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Special article

Magnetic resonance in patients with cardiovascular devices. SEC-GT CRMTC/SEC-Heart Rhythm Association/SERAM/SEICAT consensus document

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ABSTRACT

Magnetic resonance has become a first-line imaging modality in various clinical scenarios. The number of patients with different cardiovascular devices, including cardiac implantable electronic devices, has increased exponentially. Although there have been reports of risks associated with exposure to magnetic resonance in these patients, the clinical evidence now supports the safety of performing these studies under specific conditions and following recommendations to minimize possible risks. This document was written by the Working Group on Cardiac Magnetic Resonance Imaging and Cardiac Computed Tomography of the Spanish Society of Cardiology (SEC-GT CRMTC), the Heart Rhythm Association of the Spanish Society of Cardiology (SEC-Heart Rhythm Association), the Spanish Society of Medical Radiology (SERAM), and the Spanish Society of Cardiothoracic Imaging (SEICAT). The document reviews the clinical evidence available in this field and establishes a series of recommendations so that patients with cardiovascular devices can safely access this diagnostic tool.

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Resonancia magnética para portadores de dispositivos cardiovasculares. Consenso SEC-GT CRMTC/SEC-Asociación del Ritmo Cardiaco/SERAM/SEICAT

Palabras clave:
Seguridad
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RESUMEN

La resonancia magnética se ha convertido en técnica de imagen de primera línea en muchas situaciones clínicas. El número de pacientes portadores de dispositivos cardiovasculares, como los dispositivos cardiovasculares electrónicos implantables, ha crecido de modo exponencial. Aunque se han descrito complicaciones y efectos adversos cuando estos pacientes se someten a exploraciones de resonancia magnética, la evidencia clínica actual respalda la seguridad de realizar estos estudios cuando se cumplen unas normas y recomendaciones dirigidas a minimizar los posibles riesgos. El Grupo de Trabajo de Cardiorresonancia Magnética y Cardiotomografía Computarizadas de la Sociedad Española de Cardiología (SEC-GT CRMTC), la Asociación del Ritmo Cardiaco de la Sociedad Española de Cardiología (SEC-Asociación del Ritmo Cardiaco de la Sociedad Española de Cardiología), la Sociedad Española de Radiología Médica (SERAM) y la Sociedad Española de Imagen Cardiotorácica (SEICAT) han elaborado el presente documento, que revisa la evidencia disponible en este campo y establece las recomendaciones necesarias para que los pacientes portadores de dispositivos cardiovasculares electrónicos implantables y otros dispositivos puedan acceder con seguridad a este instrumento diagnóstico.

Abbreviations

ICD: implantable cardioverter-defibrillator
CIED: cardiac implantable electronic device
RF: radiofrequency
MR: magnetic resonance

INTRODUCTION

In recent years, magnetic resonance (MR) has become an essential and first-line imaging technique in many clinical situations. At the same time, the number of patients with a cardiovascular device has grown exponentially. It is thus commonplace in clinical practice to encounter a recipient of one of these devices who requires an MR study.[1,2] The probability that a recipient of a cardiac implantable electronic device (CIED) will require an MR study in the first postimplantation year is estimated to be 10%, rising to 75% during the patients' lifespan.[3]

Although many of these devices do not show a contraindication to MR, some devices are not safe, are only compatible in certain specific circumstances, or require an assessment before and after the scan. In addition, given that they can lead to lower image quality, the indication for the study must be evaluated in the context of the risk-benefit ratio.

The current consensus document has been produced through the collaboration of the Working Group on Cardiac Magnetic Resonance Imaging and Cardiac Computed Tomography of the Spanish Society of Cardiology (SEC-GT CRMTC), the Heart Rhythm Association of the SEC (SEC-Heart Rhythm Association), the Spanish Society of Medical Radiology (SERAM), and the Spanish Society of Cardiothoracic Imaging (SEICAT). The document reviews the safety of MR studies in patients with CIEDs and other cardiovascular devices and establishes practical recommendations to enable all device recipients to safely access this diagnostic modality. Appendix 1 and appendix 2 respectively show the affiliations of each author and each reviewer by the scientific bodies behind the present document.

DEFINITIONS

The MR technique enables image capture due to the interaction between magnetic fields and the hydrogen nuclei of different tissues. Image generation involves application of 3 types of magnetic fields that have different effects on the human body and surrounding objects and influence the safety of the scans.[4,5]

1. *The static magnetic field (B0)*. This is the magnetic field of the scanner; it is always active and its intensity is measured in teslas (T). The most commonly used systems are 1.5 and 3 T. The interaction of this field with ferromagnetic elements can make objects move, dislodge, or be attracted to the magnet. However, this risk does not typically affect implanted medical devices because they predominantly comprise nonferromagnetic material.
2. *Dynamic gradients causing changes in the magnetic field over time (dB/dt)*. This concerns gradients that are rapidly activated and inactivated during MR studies. These gradients can induce electrical currents in specific devices in the form of heating, vibration, neuromuscular stimulation, and acoustic noise.
3. *Radiofrequency (RF) magnetic fields (B1)*. These fields are predominantly produced in scans of the thoracic area, the location of the antenna emitting the RF. Part of the energy applied is absorbed by the body (measured by the specific absorption rate in W/kg) and converted into heat, its main biological effect. The specific absorption rate increases with the magnetic field and depends on the sequence used. RF magnetic fields show risk of electromagnetic interference with CIEDs.

Depending on the safety profile of the patient undergoing the MR scan, cardiovascular devices are classified as follows:

1. *MR-compatible device*. Such devices can always safely undergo MR.
2. *MR-conditional device*. These devices are safe in an MR environment if a series of considerations are taken into account.

In the case of CIEDs, the devices have hardware (minimization of ferromagnetic material and modification of leads) and software modifications that permit the safe performance of an MR study under certain conditions.[6]

3. *Non–MR-conditional device*. These devices, due to their design or functioning, cannot be ensured to have optimal safety conditions for the performance of MR studies. CIEDs, for example, can undergo MR with a low incidence of complications, as long as certain precautions are taken with device programming, patient monitoring, and MR characteristics.[7,8]

It must be remembered that, for the determination of the compatibility of a device or set of devices (system), all of the components must be MR compatible or conditional. In the case of CIEDs, both the components (generator and lead) and their combination (ideally the same brand and combination validated for the MR setting) must be compatible and, if required, the conditions of the magnetic field and specific absorption rate must be met, which depend on each model.[9]

Although MR studies can be safely conducted in patients with compatible or conditional devices, their presence can affect image quality and, thus, test yield. This will depend on the type of the device, its location, the anatomical area being scanned, and the type of sequence used. This factor must be taken into account in the prior evaluation of patients when an MR study is being planned.

INTERACTION BETWEEN MR AND CARDIOVASCULAR DEVICES. SAFETY

Influence of devices on the MR image (artifacts)

MR artifacts are relatively frequent. They are defined as any signal increase or loss that has no anatomical basis or is the consequence of information distortion, addition, or loss, generally that related to the presence of metallic or ferromagnetic material. Although some artifacts are obvious and easily recognizable, others are much more subtle and can lead to interpretation and diagnostic errors.

In general, there are 2 types of artifacts induced by ferromagnetic material:

1. *Magnetic susceptibility artifacts*. These artifacts are the main cause of the appearance of artifacts and are due to a lack of local homogeneity in the field produced by the presence of ferromagnetic material within the magnet.
2. *Foucault current artifacts* (also called Eddy current artifacts). These artifacts occur because the RF pulse gradients induce electrical currents in the surrounding metallic material, create undesired intermittent magnetic fields that undermine the homogeneity of the field, and distort the image.

In general, artifacts appear as bands of increased or decreased intensity of the signal surrounding the metallic parts. Given that they deteriorate the resonance image, they must be recognized, because they can be confused with a pathological image.[10] The magnitude of the artifacts will depend on both the intrinsic characteristics of the device (metallic composition, size, and orientation with respect to the direction of the magnetic field) and its distance from the anatomical region being studied (infrequent in studies outside the thoracic area), the sequence used, and the intensity of the magnetic field.

Influence of MR on devices

In general terms, the cardiovascular devices with the greatest influence/interference in MR studies are circulatory assist and monitoring devices (left ventricular assist device, extracorporeal membrane oxygenation systems, and continuous cardiac output catheters) and CIEDs (pacemakers, implantable cardioverter-defibrillators [ICDs], cardiac resynchronization therapy devices, and abandoned leads). The former represent an absolute contraindication. In the case of CIEDs, complications are rare but potentially severe.[2,11] Due to their higher frequency in the clinical context, table 1 details the potential effects of the MR environment on CIEDs.

Safety of the different cardiovascular devices with 1.5- and 3-T MR

Cardiac implantable electronic devices

In recent years, numerous studies have shown that cardiothoracic and noncardiothoracic MR scans are safe in patients with a CIED as long as a series of measures are taken.[2,11]

The studies are largely homogeneous in their design (description of the possible adverse effects, device programming, sequences used) and outcomes and concordant and found no clinically significant complications when the studies were performed in 1.5- and 3-T systems according to the defined safety guidelines.[14,15] Table 2 shows a summary of the main studies in this field.

Epicardial and abandoned leads have a higher risk of heating during MR scans. The available evidence in this field is very slight (and nonexistent in the case of epicardial leads) and MR is thus not recommended in these patients and can only be conducted in patients in a severe clinical situation without an alternative diagnostic approach. Nonetheless, a recent publication, with 139 patients and 243 abandoned leads, supported the safety of MR in this clinical situation.[8] However, in the case of temporary pacemakers, the characteristics of the generator and lead show a higher risk of complications, which is why they should not be subjected to this type of scan under any circumstance, even though no pertinent clinical evidence is available.[12]

Regarding leadless pacing devices, although less experience has been accumulated, the initial work has failed to identify a higher rate of complications and they seem safe at both 1.5 and 3 T. Subcutaneous ICDs do not require a distinct approach from that of conventional ICDs, and it must be verified, based on the model and year of manufacture, if they are MR conditional or not.[12]

Loop recorders are considered safe and do not show any contraindication to scans.[27]

Other cardiovascular devices

In the last few years, the numbers and types of cardiovascular and vascular devices that are implanted for the treatment of different conditions have grown exponentially. Although most are safe or conditional in the MR environment, their specific compatibility should be checked. Table 3 lists the most commonly used devices. To summarize, the following can be considered safe, with respect to certain acquisition parameters: coronary and vascular stents, vascular tubes and surgical patches, surgical valvular prostheses (biological and mechanical), transcatheter

Table 1
Potential effects of the magnetic resonance environment on cardiac implantable electronic devices.

Effects of MR on CIEDs	Explanation
Heating and lesion of the surrounding tissue	Leads can act as antennas for electromagnetic energy and generate currents within the system that increase the temperature of the surrounding tissue, which can damage the local myocardium, elevate the capture threshold, reduce the amplitude of the sensed wave, and, theoretically, increase the threshold for ICD defibrillation In in vitro studies, the temperature increase is greater for damaged leads, abandoned leads (when there is no connection to a generator acting as a heatsink), and/or epicardial leads (given the absence of convection cooling because it is a space without blood flow). The situation is potentially worse for abandoned epicardial leads
Displacement	The magnetic field can displace the ferromagnetic material of the generator, but this is exceptionally rare. MR-compatible devices reduce this risk due to their lower quantity of ferromagnetic material Most manufacturers advise waiting 6 months after implantation (due to scarring-related "fixation" of the lead), although one series of patients underwent MR in the first few postimplantation days without complications, which is why MR could be early if clinically necessary[12]
Asynchronous pacing	RF pulses of MR can pass through the lead and stimulate the tissue and induce atrial and/or ventricular arrhythmias
Oversensing	RF pulses can generate "noise" (oversensing) that inhibits the pacemaker impulse (risk of asystole in dependent patients) or triggers inappropriate antitachycardia ICD shocks (risk of inappropriate therapies)
Magnetically activated reed switch	When the device comes close to a magnet, the device normally paces in asynchronous mode and the antitachycardia therapies of the ICD are inhibited. This behavior is modified in compatible CIEDs when the compatibility mode is activated
Electrical reset	The electromagnetic interference generated by MR triggers an electrical reset of the CIED to a manufacturer- and model-specific programming. It generally activates VVI mode (risk of asystole in dependent patients) and antitachycardia therapies can be activated, depending on the nominal diagnostic and therapeutic parameters, typically in a single region of ventricular fibrillation with high-energy discharges (risk of inappropriate therapies)
Abnormal battery drainage	Rarely, battery exhaustion can occur; this is more frequent in CIEDs that are nearing the end-of-life replacement of the generator (low battery levels).[13] It is a major complication that leads to CIED generator replacement

CIED, cardiac implantable electronic device; ICD, implantable cardioverter-defibrillator; MR, magnetic resonance; RF, radiofrequency.

prostheses and devices (septal occluders, appendage closure devices, and valve replacement and repair), and loop recorders.

PROPOSED MR-RELATED WORKFLOW FOR PATIENTS WITH DEVICES

The workflow to consider for patients with cardiovascular devices who are undergoing an MR study will depend on the type of implanted device (figure 1).

Nonelectronic implantable devices

This group includes coronary, vascular, and valvular devices. The recommendations can be seen in table 3.

Cardiac implantable electronic devices

The workflow for the performance of an MR study in patients with implanted CIEDs depends on 3 criteria: *a)* the condition of the implanted system, including all of its functioning or dysfunctioning annexes; *b)* the safety conditions of the patients themselves, largely defined by whether they are pacing dependent or not and by the risk of ventricular arrhythmias; and *c)* the need for an MR study regarding the patients' clinical condition and the possible existence of alternative diagnostic techniques.

Regardless, prior interrogation of the device is required to assess patients' pacing dependency and the antibradycardia and antitachycardia programming settings, as well as their subsequent interrogation to confirm their correct functioning and to make the corresponding reprogramming. Figure 1 shows the practical action algorithm in the different contexts.

MR-conditional pacing devices

The MR compatibility conditions of CIEDs are defined by the manufacturers, which have subjected the complete system to a validation test. However, these tests have been performed using a combination of the different system parts (leads and generator) from the same manufacturer. As specified in the data sheet, the compatibility conditions are only guaranteed under these circumstances; currently and in line with legal requirements, the manufacturers do not guarantee compatibility when materials from different manufacturers are combined, although the relevant literature has shown that this does not increase the risk of complications. Another factor to take into account is the presence of abandoned, dysfunctional, or epicardial material. Under these conditions, no manufacturer guarantees that their systems are MR compatible.

In addition, patients' pacing dependency is established before the absence of intrinsic or escape rhythms to ensure adequate cardiac output after the cessation of pacing. As a general rule, the European Society of Cardiology (ESC) establishes a threshold of 50 bpm to define patient dependency.[9]

Qualified staff must assess and revise all patients and their respective systems before the MR scan and after study completion and both actions must be recorded.[9] Given that the safety conditions are considered optimal under these circumstances, there is a greater degree of flexibility in the recommended programming modes and the recommended times for the interrogations.

Before the MR, assessment is required of patients (ensuring that they do not have abandoned, epicardial, or dysfunctional leads or extra connectors/adaptors between the lead and generator), as

Table 2
Main multicenter clinical trials and meta-analyses evaluating the safety of magnetic resonance studies in patients with different cardiac implantable electronic devices.

Study type	Device type	Field/MR type/ anatomical region	Patients	MR complications	Change in device parameters	Reference
Multicenter studies	Conditional device (9-12 wk after implantation)	1.5 T SAR ≤ 2 W/kg Brain/lumbar	464	None	Minimal	Wilkoff et al.,[16] 2011
	Conditional device (9-12 wk after implantation)	1.5 T SAR ≤ 2 W/kg Any	263	None	—	Gimbel et al.,[17] 2013
	Conditional ICD	1.5 T SAR ≤ 2 W/kg Chest, cervical, head	275	None	Minimal	Gold et al.,[18] 2015
	Conditional device	1.5 T SAR ≤ 2 W/kg Cardiac and thoracic spine	245	1 adverse effect	Without changes in pacing and sensing thresholds	Bailey et al.,[19] 2016
	Conditional device	1.5 T SAR ≤ 2 W/kg Head and lower lumbar	226	None	Minimal	Bailey et al.,[20] 2015
	Conditional ICD	1.5 T SAR ≤ 2 W/kg Thoracic spine and cardiac	170	None	None	Awad et al.,[21] 2015
	Conditional device	1.5 T SAR ≤ 2 W/kg Thoracic and head	266	None	Minimal in the pacing capture threshold None in sensing	Shenthar et al.,[22] 2015
	Conditional device	1.5 T SAR ≤ 2 W/kg Slew rate ≤ 200 T/m/s Any anatomical region	526	2 paroxysmal AFs 2 heating events 1 capture failure 1 threshold increase	4 patients (0.76%) with threshold > 0.5 V and threshold increases	Williamson et al.,[23] 2017
	Nonconditional devices (excluding dependent patients with an ICD)	1.5 T Nonthoracic MR	1500	5 AFs and 1 atrial flutter 6 partial electrical resets	Slightly increased pacing threshold Slightly decreased sensitivity	Russo et al.,[24] 2017
	Leadless pacemakers	1.5 T/3 T	14	None	Micra (Medtronic, United States), none	Blessberger et al.,[25] 2019
Meta-analyses	Nonconditional devices	1.5, 2/3 T Any	5099	3 lead failures 94 resets (none after 2006) 11 inappropriate shocks 17 symptoms	Without clinically significant changes	Shah et al.,[26] 2018
	Nonconditional devices	1.5/3 T Any	5625	1 lead failure 2 generator failures 75 on-off resets 6 inappropriate shocks 19 symptoms	> 0.5 V increase in the pacing threshold and changes > 50 Ω in the impedance (1.1% and 4.8%). Significant changes in P and R waves (1.5% and 0.4%)	Glikson et al.,[7] 2020

AF, atrial fibrillation; ICD, implantable cardioverter-defibrillator; MR, magnetic resonance; SAR, specific absorption rate.

well as interrogation of the device and selection of the MR compatibility mode, if this is one of the programming options of the device being evaluated. Good communication is essential between the MR staff and cardiology to ensure that the system is compatible and that the patient has been correctly evaluated and prepared for the diagnostic examination.

As a general rule, for patients with an intrinsic rhythm, DDI/VVI mode reprogramming is recommended because it allows the patients' pacing device to function as normal during the scan.[9] In addition, this approach permits a longer window for the reprogramming of the device after the MR, with reprogramming recommended within 48 hours after the study. As a disadvantage, these programming modes continue to be sensitive to interference from external noise and could trigger the activation of noise reversion algorithms, which give rise to asynchronous autoprogramming modes independent of the baseline heart rate. A possible alternative is reprogramming in ODO/OVO/OAO/OOO modes.[9] However, under these conditions, the pacing functionality of the device is lost, which is why reprogramming has to be performed immediately after the MR study.

In the case of pacing-dependent patients with MR-conditional devices without ICD function, an immediate postprocedural revision is not considered necessary but a revision should nonetheless be performed in the first 24 hours. The recommended

Table 3
Main types of devices without pacing currently used in cardiology and cardiac surgery: magnetic resonance compatibility and safety in 1.5- and 3-T systems.

Device group	Device type	Performance of MR study		Observations	Reference
		1.5 T	3 T		
Vascular and coronary	Coronary stent	Safe	Safe	There are numerous studies in acute myocardial infarction (from 1 h to 7 d after PCI) without reported complications	Shellock et al.[4] Symons et al.,[5] 2019 Levine et al.,[28] 2007 Jehl et al.,[29] 2009 Patel et al.,[30] 2006 Karamitsos et al.,[31] 2017 Kaya et al.,[32] 2009 Curtis et al.,[33] 2013
	Vascular tubes	Safe	Safe	-	Symons et al.,[5] 2019 Jehl et al.,[29] 2009 Karamitsos et al.,[31] 2017 Curtis et al.,[34] 2006
	Aortic endoprostheses	Conditional (follow manufacturer instructions)	Conditional (follow manufacturer instructions)	MSG: 720 Gauss/cm SAR: 3 W/kg for every 15 min study time	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Jehl et al.,[29] 2009 Dill et al.,[35] 2008
	Bare aortic stents	Conditional (follow manufacturer instructions)	Conditional (follow manufacturer instructions)	MSG: 720 Gauss/cm SAR: 2 W/kg for every 15 min study time	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Jehl et al.,[29] 2009 Dill et al.,[35] 2008 Grzyska et al.,[36] 2021
Surgical valve	Biological prosthetic valves	Safe	Conditional (follow manufacturer instructions)	-	Shellock et al.[4] Symons et al.,[5] 2019 Dill et al.,[35] 2008 Myers et al.,[37] 2012 Baikoussis et al.,[38] 2011
	Mechanical prosthetic valves	Safe	Conditional (follow manufacturer instructions)	-	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Dill et al.,[35] 2008 Myers et al.,[37] 2012
	Mechanical valve conduits	Safe	Conditional (follow manufacturer instructions)	-	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Karamitsos et al.,[31] 2017 Dill et al.,[35] 2008 Myers et al.,[37] 2012 Baikoussis et al.,[38] 2011
	Biological valve conduits	Safe	Conditional (follow manufacturer instructions)	-	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Karamitsos et al.,[31] 2017 Dill et al.,[35] 2008 Myers et al.,[37] 2012 Baikoussis et al.,[38] 2011
	Homografts/ xenografts	Safe	Safe	—	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Karamitsos et al.,[31] 2017 Dill et al.,[35] 2008 Myers et al.,[37] 2012 Baikoussis et al.,[38] 2011
	Surgical annuloplasty	Safe	Safe	Some models specify indications for immediate postimplantation scanning	Shellock et al.[4] Symons et al.,[5] 2019 Myers et al.,[37] 2012
Percutaneous valve	Transcatheter prosthetic valve	Safe	Safe	TAVI (CoreValve, Medtronic, United States; SAPIEN, Edwards Lifesciences, United States): considered safe in 1.5- and 3.0-T systems. Immediate scanning is possible after placement according to guidelines (MSG, 720 Gauss/cm; SAR, 2 W/kg for every 15 min study time). Applicable for TAVI in other valve positions (pulmonary, mitral, or tricuspid)	Shellock et al.[4] Shellock et al.,[39] 2001 Saeedi et al.,[40] 2015 Hartlage et al.,[41] 2016

Table 3 *(Continued)*
Main types of devices without pacing currently used in cardiology and cardiac surgery: magnetic resonance compatibility and safety in 1.5- and 3-T systems.

Device group	Device type	Performance of MR study		Observations	Reference
		1.5 T	3 T		
		Safe	Safe	TMVR (Tendyne, Abbott, United States)	Lin et al.,[42] 2018
	Transcatheter valve repair	Safe	Safe	Edge-to-edge repair (MitraClip, Abbott, United States)	Shellock et al.[4] Lurz et al.,[43] 2011
		Conditional (follow manufacturer instructions)	Conditional (follow manufacturer instructions)	Direct annuloplasty (Cardioband, Edwards Lifesciences, United States): scanning is possible immediately after placement in line with indications (MSG, 720 Gauss/cm; SAR, 2 W/kg for every 15 min study time)	Shellock et al.[4] Symons et al.,[5] 2019
Nonvalvular percutaneous	Septal occluders (PFO, ASD, VSD)	Conditional (unknown if loss of integrity is suspected)	Conditional (unknown if loss of integrity is suspected)	A window of 6 postimplantation wk can be considered. Not recommended if loss of system integrity is suspected	Shellock et al.[4] Myers et al.,[37] 2012 Shellock et al.,[44] 2005
	Atrial appendage closure	Conditional (unknown if loss of integrity is suspected)	Conditional (unknown if loss of integrity is suspected)	A window of 6 postimplantation wk can be considered. Not recommended if loss of system integrity is suspected	Shellock et al.[4] Myers et al.,[37] 2012 Mohrs et al.,[45] 2011
	Other closures (PVL, PDA)	Conditional (unknown if loss of integrity is suspected)	Conditional (unknown if loss of integrity is suspected)	A window of 6 postimplantation wk can be considered. Not recommended if loss of system integrity is suspected	Shellock et al.[4] Symons et al.,[5] 2019 Myers et al.,[37] 2012
Monitoring and circulatory assist	Ventricular assistance (IABP, ECMO, LV/RVAD)	Not Safe	Not Safe	—	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Dill et al.,[35] 2008 Baikoussis et al.,[38] 2011 Lee et al.,[46] 2014
	Swan-Ganz catheter	Not Safe	Not Safe	Can be performed if the catheter does not have thermodilution systems or pacing leads	Shellock et al.[4] Symons et al.,[5] 2019 Dill et al.,[35] 2008
	Continuous output catheter	Not Safe	Not Safe		Symons et al.,[5] 2019 Levine et al.,[28] 2007 Dill et al.,[35] 2008
	Continuous monitoring of pulmonary pressure	Follow manufacturer instructions	Follow manufacturer instructions	CardioMEMS, Abbott, United States: scanning can be performed according to indications (MSG, 720 Gauss/cm; SAR, 2 W/kg for every 15 min study time)	Shellock et al.[4] Symons et al.,[5] 2019
Others	Event recorders	Follow manufacturer instructions	Follow manufacturer instructions	MSG: 720 Gauss/cm	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Baikoussis et al.,[38] 2011
	Surgical patches	Safe	Safe	-	Symons et al.,[5] 2019 Levine et al.,[28] 2007 Dill et al.,[35] 2008 Myers et al.,[37] 2012
	Metallic sternal sutures	Safe	Safe	-	Shellock et al.[4] Symons et al.,[5] 2019

ASD, atrial septal defect; ECMO, extracorporeal membrane oxygenator; IABP, intra-aortic balloon pump; LV/RVAD, left ventricular/right ventricular assist device; MSG, maximum spatial gradient; PCI, percutaneous coronary intervention; PDA, patent ductus arteriosus; PFO, patent foramen ovale; PVL, paravalvular leak; SAR, specific absorption rate; TAVI, transcatheter aortic valve implantation; TMVR, transcatheter mitral valve repair; VSD, ventricular septal defect.

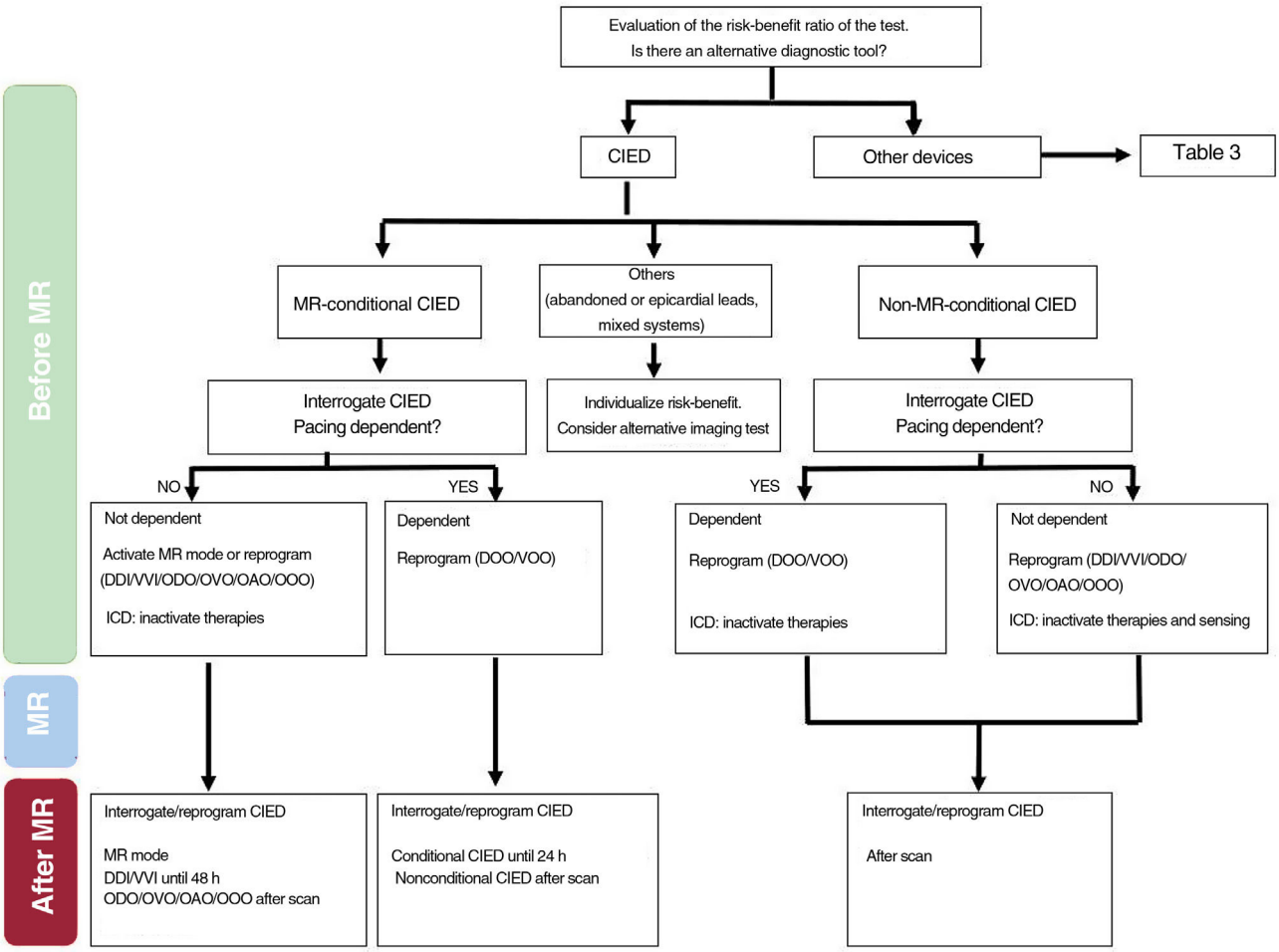


Figure 1. Central figure. Workflow algorithm for MR studies in different clinical situations. CIED, cardiac implantable electronic device; ICD, implantable cardioverter-defibrillator; MR, magnetic resonance.

pacing mode under these conditions is DOO/VOO, with a pacing heart rate 20 bpm higher than the intrinsic heart rate, if there is one, or adapted to the hemodynamic needs of the patient if there is no intrinsic rhythm.[9]

Other programming-related aspects of devices in these circumstances are shown in table 4, in terms of pacing output, sensing parameters, and the additional functions of devices, among others.

For patients with an MR-conditional ICD, activation of the MR safety mode inactivates ventricular antitachycardia therapies. This situation makes the patient vulnerable to ventricular arrhythmias that could occur before and during the MR study.[2]

Non–MR-conditional pacing devices or abandoned leads

This section includes patients with abandoned leads, non–MR-conditional systems (lead and/or generator), epicardial leads, or connectors between the lead and generator.

Studies have shown that, when necessary, MR can be safely performed in such patients with few adverse effects. Both the patient and the physician ordering the MR must be fully cognizant of the type of device and the absence of MR compatibility, the potential risks for the patient, and the possible subsequent dysfunction of the device. Accordingly, the risk-benefit balance must be assessed to determine if the MR scan is required or if it can be replaced by another imaging test.

If, after all of the information is obtained, the MR is considered essential and must be performed, non–MR-conditional pacing devices must be assessed before and immediately after the MR study to ensure their correct functioning. The programming of these devices is summarized in table 4.

Devices with ICD function must also be evaluated and revised before and immediately after the MR study, in this case to reprogram and activate the sensing and antitachycardia therapy functions.[2] For ICDs, all antitachycardia therapies must be deactivated, which leaves the patient in a state of vulnerability to ventricular arrhythmias that could occur before and during the MR study.[2]

In addition, the particular conditions of this group of patients and devices make them vulnerable, which leads to the need for stricter monitoring guidelines and vigilance during MR studies. The general recommendations in this regard, in line with the more recent recommendations of the ESC, are shown in table 4. Regarding the longer-term follow-up, the ESC recommends assessment of system integrity within 1 week. Although there

Table 4
Practical recommendations on the different aspects of safety in patients with cardiac implantable electronic devices undergoing magnetic resonance studies.

Condition	Recommendation	Comment
Interrogation before MR	In all cases	Independently of the system condition and in order to perform a prior check of its status
MR mode available	Its activation is recommended	Parameter adjustment in line with the particular needs of each patient
Pacing mode	DOO/VOO	Dependent patients
	DDI/VVI	Patients with intrinsic rhythm (not dependent)
	ODO/OVO/OAO/OOO	Nondependent patients as alternative to the previous mode
Pacing parameters	Bipolar pacing/5 V amplitude/1 ms impulse width	As a general rule in all devices
Sensing parameters	Bipolar sensing	As a general rule in all devices
Additional pacing functions	Deactivated	Response to heart rate drop, optimization functions for resynchronization (eg, response to conducted atrial fibrillation, shocks due to extrasystole detection), atrial antitachycardia therapy, etc
Antitachycardia ICD functions	Deactivated	Deactivate sensing and ventricular tachycardia/ventricular fibrillation therapies
Accompanying and monitoring patient during the MR	ECG monitoring/pulse oximetry	In all cases
	Availability of system for advanced resuscitation	In all cases
	Health care staff in room able to provide immediate assistance and vital support	In all cases
	Qualified staff in room able to perform immediate device programming	In the case of non–MR-conditional systems and dependent patients
	Qualified staff in the hospital environment able to perform immediate device programming	In the case of non–MR-conditional systems and nondependent patients In line with center policy in the case of MR-conditional systems
Reprogramming after MR	Immediate	Non–MR-conditional systems: systems programmed to ODO/OVO/OAO/OOO mode; ICD systems
	Within 24 h	Dependent patients with MR-conditional pacing systems and DOO/VOO pacing mode
	Within the first 48 h	Dependent patients with MR-conditional pacing systems and DDI/VVI pacing mode
Follow-up	At the end of 1 wk. Evaluate the possible use of remote monitoring	General interrogation of system status

ICD, implantable cardioverter-defibrillator; MR, magnetic resonance.

are no literature data supporting the use of remote monitoring for this purpose, it is the opinion of this committee that it represents a clear alternative to an in-person revision.

Risk-benefit balance

The risk-benefit balance must be assessed in all patients with a clinical indication for MR who have a cardiovascular device. As mentioned, the factors to be considered include the type of device, its compatibility with MR, the patient's pacing dependence, and the clinical need for the MR study, as well as if diagnosis can be reached using an alternative imaging technique.

With the due precautions, the presence of these devices should not be a limitation for MR with an established or urgent clinical indication. In this regard, the MagnaSafe study showed that nonthoracic MR studies with 1.5-T systems are safe in non–MR-conditional ICD or pacemaker recipients if the devices have been appropriately programmed before the scan.[24]

In general terms, there is more evidence on the compatibility of devices in 1.5-T systems than in MR systems with a stronger magnetic field. Accordingly, and if their use does not result in a study of insufficient diagnostic quality, 1.5-T systems would be preferable.

IMPROVEMENT AND OPTIMIZATION OF THE CARDIOTHORACIC MR IMAGING OF PATIENTS WITH DEVICES

In an MR study, the type of device and its location constitute the main determinants of image quality. In cardiothoracic MR, ICDs and cardiac resynchronization therapy usually produce more artifacts due to their larger size and inclusion of ferromagnetic elements and can show image distortion up to 12 cm from the generator (figure 2). For this reason, devices implanted on the left side create more artifacts than right-sided devices,[47] which generally do not affect cardiac imaging.[48]

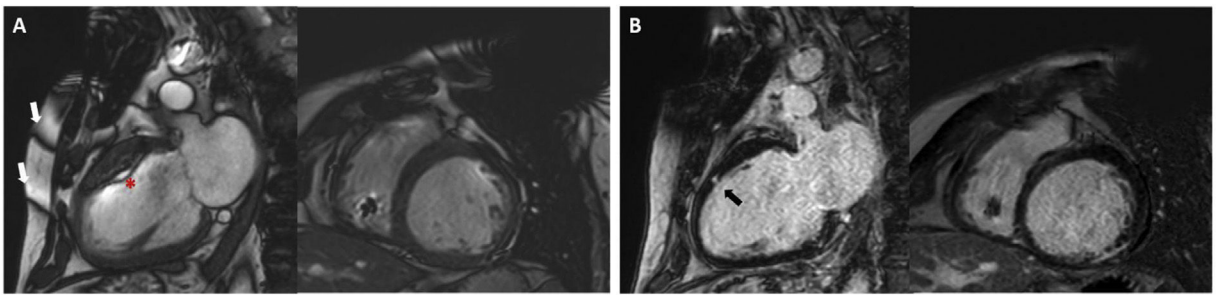


Figure 2. Images obtained with a 1.5-T MR scanner in a patient with a pacemaker. A: in a cine SSFP (steady-state free precession) sequence, artifacts are visible in the thoracic wall (white arrows) that affect the anterior region (asterisk) in the 2-chamber image; however, image measurement in the short-axis is possible. B: in late gadolinium enhancement images (IR SGE [inversion-recovery spoiled gradient echo]), the artifact is less marked and an area of late gadolinium enhancement (black arrow) can be correctly assessed in both geometries.

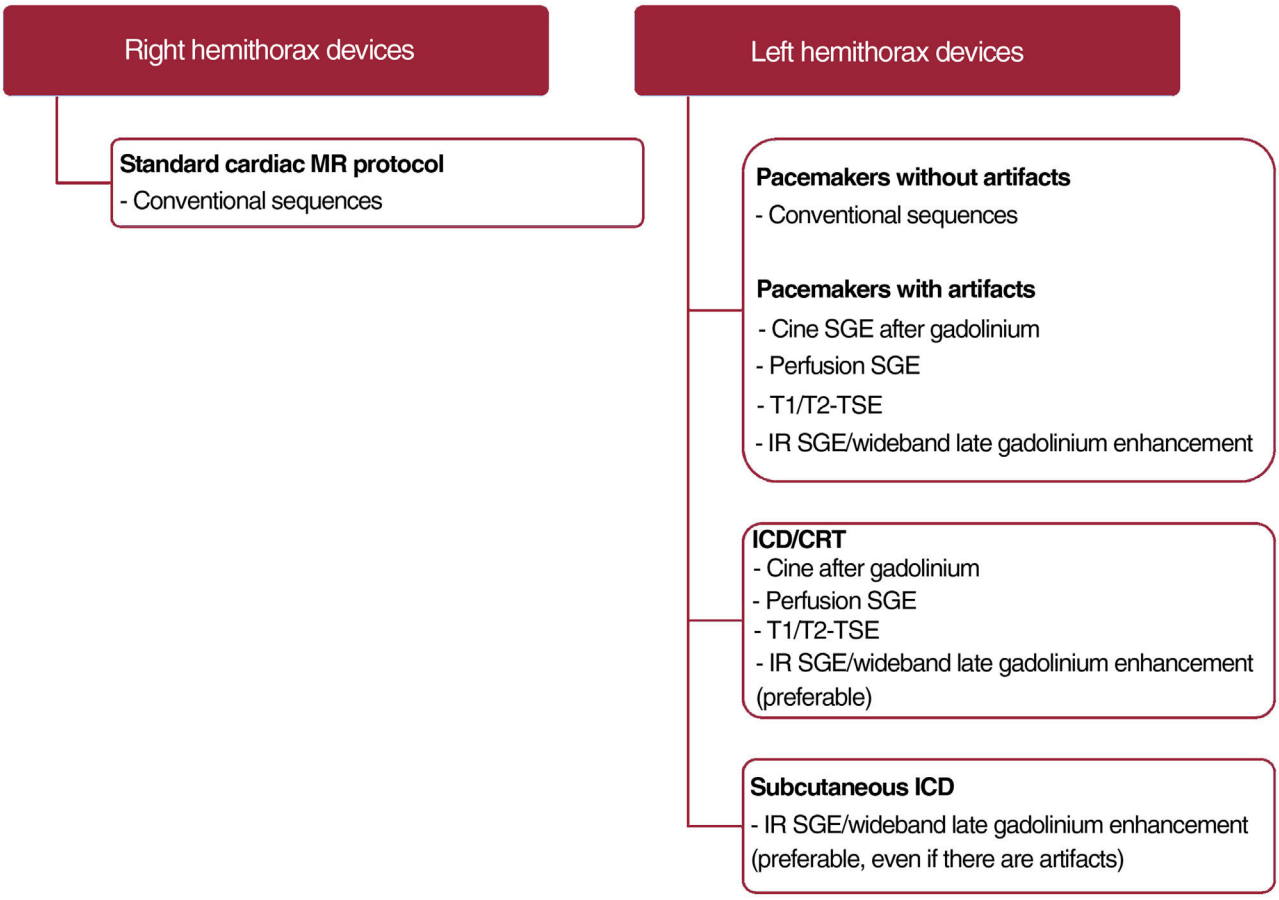


Figure 3. Practical image optimization algorithm for patients with cardiac implantable electronic devices undergoing cardiothoracic MR studies. CRT, cardiac resynchronization therapy; ICD, implantable cardioverter-defibrillator; IR SGE/wideband late gadolinium enhancement, inversion-recovery spoiled gradient echo late gadolinium enhancement; MR, magnetic resonance; SGE, spoiled echo gradient; TSE, turbo spin-echo.

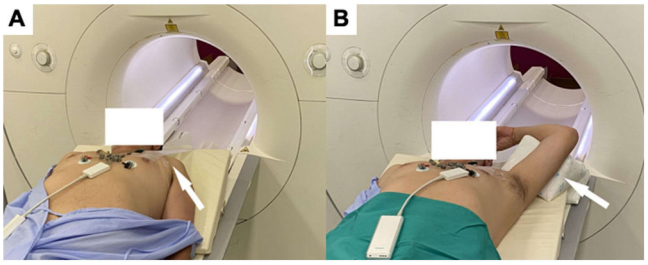


Figure 4. Preparation of a patient with an automatic implantable device in the left hemithorax for cardiothoracic MR. Increased distance between the generator and the scanning area through placement of an adhesive band (A) or with the arm ipsilateral to the device raised above the head (B).

The cardiac MR scanning protocol must be aimed at answering the clinical question, must be limited to essential sequences, and must be as short as possible (figure 3).

In general, to reduce artifacts secondary to CIEDs, attempts should be made to increase the distance between the device and the scanning area. Some of the useful maneuvers are to place the arm ipsilateral to the generator above the head or to acquire the image with deep inspiration (figure 4).

Regarding the selection of protocols and scanning sequences, the recent use must be highlighted of wideband late gadolinium enhancement to minimize the artifacts associated with CIEDs, although these sequences are still not clinically available in many centers. Table 5, figure 3, and figure 4 gather these and other

Table 5
Recommendations for improving cardiothoracic imaging according to the magnetic resonance sequence used.

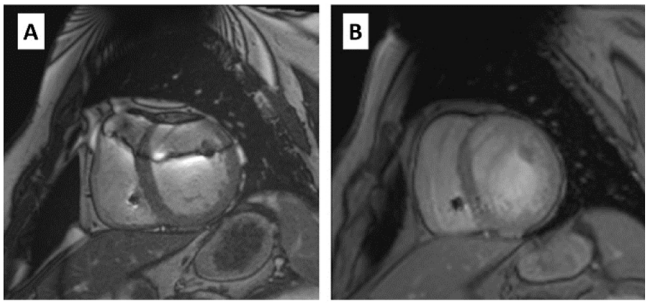
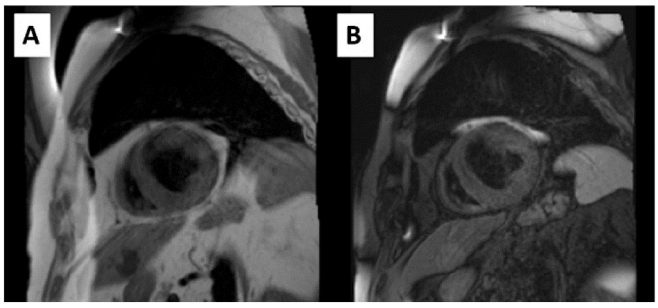
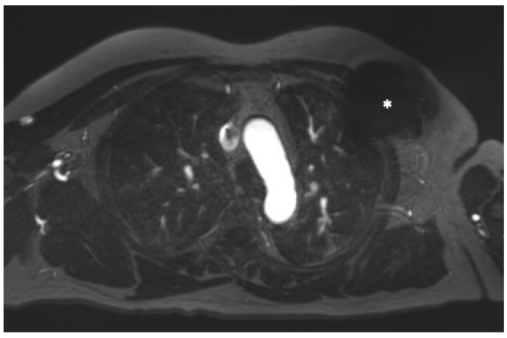
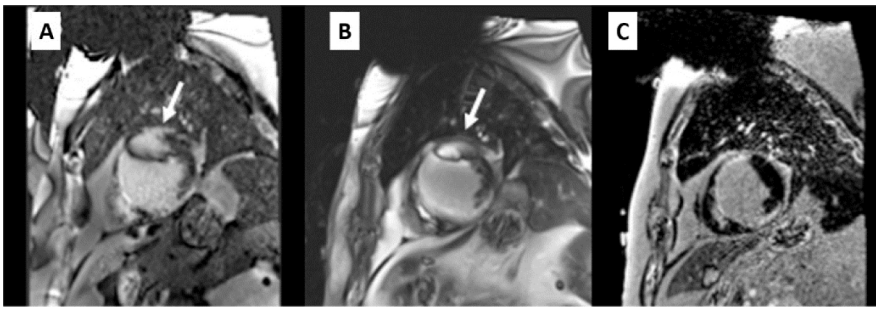
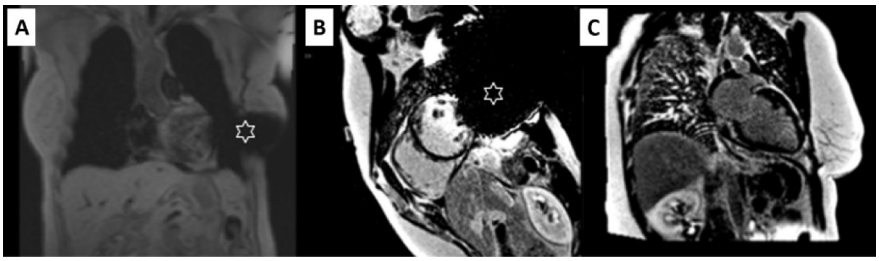
Type of sequence	Recommendations and specific adjustments	Example images
Cine	If there is a major artifact in SSFP images, an SGE sequence might improve the image. Try to use CS and reduce the TE[49,50] Acquisition of postcontrast cine permits a better detection of ventricular endocardium[51] If cine SSFP sequences are used, evaluate: *a)* the use of frequency scouting to identify where the artifacts are less impactful; *b)* increase the bandwidth and slightly decrease the resolution to reduce the TR as much as possible[50]	 Left ICD. a: cine SSFP with a large resonance banding artifact. B: cine SGE in the same scan position
T_1 and T_2 tissue characterization	In general, dark-blood T_1- and T_2-weighted TSE images are less sensitive to the artifacts produced by these devices, and good image quality is obtained[48]	 Left ICD. A: T1W-TSE short-axis without artifact. B: T2W-TSE short-axis without artifact. 1.5-T system
Perfusion and 3D angiography	SGE perfusion sequences show fewer artifacts than SSFP sequences[51] 3D angiography: artifact-free sequences. They permit good visualization of the major vessels and their secondary branches[48,51]	 3D angiography: T_1-weighted axial imaging with few artifacts except in the region closest to the generator

Table 5 *(Continued)*
Recommendations for improving cardiothoracic imaging according to the magnetic resonance sequence used.

Type of sequence	Recommendations and specific adjustments	Example images
Late gadolinium enhancement	Rapid acquisition (single-shot) SSFP sequences (useful for irregular rhythm or impossibility of prolonged apnea) are more prone to artifacts, which is why they would not be recommended IR SGE sequences can cause hyperintense or zero fill artifacts. If available, the bandwidth should be widened using IR-WB, which enables a reduction or displacement of the artifact outside the scan area[52] Before IR-WB, a scan is recommended before contrast agent administration of the 4- and 2-chamber geometries with 3 different frequencies (−1500, 0, and +1500 Hz) in order to determine the frequency at which hyperintense artifacts are less likely. This optimum frequency will be applied to the subsequent IR-WB acquisition[53] The optimal frequency change depends on patient factors, such as laterality and device type. In patients implanted on the right side, artifacts are minimal in both standard and WB images. In patients with left-sided implants, artifacts can be minimized with a WB sequence for pacemakers and ICDs. However, this sequence has lower impact for cardiac resynchronization therapy and subcutaneous devices, more commonly showing a zero fill artifact in the side wall[53]	 Left ICD. A: single-shot SSFP (artifact, arrow) B: IR SGE (artifact, arrow). C: IR-WB 6 KHz without artifacts  Left subcutaneous ICD. A: coronal location, side wall artifact (star). B: IR-WB, with side wall artifact persisting after multiple adjustments. C: 2-chamber IR-WB, single plane without artifact

3D, 3-dimensional; CS, compressed sensing; ICD, implantable cardioverter-defibrillator; IR, inversion-recovery; SGE, spoiled gradient echo; SSFP, steady-state free precession; TE, echo time; TR, repetition time; TSE, turbo spin-echo; WB, wideband.

specific recommendations related to the scanning sequences used in cardiac MR studies.

CONCLUSIONS

MR studies can be performed in patients with a cardiovascular device with the appropriate precautions. The present document reviews the evidence and provides management guidelines to minimize interference of the magnetic field with the electronic device and to reduce the image artifacts generated with cardiovascular devices in the region of the cardiothoracic scan.

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AUTHORS' CONTRIBUTIONS

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CONFLICTS OF INTEREST

None.

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