Metal Artifact Reduction Techniques
mART & mART+

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Background

The number of patients with knee and hip replacement is rapidly increasing, particularly in developed countries, as the population continues to age. In fact, the number of knee replacement surgeries is expected to grow by 143% by 2050 compared to 2012.[1] Furthermore, there are more and more patients with shoulder prostheses, vessel clips and stents, cardiac pacemakers, dental fillings, tooth replacements, and metallic screws or rods within the body, who require medical imaging for their clinical diagnosis and treatment.

MRI has an essential role in medical imaging, owing to its superior soft-tissue contrast, assisting an accurate visualization of bony anatomies, muscles, tendons, ligaments, and in general, soft tissues that are not clearly visible in CT scans. However, MRI scans are very sensitive to the presence of metal objects in the area of imaging. The metal objects and implants introduce significant image disturbances, and metal artifacts appear as signal loss and pile-up, which complicate image interpretation. This complication hinders the broad utilization of MRI in patients with implants and metal within their bodies.

As metal implant utilization continues to rise, to obtain reliable images for accurate diagnosis, it is necessary to develop improved metal Artifact Reduction Techniques *(mART)* in MR imaging. Several studies indicate that pulse sequence optimization significantly reduces metal artifact.[2,3] Yet, the remaining artifact and distortion can degrade the image quality and reduce the accuracy of diagnosis.

Various techniques have been developed in the past decade to reduce metal artifact. These techniques include Metal Artifact Reduction Sequence (MARS)[4], View Angle Tilting (VAT)[5] to correct in-plane distortion, and Slice Encoding for Metal Artifact Correction (SEMAC)[6] or Multi-Acquisition with Variable Resonances Image Combination (MAVRIC)[7] to partially correct through-plane distortion. The combination of these techniques has also been used to further reduce the artifact in both in-plane and through-plane directions; however, the scan time is generally very long in these sequences, and hence limits the clinical application of these techniques.

Canon Medical Systems has introduced a family of metal Artifact Reduction Techniques *(mART)*, which employs some of the techniques mentioned above, to reduce the in-plane metal artifact while keeping the scan time clinically reasonable.

Technical Description

Metal artifact and image distortion

MR physics is heavily dependent on a homogenous magnetic field. In MRI, a linear magnetic field variation is introduced across the patient using magnetic field gradients. Therefore, the magnetic field strength and the resonant frequency of tissues is related to the position within the body. This variation in resonance frequency across the body is used to encode the MR signal. Metal has a significant magnetic susceptibility, and when placed within a magnetic field, induces a large local magnetic field gradient. This local magnetic field gradient disturbs the linear magnetic field and creates a resonance frequency shift in the surrounding tissues. Consequently, the unwanted resonance frequency alteration causes misplacement of the encoding MR signal. In other words, metal object distorts the homogenous magnetic field and causes susceptibility artifact, distortion in adjacent anatomies, and signal dephasing which appears as signal loss and signal pile-up. These distortion and signal dephasing appear in both in-plane and through-plane orientations.

Metal Artifact Reduction Approaches

MR sequences can be customized to reduce metal artifact. For instance, spin echo based sequences are less sensitive to metal artifact than gradient echo sequences, and therefore, a fast spin echo (FSE) technique is a better candidate for imaging patients with metal implants. Here some of these techniques are described:

Metal Artifact Reduction Sequence (MARS) – As mentioned before, FSE sequences show less metal artifact compared to gradient echo sequences due to the application of refocusing pulses. Shorter echo spacing and higher echo factors can further reduce the artifact. In addition, increasing the sequence readout bandwidth helps to minimize the metal artifact. Metal Artifact Reduction Sequence (MARS) employs these modifications to reduce the artifact in clinical FSE sequences.

View Angle Tilting (VAT) – VAT is a modified sequence acquisition scheme that compensates for in-plane distortions. It is implemented as an optional feature of an FSE sequence. VAT applies an additional slice select (SS) gradient simultaneous with the readout (RO). The SS gradient amplitude applied during the RO gradient is the same as the SS amplitude applied during the excitation RF pulse. The additional SS gradient causes shearing of the imaged pixels as if the slice were viewed at an angle. From a different point-of-view, the VAT gradient refocuses all excited spins within the RF bandwidth. Thus, all in-plane off-resonant spines are refocused. Hence, the pixel shift in the readout direction is fully compensated. A more detailed description on VAT is provided below in Section *mART*+ (Metal Artifact Reduction Technique Plus).

Slice Encoding for Metal Artifact Correction (SEMAC) – SEMAC acquires additional z-encodings to resolve off-resonant signal in the through-plane dimension. For each slice in the volume, phase encodings are applied in z (through-plane) dimension. These through-plane phase encoding steps define the strength of through-plane artifact removal; i.e. higher number of through-plane steps results in stronger metal artifact removal (with the cost of longer scan time). Due to the collection of a 3D volume per slice, the total scan time is long and makes the application of SEMAC more challenging in clinical practice. There have been several efforts to reduce the scan time by employing rapid imaging techniques such as Compressed Sensing.[8,9]

Multi-Acquisition with Variable Resonances Image Combination (MAVRIC) – MAVRIC is based on a 3D FSE sequence. In a routine 3D FSE sequence, off-resonance spins are not captured due to limited spatial coverage in the vicinity of metal implants. In MAVRIC, a slice selective 3D excitation is applied with non-selective refocusing. The same acquisition is then repeated at multiple off-resonance frequencies in order to recapture off-resonance spins.

Canon Medical's Approach: *mART* Family

mART is a set of techniques designed to reduce metal artifacts in MR while keeping the scan time similar to routine clinical sequences. These protocol settings include the use of FSE sequences, high-bandwidth readout frequency, high matrix size (high resolution), shorter echo spacing, thinner slice thickness and the absence of parallel imaging techniques.

In acquisitions using FSE2D sequences, *mART* may reduce artifacts at locations with a high magnetic susceptibility (which can be caused by the presence of metal) by optimizing parameters for bandwidth, slice thickness, readout matrix and acceleration factor (SPEEDER factor). Note that this technique cannot eliminate susceptibility artifacts completely.

mART (Metal Artifact Reduction Technique)

In static magnetic fields, metal objects cause high magnetic susceptibility gradients, which disturb the static magnetic field. Consequently, the objects are spatially encoded in a wrong location. The severity of this incorrect spatial encoding can vary upon a variety of different factors. The goal of metal artifact reduction is to minimize displacement due to incorrect spatial encoding. To reduce artifacts at locations with a high magnetic susceptibility, the following strategies for *mART* parameter optimization can be implemented for FSE sequences (Note that *mART* is Canon Medical's equivalent of MARS).

a) **Increase Bandwidth:** Metal artifacts can be reduced by increasing the receiver bandwidth (BW), causing the range of resonant frequencies, over which the distortion exists, to cover a smaller pixel range. This will confine in-plane geometric distortion to a smaller region within the FOV.
b) **Acquire Thinner Slices:** Susceptibility effects from metal cause signal loss and both in-plane and through-plane distortion. Thinner slices experience

less through plane distortion resulting in increased signal fidelity around metal implants. SNR will decrease in the rest of the image as normal.

c) **Increase RO Matrix:** By maintaining FOV and increasing RO matrix, pixel size can be decreased and in-plane resolution is increased. Although this reduces overall SNR, distortion over anatomy in the frequency direction is reduced due to the reduction of the pixel size.

d) **Avoid the use of SPEEDER:** Many of the parameter adjustments used for metal artifact reduction techniques will also cause SNR reduction; further SNR loss may be avoided by removing parallel imaging (SPEEDER). In addition, SPEEDER can cause a significant signal loss in the presence of metal, obscure the adjacent anatomies.

e) **Decrease Echo Spacing:** Decreasing echo spacing reduces the distortion from the metal. It allows more echoes to be collected before the signal decays.

mART+ (Metal Artifact Reduction Technique Plus)

mART+ is the application of the *mART* technique in combination with VAT (View Angle Tilting). VAT technique applies an extra slice direction gradient during readout to cancel the readout direction shift. It reduces metal related artifact caused by high off-resonance frequency, however it is known that VAT can cause blurring in the images. One way to reduce the blurring caused by VAT is to increase the readout BW. This can be achieved in *mART+* by combining VAT with techniques described in *mART*, which benefit from larger BW compared to regular FSE sequences.

Technical Details of VAT

In static magnetic fields, metals cause high magnetic susceptibility gradients, which disturb the static magnetic field. When frequency encoding is applied in the RO and SS directions, the magnetic field disturbance causes a frequency offset that results in signal overlap (pile-up) or signal loss (void), leading to artifacts in images. This phenomenon is similar to the chemical shift that occurs at the boundary between water and fat. Figure 1 (a) shows an example where chemical shift appears only in Z direction. When a frequency encoding gradient is applied in both RO and SS directions, the chemical shift is refocused in both X and Z directions, as shown in Figure 1 (b).

To reduce artifacts at locations with high magnetic susceptibility, the VAT technique applies a gradient field not only in the readout direction but also in the slice direction at the time of acquisition.

When a gradient field is applied in the slice direction, each pixel is viewed at angle θ defined as follows.

$$\tan\theta = \frac{G_{SS}}{G_{RO}}$$

Figure 1 (c) shows the projection of slices with no signal loss or pile-up. As a result, however, image blurring occurs in the RO direction. VAT is used in combination with a high-bandwidth readout and large RO matrix size. Although it reduces the SNR, this approach has the following advantages.

- Reduction of image blurring due to reduction of the tilt angle (reduction of the ratio between GSS and GRO in the above formula)
- Reduction of frequency direction's distortion due to reduction of pixel size

Note that VAT is effective only within the imaging plane. It does not correct distortions in the slice direction. To reduce the slice direction signal drop out, thin slice thickness is recommended.

Note that VAT cannot eliminate susceptibility artifacts completely. VAT only addresses the in-plane image

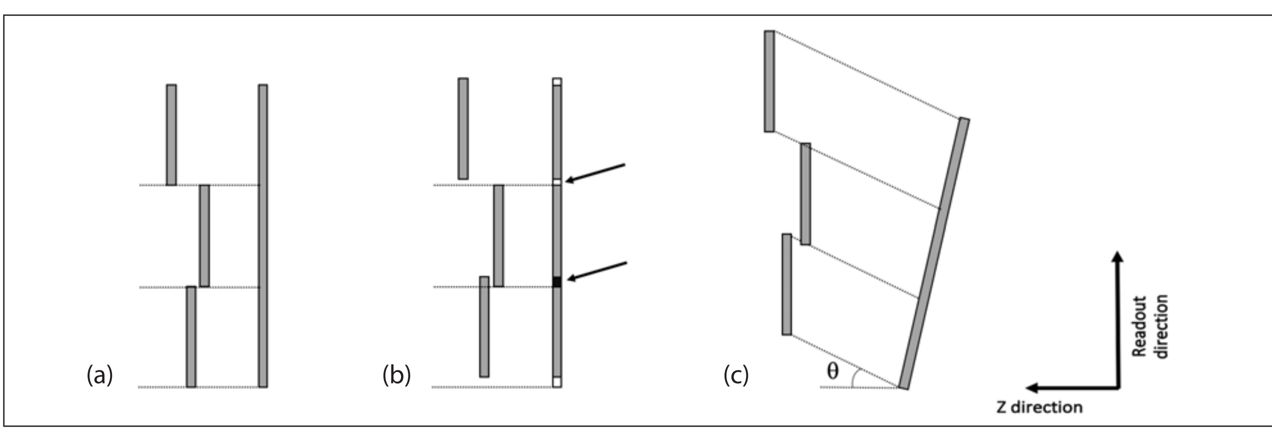

Figure 1. (a) Chemical shift only in Z direction, (b) chemical shift in both X (Readout) and Z directions, (c) two combined shifts and images seen by tilted view angle θ. In (b) chemical shift in X direction causes the signal void and pile-up as shown with arrows. VAT technique results in tilted view in (c) with no signal loss or pile up.

artifact—it does not address the through-plane distortion. Therefore, the signal can never be fully recovered with VAT. Signal voids remain, especially in the vicinity of the metal object itself. By using thin slices, this residual through-slice artifact may be reduced.

Evaluation of *mART* Family: Phantom Study

To evaluate the effectiveness of Canon Medical *mART* techniques, a conventional FSE sequence is compared with *mART* and *mART+* in two phantoms containing either a metal object or a hip implant. The scans were performed on 3T scanner.

For the metal object phantom the scan parameters were:

Routine FSE (a): spatial resolution = 1.0x0.8 mm^2, matrix size = 256x320, FOV = 26x24 cm^2, NAQ = 2, Slice thickness = 3 mm, BW = 195 Hz/pixel, scan time = 4:09 min;

***mART* (b):** spatial resolution=1.0x0.7 mm^2, matrix size = 256x368, FOV = 26x24 cm^2, NAQ = 2, Slice thickness = 3 mm, BW = 488 Hz/pixel, scan time = 3:11 min;

***mART+* (c):** spatial resolution = 1.0x0.7 mm^2, matrix size = 256x368, FOV= 26x24 cm^2, NAQ = 2, Slice thickness = 3 mm, BW = 651 Hz/pixel, scan time = 3:11 min.

For the hip implant phantom the scan parameters were:

Routine FSE (a): spatial resolution = 1.2x1.2 mm^2, matrix size = 256x256, FOV = 30x30 cm^2, NAQ = 1, Slice thickness = 3 mm, BW = 244 Hz/pixel, scan time = 1:27 min;

***mART* (b):** spatial resolution = 0.8x0.8 mm^2, matrix size = 384x384, FOV = 30x30 cm^2, NAQ = 1, Slice thickness = 2.5 mm, BW = 488 Hz/pixel, scan time = 2:09 min;

***mART+* (c):** spatial resolution = 0.8x0.8 mm^2, matrix size = 384x384, FOV = 30x30 cm^2, NAQ = 1, Slice thickness = 2.5 mm, BW = 651 Hz/pixel, scan time = 2:09 min.

Routine FSE Sequence

In the absence of specialized metal artifact reduction techniques, two artifact types are created in the presence of the strong magnetic field gradient produced by the metal object and the implant:

- **Hyper-intensities** – signals that are excited from a different slice location but get imaged as part of the current slice (through-plane artifacts).
- **Hypo-intensities** – part of the slice that its signal is shifted to a different location and is appeared as signal void (through-plane artifacts).
- **Spatial distortions** – signals that are spatially encoded in the wrong location and warp the image (in-plane artifacts). The grid lines near the metal object and the implant are no longer straight (Figure 2 (a)).

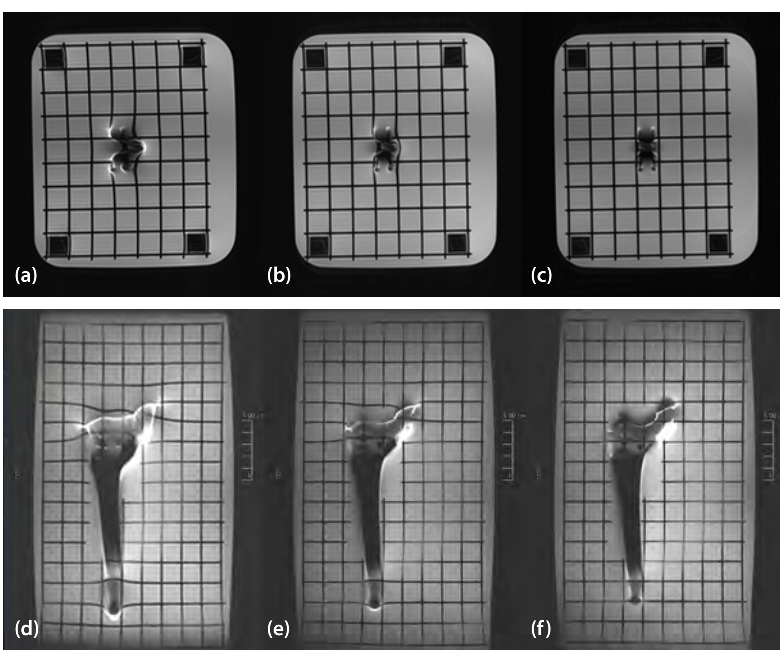

Figure 2. Images acquired in two phantoms, one contains a VertiFlex Superion Interspinous Spacer scanned at 3T (a-c), and the other includes a hip surgical implant scanned at 3T (d-f). Both phantoms were scanned using a routine FSE (a,d), *mART* (b,e), and *mART+* (c,f) sequences. The grids are significantly distorted in the vicinity of the metal object and hip implant in (a) and (d) due to metal artifact. In (b) and (e), the grids are less distorted thanks to *mART* sequence and metal artifacts are reduced but not completely eliminated. In (c) and (f), the grids are not distorted anymore due to better metal artifact reduction using *mART+*. Note that there are still hyper- and hypo-intensities around the metal object and hip implant, so VAT cannot completely remove through-plane artifacts, but it significantly reduces the in-plane artifact.

FSE with *mART*

Application of *mART* consists of (and has the following effects)

- Thinner slices – utilizes stronger slice selective gradient strength and subsequently reduces through-plane artifacts (reduced hyper-intensities).
- Higher readout bandwidth and tighter echo spacing utilizes higher readout gradient strengths and subsequently reduces in-plane encoding errors (i.e., reduced warping). The grid lines are not as distorted (Figure 2 (b)).

FSE with *mART+*

Application of *mART+* builds on *mART* with the application of View Angle Tilting (VAT):

- View Angle Tilting further reduces the erroneous spatial encoding created by the implant. It is observed in Figure 2c that the straight lines have been restored and the in-plane artifacts resolved. VAT incurs a slight blurring effect, so resolution can be recovered with a higher sampling matrix.

Clinical Applications

This section demonstrates several clinical applications of Canon Medical's *mART* family using a Vantage Galan 3T scanner in patients with surgical hip implants, knee surgical hardware, and cervical surgical hardware. In all these cases, a routine clinical FSE sequence is compared to *mART* and *mART*+ sequences.

Figure 3 demonstrates sagittal images of a patient with total left knee implant at Vantage Galan 3T scanner collected using a routine FSE sequence with BW of 244 (a), *mART* sequence with BW of 488 (b), and *mART*+ sequence with BW of 651 (c). Three scans were performed using the following parameters:

Routine FSE (a): spatial resolution = 0.6x0.6 mm^2, matrix size = 256x256, FOV = 16x16 cm^2, NAQ = 1, Slice thickness = 3 mm, BW = 244, scan time = 3:48 min;

mAR**T (b):** spatial resolution = 0.6x0.6 mm^2, matrix size = 256x256, FOV = 16x16 cm^2, NAQ = 2, Slice thickness = 2.5 mm, BW = 488, scan time = 6:57 min;

mART**+ (c):** spatial resolution = 0.6x0.6 mm^2, matrix size = 256x256, FOV = 16x16 cm^2, NAQ = 2, Slice thickness = 2.5 mm, BW = 651, scan time = 6:57 min.

The images with grid clearly show the reduction of distortion in the readout direction in *mART*+ images compared to routine FSE and *mART*, allowing more of the knee anatomy to be observed.

Figure 4 demonstrates sagittal head and neck images of a patient with post anterior fusion of the C 05/06 and seven vertebral bodies obtained using routine FSE

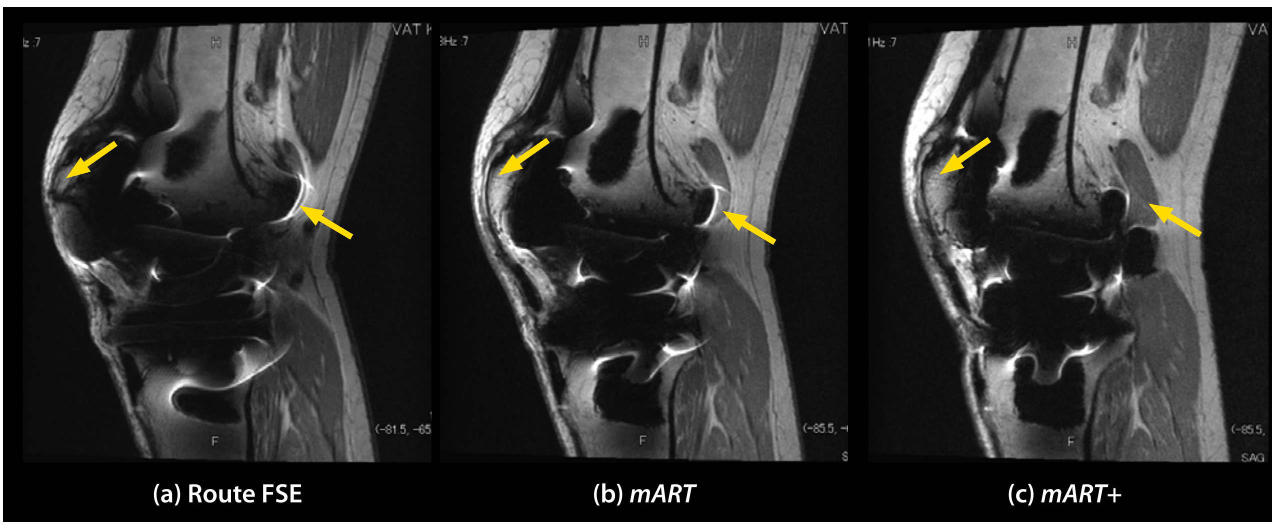

Figure 3. A patient with knee implant scanned on Vantage Galan 3T scanner using a routine FSE (a), *mART* (b), and *mART*+ (c) sequences. Reduced signal void and image distortion can be seen in the images obtained using *mART*+ sequence.

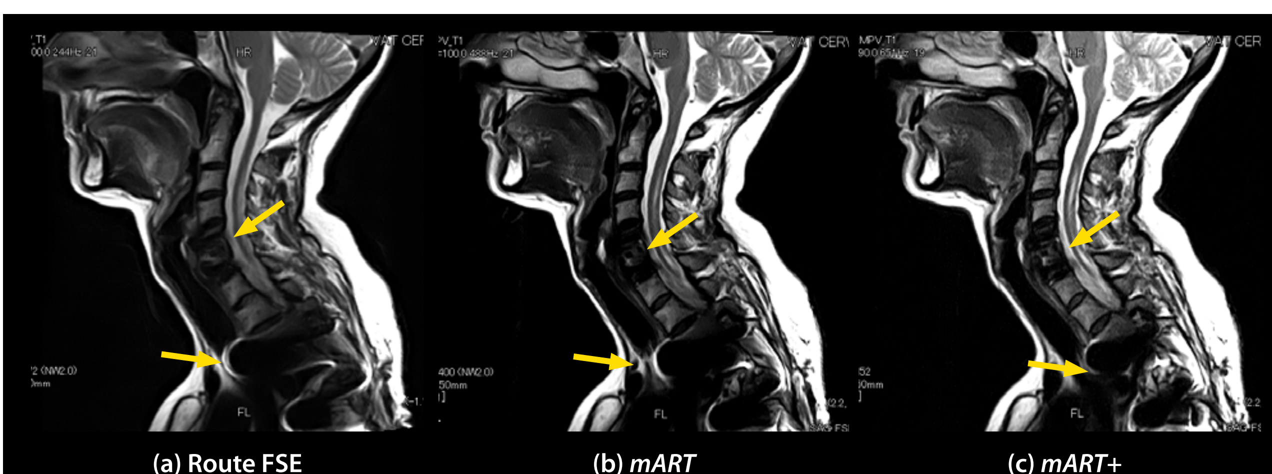

Figure 4. Sagittal images of a patient with cervical surgical Hardware. *mART* (b) and *mART*+ (c) images show metal artifact reduction compared to the routine FSE sequence. The images with the least metal artifact are acquired with *mART*+ where VAT is combined with *mART* technique. The yellow arrows indicate significant reduction in surgical hardware metal artifact and consequently better visualization of the posterior vertebral body and discs.

sequence (a), *mART* sequence (b), and *mART*+ sequence (c) on a Vantage Galan 3T scanner. Three scans were performed using the following parameters:

Routine FSE (a): spatial resolution = 1.0x0.8 mm^2, matrix size = 224x272, FOV = 22x22 cm^2, NAQ = 3, Slice thickness = 3 mm, BW = 244, scan time = 3:15 min;

***mART* (b):** spatial resolution = 1.0x0.6 mm^2, matrix size = 224x400, FOV = 22x22 cm^2, NAQ = 3, Slice thickness = 2.5 mm, BW = 488, scan time = 3:21 min;

***mART*+ (c):** spatial resolution = 1.0x0.6 mm^2, matrix size = 224x352, FOV = 22x22 cm^2, NAQ = 2, Slice thickness = 2.5 mm, BW = 651, scan time = 3:41 min.

Metal artifact due to surgical hardware degraded the image quality in the routine FSE sequence, making image interpretation impossible at the fusion site. The BW in *mART* and *mART*+ is increased compared to the routine FSE and the metal artifact is reduced. The best metal artifact reduction was achieved using *mART*+ with the largest BW and employment of VAT technique. When comparing the routine FSE technique to the *mART* family techniques, there is mild improvement with the *mART* but the evaluation of the posterior vertebral body and discs at the fusion site is still limited. With the *mART*+ technique, the posterior aspect of the vertebral bodies can be evaluated with minimal artifact and discs adequately visualized and the compression of the thecal sac evaluated.

Figure 5 shows coronal (top row) and axial (bottom row) proton density (PD) images of a patient with knee surgical hardware. The images were acquired on a Vantage Galan 3T Canon Medical scanner with 4 channel flex coil. The common parameters are: the spatial resolution = 0.6x0.6 mm^2, matrix size = 256x256, FOV = 15-16 cm^2. The sequence-specific parameters are:

Routine FSE (a): NAQ = 1, Slice thickness = 3mm, BW = 244, scan time = 3:48 min;

***mART* (b):** NAQ = 2, Slice thickness = 2.5mm, BW = 488, scan time = 6:57 min;

***mART*+ (c):** NAQ = 2, Slice thickness = 2.5mm, BW = 651, scan time = 6:57 min.

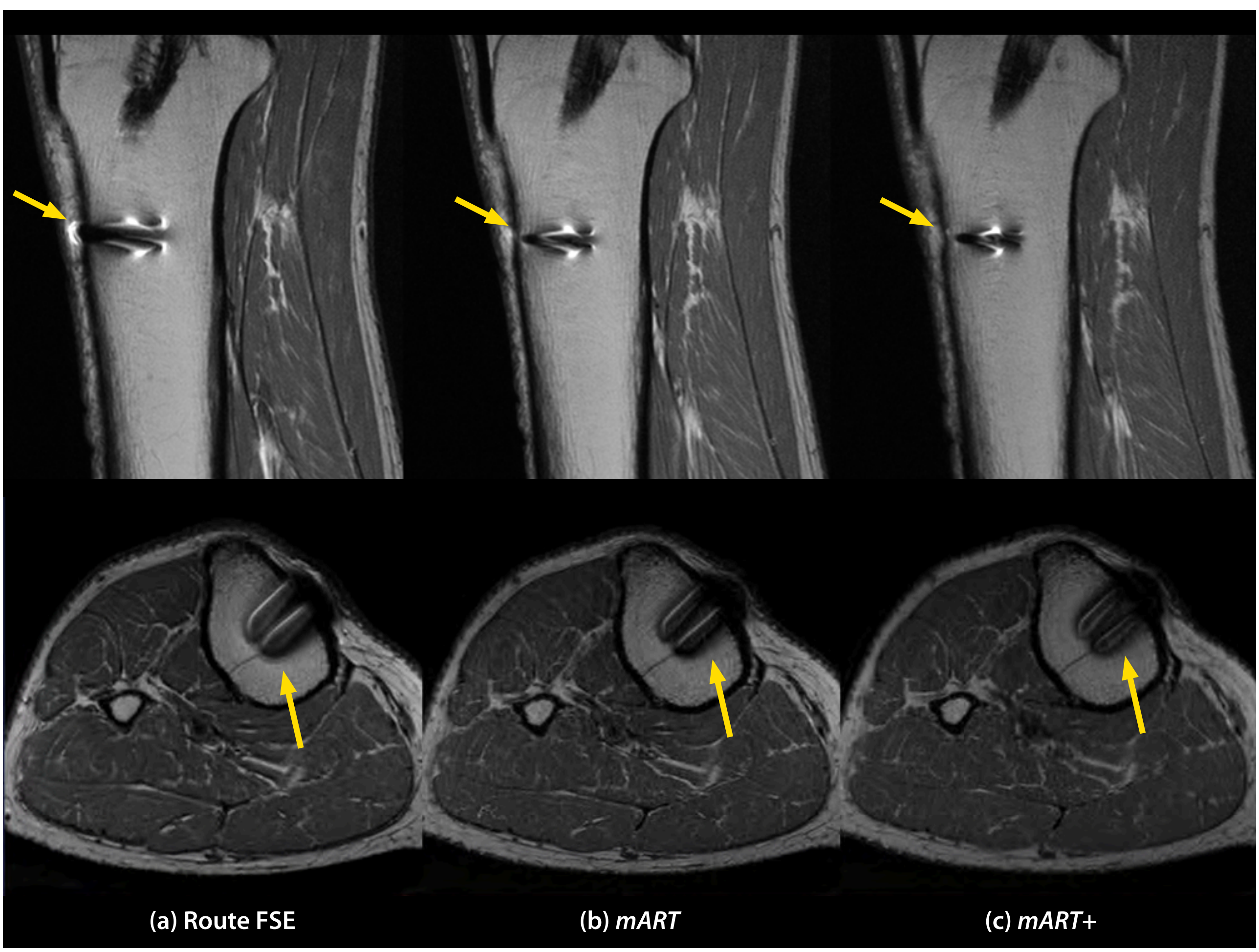

Figure 5. Sagittal (top row) and Axial (bottom row) PD images of a patient with knee surgical Hardware. *mART* (b) and *mART*+ (c) images show metal artifact reduction compared to the routine FSE sequence. The images with the least metal artifact are acquired with *mART*+ where VAT is combined with *mART* technique. The yellow arrows indicate the signal pile up at the surgical hardware.

The BW in *mART* is double that of routine FSE and the metal artifact is reduced. *mART+* has the largest BW and as a result the lowest metal artifact. Please note that the number of averaging (NAQ) is 2 in *mART* and *mART+* to compensate the SNR drop due to higher BW and as a result the scan time is longer than the routine FSE sequence.

Figure 6 shows axial (top row) and coronal (bottom row) proton density (PD) images of a patient with unilateral right hip implant. The images were acquired on a Vantage Galan 3T Canon Medical scanner. Three scans were performed using the following parameters:

Routine FSE (a): spatial resolution = 1.6x1.1 mm^2, matrix size = 256x368, FOV = 40x40 cm^2, NAQ = 1, Slice thickness = 5 mm, BW = 195, scan time = 2:20 min;

***mART* (b):** spatial resolution = 1.0x0.8 mm^2, matrix size = 416x512, FOV = 40x40 cm^2, NAQ = 2, Slice thickness = 4 mm, BW = 488, scan time = 4:08 min;

***mART+* (c):** spatial resolution = 1.0x0.8 mm^2, matrix size = 416x512, FOV = 40x40 cm^2, NAQ = 2, Slice thickness = 4 mm, BW = 651, scan time = 4:08 min.

The BW in *mART* and *mART+* is significantly increased compared to the routine FSE and the metal artifact is reduced. *mART+* has the largest BW and as a result the least metal artifact. The shape of the implanted femoral head can be clearly visualized using *mART+*. Please note that the number of averaging (NAQ) is 2 in *mART* and *mART+* in order to compensate the SNR drop due to the higher BW and as a result the scan time is longer than routine FSE sequence.

Conclusions

The number of patients with metal implants is significantly growing[1,10,11], and the presence of these metal implants induce magnetic field disturbance and susceptibility artifacts. This can be reflected as signal loss, signal pile-up, and distortion of the image.

Several MR image approaches were evaluated in this study. In general, a higher bandwidth and spatial resolution can reduce the metal artifact with a slight compromise in SNR. Canon Medical's *mART* family decreases the artifact associated with the metal implants in the body including susceptibility artifact. The *mART* sequence is based on the MARS technique with high BW, increased RO matrix, thinner slices, reduced echo spacing, and no SPEEDER, thereby reducing metal artifact compared to routine FSE sequences. The *mART+* method is a combination of *mART* and VAT to further reduce the in-plane distortion and metal artifact. The through-plane distortion can be reduced by smaller slice thickness. The MR images with *mART* family (*mART* family includes both *mART* and *mART+*) support high quality imaging and can be used for reliable clinical diagnostic images in patients with metal implants.

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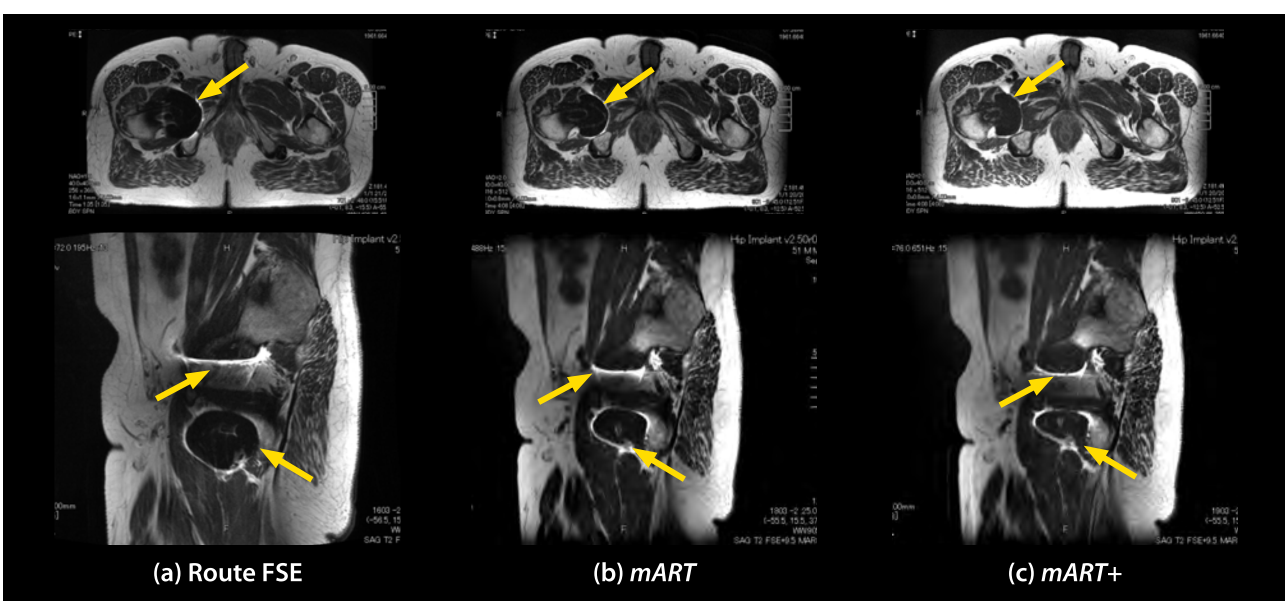

Figure 6. Axial (top row) and sagittal (bottom row) PD images of a patient with right hip implant. *mART* (b) and *mART+* (c) images show metal artifact reduction compared to the routine FSE sequence. The images with the least metal artifact are acquired with *mART+* where VAT is combined with *mART* technique and the shape of hip implant is clearly visible. The yellow arrows indicate that the metal artifact is significantly reduced using the *mART+* sequence and the tissue in the vicinity of the implant can be better visualized.

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