



Society Position Statement

2021 Update on Safety of Magnetic Resonance Imaging: Joint Statement From Canadian Cardiovascular Society/ Canadian Society for Cardiovascular Magnetic Resonance/ Canadian Heart Rhythm Society

Primary Panel: D. Ian Paterson, MD (Co-chair),^a James A. White, MD (Co-chair),^b Craig R. Butler, MD, MSc,^a Kim A. Connelly, MBBS, PhD,^c Peter G. Guerra, MD,^d Michael D. Hill, MD,^b Matthew T. James, MD, PhD,^b Anish Kirpalani, MD,^c Carmen P. Lydell, MD,^b Idan Roifman, MD, MSc,^e Bradley Sarak, (Trainee Representative), MD,^c Laurence D. Sterns, MD,^f Atul Verma, MD,^g Douglas Wan, MBChB,^e **Secondary Panel:** Andrew M. Crean, MBChB,^h Lars Grosse-Wortmann, MD,ⁱ Kate Hanneman, MD,^j Jonathon Leipsic, MD,^k Jaimie Manlucu, MD,^l Elsie T. Nguyen, MD,ⁱ Roopinder K. Sandhu, MD, MPH,^a Christine Villemaire, MSc,^d Rachel M. Wald, MD,^m and Jonathan Windram, MBChB^a

^aMazankowski Alberta Heart Institute, University of Alberta, Edmonton, Alberta, Canada; ^bCalgary Foothills Medical Centre, University of Calgary, Calgary, Alberta, Canada; ^cSt Michael's Hospital, University of Toronto, Toronto, Ontario, Canada; ^dInstitut de Cardiologie de Montréal, Université de Montréal, Montréal, Québec, Canada; ^eSunnybrook Health Sciences Centre, University of Toronto, Toronto, Ontario, Canada; ^fRoyal Jubilee Hospital, University of British Columbia, Victoria, British Columbia, Canada; ^gSouthlake Regional Health Centre, Newmarket, Ontario, Canada; ^hOttawa Heart Institute, University of Ottawa, Ottawa, Ontario, Canada; ⁱDoernbecher Children's Hospital, Oregon Health and Science University, Portland, Oregon, USA; ^jToronto General Hospital, University of Toronto, Toronto, Ontario, Canada; ^kSt Paul's Hospital, University of British Columbia, Vancouver, British Columbia, Canada; ^lLondon Health Sciences Centre, Western University, London, Ontario, Canada; ^mMount Sinai Hospital, University of Toronto, Toronto, Ontario, Canada

ABSTRACT

Magnetic resonance imaging (MRI) is often considered the gold-standard test for characterizing cardiac as well as noncardiac structure and function. However, many patients with cardiac implantable electronic devices (CIEDs) and/or severe renal dysfunction are unable to undergo this test because of safety concerns. In the past 10 years, newer-generation CIEDs and gadolinium-based contrast agents (GBCAs) as well as coordinated care between imaging and heart rhythm device teams have mitigated risk to patients and improved

RÉSUMÉ

L'imagerie par résonance magnétique (IRM) est souvent considérée comme l'examen par excellence pour caractériser les structures et les fonctions cardiaques et non cardiaques. Cependant, beaucoup de patients porteurs d'un dispositif cardiaque électronique implantable (DCEI) ou dont la fonction rénale est gravement atteinte ne peuvent pas passer ce type d'examen pour des raisons de sécurité. Depuis une dizaine d'années, les DCEI de nouvelle génération et les nouveaux produits de contraste à base de gadolinium (PCBG), ainsi que la

Received for publication August 27, 2020. Accepted February 18, 2021.

Corresponding author: Dr D. Ian Paterson, University of Alberta Hospital, 8440 – 112 Street, 2C2.43 Walter C. Mackenzie Health Sciences Centre, Edmonton, Alberta T6G2B7, Canada. Tel.: +1-780-407-1857; fax: +1-780-407-6452.

E-mail: ip3@ualberta.ca

The disclosure information of the authors and reviewers is available from the CCS on their guidelines library at www.ccs.ca.

This statement was developed following a thorough consideration of medical literature and the best available evidence and clinical experience. It represents the consensus of a Canadian panel comprised of multidisciplinary experts on this topic

with a mandate to formulate disease-specific recommendations. These recommendations are aimed to provide a reasonable and practical approach to care for specialists and allied health professionals obliged with the duty of bestowing optimal care to patients and families, and can be subject to change as scientific knowledge and technology advance and as practice patterns evolve. The statement is not intended to be a substitute for physicians using their individual judgement in managing clinical care in consultation with the patient, with appropriate regard to all the individual circumstances of the patient, diagnostic and treatment options available and available resources. Adherence to these recommendations will not necessarily produce successful outcomes in every case.

access to MRI at many hospitals. The purpose of this statement is to review published data on safety of MRI in patients with conditional and nonconditional CIEDs in addition to patient risks from older and newer GBCAs. This statement was developed through multidisciplinary collaboration of pan-Canadian experts after a relevant and independent literature search by the Canadian Agency for Drugs and Technologies in Health. All recommendations align with the Grading of Recommendations Assessment, Development and Evaluation (GRADE) system. Key recommendations include: (1) the development of standardized protocols for patients with a CIED undergoing MRI; (2) patients with MRI nonconditional pacemakers and pacemaker dependency should be programmed to asynchronous mode and those with MRI nonconditional transvenous defibrillators should have tachycardia therapies turned off during the scan; and (3) macrocyclic or newer linear GBCAs should be used in preference to older GBCAs because of their better safety profile in patients at higher risk of nephrogenic systemic fibrosis.

Magnetic resonance imaging (MRI) is commonly used to evaluate patients with cardiac and noncardiac disease. In 2018, the Canadian Medical Imaging Inventory identified 366 MRI units in Canada that had performed 1.86 million scans in that fiscal year.¹ However, perceived risks to patients, either from high magnetic fields or from gadolinium contrast administration have often been a barrier to this imaging modality. There are approximately 250,000 Canadians with a permanent pacemaker or implantable defibrillator and it is estimated that 50%-75% will require an MRI over the lifetime of their device.² Until recently, patients with cardiac implantable electronic devices (CIEDs) were excluded from undergoing these examinations because of safety concerns regarding the potential for device damage, malfunction, or heating. However, in the early 2000s, single-site studies reported few adverse events for patients with a CIED undergoing MRI when close coordination was implemented between the imaging and heart rhythm device teams.^{3,4} In parallel, manufacturers developed MRI conditional devices with nonferromagnetic components and improved shielding to protect against unwanted effects from high magnetic fields. The result is that an increasing number of patients with CIEDs previously deemed unsafe are now undergoing MRI. A 2019 Canadian Heart Rhythm Society informal survey of 24 Canadian academic and community-based institutions showed that 14 were currently scanning patients with MRI nonconditional CIEDs, including 13 with formal protocols developed locally to optimize safety.

Gadolinium-based contrast is used in MRI to improve tissue characterization and for the performance of angiography. For cardiac MRI examinations, it is commonly used to provide information regarding myocardial perfusion, viability, or fibrosis and tissue infiltration. However, in 2007 a black box warning on

coordination des soins entre l'équipe d'imagerie et celle qui s'occupe des dispositifs de régulation du rythme cardiaque, contribuent à atténuer les risques pour les patients et facilitent l'accès à l'IRM dans de nombreux hôpitaux. Le présent énoncé a pour but de passer en revue les données publiées sur le caractère sécuritaire de l'IRM pour les patients porteurs d'un DCEI compatible ou non, ainsi que les risques pour les patients associés aux anciens et aux nouveaux PCBG. Il a été rédigé par des spécialistes de partout au Canada dans le cadre d'une initiative de collaboration multidisciplinaire, et est fondé sur les résultats d'une recherche indépendante dans la littérature effectuée par l'Agence canadienne des médicaments et des technologies de la santé. Toutes les recommandations respectent le système GRADE (*Grading of Recommendations Assessment, Development, and Evaluation*). Voici les principales recommandations : 1) mettre en place des protocoles normalisés pour les patients porteurs d'un DCEI devant passer un examen d'IRM; 2) programmer en mode asynchrone le dispositif des patients porteurs d'un stimulateur cardiaque non compatible avec l'IRM ou qui dépendent de leur stimulateur cardiaque et interrompre le traitement antitachycardique le temps de l'examen dans le cas des patients porteurs d'un défibrillateur transveineux non compatible avec l'IRM; et 3) utiliser des PCBG macrocycliques ou les nouveaux PCBG linéaires plutôt que des PCBG plus anciens, en raison de leur meilleur profil d'innocuité pour les patients présentant un risque élevé de fibrose néphrogénique systémique.

gadolinium contrast was issued by the Food and Drug Agency in the United States after determining that patients with advanced renal disease were at increased risk of developing nephrogenic systemic fibrosis (NSF), a debilitating and potentially fatal disease. Since then, newer linear and macrocyclic gadolinium-based contrast agents (GBCAs) with better safety profiles have largely replaced older agents linked to NSF in clinical practice. However, MRI centres continue to screen patients with renal dysfunction and preclude any GBCA administration in those with estimated glomerular filtration rates (eGFRs) < 30 mL/min/1.73 m². More recently, potential health concerns have also been raised regarding evidence of long-term tissue retention of GBCAs.

This statement was developed through collaboration between the Canadian Society for Cardiovascular Magnetic Resonance and Canadian Heart Rhythm Society with input from content experts in radiology, neurology, and nephrology. The purpose of this statement is to provide health care providers with guidance on best practices for MRI in patients with CIEDs and/or renal dysfunction. The methodology and processes for development are described on the Canadian Cardiovascular Society Web site (www.ccs.ca/about-guidelines/). Additionally, an independent and relevant literature review and appraisal of the evidence was performed by the Canadian Agency for Drugs and Technologies in Health (<https://www.cadth.ca/magnetic-resonance-imaging-patients-implantable-cardiac-devices-review-safety-and-guidelines> and <https://www.cadth.ca/macrocylic-and-linear-gadolinium-based-contrast-agents-adults-undergoing-magnetic-resonance-imaging>). Recommendations are aligned with the Grading of Recommendations Assessment, Development and Evaluation (GRADE) system, which has been adopted by the Canadian Cardiovascular Society Guidelines Committee to promote quality and rigour in guideline development.

MRI in Patients With CIEDs

Preamble and definitions

This section is an update on the previous position statement by the Canadian Heart Rhythm Society for MRI in patients with CIEDs.⁵ Shared decision-making between the care provider(s) and the patient is needed to ensure that the patient's values, needs, and expectations are respected. In this document, CIED is defined as leadless, single- or dual-chamber pacemakers, cardiac resynchronization pacemakers, transvenous or subcutaneous cardioverter-defibrillators, internal loop recorders, and implanted pulmonary artery pressure monitors.

Definition of MRI unconditional (equivalent terms: non-MRI-conditional, non-MRI compatible) is the failure to meet both of the following criteria:

- A. Device components must all be MRI-conditional and of the same manufacturer. Any combination of products from different manufacturers have not been tested together and therefore cannot be classified as MRI-conditional.
- B. Allowable MRI field strength (1.5 or 3.0 Tesla) set by the product specifications. No devices have been tested or approved at higher field strengths (> 3.0 Tesla).

Pre-MRI scan planning and considerations

RECOMMENDATION

1. All patients with CIEDs undergoing MRI should be managed according to a standardized protocol (Strong Recommendation; Moderate-Quality Evidence).

Values and preferences. Two large, multicentre registries have shown that the use of a standardized protocol for device management of patients with a nonconditional CIED undergoing MRI minimizes risk of adverse events.^{6,7}

A standardized protocol should be developed collaboratively by the imaging and heart rhythm device teams and adhered to for all patients with CIEDs undergoing MRI (see *Recommended Protocol for MRI in Patients With CIEDs* section and Figs. 1-3). Although these clinical MRI studies have excluded patients with a recent implantation (< 6 weeks), the actual patient risk is likely low⁸ and MRI should still be considered when the clinical need is high and alternative imaging is not available.

RECOMMENDATION

2. For patients with left pectoral CIEDs undergoing cardiac MRI, we suggest the use of fast gradient echo sequences for cine imaging and wide band sequences for late gadolinium enhancement imaging (Weak Recommendation; Low-Quality Evidence).

Values and preferences. Patients with a left pectoral CIED undergoing cardiac MRI are prone to susceptibility artifacts from steady state free precession cine imaging and late gadolinium enhancement (LGE) imaging.

Severe artifacts can preclude cine analysis in up to 15% of cardiac magnetic resonance images, particularly with left-sided implantable cardioverter-defibrillator (ICD) or cardiac resynchronization therapy defibrillator (CRT-D) devices.^{9,10} Similar to cine imaging, image quality of LGE imaging is most affected by left-sided ICD or CRT-D devices.⁹ Image quality might be improved by using gradient recalled echo sequences for cine imaging¹⁰ and wide band techniques for LGE imaging.^{11,12} There are limited data on image artifacts on MRI at 1.5 T in conditional vs nonconditional devices.¹³

RECOMMENDATION

3. For patients with a previous CIED undergoing MRI, we recommend reviewing all available medical information, including chest radiography, to identify lead extenders, retained epicardial leads, abandoned transvenous leads, and/or fractured leads. We recommend that patients with lead extenders or fractured leads should not undergo MRI. However, MRI might be considered in patients with epicardial or abandoned transvenous leads when the clinical need is strong and believed to outweigh potential risks (Weak Recommendation; Low-Quality Evidence).

Values and preferences. Patients with existing or explanted pacemakers or defibrillators might have abandoned transvenous or epicardial leads that are not connected to a device generator. The MRI physician should review available medical data including chest radiography, operative reports, and device clinic notes.

In phantom studies, abandoned or fractured leads are at increased risk for thermal injury to vascular and/or myocardial tissue from radiofrequency induced heating of the lead tip.¹⁴⁻¹⁶ However, 2 small prospective studies (N = 19 and N = 80) of abandoned transvenous leads identified no risk to patients in terms of troponin T elevation, patient discomfort, or device malfunction.^{17,18} The risk of thermal-mediated cardiovascular injury is likely even lower for active or retained epicardial leads, especially those used for temporary pacing after cardiac surgery.¹⁹ There are no clinical data on safety of MRI in patients with fractured leads or lead extenders. Because existing clinical data suggest the absence of harm, MRI at 1.5 T could be considered in patients with abandoned transvenous or epicardial leads after obtaining informed consent.

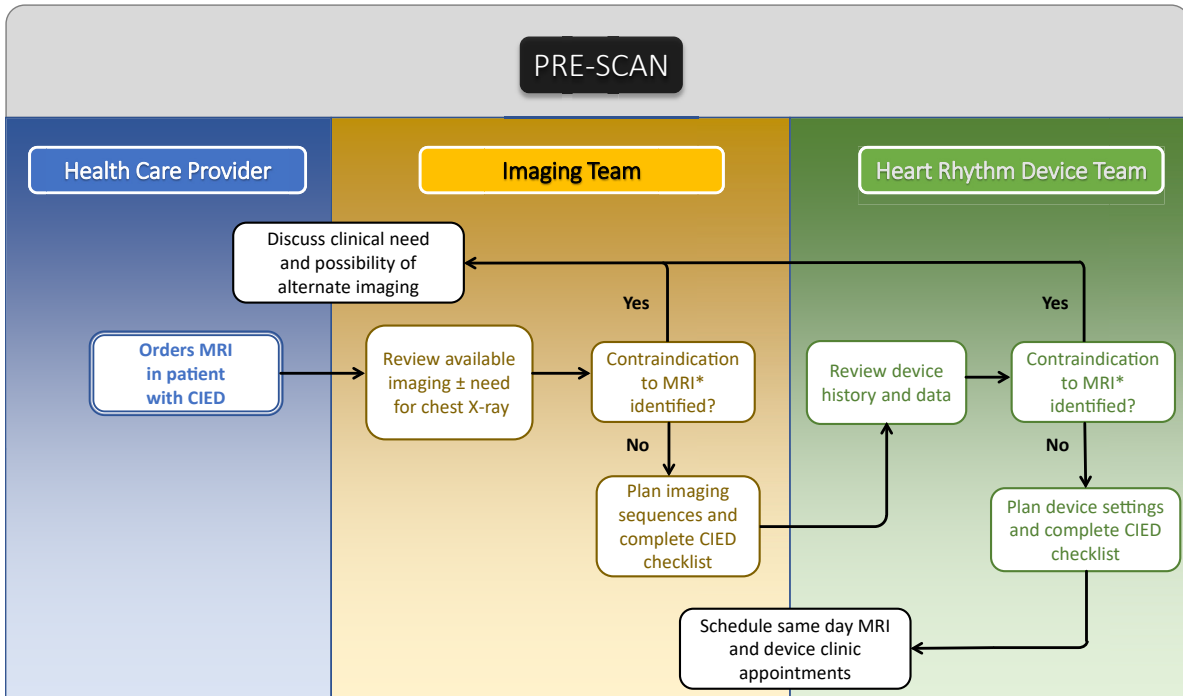


Figure 1. Summary of the recommended protocol for magnetic resonance imaging (MRI) in patients with cardiac implantable electronic devices (CIEDs); pre-scan. The text box with a **double outline** indicates the start of the flow chart. * Absolute contraindications: fractured leads, lead extenders, or adaptors. Relative contraindications: leads implanted < 6 weeks from MRI, epicardial lead, abandoned transvenous lead, device generator overlaps with scan region.

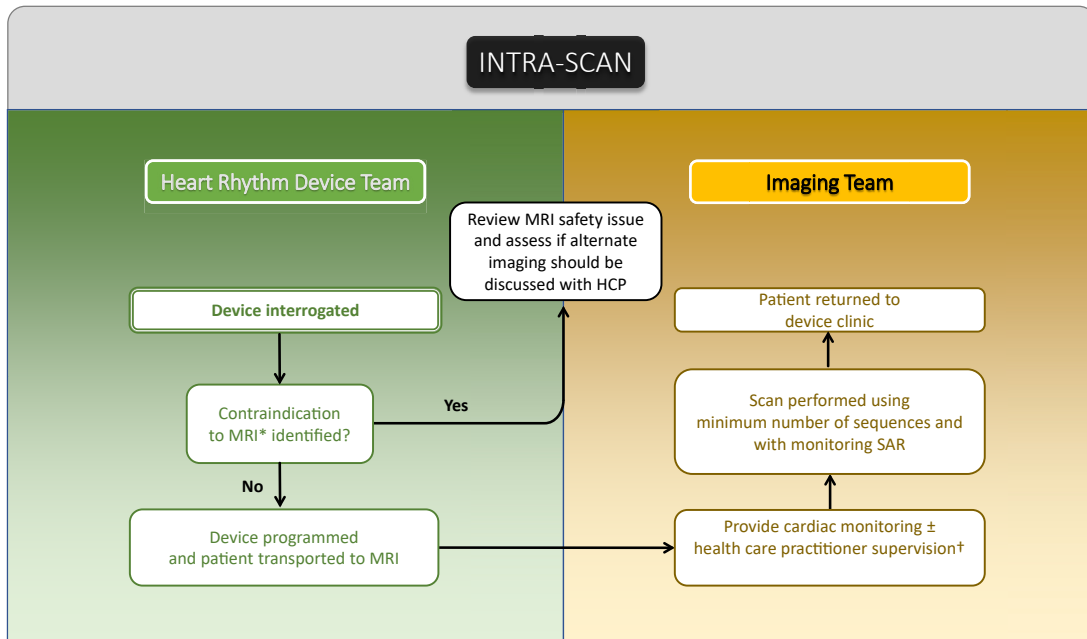


Figure 2. Summary of the recommended protocol for magnetic resonance imaging (MRI) in patients with cardiac implantable electronic devices; intra-scan. The text box with a **double outline** indicates the start of the flow chart. * Absolute contraindications: fractured leads, lead extenders, or adaptors. Relative contraindications: leads implanted < 6 weeks from MRI, epicardial lead, abandoned transvenous lead, device generator overlaps with scan region. † Health care practitioner required for MRI nonconditional pacemaker with pacemaker dependency or for MRI nonconditional transvenous defibrillator. HCP, health care provider, SAR, specific absorption rate.

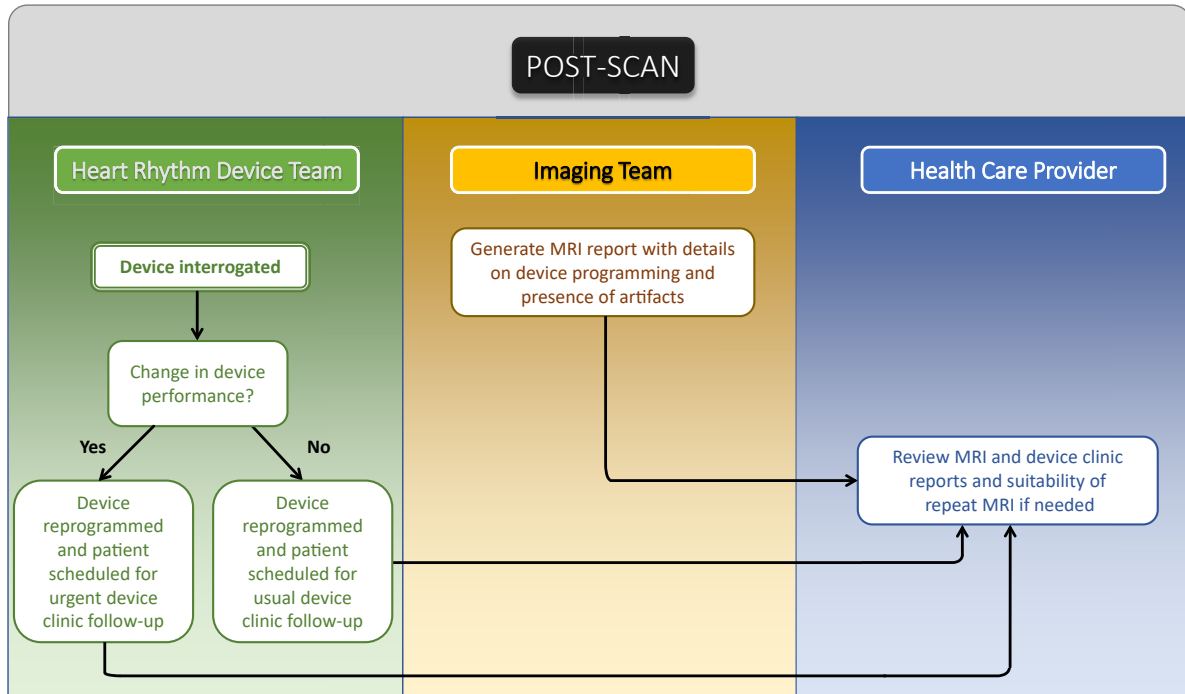


Figure 3. Summary of the recommended protocol for magnetic resonance imaging (MRI) in patients with cardiac implantable electronic devices (CIEDs); post-scan. The text box with a **double outline** indicates the start of the flow chart.

MRI for conditional devices

RECOMMENDATION

4. For patients with an MRI-conditional CIED undergoing MRI, we recommend performing scans at 1.5 T when possible, in a monitored setting and with access to the device team. The device team will provide pre-scan programming to MRI compatible mode as well as post-scan return to pre-scan settings (Strong Recommendation; Low-Quality Evidence).

Values and preferences. MRI-conditional electronic implantable systems are devices that have undergone modifications to the generator and leads to minimize device damage cause by heating. The term “conditional” denotes that these systems were developed for and tested only at specific MRI field strengths.

In prospective studies of MRI performance in patients with conditional devices scanned at 1.5 T, no changes in pacing or sensing thresholds were observed.²⁰⁻²³ There is currently no published, externally validated data for the scanning of MRI-conditional pacemakers or defibrillators at 3 T. However, several CIEDs have been certified as conditional at 3 T according to manufacturer testing.

Practical tip. In patients with conditional systems undergoing MRI, the device team should perform a pre-scan device interrogation to evaluate the underlying rhythm, screen for recent arrhythmias, ensure stable sensing, and program the device to MRI-compatible mode. For patients with a defibrillator, tachycardia therapies will be turned off and such patients should therefore be scanned at centres with access to the code team in the

unlikely event of a malignant arrhythmia. Patients should have cardiac rhythm monitoring during the MRI and the device team should be available for troubleshooting rhythm disturbances or device-related concerns. After the MRI, device sensing and pacing performance must be rechecked and reprogrammed back to pre-scan settings. Some CIED systems now have auto-detection features which can automatically trigger a safe mode when placed in the MRI without the need for preprogramming. However, a post-MRI device interrogation is still recommended to ensure lead integrity and return to normal pacing parameters.

RECOMMENDATION

5. For patients with subcutaneous ICDs (S-ICDs), we recommend scanning at 1.5 T in a monitored setting, supervised by a health care practitioner trained in advanced cardiac life support (ACLS) and with access to the code and device teams. The device team will provide pre-scan programming to turn off tachycardia therapies, post-scan interrogation, and reprogramming to pre-scan settings (Strong Recommendation; Low-Quality Evidence).

Values and preferences. This recommendation places high value on patient safety regarding scanning patients with S-ICDs.

The only currently available S-ICD (EMBLEM; Boston Scientific, Marlborough, MA) is rated as MRI-conditional at 1.5 T. Because this is still relatively new technology, real-world data regarding safety during MRI are limited. Observational studies of patients with older or newer-generation

S-ICDs showed no significant adverse outcomes to patient or device during various MRI scans at 1.5 T.^{24,25} In one study of 23 patients undergoing cardiac MRI, a permanent loss of the S-ICD beeper volume was observed in 52% of subjects, however, this was not believed to represent a major safety issue with current follow-up protocols.²⁵

RECOMMENDATION

- For patients with leadless pacemakers, we recommend scanning at an MRI field strength that does not exceed the manufacturer's specification, in a monitored setting and with access to the device team. The device team will provide pre-scan programming and post-scan reprogramming to pre-scan settings (Strong Recommendation; Low-Quality Evidence).

Values and preferences. This recommendation places high value on patient safety on the basis of differences in the product specifications and advisory status.

In a phantom study²⁶ and a small cohort study of 15 patients²⁷ with leadless pacemakers undergoing MRI at 1.5 T and 3 T were evaluated and no adverse patient outcomes or device malfunctions were reported. Currently, only Micra (Medtronic, Fridley, MN) is available, which is MRI-conditional up to 3.0 T. Nanostim (Abbott, Chicago, IL) was recalled but there are still patients with these devices implanted. Nanostim product specification is MRI-conditional up to 1.5 T.

MRI for nonconditional devices

RECOMMENDATION

- For patients with an MRI-nonconditional pacemaker and no pacemaker dependency undergoing MRI, we recommend performing scans at 1.5 T in a monitored setting and with access to the device team. The device team will provide pre-scan programming to sense mode (ie, OAO, OVO, or ODO) and post-scan interrogation and reprogramming to pre-scan settings (Strong Recommendation; High-Quality Evidence).
- For patients with an MRI-nonconditional pacemaker and pacemaker dependency undergoing MRI, we recommend performing scans at 1.5 T in a monitored setting, supervised by a health care practitioner trained in ACLS and with access to the code and device teams. The device team will provide pre-scan programming to asynchronous mode (ie, AOO, VOO or DOO) and post-scan interrogation and reprogramming to pre-scan settings (Strong Recommendation; High-Quality Evidence).
- For patients with MRI-nonconditional implantable transvenous defibrillators undergoing MRI, we recommend performing scans at 1.5 T in a monitored setting, supervised by a health care practitioner trained in ACLS and with access to the code and device teams. The device team will

provide pre-scan programming to turn off tachycardia therapies and post-scan interrogation and reprogramming to pre-scan settings (Strong Recommendation; High-Quality Evidence).

Values and preferences. Two large prospective studies (with > 1500 patients each) of MRI scans performed at 1.5 T in patients with nonconditional cardiac implantable electronic systems, including patients with pacemaker dependency and patients undergoing thoracic MRI studies showed a low incidence of adverse events.^{6,7}

The most common observed event was transient electrical reset in up to 0.6% of cases. One patient in each study required device replacement, 1 pacemaker for battery near end of life and 1 ICD generator malfunction because of failure to turn off tachycardia therapies. A meta-analysis of > 5000 patients with nonconditional CIEDs (including 511 with pacemaker dependency) undergoing thoracic and nonthoracic MRI studies also showed a low adverse event rate.²⁸ Two prospective studies of patients (N = 111 and N = 438) with MRI-nonconditional pacemakers, defibrillators, or CRT-Ds underwent a standardized protocol for MRI including cardiac or thoracic scans and showed no harm to patients and minor effects on lead impedance.^{11,29} None of these large studies identified the induction of atrial or ventricular arrhythmias as a potential risk to the patient.

Practical tip. In patients with nonconditional systems undergoing MRI, the device team should perform a pre-scan device interrogation to determine pacemaker dependency as well as sensing and pacing thresholds. Devices in patients with unstable intrinsic rhythms should be programmed to asynchronous pacing, whereas devices in patients without pacemaker dependency can be programmed to sense mode. In patients with ICDs, tachycardia therapies should be turned off. During the MRI, patients should have electrocardiogram monitoring and be supervised by a health care practitioner, affiliated with either the imaging or device team, with training in ACLS. Additionally, the device team should be available for troubleshooting rhythm disturbances or device-related concerns. After the MRI, device sensing and pacing performance will be rechecked and reprogrammed to pre-scan settings. Patients with parameter changes (see the *Recommended Protocol for MRI in Patients With CIEDs* section) determined important by the device team should undergo intensified follow-up in the device clinic for further management.

Few data exist on safety at 3 T for patients with MRI-nonconditional CIEDs. However, the meta-analysis by Shah et al. identified field strength > 1.5 T to be a risk factor for safety-related events, primarily related to power on resets, in patients with MRI-nonconditional devices.²⁸ Therefore, on the basis of currently available data, the scanning of patients with nonconditional devices at high field strength (ie, 3 T) is not recommended.

MRI for other CIEDs

RECOMMENDATION

10. For patients with an implantable/injectable loop recorder (ILR), we recommend scanning at an MRI field strength that does not exceed the manufacturer's specification. Standard requirements for monitoring and access to the device team is good practice, but no special requirements are necessary. However, we recommend downloading the stored data before MRI scanning and clearing unwanted data after the MRI scan (Weak Recommendation, Low-Quality Evidence).

Values and preferences. This recommendation places value on patient safety, protecting data integrity, and work flow efficiency for a subcutaneous device with limited function.

ILRs have a sensing function only and do not have the ability to pace or deliver therapies. All currently available ILRs are implanted subcutaneously and are MRI-conditional: Reveal/Reveal Linq (Medtronic) and BioMonitor (Biotronik, Berlin, Germany) are conditional for 1.5 T and 3.0 T, whereas Confirm/Confirm Rx (Abbott) is conditional for only 1.5 T. However, the MRI environment might alter or erase stored data and can commonly cause electromagnetic interference that can be incorrectly diagnosed as arrhythmia events. Observational studies reported no adverse events in patients with ILRs in the MRI environment up to 3.0 T, however, MRI-related artifacts were commonly observed.³⁰⁻³³

RECOMMENDATION

11. For patients with implanted pulmonary artery pressure monitors, we recommend performing scans at 1.5 T when possible, in a monitored setting (Weak Recommendation; Low-Quality Evidence).

Values and preferences. This recommendation places value on patient safety on the basis of the product specification and location of this device.

CardioMEMS (Abbott) is the only available implantable device of this kind and is considered MRI-conditional at 1.5 T or 3 T. It functions purely as a sensor to measure heart failure diagnostics through intravascular monitoring. It does not have any pacing or therapeutic capabilities. A small case series of 29 patients with pulmonary artery sensors undergoing cardiac MRI at 1.5 T reported no patient adverse events, device alterations, or image degradation.³⁴ However, only the body coil integrated within the MRI gantry was used for imaging because surface coils interfered with the CardioMEMS transmit/receive function.

Recommended Protocol for MRI in Patients With CIEDs

The recommended protocol for MRI in patients with CIED is summarized in [Figures 1-3](#). This protocol complements Supplemental Figure S1 published in the Canadian

Heart Rhythm Society and Canadian Association of Radiologists Consensus Statement.⁵

Pre-scan

See [Supplemental Table S1](#) for the pre-scan checklist.

1. The MRI department receives a request to perform MRI of a patient with a CIED.
2. The MRI department arranges posterior-anterior and lateral chest radiograph if none is available since the last device-related intervention or if status is unknown.
3. The MRI department sends the local CIED MRI checklist form to the heart rhythm device clinic.
4. The device clinic completes CIED-related pre-scan information on the checklist form.
 - A. Contraindications identified
 - i. Absolute contraindications:
 - Fractured leads
 - Presence of lead extenders or adapters
 - ii. Relative contraindications:
 - Leads implanted < 6 weeks before the planned MRI date
 - Epicardial leads
 - Abandoned transvenous leads
 - Scan region (eg, cardiac, thorax, or brachial plexus) overlaps with the region of the CIED
 - iii. Send requisition back to MRI department to review clinical need with requesting health care provider and plan alternative imaging if clinical benefit perceived to be low relative to the risk of MRI. In difficult cases, an independent review by relevant imaging and nonimaging colleagues might also be advisable.
 - B. MRI-conditional status not confirmed
 - i. Send requisition back to MRI department and request health care provider to assess whether MRI is necessary
 - C. Planned device settings:
 - i. Conditional device: MRI-compatible mode
 - ii. Pacemaker dependence: asynchronous pacing
 - iii. No pacemaker dependence: sense mode
 - iv. ICD: turn off tachycardia therapies
 - v. ILR: download data before scan
 - D. Confirm CIED patient scanning eligibility with MRI department
5. If proceeding with scan, MRI department informs heart rhythm device clinic of planned date of scan.
6. Heart rhythm device clinic arranges patient to attend clinic on day of scan
7. The MRI department provides the patient with information regarding the MRI scan in the context of a CIED to prepare them for consent on the day of the scan

Intra-scan

1. CIED interrogation performed and documented
 - A. If concerns regarding device parameters—discussion between heart rhythm device and MRI physicians to reconsider MRI

- B. If no significant concerns, then device is programmed as per heart rhythm device physician orders. Notify MRI department of device programming changes
2. Transport patient to MRI accompanied by hospital personnel
3. Consent obtained for patients with MRI-nonconditional devices or when applicable
4. Review MRI safety procedures with non-MRI medical personnel including who those may enter the scan room in the event of an emergency or safety event
5. Patient attached to MRI-compatible continuous electrocardiography, noninvasive blood pressure, and pulse oximetry monitoring.
6. MRI scan performed. During scan:
 - A. Device nurse/technician present at the discretion of the heart rhythm device team
 - B. Health care practitioner with ACLS training supervising for nonconditional devices (except pacemakers and no dependency) or MRI-conditional defibrillators.
 - C. Cardiac arrest cart readily available for transcutaneous pacing/defibrillator pads
 - D. MRI physician present in MRI department to ensure the following:
 - i. Minimum number of sequences
 - ii. Monitor and documentation of specific absorption rate—recommend pulse sequence parameters set to achieve a specific absorption rate < 2 W/kg for all sequences.⁴
 - iii. Avoid extending field of view or slices to include areas where device is implanted
 - E. Heart rhythm device physician available in hospital
3. If any significant changes with device testing, discuss with heart rhythm device physician.
 - A. Threshold for significant changes depend on individual patient and local policy. As a general guide the following thresholds, compared with pre-scan values, can be considered clinically relevant:
 - i. Capture threshold increase ≥ 1.0 V.
 - ii. Sensing decrease $\geq 50\%$.
 - iii. Pacing impedance change $\geq 50 \Omega$.
 - iv. Shock impedance change $\geq 5 \Omega$.
4. Continue routine follow-up with heart rhythm device clinic, unless earlier follow-up is indicated by:
 - A. Significant changes (as noted in 3A)—recommend 1-week follow-up.
 - B. Discretion of heart rhythm device physician.

Use of Gadolinium-Based Contrast Agents

Preamble

NSF is an often progressive disease that has been reported in patients with renal insufficiency and previous gadolinium exposure. It is typically characterized by thickening of the skin, especially of the arms and legs, and is associated with reduced range of motion. Rarely, NSF might also involve skeletal muscles, the diaphragm, dura, or mesothelium. To reduce the potential for this rare toxicity GBCAs are routinely bound to ligands using either a linear or macrocyclic molecular structure. According to the definition provided in the Canadian Association of Radiologists guidelines, or the American College of Radiology's classification of GBCAs, group I agents refer to older linear agents most commonly associated with NSF, group II agents refers to newer linear agents and some macrocyclic agents with few if any associated cases of NSF, and group III agents refer to macrocyclic agents with limited data on possible association with NSF (Table 1). Estimation of risk is on the basis of the presence of renal dysfunction, defined by the eGFR, which is calculated from serum creatinine using either the Chronic Kidney Disease Epidemiology Collaboration equation or the Modification of Diet in Renal Disease study equation. The following recommendations pertain to use of GBCAs in adults, defined as 18 years of age or older.

Post-scan

The recommended post-scan checklist is shown in Supplemental Table S2.

1. Transport patient to heart rhythm device clinic accompanied by hospital personnel.
2. CIED testing and reprogramming by heart rhythm device nurse/technician.

Table 1. The American College of Radiology manual classification of gadolinium-based agents and recommended use in patients with renal dysfunction

Group	Gadolinium-based contrast agent	Use of GBCA
Group I ("older linear agents"); agents associated with the greatest number of NSF cases	Gadodiamide (Omniscan; GE Healthcare, Chicago, IL) Gadopentetate dimeglumine (Magnevist; Bayer HealthCare Pharmaceuticals, Whippany, NJ) Gadoversetamide (OptiMARK, Guerbet, Villepinte, France)	Contraindicated in patients with eGFR < 30 mL/min/1.73 m ²
Group II ("newer linear and macrocyclic agents"); agents associated with few, if any, unconfounded cases of NSF	Gadobenate dimeglumine (MultiHance; Bracco Diagnostics, Monroe Township, NJ) Gadobutrol (Gadavist; Bayer HealthCare Pharmaceuticals; Gadovist in many countries) Gadoterate acid (Dotarem; Guerbet) Gadoteridol (ProHance; Bracco Diagnostics)	Can be safely administered for patients with eGFR between 30 and 90 mL/min/1.73 m ² Consider on case-by-case basis for patients with acutely unstable renal function (AKI), eGFR < 30 mL/min/1.73 m ² and/or receiving dialysis
Group III ("macrocyclic agents"); agents for which data remain limited regarding NSF risk, but for which few, if any unconfounded cases of NSF have been reported	Gadoxetate disodium (Eovist; Bayer HealthCare Pharmaceuticals; Primovist in many countries)	

AKI, acute kidney injury; eGFR, estimated glomerular filtration rate; GBCA, gadolinium-based contrast agent; NSF, nephrogenic systemic fibrosis. Table derived from McDonald et al.³⁵ American College of Radiology,³⁶ and Schieda et al.³⁷

RECOMMENDATION

12. We recommend that when GBCAs are used, macrocyclic or newer linear agents (group II or III) are used in preference to older linear agents (group I) (Strong Recommendation; High-Quality Evidence).

Values and preferences. Nearly all nonadjudicated cases of NSF have been reported after exposure to first-generation group I linear agents, whereas few, if any, have been associated with group II or III agents.³⁸⁻⁴⁰

As a class, macrocyclic GBCAs have greater kinetic stability than linear agents, leading to lower amounts of gadolinium tissue retention.⁴¹ Nonallergic toxicity results from direct cellular effects of gadolinium salts and competition with calcium-dependent biologic processes; gadolinium chelates (including GBCAs) do not have the same effect.³⁵ However, macrocyclic agents appear to be associated with a higher rate of allergic-like adverse events in patients injected with GBCAs.⁴²

Group I agents are contraindicated in patients with an eGFR < 30 mL/min/1.73 m².^{43,44} The risk of NSF with these agents in patients with acute kidney injury (AKI) or severe renal impairment is estimated between 1% and 7%.³⁶ However, at the present time, there is insufficient evidence to recommend macrocyclic agents (gadoteridol, gadobutrol, gadoteric acid) over newer linear agents (gadobenate dimeglumine, gadoxetate disodium) to reduce the risk of NSF or gadolinium tissue retention.⁴⁵

Practical tip. We suggest that the lowest dose of GBCA required to obtain the needed clinical information should be used only when necessary, and that institutions internally review which GBCAs are used locally to establish a safe time interval before repeated administration.

Regular vendor-suggested dosing is recommended according to body surface area and the indication for the study.⁴⁶⁻⁴⁸ Half- or quarter-dosing is not recommended because of the possibility of obtaining nondiagnostic images and double-dosing should be avoided unless for LGE imaging or large vessel angiography, where it is routinely used. Patients should not receive multiple doses of GBCA until sufficient time has passed to allow for excretion, as determined by individual institutions and clinical necessity. In general, at least 24 hours is suggested between repeat dosing in those with normal renal function; > 90% of each delivered dose is excreted in the urine by 12 hours⁴⁶ or 24 hours^{47,48} and longer in those with impaired renal function. When repeat studies are anticipated, the use of group II or III agents are recommended.

RECOMMENDATION

13. We recommend that outpatients undergoing GBCA-enhanced MRI with macrocyclic or newer linear agents (group II or III) who are identified as low risk for NSF do not undergo further screening for renal dysfunction (Strong Recommendation; Low-Quality Evidence).

14. We suggest that patients identified as high risk for NSF are considered for screening with an assessment of eGFR within 3 months before GBCA administration (Weak Recommendation; Low-Quality Evidence).

Values and preferences. Patients considered at low risk for NSF are those with no, mild, or moderate renal impairment (previous eGFR > 30 mL/min/1.73 m²) and/or without a history of renal transplantation, previous dialysis, or hospitalization for AKI. Patients considered at high risk for NSF are those admitted to hospital with significant or decompensated cardiac disease, AKI in the past month, or an eGFR of < 30 mL/min/1.73 m² in the past 6 months (Table 2).

Overall, for patients with an eGFR between 30 and 90 mL/min/1.73 m², group II or III GBCAs can be safely administered. For patients with mild renal impairment (eGFR between 60 and 90 mL/min/1.73 m²), there is no evidence to suggest an increased risk of NSF and no special precautions, including screening, are required before group II or III GBCA administration.⁴⁸ The risk of developing NSF with moderate renal impairment (eGFR between 30 and 60 mL/min/1.73 m²) is exceedingly low, and in these patients, group II and III GBCAs can also be administered safely without any substantial risk of developing NSF, need for screening or informed consent, recognizing that consent might still be considered for other reasons.³⁷ Although the association between NSF development and exposure to GBCAs is most likely to occur in those with impaired renal function, in reports of NSF in patients with moderate renal dysfunction, it generally occurred in those with AKI.^{49,50} Screening in this population with either questionnaires or eGFR is resource-consuming, and a potential barrier to timely and appropriate investigation.

Patients taking part in research studies should adhere to these criteria and principles.

RECOMMENDATION

15. We recommend that for patients with acutely unstable renal function, eGFR < 30 mL/min/1.73 m², and/or receiving dialysis that GBCA administration be considered on a case by case basis. In those who require renal replacement therapy, dialysis should be performed within 24 hours, ideally within 2 hours (Strong Recommendation; Moderate-Quality Evidence).

Values and preferences. Limiting the use of GBCAs in at-risk patients has dramatically reduced, and possibly eliminated new cases of NSF. The risk of administering a GBCA must be balanced against the risk of not performing a necessary contrast-enhanced MRI and the effect on clinical outcomes.

For patients with known severely reduced renal function and those receiving dialysis, GBCA-enhanced examinations should be assessed on an individual basis. Alternative diagnostic imaging tests (eg, unenhanced MRI, computed tomography, ultrasound, nuclear scans, etc) should be considered. The decision should be left to the discretion of individual clinicians including the patient's nephrologist. Informed consent should be considered and local practices followed if the GBCA-enhanced MRI is considered necessary with no reasonable available alternative.³⁷

Hemodialysis efficiently removes GBCA with approximately 70% clearance in 1 session and > 95% clearance after 3 sessions,⁵⁰ with the duration of the session left to the discretion of the treating nephrology team. Multiple, frequent dialysis sessions have previously been advocated to promote gadolinium clearance, however, there are no formal studies showing that these practices reliably reduce the incidence of, or prevent NSF.⁵¹ Routine nephrology consultation is not mandatory, but should be considered on an individual basis, and in line with local practices for patients with eGFR < 30 mL/min/1.73 m² who are deemed to require GBCA. For patients who are dialysis-dependent, the dialysis service should be contacted to coordinate scheduling and/or to consider potential changes in dialysis prescription as per the discretion of a nephrologist. For patients receiving peritoneal dialysis, it is unclear as to whether switching to hemodialysis will reduce the risk of NSF.^{37,52}

Patients with eGFR < 30 mL/min/1.73 m² or receiving dialysis who receive GBCA as well as the referring health care provider should be advised by the MRI physician to monitor for NSF for a 2-year period on the basis of signs or symptoms or at routine physical evaluation. Potential cases should be investigated with histopathological confirmation (eg, skin biopsy) and should be reported to Health Canada's Adverse Reaction Database.

RECOMMENDATION

16. We suggest that GBCA administration is not withheld over concerns for tissue retention (Strong Recommendation; Low-Quality Evidence).

Values and preferences. Preliminary evidence has identified GBCA retention in the brain and other non-central nervous system tissues including skin, bone, and liver without associated symptoms, adverse effects, or clinical relevance.^{35,53-55}

Dose-dependent increases in signal intensity on T1-weighted MRI of the brain have been identified in patients who have received a linear GBCA. In other studies, there are also reports of similar, but less pronounced, changes with macrocyclic agents. However, studies of human and animal brain tissues have consistently failed to show histopathologic evidence of injury to neurons or the neural interstitium.³⁵

At the present time, the clinical significance of gadolinium retention is unknown. There is insufficient evidence to withhold GBCA administration or to select a specific GBCA agent over this concern, particularly when its use is clinically

indicated.^{42,53} However, because of the lack of information regarding the effect of GBCA retention, it is prudent to limit GBCA use unless it is clinically indicated and will modify management. Older linear agents should be avoided altogether whenever possible.

Conclusions and Future Directions

The past decade has seen significant changes surrounding the clinical appropriateness and safe performance of MRI in patients with cardiovascular disease. Expanding clinical need for this technique to assist in cardiac and noncardiac disease management has required contextualization to the unique demographic characteristics of this population, inclusive of higher rates of renal insufficiency and implantable cardiac devices. Furthermore, the proportion of higher field strength scanners (> 1.5 T) in Canada has shown an interval increase from 14% in 2017¹ to 17% in 2020⁵⁶ demonstrating a trend toward increasing barriers to MRI in patients with non-conditional devices. Focused attention toward these concerns has led to substantive shifts in practice with recommendations for routine use of macrocyclic gadolinium chelates, MRI-conditional devices, and adherence to standardized protocols aimed at improving patient safety in those with nonconditional devices. These parallel efforts have culminated in new practice standards that expand the availability of MRI for patients with cardiovascular disease.

In this position statement we have summarized contemporary knowledge for, and provided clinical recommendations surrounding the safe use of MRI in cardiovascular patients with targeted focus on contrast administration and the management of implantable cardiac devices. We acknowledge the need for iterative consideration of emerging data and the ever-persistent requirement for contextualization to individual patients.

Future work will inherently benefit from improved capture of clinical data surrounding patient referral demographic characteristics, procedural work flow, and periprocedural complications. Coordinated efforts to collect these data in clinical practice is of expanding importance for patient care optimization and provides essential real-world data to assess implementation success, guide best practice recommendations, and inform innovation. Although the latter pursues novel approaches to MRI performance without need for contrast administration, and optimization of imaging at low field strengths, the previously described recommendations provide foundational guidelines upon which to engage MRI services while maximizing patient safety.

Acknowledgements

The authors thank Ms Christianna Brooks for her administrative and managerial support throughout this position paper development. Additionally, we thank the Canadian Cardiovascular Society Executive and Guidelines Committees for their thorough review of and feedback on this document. We also thank the Canadian Agency for Drugs and Technologies in Health for their independent literature review and grading of evidence. Finally, we thank Mr Steve Trempe for his help in developing the illustrations.

Table 2. Risk of nephrogenic systemic fibrosis eGFR screening and follow-up

Risk profile	Patient population	eGFR screening	NSF follow-up
Low risk	No, mild, or moderate renal impairment (previous eGFR > 30 mL/min/1.73 m ²) and/or without a history of renal transplant, previous dialysis, or hospitalization for AKI	Not recommended	Not recommended
High risk	Admitted to hospital with significant or decompensated cardiac disease, AKI in the past month, or an eGFR of < 30 mL/min/1.73 m ² in the past 6 months	Consider for screening with an assessment of eGFR within 3 months before GBCA administration	Two-year follow-up by general practitioner post GBCA exposure

AKI, acute kidney injury; eGFR, estimated glomerular filtration rate; GBCA, gadolinium-based contrast agent; NSF, nephrogenic systemic fibrosis.

References

- CADTH: The Canadian Medical Imaging Inventory. Available at: <https://cadth.ca/canadian-medical-imaging-inventory-2017>. Accessed August 27, 2020.
- Kalin R, Stanton MS. Current clinical issues for MRI scanning of pacemaker and defibrillator patients. *Pacing Clin Electrophysiol* 2005;28:326-8. *Pacing Clin Electrophysiol* 2005;28:326-8.
- Martin ET, Coman JA, Shellock FG, et al. Magnetic resonance imaging and cardiac pacemaker safety at 1.5-Tesla. *J Am Coll Cardiol* 2004;43:1315-24.
- Nazarian S, Roguin A, Zviman MM, et al. Clinical utility and safety of a protocol for noncardiac and cardiac magnetic resonance imaging of patients with permanent pacemakers and implantable-cardioverter defibrillators at 1.5 Tesla. *Circulation* 2006;114:1277-84.
- Verma A, Ha AC, Dennie C, et al. Canadian Heart Rhythm Society and Canadian Association of Radiologists consensus statement on magnetic resonance imaging with cardiac implantable electronic devices. *Can J Cardiol* 2014;30:1131-41.
- Nazarian S, Hansford R, Rahsepar AA, et al. Safety of magnetic resonance imaging in patients with cardiac devices. *N Engl J Med* 2017;377:2555-64.
- Russo RJ, Costa HS, Silva PD, et al. Assessing the risks associated with MRI in patients with a pacemaker or defibrillator. *N Engl J Med* 2017;376:755-64.
- Friedman HL, Acker N, Dalzell C, et al. Magnetic resonance imaging in patients with recently implanted pacemakers. *Pacing Clin Electrophysiol* 2013;36:1090-5.
- Sasaki T, Hansford R, Zviman MM, et al. Quantitative assessment of artifacts on cardiac magnetic resonance imaging of patients with pacemakers and implantable cardioverter-defibrillators. *Circ Cardiovasc Imaging* 2011;4:662-70.
- Schwiter J, Gold MR, Al Fagih A, et al. Image quality of cardiac magnetic resonance imaging in patients with an implantable cardioverter defibrillator system designed for the magnetic resonance imaging environment. *Circ Cardiovasc Imaging* 2016;9:e004025.
- Do DH, Eyvazian V, Bayoneta AJ, et al. Cardiac magnetic resonance imaging using wideband sequences in patients with nonconditional cardiac implanted electronic devices. *Heart Rhythm* 2018;15:218-25.
- Rashid S, Rapacchi S, Vaseghi M, et al. Improved late gadolinium enhancement MR imaging for patients with implanted cardiac devices. *Radiology* 2014;270:269-74.
- Camacho JC, Moreno CC, Shah AD, et al. Safety and quality of 1.5-T MRI in patients with conventional and MRI-conditional cardiac implantable electronic devices after implementation of a standardized protocol. *AJR Am J Roentgenol* 2016;207:599-604.
- Langman DA, Goldberg IB, Finn JP, Ennis DB. Pacemaker lead tip heating in abandoned and pacemaker-attached leads at 1.5 Tesla MRI. *J Magn Reson Imaging* 2011;33:426-31.
- Mattei E, Gentili G, Censi F, Triventi M, Calcagnini G. Impact of capped and uncapped abandoned leads on the heating of an MR-conditional pacemaker implant. *Magn Reson Med* 2015;73:390-400.
- Balmer C, Gass M, Dave H, Duru F, Luechinger R. Magnetic resonance imaging of patients with epicardial leads: in vitro evaluation of temperature changes at the lead tip. *J Interv Card Electrophysiol* 2019;56:321-6.
- Higgins JV, Gard JJ, Sheldon SH, et al. Safety and outcomes of magnetic resonance imaging in patients with abandoned pacemaker and defibrillator leads. *Pacing Clin Electrophysiol* 2014;37:1284-90.
- Padmanabhan D, Kella DK, Mehta R, et al. Safety of magnetic resonance imaging in patients with legacy pacemakers and defibrillators and abandoned leads. *Heart Rhythm* 2018;15:228-33.
- Homsy R, Mellert F, Luechinger R, et al. Safety and feasibility of magnetic resonance imaging of the brain at 1.5 Tesla in patients with temporary transmucosal pacing leads. *Thorac Cardiovasc Surg* 2019;67:86-91.
- Gimbel JR, Bello D, Schmitt M, et al. Randomized trial of pacemaker and lead system for safe scanning at 1.5 Tesla. *Heart Rhythm* 2013;10:685-91.
- Shenthar J, Milasinovic G, Al Fagih A, et al. MRI scanning in patients with new and existing CapSureFix Novus 5076 pacemaker leads: randomized trial results. *Heart Rhythm* 2015;12:759-65.
- Awad K, Griffin J, Crawford TC, et al. Clinical safety of the Iforia implantable cardioverter-defibrillator system in patients subjected to thoracic spine and cardiac 1.5-T magnetic resonance imaging scanning conditions. *Heart Rhythm* 2015;12:2155-61.
- Ching CK, Chakraborty RN, Kler TS, et al. Clinical safety and performance of a MRI conditional pacing system in patients undergoing cardiac MRI. *Pacing Clin Electrophysiol* 2017;40:1389-95.

24. Keller J, Neuzil P, Vymazal J, et al. Magnetic resonance imaging in patients with a subcutaneous implantable cardioverter-defibrillator. *Europace* 2015;17:761-6.
25. Holtstiege V, Meier C, Bietenbeck M, et al. Clinical experience regarding safety and diagnostic value of cardiovascular magnetic resonance in patients with a subcutaneous implanted cardioverter/defibrillator (S-ICD) at 1.5 T. *J Cardiovasc Magn Reson* 2020;22:35.
26. Soejima K, Edmonson J, Ellingson ML, et al. Safety evaluation of a leadless transcatheter pacemaker for magnetic resonance imaging use. *Heart Rhythm* 2016;13:2056-63.
27. Blessberger H, Kiblböck D, Reiter C, et al. Monocenter Investigation Micra(R) MRI study (MIMICRY): feasibility study of the magnetic resonance imaging compatibility of a leadless pacemaker system. *Europace* 2019;21:137-41.
28. Shah AD, Morris MA, Hirsh DS, et al. Magnetic resonance imaging safety in nonconditional pacemaker and defibrillator recipients: a meta-analysis and systematic review. *Heart Rhythm* 2018;15:1001-8.
29. Nazarian S, Hansford R, Roguin A, et al. A prospective evaluation of a protocol for magnetic resonance imaging of patients with implanted cardiac devices. *Ann Intern Med* 2011;155:415-24.
30. Gimbel JR, Zarghami J, Machado C, Wilkoff BL. Safe scanning, but frequent artifacts mimicking bradycardia and tachycardia during magnetic resonance imaging (MRI) in patients with an implantable loop recorder (ILR). *Ann Noninvasive Electrocardiol* 2005;10:404-8.
31. Wong JA, Yee R, Gula LJ, et al. Feasibility of magnetic resonance imaging in patients with an implantable loop recorder. *Pacing Clin Electrophysiol* 2008;31:333-7.
32. Haeusler KG, Koch L, Ueberreiter J, et al. Safety and reliability of the insertable Reveal XT recorder in patients undergoing 3 Tesla brain magnetic resonance imaging. *Heart Rhythm* 2011;8:373-6.
33. Blaschke F, Lacour P, Walter T, et al. Cardiovascular magnetic resonance imaging in patients with an implantable loop recorder. *Ann Noninvasive Electrocardiol* 2016;21:319-24.
34. Biederman RWW, Doyle M, Correa-Jaque P, Rayarao G, Benza RL. Integrated use of cardiac MRI and the CardioMEMS HF system in PAH: the utility of coincident pressure and volume in RV failure—the NHLBI-VITA trial. *Cardiovasc Diagn Ther* 2019;9:492-501.
35. McDonald RJ, Levine D, Weinreb J, et al. Gadolinium retention: a research roadmap for the 2018 NIH/ACR/RSNA Workshop on Gadolinium Chelates. *Radiology* 2018;289:517-34.
36. American College of Radiology: Manual on contrast media v10.3; chapter 15 nephrogenic systemic fibrosis (NSF). Available at: https://www.acr.org/-/media/ACR/files/clinical-resources/contrast_media.pdf. Accessed February 25, 2020.
37. Schieda N, Maralani PJ, Hurrell C, Tsampalieros AK, Hiremath S. Updated clinical practice guideline on use of gadolinium-based contrast agents in kidney disease issued by the Canadian Association of Radiologists. *Can Assoc Radiol J* 2019;70:226-32.
38. de Kerviler E, Maravilla K, Meder JF, et al. Adverse reactions to gadoterate meglumine: review of over 25 years of clinical use and more than 50 million doses. *Invest Radiol* 2016;51:544-51.
39. Soyer P, Dohan A, Patkar D, Gottschalk A. Observational study on the safety profile of gadoterate meglumine in 35,499 patients: the SECURE study. *J Magn Reson Imaging* 2017;45:988-97.
40. Young LK, Matthew SZ, Houston JG. Absence of potential gadolinium toxicity symptoms following 22,897 gadoteric acid (Dotarem(R)) examinations, including 3,209 performed on renally insufficient individuals. *Eur Radiol* 2019;29:1922-30.
41. Frenzel T, Lengsfeld P, Schirmer H, Hutter J, Weinmann HJ. Stability of gadolinium-based magnetic resonance imaging contrast agents in human serum at 37 degrees C. *Invest Radiol* 2008;43:817-28.
42. Behzadi AH, Zhao Y, Farooq Z, Prince MR. Immediate allergic reactions to gadolinium-based contrast agents: a systematic review and meta-analysis. *Radiology* 2018;286:471-82.
43. Government of Canada: Gadolinium-containing contrast agents - update on nephrogenic systemic fibrosis/nephrogenic fibrosing dermopathy (NSF/NFD) – Notice to hospitals. Available at: <http://healthycanadians.gc.ca/recall-alert-rappel-avis/hc-sc/2013/36711a-eng.php>. Accessed October 9, 2019.
44. U.S. Food and Drug Administration: FDA drug safety communication: new warnings for using gadolinium-based contrast agents in patients with kidney dysfunction. Available at: <https://www.fda.gov/Drugs/DrugSafety/ucm223966.htm>. Accessed October 9, 2019.
45. Kuwatsuru R, Takahashi S, Umeoka S, et al. A multicenter, randomized, controlled, single-blind comparison phase III study to determine the efficacy and safety of gadobutrol 1.0 M versus gadopentetate dimeglumine following single injection in patients referred for contrast-enhanced MRI of the body regions or extremities. *J Magn Reson Imaging* 2015;41:404-13.
46. Bayer Inc: GADOVIST 1.0 (gadobutrol) product monograph. Available at: <https://www.bayer.ca/omr/online/gadovist-pm-en.pdf>. Accessed June 16, 2020.
47. Bracco Diagnostics. MultiHance (gadobenate dimeglumine) product monograph. Available at: https://pdf.hres.ca/dpd_pm/00053801.PDF. Accessed June 16, 2020.
48. Bracco Diagnostics. Prohance (gadoteratol) product monograph. Available at: https://pdf.hres.ca/dpd_pm/00044182.PDF. Accessed June 16, 2020.
49. Prince MR, Zhang H, Morris M, et al. Incidence of nephrogenic systemic fibrosis at two large medical centers. *Radiology* 2008;248:807-16.
50. Sadowski EA, Bennett LK, Chan MR, et al. Nephrogenic systemic fibrosis: risk factors and incidence estimation. *Radiology* 2007;243:148-57.
51. Rodby RA. Dialytic therapies to prevent NSF following gadolinium exposure in high-risk patients. *Semin Dial* 2008;21:145-9.
52. Murashima M, Drott HR, Carlow D, et al. Removal of gadolinium by peritoneal dialysis. *Clin Nephrol* 2008;69:368-72.
53. Costa AF, van der Pol CB, Maralani PJ, et al. Gadolinium deposition in the brain: a systematic review of existing guidelines and policy statement issued by the Canadian Association of Radiologists. *Can Assoc Radiol J* 2018;69:373-82.
54. Olchowyc C, Cebulski K, Lasecki M, et al. The presence of the gadolinium-based contrast agent depositions in the brain and symptoms of gadolinium neurotoxicity - a systematic review. *PLoS One* 2017;12:e0171704.
55. McDonald RJ, McDonald JS, Therneau T, et al. Assessment of the neurologic effects of intracranial gadolinium deposition using a large population based cohort. Presented at: Radiological Society of North America 2017 Scientific Assembly and Annual Meeting, November 26–December 1,

2017; Chigago, IL. Available at: <http://archive.rsna.org/2017/17017717.html>. Accessed August 27, 2020.

56. CADTH. The Canadian Medical Imaging Inventory. Available at: <https://www.cadth.ca/canadian-medical-imaging-inventory-2019-2020>. Accessed August 27, 2020.

Supplementary Material

To access the supplementary material accompanying this article, visit the online version of the *Canadian Journal of Cardiology* at www.onlinecjc.ca and at <https://doi.org/10.1016/j.cjca.2021.02.012>.