weighting. Susceptibility artifacts encountered in these sequences can be decreased by increasing the bandwidth.[18] However, the utility of this method in CMR for patients with CIEDs, has not been well established. Fat suppression may be used in these sequences, particularly in the evaluation of myocardial edema. A technique for suppressing fat is to add a frequency-selective fat saturation pulse, which selectively excites fat protons, which resonate 200 Hz below that of water protons at 1.5 T. Because of magnetic field inhomogeneities and frequency shifts associated with CIEDs, the fat saturation pulse fails to match the resonant frequency of fat near the metal, resulting in incomplete fat signal suppression and

TABLE 5. Strategies to Decrease Cardiac MRI Artifacts From Devices

Principle	Technique
Reduce local inhomogeneity in the region of the heart	Move generator—lift patient ipsilateral arm and/or push up generator in pocket and tape
	Optimize shimming—additional, new, or higher-order shimming
Technical adjustments	Decrease voxel size, including reduction of slice thickness and increase matrix
	Use shortest TE
	Use the highest bandwidth
	Use parallel imaging
	Use reconstruction algorithms correcting phase errors periodically
	b-SSFP
	Use shorter TR
	Use shorter TE
	Use higher bandwidth
	Gradient echo
	Use shorter TE
	Fast spin-echo
	Avoid fat saturation
	Use high bandwidth
	Late gadolinium enhancement
	Use high bandwidth
Use sequences with lesser artifacts	*Morphologic imaging*
	Spin-echo is better than gradient echo due to 180 degrees refocusing pulse
	Fat suppression
	STIR sequence is superior to spectral fat saturation
	Cine imaging
	Gradient recalled echo (GRE) is better than SSFP
	Late gadolinium enhancement
	Wideband sequence has lesser artifacts
	First-pass perfusion imaging
	Wideband sequence may be of potential use
	T1 mapping
	Wideband sequence may be of potential use

potentially water suppression due to off-resonance. Hence, it is better to use FSE with fat-saturation pulse turned off and a relatively high bandwidth[18] to improve the image quality. Alternative methods of fat suppression, such as short tau inversion recovery (STIR) (Fig. 11), and multiple-echo separation techniques such as DIXON separation, can provide improved fat saturation. STIR is the best choice, as it is independent of the resonance frequency, but uses an inversion pulse to null fat based on short T1 recovery time. A limitation of STIR imaging is its relatively low signal-to-noise ratio (SNR) due to the attenuation of the nonfat signal given the inversion pulse.[54] DIXON can track magnetic field variations and perform well some distance from the metal.

Displacement Artifacts

Another imaging artifact related to the off-resonance is geometric distortion. An off-resonance in the kilohertz (kHz) range could translate to prominent errors in the position that is selected by the slice-selection gradient (through plane) and the sampled readout encoding gradient (in plane) with resultant image distortion.[54,57] The spatial distortion in the slice direction can be reduced by using thin slices and maximizing the slice selection bandwidth. Unfortunately, these result in increased scan time, reduced SNR, and increased SAR, which may require longer TRs or fewer interleaved slices per repetition. Similarly, increasing the readout bandwidth will minimize displacement artifacts. Again, increasing the readout bandwidth results in lower SNR. More advanced techniques including multiacquisition variable-resonance image combination (MAVRIC) and slice encoding for metal artifact correction (SEMAC) are not commonly used in CMR.

Cine Imaging

The most relevant artifacts in CMR are those that affect the two most important sequences, cine imaging and late gadolinium enhancement (LGE). Cine imaging is used to provide morphologic and functional information, both qualitative and quantitative. This is typically carried out with balanced SSFP (b-SSFP) sequence, which relies on T2/T1 weighting and provides high SNR, high CNR, high spatiotemporal resolution, and short acquisition time. It also allows the use of parallel imaging. B-SSFP requires a homogeneous magnetic field for effective balancing of gradients and is extremely sensitive to field inhomogeneities with pronounced artifacts near implanted devices.[56,58] These artifacts can be reduced by reducing the repetition time (TR), reducing echo time (TE), or by using a frequency scout. TR is an important determinant of susceptibility artifact in b-SSFP, with prominent dark bands seen at long TR, even at long distances from the device.[18] Artifacts can be reduced by reducing TR, by steps such as using a short RF pulse, asymmetrical/partial Fourier readouts, higher bandwidth, and opting for a lower spatial resolution.[59] However, the use of these techniques could lead to reduced image quality and more artifacts. For example, higher bandwidth comes at the expense of reduction in SNR,[18] which, however, is acceptable in patients with metal artifacts. These artifacts can also be decreased by reducing the TE, by partial Fourier readout and higher bandwidth, but at the cost of lower resolution and SNR. A frequency scout acquisition can be used to determine the optimal imaging frequency and move the dark band artifacts away from the heart.[60,61] The artifacts in static b-SSFP can be mitigated by using sequences that are less sensitive to field inhomogeneity. For example, on the localizer and other static imaging, use of spin-echo dark blood will often decrease artifact, particularly when TE times are shortened.

Cine imaging is often improved with the use of nonbalanced gradient-echo sequences, such as spoiled gradient echo (GRE) (Fig. 12, Movies 2, Supplemental Digital Content 2, http://links.lww.com/JTI/A156 3, Supplemental Digital Content 3, http://links.lww.com/JTI/A157) or fast gradient echo (FGE). This sequence eliminates the TR dependency of b-SSFP, but may have lower SNR, shows some metal artifacts, and there is residual obscuration of cardiac anatomy.[18] The sensitivity of artifact in this sequence is determined by TE.[55] TE can be reduced by turning off flow compensation or using partial Fourier readouts, weak asymmetrical echo, and high receiver bandwidth (1000 Hz/pixel).[18] All these come at the expense of lower resolution and SNR,[18] which, however, is acceptable in the context of metal artifacts. SNR can be improved by signal averaging, and CNR between blood

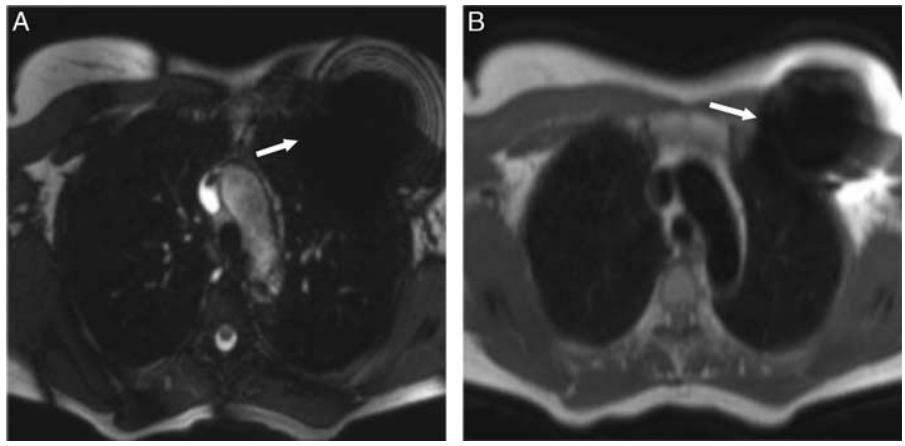

FIGURE 9. A, Axial b-SSFP image (Philips Ingenia 1.5T, TR/TE 2.27/1.14 ms, matrix 176×175, FOV 305 mm, slice thickness 8 mm) in a patient with a pacemaker in the left anterior chest wall shows extensive metallic artifacts (arrow) adjacent to the device. B, Axial single-shot fast spin-echo image (Philips Ingenia 1.5T, TR/TE 5.47/4.7 ms, matrix 176×175, FOV 305 mm, slice thickness 8 mm) in the same patient shows significant reduction in the size and extent of the artifact (arrows).

pool and myocardium can be improved by acquiring GRE cine after administration of intravenous contrast.[61] A study on Evera devices showed that FGE sequence performs better than b-SSFP in patients with devices, with good to moderate quality images obtained in 84% of RV acquisitions and 74% of LV acquisitions, compared with 69% and 53% with SSFP.[56] For ICD, mean artifact size is 16.9 cm for b-SSFP short-axis image versus 10.9 for FGE.[56]

LGE

LGE is a critical sequence in CMR that is obtained 10-15 minutes after administration of contrast and using an inversion pulse to suppress the normal myocardium. On the basis of patterns of enhancement, cardiomyopathies can be characterized, and myocardial viability assessed. In patients with CIEDs, it can define the scar and border zone in patients with ventricular tachycardia, which can be integrated with electrical mapping systems to guide ablation.[14] The RF inversion pulse in the standard LGE is usually a hyperbolic-secant adiabatic inversion pulse with a spectral bandwidth of 1.1 kHz. With a pulse generator typically 5-10 cm away from the heart, the expected resonance offset of the myocardium is in the 2-6 kHz range, which is beyond the bandwidth of the inversion pulse (Fig. 13A). In addition to the dark artifact adjacent to the generator, this also results in incomplete or lack of myocardial signal nullification with a typically hyperintense signal frequently limiting the evaluation of myocardial scar. This is more commonly seen in the anterior LV wall, and less commonly in septal, lateral, and inferior walls, depending on the location of the implant.[14] This artifact results in false-positive areas of apparent enhancement and limits evaluation of the exact amount and extent of LGE in the underlying myocardium. Artifacts have been shown in

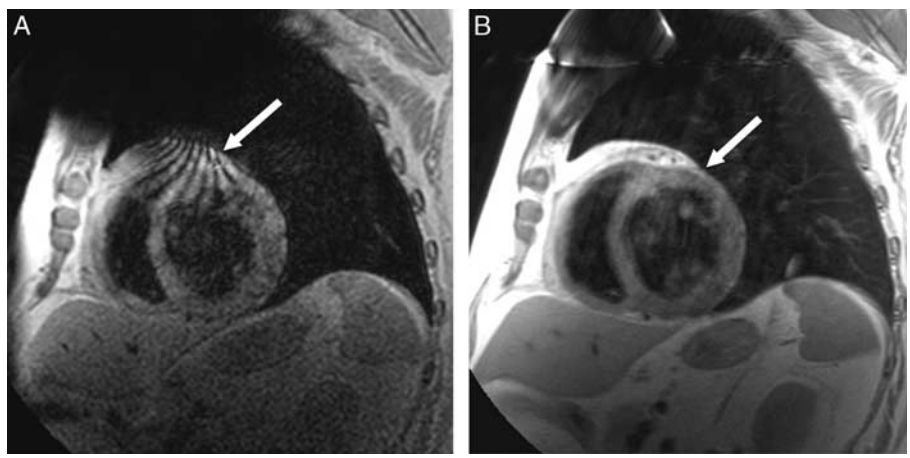

FIGURE 10. A, Short axis T1 black-blood gradient echo image (Philips Ingenia 1.5T TR/TE 6.5/4.6 ms, matrix 152×144 mm, FOV 300 mm, slice thickness 6.678 mm, flip angle 25 degrees) shows extensive artifact related to pulse generator extending to and obscuring predominantly the LV anterior wall (arrow). B, Short-axis TSE T1-weighted black-blood image (Philips Ingenia 1.5T TR/TE 1034/10 ms, matrix 216×160 mm, FOV 300 mm, slice thickness 8 mm, flip angle 90 degrees) at the same level demonstrates pronounced decrease of the artifact with improved visualization of the superior aspect of the heart (arrow).

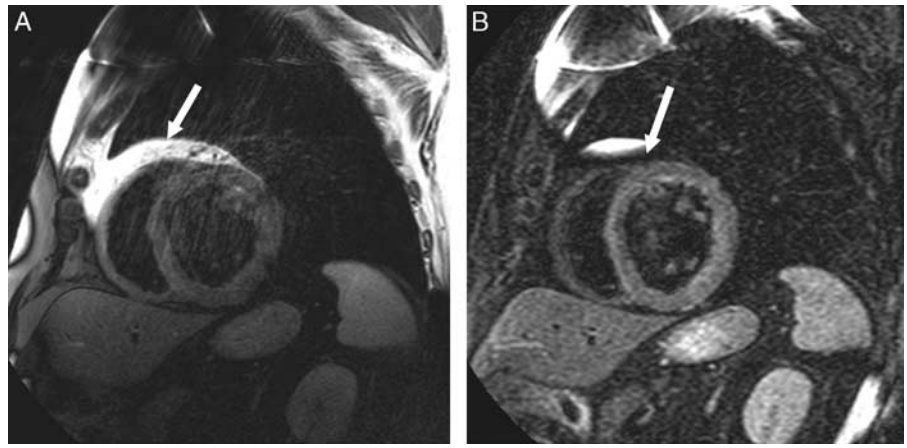

FIGURE 11. A, Short-axis TSE T2 black blood with fat saturation (Philips Ingenia 1.5T TR/TE 1714/70 ms, matrix 216×171 mm, FOV 300 mm, slice thickness 8 mm) reveals incomplete fat saturation through most of the upper and mid thorax (arrow). B, Short axis STIR image (Philips Ingenia 1.5T TR/TE 2069/68 ms, matrix 168×112 mm, FOV 300 mm, slice thickness 6.67 ms) at the same level demonstrates a marked improvement in fat saturation (arrow) with decrease in signal-to-noise ratio.

up to 33% of patients with traditional LGE sequences in patients with devices.[14,62–64] Supplementary signs of abnormality in other sequences, such as wall thinning and hypocontractility in cine images and hypoenhancement in perfusion images,[14] can be used.

A simple solution to mitigate the LGE artifacts is to increase the bandwidth of the inversion recovery pulse. This makes the inversion more uniform and the artifact smaller.[65,66] A wideband LGE sequence has also been described,[65–67] which counters the frequency shift, and decreases artifacts.[68] The wideband hyperbolic secant inversion pulse has a bandwidth of 3.8 kHz bandwidth that ensures the myocardium is properly inverted. (Fig. 13B). This allows accurate identification and quantification of LGE (Fig. 14), which may be obscured by the artifact (Fig. 15). To determine the optimal frequency offset of the inversion pulse, the wideband LGE acquisition of a typical four-chamber and/or two-chamber is performed with zero, positive, and negative offsets in the range of 1500 Hz (Fig. 14). The frequency offset that results in the artifact-free image is then chosen and used for subsequent imaging (Fig. 16). Wideband LGE sequence has been shown to generate high-quality LGE images in CIEDs. One study on 111 patients with non-Conditional devices and wideband sequences showed that only 13% of patients had artifacts and only 3% had significant artifacts, including those with left-sided ICD/CRT-D.[13] An inherent disadvantage of using this technique is the higher SAR related to the wideband inversion pulse. The tradeoff between higher SAR and improved image quality is acceptable in this situation. As MR scanners limit SAR to <2 W/kg, the software will make adjustments and keep the overall SAR limit <2 W/kg. In addition, this sequence cannot correct for image voids from devices that are directly over the heart.

Parametric Mapping

Parametric mapping techniques such as T1, T2, T2* and extracellular mapping allow visualization and quantification of changes in myocardial composition. This is particularly useful in the evaluation of diffuse processes

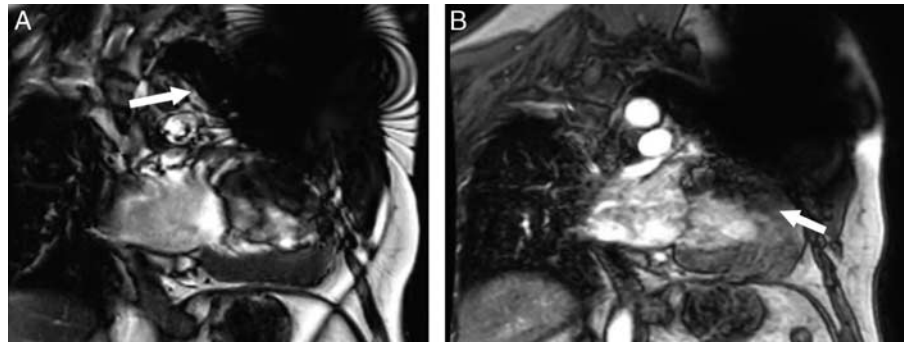

FIGURE 12. A, Two-chamber cine b-SSFP image (Philips Ingenia 1.5T, TR/TE 2.27/1.1 ms, matrix 152×121, FOV 300 mm, slice thickness 8 mm) in a patient with an implanted pacemaker in the left anterior chest wall shows extensive artifacts emanating from the device, which extends into the heart and significantly compromises the image quality. SSFP sequence requires a homogenous magnetic field and is vulnerable to susceptibility artifacts due to the induced magnetic field inhomogeneity. B, Two-chamber cine gradient-echo (GRE) image (Philips Ingenia 1.5T, TR/TE 5.19/3.1 ms, matrix 152×121, FOV 300 mm, slice thickness 8 mm) in the same patient as above shows significant decrease in the pacemaker artifact (arrows). The SNR of the sequence is slightly lower, but there is good visualization of the cardiac chambers, which improves the diagnostic confidence compared with b-SSFP image.

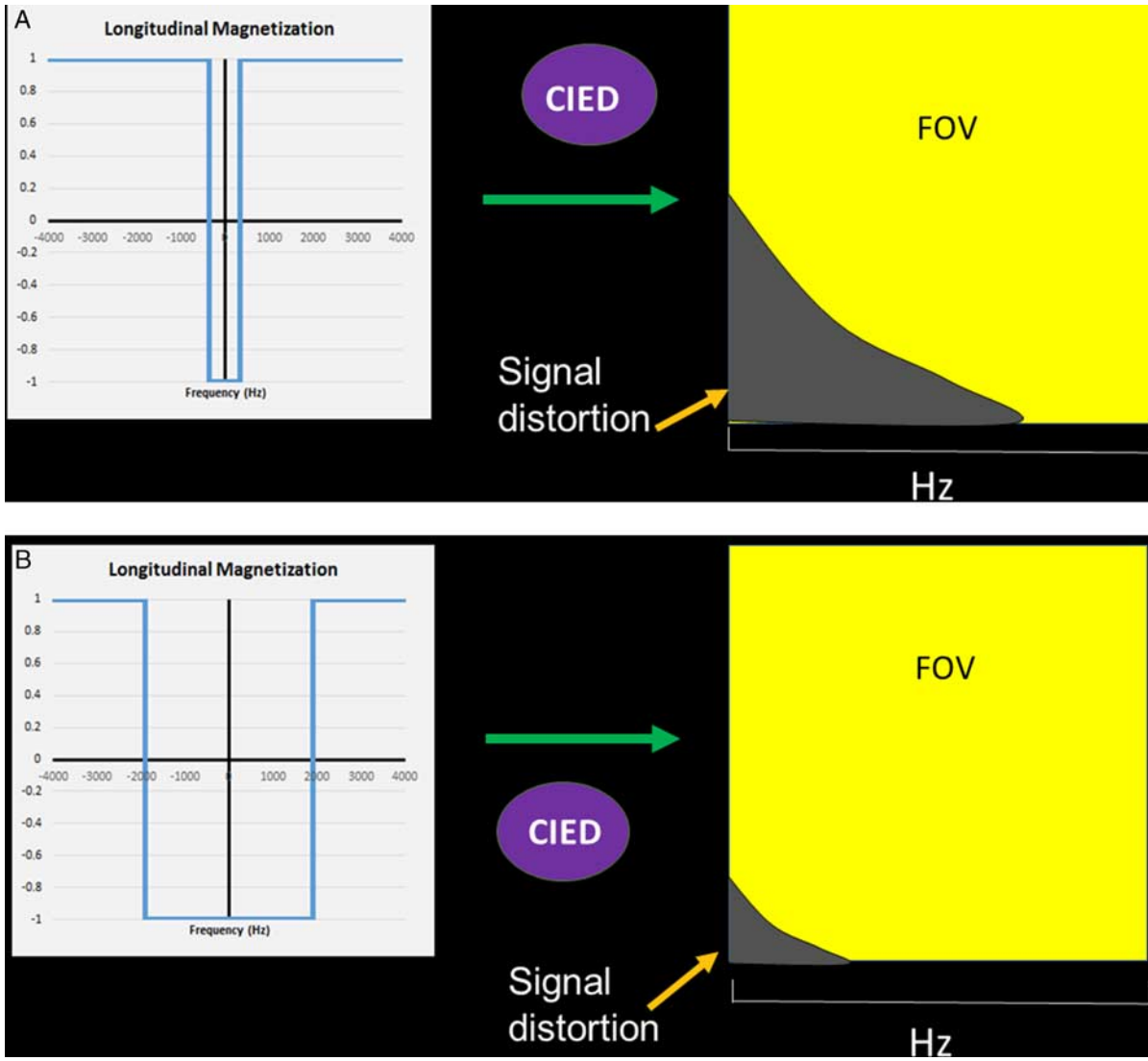

FIGURE 13. A, Illustration showing the generation of artifact in LGE sequence from CIED. The radiofrequency inversion pulse in the standard LGE is usually a hyperbolic secant adiabatic inversion pulse with a spectral bandwidth of 1.1 kHz. With a pulse generator typically 5 to 10 cm away from the heart, the expected resonance offset of the myocardium is in the 2 to 6 kHz range, which is beyond the bandwidth of the inversion pulse, resulting in artifact due to incomplete or lack of myocardial nulling. B, Illustration showing the effect of a wideband hyperbolic secant inversion pulse, with 3.8 kHz bandwidth that ensures that the myocardium is properly inverted.

that may not be evident on LGE imaging.[69] In patients with CIEDs, T1 mapping may help in the detection of myocardial fibrosis, particularly in patients with non-ischemic cardiomyopathy.[70] With CIEDs, traditional inversion or saturation recovery–based T1 mapping techniques are limited by off-resonance artifacts, and b-SSFP readouts are additionally limited by banding artifacts.[70] A wideband arrhythmia-insensitive saturation-recovery rapid sequence has been described on phantoms and healthy volunteers, but this has a low SNR or spatial resolution.[71] A wideband (bandwidth of 3.8 kHz) inversion recovery-based MOLLI sequence with FLASH readout and additional M0-weighted image before the first inversion has also been described in phantoms, healthy volunteers, and patients.[70] This sequence, which is not yet commercially available, has higher precision and reproducibility.[70] While ICD-induced artifacts were seen in bSSFP-MOLLI and FLASH-MOLLI, negligible artifacts were seen with wideband-FLASH-MOLLI.[70]

Myocardial Perfusion

First-pass myocardial perfusion imaging is used in the evaluation of myocardial ischemia, microvascular dysfunction, and other cardiac masses. Conventional perfusion images are associated with significant artifacts. A wideband saturation pulse-based perfusion sequence has been described (not commercially available), which has significantly lower artifacts than a traditional sequence, fewer variations in mean myocardial signal intensity, and SAR below the acceptable upper limit of 2.0 W/kg.[72]

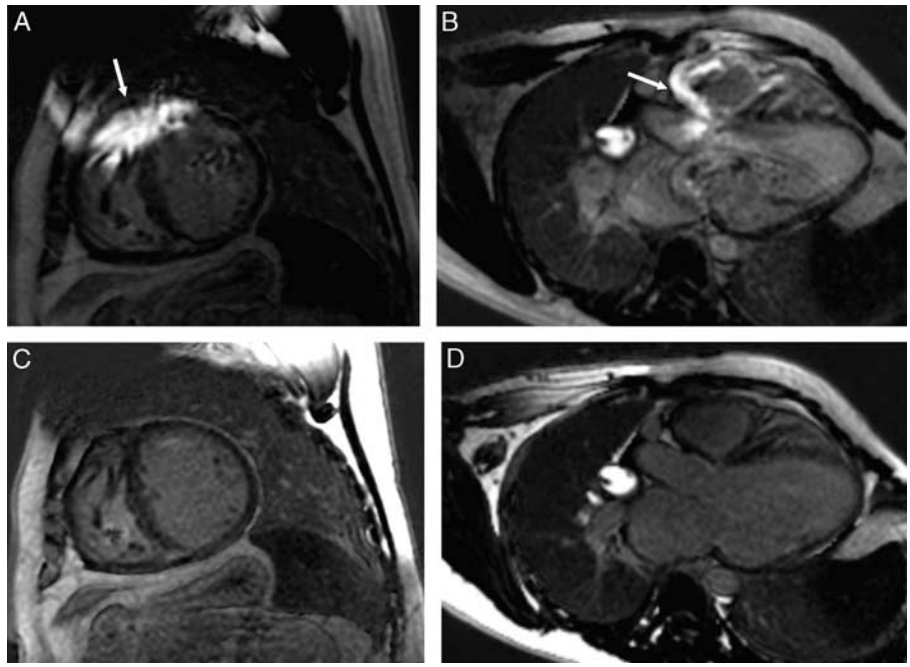

FIGURE 14. Short-axis (A) (Philips Ingenia 1.5T, TR/TE 3.94/1.92 ms, matrix 136×125, FOV 340 mm, slice thickness 10 mm) and 3-chamber (B) (Philips Ingenia 1.5T, TR/TE 3.98/1.95 ms, matrix 144×125, FOV 360 mm, slice thickness 10 mm) late gadolinium enhancement images from a phase-sensitive inversion recovery pulse in a patient with an implanted ICD shows abnormal areas of high signal intensity in the myocardium (arrows). It is uncertain whether these are artifactual or pathologic lesions. C and D, Wideband images. Short-axis (C) (Philips Ingenia 1.5T, TR/TE 3.98/1.95 ms, matrix 144×125, FOV 360 mm, slice thickness 10 mm) and 3-chamber (D) (Philips Ingenia 1.5T, TR/TE 3.98/1.95 ms, matrix 144×125, FOV 360 mm, slice thickness 10 mm, wideband centered at +1500 Hz) late gadolinium enhancement images obtained using a wideband pulse sequence in the same patient shows that the high attenuating areas have disappeared, indicating they were artifactual. Using the conventional sequence in this patient would have resulted in misdiagnosis.

CONCLUSIONS

CMR can be securely performed in patients with MR Conditional and MR-non-Conditional/legacy devices by following safety precautions with robust institutional guidelines and workflow utilizing a well-trained multidisciplinary team. Protocols typically use asynchronous mode in pacemaker-dependent patients, inhibited modes in non–pacemaker-dependent patients, and disabling of tachyarrhythmia detection and therapies in ICDs. CMR in these patients is associated with significant artifacts, which can be mitigated by using appropriate alternative sequences or technical adaptations.

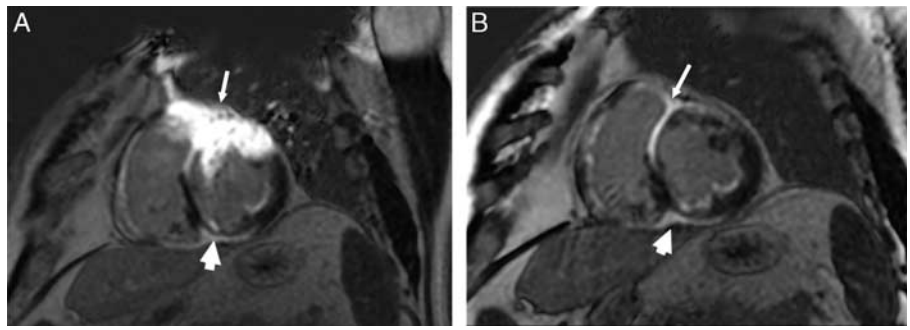

FIGURE 15. A, Short-axis late gadolinium enhancement image (Philips Ingenia 1.5T, TR/TE 3.9/1.9 ms, matrix 132×125, FOV 339 mm, slice thickness 10 mm) in a patient with implanted ICD shows abnormal areas of LGE in the inferior and lateral segments (arrowhead), which are clearly pathologic. In addition, there is intense high signal anteriorly (arrow), which appears artifactual, and an accurate evaluation of the myocardium is not possible. B, Short-axis late gadolinium enhancement (Philips Ingenia 1.5T, TR/TE 3.9/1.9 ms, matrix 128×125, FOV 320 mm, slice thickness 10 mm, wideband centered at +1500 Hz) in the same patient using a wideband pulse shows that the artifacts have disappeared. This enables accurate quantification of the LGE present under the area of artifacts (arrow). Abnormal areas of LGE in the inferior and lateral segments (arrowheads).

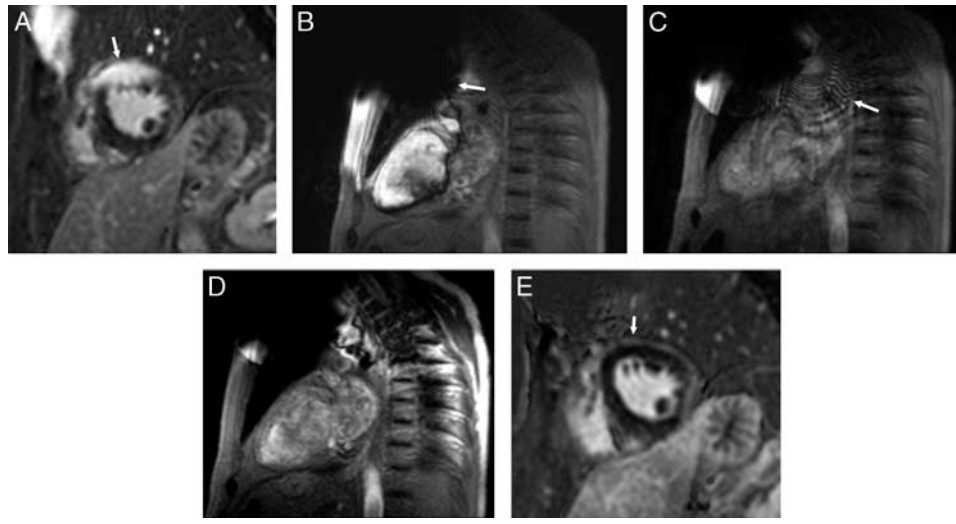

FIGURE 16. Frequency scouting. A, Short-axis late gadolinium enhancement images (Philips Ingenia 1.5T, TR/TE 4.0/1.9 ms, matrix 132×120, FOV 330 mm, slice thickness 10 mm) from a phase-sensitive inversion recovery pulse in a patient with an implanted ICD show abnormal areas of high signal intensity in the anterior myocardium (arrow). B, To identify the optimal frequency of wideband sequence to be used in this patient, a frequency scout (Philips Ingenia 1.5T, TR/TE 3.8/1.8 ms, matrix 152×130, FOV 380 mm, slice thickness 10 mm) was used. At a frequency of −1500 Hz, artifacts (arrow) are noted. C, The frequency scout image obtained at 0 Hz also shows artifacts (arrow). D, The frequency scout image obtained at 1500 Hz does not show any artifact, indicating that this is the ideal frequency for the wideband image. E, Short-axis LGE image (Philips Ingenia 1.5T, TR/TE 4.0/1.9 ms, matrix 132×120, FOV 330 mm, slice thickness 10 mm) obtained at a frequency of 1500 Hz shows elimination of the artifact (arrow).

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