Managing Metallic Artifacts in MRI
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Background
Magnetism is a fundamental property of matter. As such, all substances have some type of magnetic property. Magnetic susceptibility refers to an object’s or substance’s ability to become magnetized. If two substances with different magnetic susceptibilities are close to one another, a small local magnetic field gradient is induced. The greater the difference in magnetic susceptibility between the two, the greater the induced gradient magnetic field will be. This induced gradient magnetic field can result in an image artifact seen as signal loss and even geometric distortion of the anatomy.

The presence of metal typically induces a fairly significant local magnetic field gradient. The images in Figure 1 demonstrate the effect on the local magnetic field and the resultant image distortion due to the presence of a paper clip.

![Image of local magnetic field and image distortion due to paper clip](image)

The larger or more ferromagnetic the metallic object, the larger and more significant the artifactual loss of signal and distortion will be.

There are several technical factors which can also affect the size of the susceptibility artifact. The parameters and recommended adjustments are shown in the table below.

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Image artifacts associated with the presence of metal are a type of artifact due to magnetic susceptibility differences between substances. While they cannot be eliminated entirely, they can be minimized by strategically selecting the pulse sequence (when possible) and specific sequence parameters.

Pulse Sequence
A spin echo sequence uses a 180-degree RF pulse prior to the formation and sampling of the echo. The main purpose of this 180-degree pulse is to correct for the effects of chemical shift and local field inhomogeneities. A gradient echo pulse sequence does not utilize such a “refocusing” pulse. As such, local field inhomogeneities are much more readily apparent when gradient echo sequences are utilized. Figure 2 shows two axial cervical spine images acquired on a patient with surgical wire in the posterior aspect of the cervical vertebrae. The signal loss and distortion is much more significant on the image acquired with the gradient echo sequence.

![Image of cervical spine with surgical wire](image)

Cardiac studies with MRI rely on the use of very rapid gradient echo sequences. Historically, the most commonly used sequences are variants of SSFP (Steady State Free Precession). When performing a cardiac MRI study on a patient with a SureScan® system, the leads and certainly the device itself can contribute to susceptibility artifacts. The SSFP-based sequences are more prone to susceptibility-induced phase errors artifacts due to the underlying principles of the pulse sequence. Fast gradient echo FGE sequences are less susceptible to these errors. See examples on the following page that were acquired on a patient with an Evera MRI® ICD system courtesy of Torsten Sommer, MD, PhD.
As is readily apparent, the use of an FGE sequence results in reduced susceptibility artifacts from the leads and the ICD device.

In a clinical study that was conducted to confirm the safety and efficacy of the Evera MRI ICD system, image quality of cardiac scans was assessed. Following implantation (9 - 12 weeks) 156 patients underwent a cardiac MRI exam. The study concluded that FGE produced better image quality and smaller artifacts for cardiac MRI than SSFP. For studies of the left ventricle, diagnostic image quality was obtainable in 74% of the patients. For studies of the right ventricle, 84% of the exams were of diagnostic quality. (Analysis by Evera MRI clinical study scan committee physicians).

Voxel Volume and TE
Voxel volume is determined by the Field-of-View (FOV), acquisition matrix, and slice thickness. Figure 5 shows two images acquired on the same patient. The patient has an MR-Conditional intracranial aneurysm clip implanted in the area of the left middle cerebral artery. The image on the left is from a 3D Time-of-Flight (TOF) MRA sequence. For optimum visualization of flow in smaller vessels, 3D TOF sequences use small voxels and a short TE. The image on the right is a 2D gradient echo sequence acquired with a much thicker slice, reduced acquisition matrix, slightly larger FOV and a longer TE. The result is a significantly larger area of signal void due to the presence of the metallic clip.

Receiver Bandwidth
When the echo is sampled in the presence of the readout gradient, a range of frequencies is collected. This range of frequencies sampled is what is referred to as the "receiver bandwidth." The receiver bandwidth can be expressed several ways. One way is to simply state the range of frequencies in units of kilohertz (kHz). One (1) kHz is a thousand (1,000) hertz. For example, if the range of frequencies sampled during the formation of an echo was from 0 (center) to +8,000 Hz and from 0 to -8,000 Hz, this could be expressed as either 16 KHz or +/- 8 KHz.

Another way to express the receiver bandwidth is in units of Hz per pixel. Given that the readout gradient is also known as the "frequency encoding" gradient, the pixels are those along the frequency matrix of the FOV. For example, selecting a frequency matrix of 256 pixels and a receiver bandwidth of 32 kHz would result in a receiver bandwidth of 125 Hz per pixel (Figure 6).

\[
\text{Frequency Matrix} = 256
\]
\[
\text{Receiver Bandwidth} = 32 \text{ kHz (32,000 Hz)}
\]
\[
\frac{32,000 \text{ Hz}}{256 \text{ pixels}} = 125 \text{ Hz / pixel}
\]

As previously mentioned, the presence of metal produces a non-uniform or gradient field around the metallic object or device. For a metallic object of a given size and susceptibility, the frequencies of the hydrogen protons will be altered a certain amount. Reducing the Hz/pixel will increase the number of pixels affected by the variance in frequencies and thus increase the size of the susceptibility artifact.
Reducing/Minimizing Susceptibility Artifact Due to Presence of Metal

Pulse Sequence Selection
As a general rule, images acquired with Fast or Turbo Spin Echo sequences (FSE/TSE) will result in images with fewer susceptibility artifacts than those acquired using gradient echo sequences. However, it is not always possible to replace gradient echo sequences with FSE sequences. Strategic selection of sequence parameters can be very effective.

Slice Thickness
Reducing slice thickness reduces voxel volume and therefore reduces the size of susceptibility artifacts associated with metal. However, signal-to-noise ratio (SNR) is directly proportional to the slice thickness. Reducing the slice thickness by a factor of 2 will reduce SNR by a factor of 2 as well. The use of 3D techniques allows for very thin slices but with much higher SNR than thin 2D slices.

Receiver Bandwidth
Increasing the receiver bandwidth will reduce the size of susceptibility artifacts associated with metal. An example is shown in Figure 7. The patient has a significant amount of metallic dental work. Significant artifact and distortion is seen on the sagittal image (6a). The axial image (6b) was acquired using a receiver bandwidth of +/- 16 kHz and also shows significant artifact. The image 6c was acquired using a receiver bandwidth of +/- 64 kHz. All other parameters were identical. Although the SNR is reduced, the artifact from the metal dental work is significantly reduced, resulting in a more diagnostic image.

Specialized Pulse Sequences
Recently, several MR vendors have introduced specialized pulse sequences designed to be used when significant metal is present. An example of one type of these metal artifact reduction sequences is shown in Figure 10. The image on the left was acquired using a standard FSE sequence. The image on the right utilizes the specialized pulse sequence designed to significantly reduce metallic artifacts.
Summary
Image artifacts associated with the presence of metal are a type of artifact caused by magnetic susceptibility differences between substances. While they cannot be eliminated entirely they can be minimized by strategically selecting the pulse sequence (when possible) and specific sequence parameters.

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What image artifact do you expect with Medtronic SureScan MR-Conditional pacemakers and ICDs?

**Medtronic SureScan MR-Conditional pacemakers**
- A clinical study demonstrated that the presence of a SureScan pacemaker system did not reduce the likelihood of obtaining a cardiac MRI exam of good diagnostic quality. The study found that 98% of Left Ventricular and 95% of Right Ventricular acquisitions were of diagnostic quality.1

**Medtronic SureScan MR-Conditional ICDs**
- Magnetic susceptibility artifact will be significantly greater in SureScan ICD patients compared to patients implanted with Advisa MRI® SureScan pacemakers. The impact on the diagnostic quality of cardiac MRI scans is strongly related to the distance between the ICD and the region being imaged.
- According to Torsten Sommer, MD, PhD, Professor of Radiology, Chief of Cardiovascular Imaging, University of Bonn, the image artifact will typically overlap most of the LV for patients with a SureScan ICD implanted on the left side, but it is generally possible to image the RV with acceptable image quality.
- Sasaki, et al.2 characterized cardiac MRI image artifact in patients with pacemakers and implantable cardioverter-defibrillators and concluded that: “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.” And “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.”

Why is there greater artifact with a SureScan ICD than with a SureScan pacemaker?
- The difference is due to the larger battery relative to Advisa MRI SureScan pacemaker and ferromagnetic material in the high-voltage transformer of the SureScan ICD.
Contraindications
designs may have different failure signatures and conditions that may or may not be detected lead as it does when used with a Medtronic Sprint Fidelis lead. This is because different lead 
medtronic.com

SureScan™ Pacing, Defibrillation, and Cardiac Resynchronization Therapy Defibrillation
(CRT-D) System

The SureScan system are MR Conditional, and as such are designed to allow patients to undergo MRI under the specified conditions for use. When programmed to On, the MRI SureScan feature allows the patient to be safely scanned while the device continues to provide appropriate pacing. A complete SureScan system, which is a SureScan device with appropriate SureScan leads, is required for use in the MRI environment. To verify that components are part of a SureScan system, visit http://www.mrisurescan.com/. Any other combination may result in a hazard to the patient during an MRI scan.

Indications
The SureScan pacing systems are indicated for rate adaptive pacing in patients who may benefit from increased pacing rates concurrent with increases in activity. Accepted patient conditions warranting chronic cardiac pacing include symptomatic paroxysmal or permanent second- or third-degree AV block, symptomatic bilateral bundle branch block, symptomatic paroxysmal or transient sinus node dysfunctions with or without associated AV conduction disorders, or bradycardia-tachycardia syndrome to prevent symptomatic bradycardia or some forms of symptomatic tachyarrhythmias. Dual chamber SureScan pacing systems are also indicated for dual chamber and atrial tracking modes in patients who may benefit from maintenance of AV synchrony. Dual chamber modes are specifically indicated for treatment of conduction disorders that require restoration of both rate and AV synchrony, which include various degrees of AV block to maintain the atrial contribution to cardiac output, VI intolerance (for example, pacemaker syndrome) in the presence of persistent sinus rhythm, or vasovagal reactions in patients with chronic cardiac syncope. The RV Lead Integrity Alert (LIA) feature is intended for use in patients with atrial tachyarrhythmias; or those patients who are at significant risk of developing atrial tachyarrhythmias.

SureScan CRT-D systems are indicated for ventricular antitachycardia pacing and ventricular defibrillation for automated treatment of life-threatening ventricular arrhythmias. In addition, the dual chamber devices are indicated for use in the above patients with atrial tachyarrhythmias, or those patients who are at significant risk of developing atrial tachyarrhythmias. The RV Lead Integrity Alert (LIA) feature is intended for patients whose device will be programmed to an asynchronous pacing mode. Optimization of heart failure medical therapy that is limited due to AV block or the urgent need for pacing should be done post-implant. Some CRT-D system are also indicated for use in patients with atrial tachyarrhythmias, or those patients who are at significant risk for developing atrial tachyarrhythmias. The RV Lead Integrity Alert (LIA) feature is intended primarily for patients who have a Medtronic ICD or CRT-D device and a Sprint Fidelis lead (Models 6949, 6948, 6931, and 6930), based on performance data. The RV LIA feature may not perform as well with a St. Jude Medical Rara™/Durata™ lead or a Boston Scientific Endotak lead as it does when used with a Sprint Fidelis lead. This is because different lead designs may have different failure signatures and conditions that may or may not be detected early by the RV LIA feature.

Contraindications
The SureScan pacing systems are contraindicated for implantation with unipolar pacing leads (Revo MRI™) only, concomitant implantation with another bradycardia device or an implantable cardioverter defibrillator. Rate-responsive modes may be contraindicated in those patients who cannot tolerate pacing rates above the programmed Lower Rate. Dual chamber sequential pacing is contraindicated in patients with chronic or persistent supraventricular tachycardias, including atrial fibrillation or flutter. Asynchronous pacing is contraindicated in the presence (or likelihood) of competition between paced and intrinsic rhythms. Single chamber atrial pacing is contraindicated in patients with an AV conduction disturbance. ATP therapy is contraindicated in patients with an accessory antegrade pathway. SureScan defibrillation and CRT-D systems are contraindicated for patients experiencing tachycardia episodes with transient or reversible causative factors including, but not limited to, the following: acute myocardial infarction, drug intoxication, drowning, electric shock, electrolyte imbalance, hypoxia, or sepsis. The device is contraindicated for patients who have an unipolar pacemaker implanted. The device is contraindicated for patients whose primary disorder is atrial tachyarrhythmia. For dual chamber and CRT-D devices, the device is contraindicated for patients whose primary disorder is chronic atrial tachyarrhythmia with no concomitant VT or VF. For single chamber devices, the device is contraindicated for patients whose primary disorder is atrial tachyarrhythmia.

Warnings and Precautions
Changes in patient’s disease and/or medications may alter the efficacy of the device's programmed parameters. Patients should avoid sources of magnetic and electromagnetic radiation to avoid possible underdetection, inappropriate sensing and/or therapy delivery, tissue damage, induction of an arrhythmia, device electrical reset, or device damage. Do not place transthoracic defibrillation paddles directly over the device.

Additionally, for CRT-D devices, certain programming and device operations may not provide cardiac resynchronization. Use of the device should not change the application of established anticoagulation protocols. Patients and their implanted systems must be screened to meet the following requirements for MRI:

- SureScan pacing and defibrillation systems: no lead extenders, lead adaptors or abandoned leads present; no broken leads or leads with intermittent electrical contact as confirmed by lead impedance history; and the system must be implanted in the left or right pectoral region. Patient must have pacing capture thresholds of ≤ 2.0 V at a pulse width of 0.4 ms and no diaphragmatic stimulation at a pacing output of 5.0 V and at a pulse width of 1.0 ms in patients whose device will be programmed to an asynchronous pacing mode when MRI SureScan is on. For the SureScan pacing and defibrillation systems: no lead extenders, lead adaptors or abandoned leads present;
- SureScan CRT-D systems: no lead extenders, lead adaptors or abandoned leads present; no broken leads or leads with intermittent electrical contact as confirmed by lead impedance history; and the system must be implanted in the left or right pectoral region. Patient must have pacing capture thresholds of ≤ 2.0 V at a pulse width of 0.4 ms and no diaphragmatic stimulation at a pacing output of 5.0 V and at a pulse width of 1.0 ms in patients whose device will be programmed to an asynchronous pacing mode when MRI SureScan is on.

Additionally for CRT-D systems, for pacemaker-dependent patients, it is not recommended to perform an MRI scan if the right ventricular (RV) lead pacing capture threshold is greater than 2.0 V at 0.4 ms. A higher pacing capture threshold may indicate an issue with the implanted lead.

Patients may be scanned using a horizontal field, cylindrical bore, clinical 1.5T MRI system with operating frequency of 64 MHz, maximum spatial gradient ≤ 20 T/m, and maximum gradient slew rate performance per axis ≤ 200 T/m/s. Scanner must be operated in Normal Operating Mode (whole body averaged specific absorption rate (SAR) ≤ 2.0 W/kg, head SAR ≤ 3.2 W/kg). For SureScan pacing systems, proper patient monitoring must be provided during the MRI scan.

For SureScan defibrillation and CRT-D systems, continuous patient monitoring is required while MRI SureScan is programmed to On. The patient is not to be moved once they have been programmed to On. If the patient experiences arrhythmias, the patient should be monitored and the device should be programmed to Off. If the patient continues to have arrhythmias, the MRI scan should be stopped and the patient should receive appropriate medical treatment.

Potential Complications
Potential complications include, but are not limited to, rejection phenomena, erosion through the skin, muscle or nerve stimulation, oversensing, failure to detect and/or terminate arrhythmia episodes, induction of tachycardia, cardiac perforation, heart wall rupture, cardiac tamponade, pericardial rub, infection, myocardial irritability, and pneumothorax. Other potential complications related to the lead may include lead dislodgement, lead conductor fracture, insulation failure, threshold elevation, or exit block. Potential MRI complications include, but are not limited to, lead electrode heating and tissue damage resulting in loss of sensing or capture or both, or MRI-induced stimulation on leads resulting in continuous capture, VT/VF, and/or hemodynamic collapse.

See the appropriate product MRI SureScan Technical Manual before performing an MRI scan and see the device manuals for detailed information regarding the implant procedure, indications, contraindications, warnings, precautions, and potential complications.

Caution: Federal law (USA) restricts these devices to sale by or on the order of a physician.