HANDS ON

# How to perform magnetic resonance imaging on patients with implantable cardiac arrhythmia devices

Saman Nazarian, MD, Henry R. Halperin, MD, MA, FHRS

*From the Division of Cardiology/Cardiac Arrhythmia, Johns Hopkins University, Baltimore, Maryland.*

## Introduction

Magnetic resonance imaging (MRI) offers unrivaled soft tissue resolution and multiplanar imaging capabilities. Cardiac MRI is capable of accurate characterization of cardiac function and is uniquely capable of identifying scar fibrosis and fat deposition, thus making it an ideal imaging modality for the evaluation of patients presenting with arrhythmia. In addition, the absence of x-ray radiation makes MRI suitable for follow-up of chronic disease and for imaging in young patients and women of childbearing age. Due to the ever expanding indications for implantation of permanent pacemakers and implantable cardioverter-defibrillators (ICDs), advancing severity of disease and age of the population, and advances in device technology, the number of patients with implantable cardiac devices will continue to increase. It has been estimated that each patient with a pacemaker or ICD has a 50% to 75% likelihood of having a clinical indication for MRI over the lifetime of their device. When performed with appropriate supervision and following a protocol for safety, many studies over the past 10 years have reported the safety of MRI with selected devices. However, catastrophic complications with older devices have been reported. Familiarity with each device class and its potential for electromagnetic interaction is essential for electrophysiologists whose patients may require MRI.

## Potential for interaction with implanted devices

The static and gradient magnetic fields and radiofrequency energy of MRI are associated with several potential risks involving implanted devices.

*Force and torque.* Ferromagnetic devices in a magnetic field are subject to static and gradient magnetic field–induced force and torque. The potential for movement of an implanted device in the MRI environment depends on the magnetic field strength, the ferromagnetic properties of the device, the implant distance from the magnet bore, and the stability of the implant. In our *in vitro* analysis of modern permanent pacemakers (manufactured after 1996) and ICDs (manufactured after 2000), we found that the maximal force acting upon devices was less than 100 g in a 1.5-T MRI scanner.[1] This amount of force is unlikely to dislodge a chronic device that is anchored to the surrounding tissue. However, this observation led to our adaptation of a 6-week waiting period prior to MRI after device implantation.

*Current induction.* The radiofrequency and pulsed gradient magnetic fields in the MRI environment may induce electrical currents in leads within the field. Lead length (vs radiofrequency wavelength) and conformations such as loops favor improved transition of energy to the implanted device. A study from our laboratory assessed the magnitude of MRI-induced current using a current recorder connected in series to single-chamber permanent pacemakers programmed to subthreshold asynchronous output during unipolar and bipolar pacing. Under conventional implant conditions (without additional lead loops), the magnitude of induced current was less than 0.5 mA. With the addition of five lead loops, current induction at greater than 30 mA was possible and resulted in myocardial capture. Additionally, breaking the return pathway by electrically isolating the pulse generator case from the circuit abolished low-frequency–induced current.[2]

*Heating.* The extent of radiofrequency energy deposition in tissues is described by the specific absorption rate (SAR). Metallic devices and leads can act as an antenna, thus amplifying local radiofrequency energy deposition, which may lead to heating and tissue damage at the device–tissue interface. Fractured leads or lead loop configurations may increase the potential for heating. Epicardial leads that are not cooled by blood flow may also be prone to increased heating. In our *in vivo* analysis of modern permanent pacemakers and ICDs, when performing clinical MRI protocols (SAR $<2.0$ W/kg), temperature changes were limited to 0.5°C.[1] However, it is important to note that due to poor correlation of heating at different SAR of sequences across different scanners, even within the same manufacturer, the

**KEYWORDS** Magnetic resonance imaging; Permanent pacemaker; Implantable cardioverter-defibrillator; Safety (Heart Rhythm 2009;6:138–143)

Dr. Halperin is a scientific advisor for Boston Scientific Inc. The Johns Hopkins University Advisory Committee on Conflict of Interest manages all commercial arrangements. **Address reprint requests and correspondence:** Dr. Saman Nazarian, Department of Medicine, Division of Cardiology, Johns Hopkins Hospital, Carnegie 568, 600 North Wolfe Street Baltimore, Maryland 21287. E-mail address: snazari1@jhmi.edu.

1547-5271/$ -see front matter  doi:10.1016/j.hrthm.2008.10.021

SAR limits from each study should not be directly applied to other MRI systems.

*Inappropriate pacing and shocks or inhibition of therapies.* Pacemakers and ICDs have the potential for receiving electromagnetic interference in the MRI environment, resulting in radiofrequency noise tracking, asynchronous pacing, inhibition of demand pacing, delivery of ICD therapies, programming changes, or loss of function. The static magnetic field of the MRI scanner can alter device function by inducing unexpected reed switch opening or closure.

Such potential risks have led to concerns from device manufacturers and MRI authorities regarding the performance of MRI procedures in cardiac implantable device recipients. However, several studies have assessed techniques to safely perform MRI in recipients of implanted cardiac devices.

## Implantable monitors

Patients with an implantable loop recorder (Reveal, Medtronic, Inc., Minneapolis, MN, USA) can be safely scanned.[3] However, the device may record MRI electromagnetic interference artifacts as arrhythmia. Care should be taken to clear episodes recorded during MRI to prevent future misinterpretation of artifact as clinically significant arrhythmia.

## Temporary pacemakers

The majority of temporary pacemakers (implanted outside of the electrophysiology laboratory) have no-fixation leads that are prone to movement. Furthermore, the leads are longer and potentially more susceptible to induction of lead currents and heating. An *in vitro* study of temporary transvenous pacing leads showed that lead heating exceeding 15°C is common, and temperature rises up to 63.1 °C are possible.[4] Additionally, the electronic platform of external temporary pacemakers is less sophisticated and has less filtering compared with modern permanent pacemakers. Therefore, such devices likely are more susceptible to electromagnetic interference in the MRI environment, and imaging of patients with temporary pacemakers cannot be recommended.

## Permanent pacemakers

Previous studies of clinical MRI in the setting of implanted devices are reviewed in Table 1. At our institution, we began the process of imaging patients with permanent pacemakers by extensive *in vitro* testing. Roguin et al[1] tested *in vitro* and *in vivo* lead heating, device function, torque, and image distortion at 1.5 T. Based on our *in vitro* and *in vivo* analyses, we then developed a protocol that included (1) device selection based on previous testing, (2) device programming to minimize inappropriate activation or inhibition of brady/tachyarrhythmia therapies, and (3) limitation of the specific absorption rate of MRI sequences (<2.0 W/kg).[5] The protocol is discussed in detail below. Using this protocol, we now have safely performed MRI on more than 200 patients with implantable devices. Our initial report of safety included 31 patients with permanent pacemakers, 22% of whom were pacemaker dependent. Pacing mode was changed to an asynchronous mode for pacemaker-dependent patients and to demand mode for other patients. Blood pressure, ECG, oximetry, and symptoms were monitored. In this initial study, we successfully limited the system-estimated whole-body average SAR to 2.0 W/kg in more than 99% of sequences while maintaining the diagnostic capability of MRI. No episodes of inappropriate inhibition or activation of pacing were observed, and there were no significant differences between baseline and immediate or long-term (median 99 days after MRI) sensing amplitudes, lead impedances, or pacing thresholds.[5]

## Implantable cardioverter-defibrillators

During our *in vitro* testing of ICDs, several generators (manufactured before 2000) were damaged by MRI. Therefore, we focused our *in vivo* testing on ICDs manufactured after 2000. Such systems from the three major manufacturers were implanted in 18 dogs. After 4 weeks, 3- to 4-hour MRI scans were performed under worst-case scenario conditions (imaging over the region containing the generator and SAR up to 3.5 W/kg). No device dysfunction occurred. After 8 weeks of follow-up, pacing threshold and intracardiac electrogram amplitude were unchanged, except for one animal with transient (<12 hours) capture failure. Due to this observation, we currently do not perform MRI on pacemaker-dependent ICD patients. ICD leads are generally longer than pacemaker leads and therefore may be at higher risk for heating at the lead tip. Pathologic data of the scanned animals revealed very limited necrosis or fibrosis at the tip of the lead area, which was not different from controls not subjected to MRI.[1]

Based on our prior *in vitro* and *in vivo* testing, the safety protocol now has been used to safely scan more than 75 patients with ICDs. Our initial report of safety included 24 patients with ICDs. No episodes of inappropriate inhibition or activation of pacing were observed, and there were no significant differences between baseline and immediate or long-term sensing amplitudes, lead impedances, or pacing thresholds.[5]

## Retained leads

No systematic studies assessing the potential risks associated with retained permanent pacemaker and ICD leads have been performed. Retained leads are prone to previously described risks of movement, heating, and current induction. Depending on their length and configuration, retained segments may be prone to significant temperature rises than leads that are attached to pulse generators. It has been our practice to exclude patients with retained lead fragments and unused capped leads from MRI. More studies to delineate risks in this patient group are warranted.

**Table 1** Previous studies of clinical MRI in the setting of permanent pacemakers and ICDs

| Source | No. of patients | Device type | Findings |
|---|---|---|---|
| Gimbel et al[7] | 5 (1 pacemaker dependent) | Permanent pacemaker | No device abnormalities were noted after MRI (0.5 T). A 2-second pause was noted on pulse oximetry in the pacemaker-dependent patient whose device (with unipolar leads) was programmed to dual-chamber asynchronous pacing. Patients were otherwise asymptomatic and did not report any feeling of torque or heat. |
| Sommer et al[8] | 44 | Permanent pacemaker | MRI at 0.5 T did not inhibit pacing output or cause pacemaker malfunction. |
| Vahlhaus et al[9] | 32 | Permanent pacemaker | Lead impedance, sensing and stimulation thresholds did not change immediately or 3 months after MRI at 0.5 T. However, diminished battery voltage was noted immediately after MRI with recovery 3 months later. Reed switch temporary deactivation was seen in 12 of 32 patients when positioned in the center of the magnetic field. |
| Martin et al[10] | 54 | Permanent pacemaker | Cardiac, vascular, and general 1.5-T MRI studies were performed. Significant changes were reported in 9.4% of leads; however, only 1.9% required a change in programmed output. |
| Del Ojo et al[11] | 13 | Permanent pacemaker | MRI at 2.0 T was unassociated with pacemaker inhibition, inappropriate rapid pacing, or significant changes in device parameters. |
| Gimbel et al[12] | 7 | ICD | No changes in pacing, sensing, impedance, charge time, or battery status were observed with MRI at 1.5 T. However, one ICD (Medtronic 7227Cx, lumbar spine MRI) experienced a "power on reset." |
| Sommer et al[13] | 82 | Permanent pacemaker | MRI at 1.5 T was unassociated with inhibition of pacemaker output or induction of arrhythmias. However, increased capture threshold was noted post MRI. In 4 of 114 examinations, troponin increased from a normal baseline value to above normal after MRI (one associated with a significant increase in capture threshold). |
| Nazarian et al[5] | 55 | 31 Permanent pacemaker/24 ICD | MRI at 1.5 T was not associated with inappropriate inhibition or activation of pacing. There were no significant differences between baseline and immediate or long-term (median 99 days after MRI) sensing amplitudes, lead impedances, or pacing thresholds. |

ICD = implantable cardioverter-defibrillator; MRI = magnetic resonance imaging.

## Safety protocol for MRI of patients with implanted devices

The safety protocol followed at our institution (Figure 1) is based on selection of device generators previously tested under worst-case scenario (prolonged imaging over the region containing the generator and SAR up to 3.5 W/kg) MRI conditions.[1] To perform MRI on patients with implanted devices, we recommend that device generators prone to electromagnetic interference (generally older devices not on the tested devices list in the protocol, Figure 1) be excluded. Despite the low risk for lead and generator movement, we recommend conservative measures to exclude patients with leads that are more prone to movement. Therefore, we recommend avoiding MRI in patients with less than 6 weeks' time since device implant or patients with no fixation (superior vena cava coil) leads. However, in our

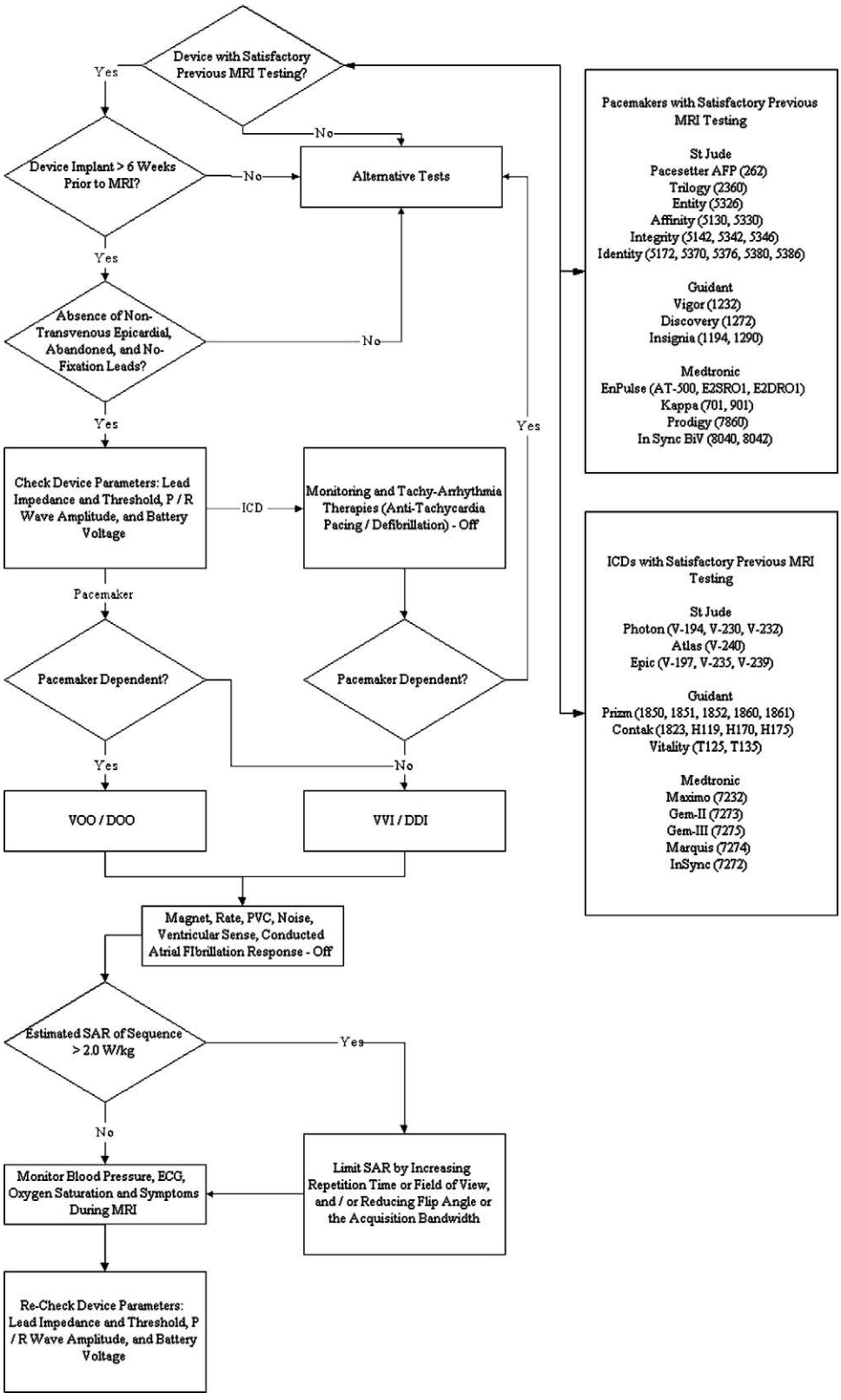


**Figure 1** Safety protocol for imaging of patients with permanent pacemaker and implantable cardioverter-defibrillator (ICD) systems. Devices listed have previously undergone satisfactory *in vitro* phantom and *in vivo* animal testing. ECG = electrocardiography; MRI = magnetic resonance imaging; PVC = premature ventricular complex; SAR = specific absorption rate. (From Nazarian et al.[5])

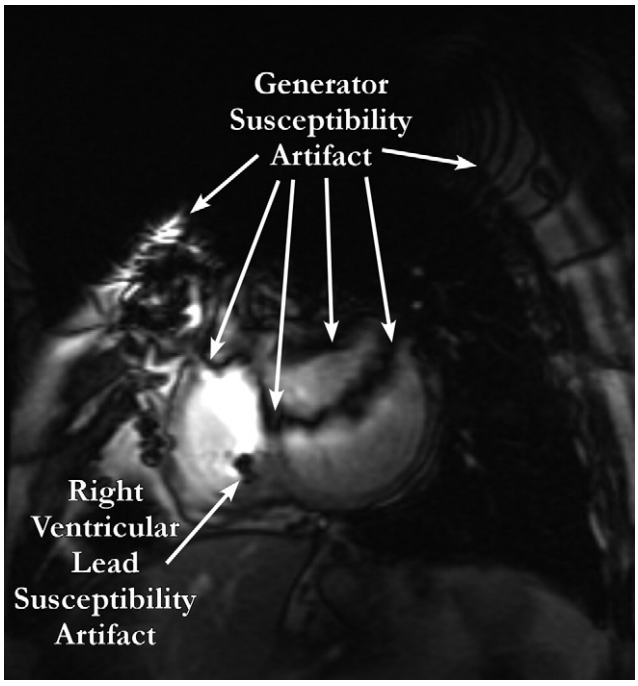


**Figure 2** Extensive susceptibility artifact on a horizontal long-axis steady-state free precession image in a patient with an implantable cardioverter-defibrillator.

experience, patients with mature active and passive fixation endocardial (and coronary sinus) leads of any diameter can safely undergo MRI. We do recommend avoiding MRI when device leads that are prone to heating, such as nontransvenous epicardial and abandoned (capped) leads, are present. To reduce the risk of inappropriate inhibition of pacing due to detection of radiofrequency pulses, we prefer device programming to an asynchronous, dedicated pacing mode in pacemaker-dependent patients. Also, given the lack of asynchronous pacing programming capability and transient loss of pacing capture after worst-case scenario (SAR 3.5 W/kg for 3 hours) *in vivo* testing of 1 of 15 animals implanted with an ICD,[1] we recommend excluding pacemaker-dependent patients with ICDs. To avoid inappropriate activation of pacing due to tracking of radiofrequency pulses, we suggest device programming in patients without pacemaker dependence to a nontracking ventricular or dual-chamber inhibited pacing mode. We also recommend deactivation of rate response, premature ventricular contraction response, ventricular sense response, and conducted atrial fibrillation response to ensure that sensing of vibrations or radiofrequency pulses does not lead to unwarranted pacing. Although asynchronous pacing for short time periods typically is well tolerated, we prefer to reduce the already minimal chance of inducing arrhythmia or causing AV dyssynchrony by minimizing asynchronous pacing in patients without pacemaker dependence through deactivation of the magnet mode when possible. We typically deactivate tachyarrhythmia monitoring to avoid battery drainage that results from recording of multiple radiofrequency pulse sequences as arrhythmic episodes. Reed switch activation in ICD systems disables tachyarrhythmia therapies. However, reed switch function in the periphery versus the bore of the magnet is unpredictable; therefore, therapies should be disabled to avoid unwarranted antitachycardia pacing or shocks. Finally, to reduce the risk of thermal injury and changes in lead threshold and impedance, we recommend limiting the estimated whole-body averaged SAR of MRI sequences (<2.0 W/kg when possible). Blood pressure, ECG, pulse oximetry, and symptoms should be monitored for the duration of the examination. We also favor the presence during all scans of a radiologist and cardiac electrophysiologist, or an individual trained in advanced cardiac life support familiar with device programming and troubleshooting.[5] At the end of the examination, all device parameters should be checked, and programming should be restored to pre-MRI settings.

## Image artifacts

The presence of ferromagnetic materials can cause variations in the surrounding magnetic field resulting in image distortion, signal voids or bright areas, and poor fat suppression. Susceptibility artifacts appear to be most pronounced on inversion recovery and steady-state free precession sequences (Figure 2). In our experience, artifacts on inversion recovery prepared delayed cardiac MRI show high signal intensity and can mimic areas of delayed enhancement, which would otherwise indicate myocardial scar. Correlation of suspect areas on different pulse sequences can help avoid misidentification of artifact as scar. Using imaging planes perpendicular to the plane of the device generator, shortening the echo time, and using spin-echo and fast spin-echo sequences appear to reduce the qualitative extent of artifact. Video 1 demonstrates an ex-

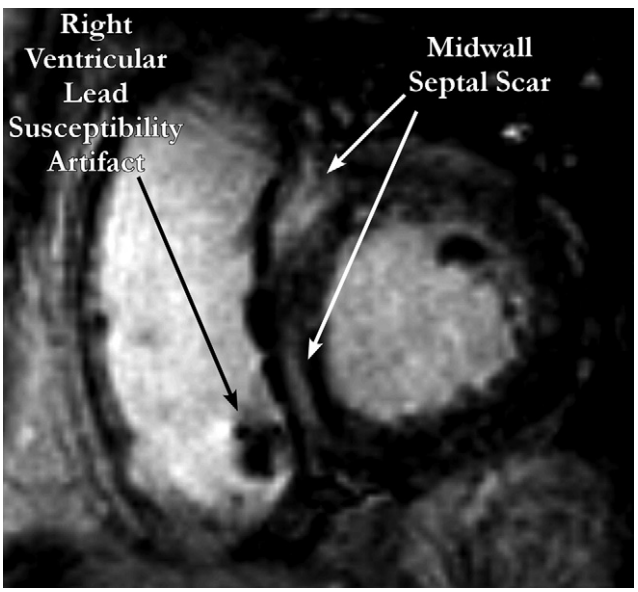


**Figure 3** Minimal susceptibility artifact on a short-axis inversion prepared gradient echo image. Areas of late gadolinium enhancement consistent with scar are visible in the midwall region of the left ventricular septum. A small susceptibility artifact associated with the distal right ventricular coil is visible in the lower right ventricle.

ample of minimal artifact using spoiled gradient recalled echo cine imaging in a patient with a biventricular pacemaker and defibrillator system. Figure 3 shows a short-axis inversion recovery gradient echo image showing midwall septal scar in the same patient. Video 1 and Figure 3 demonstrate the feasibility of diagnostic quality cardiac imaging in device recipients. In our initial report of imaging patients with permanent pacemakers and ICDs, diagnostic questions were answered in 100% of nonthoracic studies and 93% of thoracic studies. Clinical findings included diagnosis of vascular abnormalities (9 patients), diagnosis or staging of malignancy (9 patients), and assessment of cardiac viability prior to surgical ventricular reconstruction (13 patients).[5]

## Summary

Due to its superior spatial resolution, multiplanar capabilities, and lack of ionizing radiation, MRI is the preferred imaging technique in many clinical scenarios. The decision to perform MRI in patients with potential contraindications is frequently made by considering the potential benefit of MRI relative to the attendant risks. Given the potential risks, it is important to conduct a systematic review of the patient's condition and implanted device prior to proceeding with MRI. In addition to the usual MRI facility protocols and questionnaires for patient safety, safety protocols designed for implantable cardiac device recipients (Figure 1) are likely to reduce complications. The reader is encouraged to consult other resources, such as the recent American Heart Association Scientific Statement[6] and web sites that provide more specific information regarding individual devices (e.g., www.mrisafety.com), for specific device testing details.

## Appendix

### Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.hrthm.2008.10.021.

## References


1. Roguin A, Zviman MM, Meininger GR, et al. Modern pacemaker and implantable cardioverter/defibrillator systems can be magnetic resonance imaging safe: in vitro and in vivo assessment of safety and function at 1.5 T. Circulation 2004;110:475–482.
2. Tandri H, Zviman MM, Wedan SR, et al. Determinants of gradient field-induced current in a pacemaker lead system in a magnetic resonance imaging environment. Heart Rhythm 2008;5:462–468.
3. Gimbel JR, Zarghami J, Machado C, et al. Safe scanning, but frequent artifacts mimicking bradycardia and tachycardia during magnetic resonance imaging (MRI) in patients with an implantable loop recorder (ILR). Ann Noninvas Electrocardiol 2005;10:404–408.
4. Achenbach S, Moshage W, Diem B, et al. Effects of magnetic resonance imaging on cardiac pacemakers and electrodes. Am Heart J 1997;134:467–473.
5. 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;114:1277–1284.
6. Levine GN, Gomes AS, Arai AE, et al. Safety of magnetic resonance imaging in patients with cardiovascular devices: an American Heart Association scientific statement from the Committee on Diagnostic and Interventional Cardiac Catheterization, Council on Clinical Cardiology, and the Council on Cardiovascular Radiology and Intervention: endorsed by the American College of Cardiology Foundation, the North American Society for Cardiac Imaging, and the Society for Cardiovascular Magnetic Resonance. Circulation 2007;116:2878–2891.
7. Gimbel JR, Johnson D, Levine PA, et al. Safe performance of magnetic resonance imaging on five patients with permanent cardiac pacemakers. Pacing Clin Electrophysiol 1996;19:913–919.
8. Sommer T, Vahlhaus C, Lauck G, et al. MR imaging and cardiac pacemakers: in-vitro evaluation and in-vivo studies in 51 patients at 0.5 T. Radiology 2000;215:869–879.
9. Vahlhaus C, Sommer T, Lewalter T, et al. Interference with cardiac pacemakers by magnetic resonance imaging: are there irreversible changes at 0.5 Tesla? Pacing Clin Electrophysiol 2001;24:489–495.
10. Martin ET, Coman JA, Shellock FG, et al. Magnetic resonance imaging and cardiac pacemaker safety at 1.5-Tesla. J Am Coll Cardiol 2004;43:1315–1324.
11. Del Ojo JL, Moya F, Villalba J, et al. Is magnetic resonance imaging safe in cardiac pacemaker recipients? Pacing Clin Electrophysiol 2005;28:274–278.
12. Gimbel JR, Kanal E, Schwartz KM, et al. Outcome of magnetic resonance imaging (MRI) in selected patients with implantable cardioverter defibrillators (ICDs). Pacing Clin Electrophysiol 2005;28:270–273.
13. Sommer T, Naehle CP, Yang A, et al. Strategy for safe performance of extrathoracic magnetic resonance imaging at 1.5 tesla in the presence of cardiac pacemakers in non-pacemaker-dependent patients: a prospective study with 115 examinations. Circulation 2006;114:1285–1292.