MR Imaging of Patients with Implanted Metal Devices

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Objective: Metallic devices can be characterized as "MR unsafe" or "MR Conditional." Dangers usually arise from magnetic forces or torques, or from potential heating due to radiofrequency fields (See, for example, ACR White Paper on MR Safety, 2004). Devices may often be scanned following safety checks, both to assess conditions related to the device and unrelated to the device. Interactions between the metal and both static and radiofrequency (RF) magnetic fields can cause image artifacts. This presentation describes (1) mechanisms of artifacts (2) methods to reduce artifacts, (3) clinical applications enabled by artifact correction, and (4) a survey of remaining challenges for MR imaging near metal.

Artifact Mechanisms: Magnetic susceptibility differences between tissues and metals cause variations in the static magnetic field that are similar to those at air-tissue interfaces, but usually much larger. The magnetic field variations result in resonance frequency shifts in tissue that can result in (a) signal loss if the tissue is never excited, (b) signal loss due to intravoxel dephasing (c) slice distortions if the tissue is excited in the wrong slice and effectively shifted to that slice, and (d) in-plane distortions whereby the signal is mapped to the incorrect position (Fig. 1). Distortion artifacts both through-slice and in plane can manifest as geometric distortion of the object, or, when the amount of distortion changes rapidly across the object, "pile-up" and signal-loss effects. Static magnetic field shifts can also cause failure of spectroscopic methods, fat suppression, or phase-sensitive imaging methods. Static magnetic field shifts and artifact severity are greater as magnetic field strength increases (e.g. at 3.0T vs. 1.5T). Metals can also effectively distort the RF magnetic field, which typically results in shading effects, or signal loss effects in cases of RF shielding.

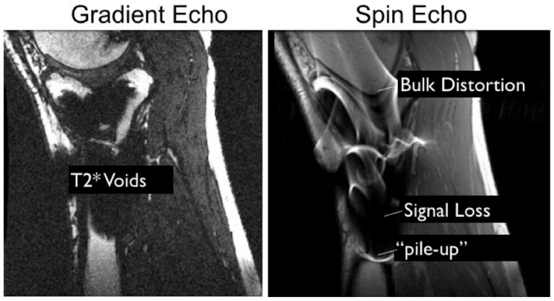

Figure 1: Sagittal knee image showing examples of metal artifacts from tibial screws. In high-bandwidth gradient-echo images, the T2* dephasing dominates. In spin-echo images, T2* loss is corrected, but both through-slice and in-plane distortions cause bulk distortion, signal loss, and "pile-up" (hypointense signal) effects.

Conventional Artifact Reduction: In conventional volumetric 2D multislice imaging, simple techniques are widely used to minimize image artifacts. Spin-echo sequences correct intravoxel-dephasing artifacts. Slice distortions are proportional to slice thickness and inversely proportional to RF bandwidth, so use of thin slices reduces spatial distortion at a cost of requiring more slices to cover a given volume. RF bandwidths should be maximized, but often already are maximized in order to reduce echo times or echo spacing. Maximizing the imaging readout bandwidth can similarly minimize in-plane distortions, at a cost of reduced signal-to-noise ratio (SNR). 3D approaches with non-selective excitation can avoid slice distortion effects, but may result in signal loss when tissue frequencies lie outside the RF bandwidth. Regarding fat suppression, frequency-selective fat saturation can be replaced with Dixon methods, which can track magnetic field variations. In cases where variations are too sharp to track, inversion-recovery (IR) fat suppression can be used, but reduces signal-to-noise ratio and precludes T_1-weighted imaging with contrast enhancement.

Specialized Artifact Reduction Methods: View-angle-tilting (VAT) is a spin-echo method that simply replays the slice-select gradient to limit the frequency range during readout, and reduces in-plane distortion to about a pixel, but also induces this distortion in cases with no frequency variation. Single-point imaging (SPRITE) or fully-phase-encoded (FPE) methods acquire all data at the same time with respect to the excitation, so avoid frequency-dependent distortions, but often a cost of long scan times and limited image contrast. Multi-spectral imaging (MSI) approaches use standard spin-echo sequences to excite multiple regions and use standard 3D imaging of each, before combining regions. Multi-acquisition variable resonance image combination (MAVRIC) excites frequency bands, and exploits knowledge of limited frequencies to reduce in-plane distortions. Slice encoding for metal artifact correction (SEMAC) excites slices or slabs and uses VAT to reduce in-plane distortions with 3D imaging to resolve slice distortions. MSI approaches can include inner-volume type excitations to reduce imaging times or simplify imaging to 2D. All MSI approaches require scan times typically lengthened by a factor of 4 to 16, but in some cases enabling signal-to-noise improvements that would otherwise require averaging. Currently, variations of MSI and VAT methods are available or under development from different MRI vendors under product names such as MAVRIC, MAVRIC-SL, WARP, Advanced WARP and OMAR.

Applications: Metal-artifact-reduction methods are seeing increased use for clinical applications. In the 1990s, VAT and high-bandwidth approaches were first described, and the latter approaches are now commonplace. Alternatives to fat saturation including Dixon and inversion-recovery are also widely used. MSI approaches generally degrade in-plane resolution by a factor of 1.5 to 2 and increase scan times by about 50%, but correct most artifacts and offer clinical contrast mechanisms. They have been applied broadly to imaging joint replacements, spinal hardware or orthopedic stabilization devices and hardware. In particular, joint replacements may fail due infection or wear-induced osteolysis. MSI approaches can help to identify infection, when combined with inversion-recovery fat suppression, or to identify wear-induced synovitis. VAT and MSI methods have also been applied to neuroimaging in the presence of dental fillings. Other applications such as imaging stents, aneurism clips, surgical clips or other small devices generally use conventional imaging with high bandwidths, and exploration with newer techniques continues.

Remaining Challenges: While substantial progress has been made regarding metal artifact reduction in MRI, numerous challenges remain. Initial investigations with parallel transmit techniques may mitigate RF inhomogeneity artifacts, but results will depend on device and coil geometry. Regarding B_0 artifact reduction, efforts to employ highly accelerated methods with parallel imaging and compressed sensing may reduce scan times. Resolution limits are a greater challenge given the fundamental need to overcome background gradients with imaging gradients, though fully-phase-encoded methods or hybrid approaches are promising. Other unmet clinical imaging needs in the presence of metal are the ability to image contrast enhancement with fat suppression, diffusion-weighted imaging, flow imaging and thermometry. Finally, the workflow of MRI exams near metal deserves consideration, as the device type, shape, size and composition all affect the choice of the best artifact reduction strategy for the clinical question.

Summary: The increased use of metal devices to very successfully treat a wide variety of medical conditions warrants a need for high quality MR imaging near metal. While numerous techniques are already being applied, continued innovation and validation in patients will further enable clinical imaging near metal devices.