Quantitative Assessment of Artifacts on Cardiac Magnetic Resonance Imaging of Patients With Pacemakers and Implantable Cardioverter-Defibrillators

Takeshi Sasaki, MD; Rozann Hansford, RN, MPH; Menekhem M. Zviman, PhD; Aravindan Kolandaivelu, MD; David A. Bluemke, MD, PhD; Ronald D. Berger, MD, PhD; Hugh Calkins, MD; Henry R. Halperin, MD, MA; Saman Nazarian, MD

Background—The safety and clinical utility of MRI at 1.5 T in patients with cardiac implantable devices such as pacemakers (PM) and implantable cardioverter-defibrillators (ICD) have been reported. This study aims to evaluate the extent of artifacts on cardiac magnetic resonance (CMR) in patients with PM and ICD (PM/ICD).

Methods and Results—A total of 71 CMR studies were performed with an established safety protocol in patients with prepectoral PM/ICD. The artifact area around the PM/ICD generator was measured in all short-axis (SA), horizontal (HLA), and vertical long-axis (VLA) SSFP cine planes. The location and extent of artifacts were also assessed in all SA (20 sectors per plane), HLA, and VLA (6 sectors per plane) late gadolinium-enhanced CMR (LGE-CMR) planes. The artifact area on cine CMR was significantly larger with ICD versus PM generators in each plane (P<0.001, respectively). In patients with left-sided ICD of biventricular ICD systems, the percentages of sectors with any artifacts on LGE-CMR were 53.7%, 48.0%, and 49.2% in SA, HLA, and VLA planes, respectively. Patients with left-sided PM or right-sided PM/ICD had fewer artifacts. Anterior and apical regions were severely affected by artifact caused by left-sided PM/ICD generators.

Conclusions—In contrast to patients with right-sided PM/ICD and left-sided PM, the anterior and apical left ventricle can be affected by susceptibility artifacts in patients with left-sided ICD. Artifact reduction methodologies will be necessary to improve the performance of CMR in patients with left sided ICD systems. (Circ Cardiovasc Imaging. 2011;4:662-670.)

Key Words: MRI ■ artifacts ■ pacemakers ■ implantable cardioverter-defibrillator

The clinical utility and safety of noncardiac and cardiac MRI at 1.5 T in patients with cardiac implantable devices such as pacemaker (PM) and implantable cardioverter-defibrillator (ICD) systems has been investigated in previous reports.1–12 Cardiac MRI (CMR) can be instrumental for the diagnosis of underlying cardiomyopathies, assessment of cardiac function and myocardial viability, assessment of disease progression, and identification of arrhythmogenic substrates.12–23 However, many patients with cardiac pathology who would otherwise derive benefit from CMR will have received a cardiac device before referral for imaging. We previously found that metallic PM and ICD (PM/ICD) can produce susceptibility artifacts caused by distortion of MRI magnetic field resulting in bright and dark artifacts surrounding the generator and leads.7 Consequently, the risk to benefit ratio of performing CMR in the setting of PM/ICD may be significantly altered compared with patients with PM/ICD who require noncardiac MRI.1–8,24 We sought to quantitatively assess susceptibility artifacts on 1.5-T CMR, using our previously reported safety protocol for patients with PM/ICD.1–3

Received April 24, 2011; accepted September 21, 2011.
From the Department of Medicine/Cardiology, Johns Hopkins University School of Medicine, Baltimore, MD (T.S., R.H., M.M.Z., A.K., R.D.B., H.C., H.R.H., S.N.); and Radiology and Imaging Sciences, NIH Clinical Center, National Institute of Biomedical Imaging and Bioengineering, Bethesda, MD (D.A.B.).
The online-only Data Supplement is available at http://circimaging.ahajournals.org/lookup/suppl/doi:10.1161/CIRCIMAGING.111.965764/-/DC1. Correspondence to Takeshi Sasaki, MD, Johns Hopkins University, Division of Cardiology, Carnegie 592C; 600 N Wolfe St; Baltimore, MD 21287. E-mail tsasaki1@jhu.edu
© 2011 American Heart Association, Inc.
Circ Cardiovasc Imaging is available at http://circimaging.ahajournals.org DOI: 10.1161/CIRCIMAGING.111.965764

Clinical Perspective on p 670

Methods

The study protocol was reviewed and approved by the Johns Hopkins Institutional Review Board. Written informed consent was obtained from all patients after potential risks of PM/ICD exposure to MRI scanning were explained.

Device Safety Protocol for CMR in Patients With PM/ICD

Patients were enrolled if they had a clinical necessity for CMR, no acceptable imaging alternative, and PM/ICD was found to be safe by previous in vivo or in vitro testing.1–3 Patients with device implantation <6 weeks before CMR and those with epicardial and abandoned leads were excluded. Specific device models included Medtronic EnTrust (T154ATG), GEMIII (7231), Insync (7272), Marquis (7274), Maximo (7232, 7278), Virtuso (D154AWG, D154VRC); Boston Scientific Confient (E030), Contak Renewal (H119, H170, H175,H210, H217, H219), Ventak Prizm (1852, 1860, 1861), Vitality (T125, T135, T165, T167, T175, T177); and St Jude Medical Atlas (V343, V366), Current (1207-36), Promote (3207-36) ICD, and BiV-ICD devices. Addition-
ally, the following PM models were included: Medtronic EnPulse (E2DR01, E2DR21), Kappa (KDR401, KDR701, KDR901); Boston Scientific Insignia (1290); St Jude Medical; Identity (5376, 5386), Integrity (5142, 5342, 5346), and Trilogy (2360). Device interrogation to assess parameters including battery voltage, lead impedance, lead capture thresholds, and sensing were performed immediately before, immediately after, and at routine clinic follow-up. Pacing mode was programmed to asynchronous in PM-dependent patients without a hemodynamically stable escape rhythm, whereas the patients without PM dependence were programmed to the ventricular or dual-chamber inhibited pacing mode. Magnet response, noise response, ventricular sense response, conducted atrial fibrillation response, and tachyarrhythmia functions (monitoring, antitachycardia pacing, and defibrillation) were turned off before CMR. Devices were reprogrammed to original settings after the completion of CMR. Blood pressure, ECG telemetry, pulse oximetry, and symptoms were monitored. In addition, a registered nurse trained in advanced cardiac life support and familiar with device programming and trouble shooting was present at all CMR scans. The specific absorption rate (SAR) of MRI sequences was limited to less than 2.0 W/kg during our initial experience (27/71 CMR studies). After the initial period, given the lack of association between SAR and device parameter changes and the unreliability of using SAR to guide MRI safety recommendations, no restrictions beyond standard manufacturer SAR limits were applied in subsequent patients.

Cardiac MRI

CMR scans were performed with a 1.5-T scanner (Avanto, Siemens Medical Systems, Malvern, PA) with multislice gradient field, with a maximum slew rate 200 T/m/s. ECG telemetry, pulse oximetry, blood pressure, and symptoms were monitored during the scan. Cine steady-state free precession (SSFP) gradient-echo images were obtained in multiple short axis (SA), horizontal long axis (HLA) and vertical long axis (VLA) planes (echo time, 1.1–1.6 ms; repetition time, 2.5–3.8 ms; average in-plane resolution, 1.4×1.4 mm²; flip angle, 45°–60°; temporal resolution, 40–45 ms). Fifteen minutes after bolus injection of 0.2 mmol/kg intravenous gadolinium contrast, late gadolinium-enhanced CMR (LGE-CMR) was obtained in 10–13 SA planes with an inversion-recovery fast-gradient-echo pulse sequence (echo time, 1.3–3.9 ms; repetition time, 5.4–8.3 ms; average in-plane resolution, 1.5×2.0 mm²; 8-mm slice thickness; flip angle, 30°). Inversion times (range, 175–300 ms) were optimized for each patient to maximize conspicuity of myocardial delayed enhanced area. Single planes of LGE-CMR were also acquired in VLA and HLA planes. In a subgroup of patients, three T2-weighted SA planes acquired by a T2-weighted LGE-CMR were also acquired in VLA and HLA planes. In a subgroup (range, 175–300 ms) were optimized for each patient to maximize the association between SAR and device parameter changes and the unreliability of using SAR to guide MRI safety recommendations. No restrictions beyond standard manufacturer SAR limits were applied in subsequent patients.

Interpretability of CMR Images

The percentage of image series qualitatively defined as “successfully interpretable,” “partially interpretable,” and “impossible to interpret” for each of 4 pulse sequences (LGE-CMR, cine CMR, perfusion CMR, and MR angiography) were calculated and stratified by location of device and underlying heart disease. All images were reviewed by 2 independent observers, and discrepancies (<5 cases) were resolved by the senior observer.

Statistical Analysis

All values are expressed as mean±SD. Comparisons of continuous variables were made using Student t test, and categorical variables were compared with χ² testing or Fisher exact test where appropriate. Spearman rank correlation test was used to assess the association between artifact size and parameters related to generator dimensions. Linear regression analysis was used to assess the relationship between the minimum distance from PM/ICD generator to heart on frontal chest radiography and percent sectors with artifact caused by the PM/ICD generator on LGE-CMR. All tests were 2-tailed, and analyses were performed using STATA 10 statistical software (StataCorp, College Station, TX).

Results

A total of 71 CMR examinations were performed in 66 patients with PM/ICD between November 2003 and March 2010. Of 71 scans, 56 (78.9%) were acquired in patients with ICD or biventricular ICD (Biv-ICD) systems, and 15 (21.1%) were acquired in patients with PM systems. All ICD/Biv-ICD systems were implanted in the left infraclavicular prepectoral area except 1 Biv-ICD, and 4 PMs, which were implanted in the right infraclavicular prepectoral area. Patient characteristics are summarized in Table 1. Patients with ICD devices were older and more likely to have structural heart disease than those with PMs. Body mass index (BMI) was similar between the 2 groups. Patient safety issues have been reported separately.

The estimated whole-body averaged SAR in each image acquisition sequence is reported in online-only Data Supplement Figure I. No clinically significant PM/ICD parameter changes requiring system revision or reprogramming were noted after CMR. The clinical indications for CMR studies

Measurements of Artifact Caused by PM/ICD

The maximum area of image susceptibility artifact was measured in SA, HLA, and VLA planes on cine CMR, and the percentage of cine CMR scans with any artifacts was also assessed in the three different planes (Figure 1A). The artifact size and the percentage of cine CMR scans with any artifacts in each plane were compared between patients with ICD/Biv-ICD and those with PMs. The association of artifact size with generator dimensions (area defined as height×width, thickness, weight, and volume) was evaluated. The feasibility of cardiac function calculation based on cine CMR (ie, clear visualization of myocardial borders free from artifact) was also evaluated in the four groups divided by the type of cardiac devices (ICD/Biv-ICD, PM) and the implanted side of device generator (left, right). The extent of artifacts on LGE-CMR in SA, HLA and VLA planes was recorded. To ascertain regional differences in artifact, the left ventricular myocardium was divided into 20 sectors in each SA plane and 6 sectors in each single HLA and VLA planes (Figure 1B). The percentage of sectors with/without artifact in the three different planes was assessed in the 4 groups described above. The percentage of sectors with artifact was summarized using the 17-segment model. The extent of artifacts in SA planes of cine CMR was assessed in the same way as the analysis of LGE-CMR. The distance from the generator to the cardiac silhouette on antero-posterior (AP) chest radiography was measured (if the generator border overlapped the cardiac silhouette the distance was reported as 0), and the association between that distance and the percentage of sectors with artifact in SA, HLA, and VLA planes was assessed. In patients with left-sided ICD/Biv-ICD, the artifact effects on cine, T2-weighted, perfusion, and LGE-CMR images were compared. Finally, artifact effects caused by PM/ICD leads were assessed by measuring the area of artifact surrounding the lead tip in SA cine CMR images. The artifact area surrounding PM/ICD leads was also measured in SA planes of cine CMR at the tip of the lead. In a subgroup of patients who had previously undergone cardiac computed tomography (CT), artifact characteristics were qualitatively compared between MRI and CT. Cardiac CT images were acquired using a 64-slice CT scanner (Aquilion, Toshiba Medical Systems Corporation, Tochigi, Japan). Image acquisition was performed during 1 breath-hold at the end-expiratory phase. The duration of scanning was approximately 10 seconds and scanning was retrospectively gated to the cardiac cycle. CT images were reconstructed every 10% of the cardiac cycle with a slice thickness of 1 mm.
were as follows: (1) general assessment of myocardial function and viability in patients with underlying heart disease (26 scans; 37%); (2) diagnosis of suspected cardiac conditions (arrhythmogenic right ventricular cardiomyopathy, cardiac sarcoidosis, myocarditis, etc) (7 scans; 10%); (3) preoperative evaluation of cardiac function, viability, and anatomy (before coronary artery bypass grafting, left ventricular plasty for ischemic left ventricular aneurysm, valve surgery, heart transplant, radiofrequency catheter ablation, or device upgrade to BiV-ICD) (27 scans; 38%); and (4) postoperative evaluation (coronary artery bypass grafting, valve surgery, or congenital heart disease) (11 scans; 15%).

**Artifact Size on Cine CMR**
Artifact sizes in SA, HLA, and VLA planes on cine CMR has been shown in the online-only Data Supplement Table. Susceptibility artifacts were present on cardiac cine CMR in 100% of SA planes, 26.9% of HLA planes, and 76.1% of VLA planes in patients with left- and right-sided PM systems. Artifacts were more likely to be present on SA planes compared with HLA planes ($P=0.0001$). In VLA planes of cine CMR, artifacts were more common in patients with ICD/BiV-ICD, artifacts were more common in patients with ICD/BiV-ICD compared with those with PMs ($P=0.012$). The artifact size on every plane of cine CMR was significantly greater in patients with ICD/BiV-ICD compared with those with PM. Artifacts size in patients with ICD/BiV-ICD systems was significantly smaller in HLA planes than in SA or VLA planes ($P<0.0001$). Online-only Data Supplement Figure II illustrates the correlation between artifact size in each plane and generator dimensions. The artifact area surrounding the tip of PM/ICD leads on cine CMR averaged $1.05\pm0.35$ cm$^2$ and $1.09\pm0.38$ cm$^2$ for PM and ICD leads, respectively.

**Artifact Effects on Cardiac Function Evaluation by Cine CMR**
CMR images of patients with left-sided ICD/BiV-ICD systems had more artifact effects on SA plane of cine CMR compared with those in patients with left-sided PM and right-sided PM/
Artifact Effects on LGE-CMR

In patients with left-sided ICD/BiV-ICD systems, artifacts on LGE-CMR were observed in 4501 of 8379 sectors (53.7%) in SA planes and 2932 of 6461 sectors (45.3%) in VLA planes. The characteristic distribution of artifacts in patients with left-sided ICD/BiV-ICD devices is summarized in Figure 2A. The characteristic distribution of artifacts in patients with left-sided ICD/BiV-ICD devices is summarized in Figure 2B. The anterior regions were more affected by artifact caused by the ICD/BiV-ICD generator in SA planes. The apical myocardial regions were also influenced by the artifact compared with basal regions in HLA planes. In VLA planes, the anterior apical regions were severely affected by the artifact. In comparison with left-sided ICD/BiV-ICD systems, fewer sectors needed to be excluded due to artifacts of left-sided PM generators (Figure 2C). The percentages of sectors with artifacts on LGE-CMR are summarized by the 17-segment model (Figure 3). The mean distance from PM/ICD generator to the silhouette of heart on AP chest radiography was 24.8±16.5 (range, 0–57) mm in patients with left-sided ICD/BiV-ICD and 29.3±20.5 (0–44.6) mm in left-sided PM. The distance from generator to heart was significantly associated with the percentage of the sectors with artifacts on LGE-CMR in each plane ($R^2=0.474, P<0.0001$ in SA planes; $R^2=0.566, P<0.0001$ in HLA planes; $R^2=0.391, P=0.0001$ in VLA planes). The artifacts caused by PM/ICD leads were much smaller than those caused by the PM/ICD generators. Fewer artifact effects caused by the PM/ICD leads were observed regardless of the image sequence and type of PM/ICD leads such as ICD, PM, or coronary sinus leads.

Comparisons of Artifact Effects on Cine CMR, LGE-CMR, T2-Weighted, and Perfusion CMR Images

Of 55 patients with left-sided ICD systems, 13 patients (23.6%) underwent all T2-weighted, perfusion, cine, and
LGE-CMR sequences. Artifact effects on the three corresponding SA planes of cine, T2-weighted, perfusion, and LGE-CMR images were compared in each myocardial region such as septal, anterior, lateral, and inferior regions (Figure 4). Compared with other image sequences, susceptibility artifacts due to the ICD/BiV-ICD generator were most extensive on LGE-CMR and affected all regions except the inferior wall (LGE-CMR versus cine CMR, T2-weighted, and perfusion CMR in septal, anterior, and lateral myocardial regions; P<0.001, respectively). Most artifacts on T2-weighted images were caused by cardiac motion or arrhythmia rather than the susceptibility artifacts from the PM/ICD generator.

**Interpretability of CMR Images**

The percentages of cine, perfusion, LGE-CMR, and MR angiography sequences with interpretable images are summa-
All CMR images were interpretable in patients with PM and right-sided ICD systems (16/16 scans; 100%). In contrast, interpretability of CMR images in patients with left-sided ICD/BiV-ICD systems was dependent on the extent of susceptibility artifacts due to PM/ICD generators. Despite the presence of some artifact in most image sequences, images were completely (18/55 scans; 32.7%) or partially (31/55 scans, 56.4%) interpretable in most patients with left-side ICD/BiV-ICD systems.

**Discussion**

Despite prior demonstration of overall safety, MRI in the setting of PM/ICD systems may be associated with risks including heating, current induction leading to arrhythmia, generator movement, and/or PM/ICD malfunction. Therefore, the risks of CMR must be weighed against the potential clinical utility of images to be acquired in each case. By reporting the extent of artifact in each sequence and associations with generator size, location, and patient characteristics, this study enables improved patient selection for CMR. The extent of each plane involved by artifact on cine CMR was dependent on the imaging plane. Artifacts were more pronounced in the SA plane compared with HLA and VLA planes, largely because of the proximity between the PM/ICD generator and affected regions of the heart in each plane. Artifact size on cine CMR was also significantly associated with the size of the PM/ICD generator. We found that the artifact size due to ICD/BiV-ICD devices was greater than that with PM devices in proportion to the size of PM/ICD generator. It was possible to evaluate cardiac function using cine CMR in 86% of patients with left sided ICD. The most significant predictors of the capability to assess cardiac function were BMI and LVEDD. Both associations are probably mediated by the distance between the PM/ICD generator and the heart. Scans with right-sided ICD/BiV-ICD and PM systems had no effects on LGE-CMR images.

---

**Figure 3.** Seventeen-segment model of artifact effects on late gadolinium-enhanced cardiac magnetic resonance imaging (LGE-CMR). Artifact effects on LGE-CMR in patients with left-sided sided implantable cardioverter-defibrillator/biventricular ICD are summarized using the 17-segment model. The percentages of sectors with artifact on LGE-CMR were divided into 4 groups (1–25%, 26–50%, 51–75%, and 76% to 100%).

**Figure 4.** Comparison of artifact effects on cine, T2-weighted, perfusion, and late gadolinium-enhanced cardiac magnetic resonance imaging (LGE-CMR). Comparison of artifact distribution and extent (asterisks) caused by the implantable cardioverter-defibrillator generator on A, cine CMR; B, LGE-CMR; C, T2-weighted; and D, perfusion CMR images. E, Percentage of the sectors without any artifacts on short-axis planes in each image sequence. Artifact effects on LGE-CMR images were greater compared with the other images in all except the inferior myocardial regions (LGE-CMR versus cine, T2-weighted, and perfusion CMR in the septal, anterior, and lateral myocardial regions; P<0.001, respectively). †P<0.001 versus LGE-CMR; ††P<0.01 versus LGE-CMR, †††P<0.001 versus T2-weighted CMR; ††††P<0.01 versus T2-weighted CMR.
patients with left-sided ICD/BiV-ICD systems, the artifacts on LGE-CMR images were most often localized to the anterior and apical myocardial regions. The artifact effects on LGE-CMR were significantly greater than cine, T2-weighted, and perfusion CMR images in patients with left-sided ICD systems. T2-weighted images scanned by the turbo spin echo sequence had fewer susceptibility artifacts caused by PM/ICD generator compared with other image sequences.25,26 Additionally, the distance between the PM/ICD generator and cardiac silhouette on frontal chest radiography (AP) was inversely associated with artifact size on LGE-CMR.

Artifact Effects on CMR Caused by PM/ICD Leads
Artifacts on CMR created by PM/ICD leads are smaller than those by PM/ICD generators. Artifacts caused by PM/ICD leads did not affect image interpretation in any patient regardless of the image sequence or the type of lead. The conducting wires and ICD coils of PM/ICD leads, although ferromagnetic, are thin and therefore associated with significantly less artifact compared with PM/ICD generators. In addition, the lead tips are made from nonferromagnetic materials such as platinum or other alloys that result in minimal artifact on CMR images. Artifacts of PM/ICD leads on cardiac CT are qualitatively larger than those on CMR (Figure 5).27 Based on our experience, CMR appears to be the superior modality for evaluation of myocardium near PM/ICD leads (eg, to rule out perforation).

Mechanism of PM/ICD Artifacts on MRI
Metallic PM/ICD components have magnetic susceptibilities that are very different from human tissue. Such disparities in magnetic susceptibility lead to significant distortion of the MRI magnetic field and result in image artifacts (Figure 5). Various metallic PM/ICD components contribute differently to the observed artifact. For example, ferromagnetic components such as stainless steel made from iron alloys result in significantly larger artifacts than components made from materials such as titanium, which have much lower relative magnetic susceptibility.25,26 The size and orientation of the artifact are associated with the direction and strength of the magnetic field, the relative magnetic susceptibility of the PM/ICD, and the type of pulse sequence being used. SSFP gradient echo and inversion recovery sequences with longer echo times are associated with increased magnetic susceptibility artifacts compared with gradient echo and spin echo sequences.25,26 Artifacts caused by PM/ICD generators can be reduced by use of lower magnetic field strength and shorter echo times; however, such adjustments may compromise the image signal intensity and contrast. The use of spin-echo techniques produces black-blood contrast, which is not always desirable and is typically associated with high SAR, which may reduce safety.1–12,24 Importantly, PM and ICD/BiV-ICD systems substantially differ from other metal implants such as orthopedic artificial joints26 and dental im-

<table>
<thead>
<tr>
<th>Underlying Heart Disease</th>
<th>Patient No.</th>
<th>LGE-CMR (n=71 Scans)</th>
<th>Cine CMR (n=71 Scans)</th>
<th>Perfusion CMR (n=36 Scans)</th>
<th>MR Angiography (n=32 Scans)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>○ Δ ×</td>
<td>○ Δ ×</td>
<td>○ Δ ×</td>
<td>○ ×</td>
</tr>
<tr>
<td>Ischemic cardiomyopathy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anteroseptal MI</td>
<td>20</td>
<td>5 90 5 85 15</td>
<td>85 0 15</td>
<td>57 43 0 100 0</td>
<td>0 100 0</td>
</tr>
<tr>
<td>Inferior MI</td>
<td>14</td>
<td>0 85 15</td>
<td>77 8 15</td>
<td>17 83 0 100 0</td>
<td>0 100 0</td>
</tr>
<tr>
<td>Diffuse</td>
<td>4</td>
<td>25 75 0</td>
<td>100 0 0</td>
<td>0 100 0 50 50</td>
<td>100 0</td>
</tr>
<tr>
<td>Dilated cardiomyopathy</td>
<td>10</td>
<td>10 80 10</td>
<td>100 0 0</td>
<td>0 50 50 100 0</td>
<td>100 0</td>
</tr>
<tr>
<td>ARVC</td>
<td>4</td>
<td>0 100 0</td>
<td>75 0 25</td>
<td>100 0 0 100 0</td>
<td>0 100 0</td>
</tr>
<tr>
<td>Cardiac sarcoidosis</td>
<td>2</td>
<td>0 100 0</td>
<td>100 0 0</td>
<td>0 100 0 100 0</td>
<td>100 0</td>
</tr>
<tr>
<td>Hypertrophic cardiomyopathy</td>
<td>1</td>
<td>0 100 0</td>
<td>100 0 0</td>
<td>0 100 0 100 0</td>
<td>100 0</td>
</tr>
<tr>
<td>Idiopathic ventricular tachycardia</td>
<td>1</td>
<td>100 0 0</td>
<td>100 0 0</td>
<td>(…) (…) (…) (…) (…) (…)</td>
<td></td>
</tr>
<tr>
<td>Left-sided PM, right-sided PM/ICD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congenital heart disease</td>
<td>7</td>
<td>86 14 0</td>
<td>100 0 0</td>
<td>100 0 0 100 0</td>
<td>0 100 0</td>
</tr>
<tr>
<td>Myocardial dystrophy</td>
<td>3</td>
<td>67 33 0</td>
<td>100 0 0</td>
<td>67 33 0 (…) (…) (…) (…) (…)</td>
<td></td>
</tr>
<tr>
<td>Dilated cardiomyopathy</td>
<td>1</td>
<td>100 0 0</td>
<td>100 0 0</td>
<td>100 0 0 (…) (…) (…) (…) (…)</td>
<td></td>
</tr>
<tr>
<td>ARVC</td>
<td>1</td>
<td>100 0 0</td>
<td>100 0 0</td>
<td>100 0 0 (…) (…) (…) (…) (…)</td>
<td></td>
</tr>
<tr>
<td>Cardiac sarcoidosis</td>
<td>1</td>
<td>100 0 0</td>
<td>100 0 0</td>
<td>100 0 0 (…) (…) (…) (…) (…)</td>
<td></td>
</tr>
<tr>
<td>Hypertrophic cardiomyopathy</td>
<td>1</td>
<td>100 0 0</td>
<td>100 0 0</td>
<td>0 100 0 (…) (…) (…) (…) (…)</td>
<td></td>
</tr>
<tr>
<td>Neuromediated syncope</td>
<td>2</td>
<td>100 0 0</td>
<td>100 0 0</td>
<td>(…) (…) (…) (…) (…) (…)</td>
<td></td>
</tr>
</tbody>
</table>

LGE-CMR indicates late gadolinium-enhanced cardiac magnetic resonance imaging; ICD, implantable cardioverter-defibrillator; BiV-ICD, biventricular ICD; MI, myocardial infarction; ARVC, arrhythmogenic right ventricular cardiomyopathy; and PM, pacemaker.

Values are shown as numbers or percentages. The interpretability of the CMR images was defined as completely interpretable (○), partially interpretable (△), and impossible to interpret (×).
plants. PM/ICD are intricate electronic devices, and their dysfunction can be directly associated with life-threatening events. These limitations must be taken into account when adjusting parameters to reduce artifact size on CMR.

**Study Limitations**
In the current study, we analyzed the artifacts on the most commonly used sequences in CMR including SSFP cine, LGE, T2-weighted, perfusion, and contrast-enhanced MR angiography. Artifacts in other image sequences were not evaluated. Additionally, newer “MRI conditional devices” were not studied. However, the modifications incorporated into such systems primarily focuses on safety rather than artifact reduction. This study included only 1 patient with a right-sided BiV-ICD system; therefore, artifact effects in this setting could not be sufficiently evaluated. All PM/ICD generators were implanted in the infracavicular prepectoral area; therefore, artifact effects due to submuscular devices were not investigated. Although interpretability was assessed by 2 independent observers and disagreements were rare, the measure is subjective and an interobserver reliability analysis was not performed. Distance between the generator and the cardiac silhouette on frontal chest radiography was considered the most readily available quantifiable parameter before CMR and was therefore used as predictor of artifact effects in this study. However, the distance on frontal radiography is a unidimensional surrogate of the true distance and 3D imaging techniques may improve the association.

**Conclusions**
This study demonstrated artifact characteristics on SSFP cine, T2-weighted, perfusion, LGE-CMR, and MR angiography in patients with PM/ICD. The utility of CMR in patients with left-sided ICD/BiV-ICD systems may be limited because of larger PM/ICD artifacts than in patients with PM or right-sided ICD/BiV-ICD systems. Artifact reduction methodologies for CMR in the setting of left-sided PM/ICD systems warrant further investigation.

**Sources of Funding**
Dr Sasaki is funded by the Francis Chiaramonte MD Private Foundation. Dr Nazarian is supported by Career Development Award K23HL089333 and Dr Halperin by grant R01-HL65795 from the National Institutes of Health.

**Disclosures**
Dr Nazarian received honoraria for lectures from St Jude Medical Inc, Boston Scientific Inc, and Biotronik Inc. Dr Halperin received research grant and consultant fees from Zoll Circulation Inc and has ownership interests in MRI International Inc and IMRICOR Medical Systems Inc. Dr Calkins received honoraria from Biosense Webster Inc and Medtronic Inc. Dr Berger received research grants from St Jude Medical Inc and Medtronic Inc and consultant fees from Boston Scientific Corp and Cameron Health Inc. The Johns Hopkins University Conflict of Interest Committee manages all commercial arrangements.

**References**
The decision to perform cardiac magnetic resonance (CMR) imaging in patients with cardiac pacemakers (PMs) and implantable cardioverter-defibrillators (ICDs) depends on the balance of risks versus benefits of imaging in each individual. Although considerable work has focused on safety considerations, this work evaluated the potential limitations imposed on CMR by susceptibility artifacts in patients with PM/ICDs. In patients with left-sided PM and right-sided PM/ICD systems, CMR images had minimal artifacts regardless of the image sequence and were completely interpretable. In contrast, in patients with left-sided ICD/biventricular (BiV)-ICD systems, artifact effects on late gadolinium-enhanced (LGE)-CMR were greater than those on MR angiography, cine, T2-weighted, and perfusion CMR. We found it particularly difficult to evaluate the anterior and apical regions on LGE-CMR of patients with left-sided ICD/BiV-ICD systems. Lower body mass index, larger generator size, larger left ventricular end-diastolic diameter, and shorter distance between the PM/ICD generator and the cardiac silhouette on chest radiography are associated with greater artifact size on CMR. The results of this study may improve patient selection for CMR in the setting of PM/ICD systems.

**CLINICAL PERSPECTIVE**


Quantitative Assessment of Artifacts on Cardiac Magnetic Resonance Imaging of Patients With Pacemakers and Implantable Cardioverter-Defibrillators
Takeshi Sasaki, Rozann Hansford, Menekhem M. Zviman, Aravindan Kolandaivelu, David A. Bluemke, Ronald D. Berger, Hugh Calkins, Henry R. Halperin and Saman Nazarian

_Circ Cardiovasc Imaging_. 2011;4:662-670; originally published online September 23, 2011; doi: 10.1161/CIRCIMAGING.111.965764
_Circulation: Cardiovascular Imaging_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2011 American Heart Association, Inc. All rights reserved.
Print ISSN: 1941-9651. Online ISSN: 1942-0080

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circimaging.ahajournals.org/content/4/6/662

Data Supplement (unedited) at:
http://circimaging.ahajournals.org/content/suppl/2011/09/23/CIRCIMAGING.111.965764.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in _Circulation: Cardiovascular Imaging_ can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to _Circulation: Cardiovascular Imaging_ is online at:
http://circimaging.ahajournals.org//subscriptions/
### Supplemental Table. Artifacts on Cine CMR

<table>
<thead>
<tr>
<th></th>
<th>ICD / BiV-ICD</th>
<th>PM</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Scans with Any Artifact on Cine CMR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short Axis</td>
<td>100% (56 / 56)</td>
<td>93.3% (14 / 15)</td>
<td>0.211</td>
</tr>
<tr>
<td>Horizontal Long Axis</td>
<td>26.9% (14 / 52)</td>
<td>23.1% (3 / 13)</td>
<td>1.0</td>
</tr>
<tr>
<td>Vertical Long Axis</td>
<td>76.1% (35 / 46)</td>
<td>33.3% (4 / 12)</td>
<td>0.012</td>
</tr>
<tr>
<td>Artifacts Size on Cine CMR [cm²]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short Axis</td>
<td>197.2±31.2</td>
<td>89.0±25.0</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Horizontal Long Axis</td>
<td>105.3±61.2</td>
<td>35.6±9.1</td>
<td>0.001</td>
</tr>
<tr>
<td>Vertical Long Axis</td>
<td>189.2±57.0</td>
<td>66.1±30.3</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Values are shown as percentage (N) and mean ± SD.
CMR=cardiac magnetic resonance; ICD=implantable cardioverter defibrillator; BiV-ICD=biventricular ICD; PM=pacemaker.
Supplemental Figure 1. Estimated Whole-Body Averaged Specific Absorption Rate (SAR) for Each Image Sequence

The estimated whole-body averaged SAR was less than 2.0 W/Kg in most image acquisition sequences except SSFP cine cardiac magnetic resonance.

SSFP=steady state free precession; LGE=late gadolinium enhanced; T2W=T2-weighted; MR=magnetic resonance.
Supplemental Figure 2. Correlation of Artifact Size on Cine CMR and Generator Dimension.

The association of artifact size on cine CMR and generator dimensions including area [cm²], thickness [mm], weight [g] and volume [ml] were demonstrated with Spearman correlation analysis in SA, HLA and VLA planes, respectively. The strongest correlation was observed in SA planes.

Significant P-value defined as P<0.05 are shown by the asterisk (*).
SA = short axis; HLA = horizontal long axis; VLA = vertical long axis.
Supplemental Figure 3. (A) Artifact effects in short axis plane of cine CMR due to the generator were quantitatively assessed in patients with left and right-sided ICD/BiV-ICD or PM systems. Artifacts on cine CMR were only observed in patients with left-sided ICD/BiV. (B) Details about the regional artifact effects on short axis plane were demonstrated in patients with left-sided ICD/BiV-ICD. A majority of the artifacts on cine CMR were observed in the anterior regions.