MR Imaging of Joint Replacements

Reto Sutter, M.D.[1]; Mathias Nittka, Ph.D.[2]

[1] Balgrist University Hospital, University of Zurich, Zurich, Switzerland
[2] Siemens Healthineers, Erlangen, Germany

Introduction

The last 10 years have seen large technological advances in MR imaging of metal implants[1], and these are coming at the right time, as the number of patients with joint replacements has increased substantially over the last decade. Patients often arrive in the imaging suite with metal implants that can produce distortion artifacts that are detrimental to image quality. Thankfully, these image distortions can be reduced or even eliminated with the use of new MR imaging techniques.

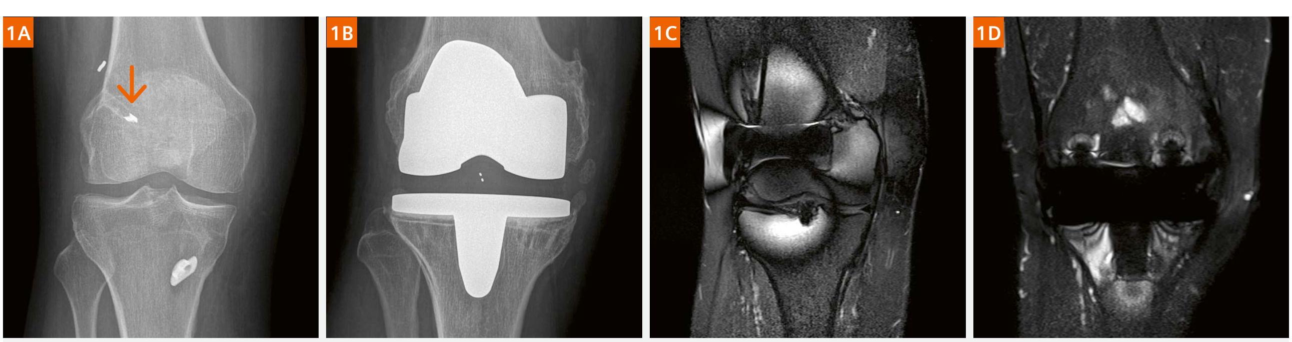
In general, MR imaging relies on a highly constant magnetic field inside the bore. Even slight perturbations, such as those occurring at interfaces between human tissue and surrounding air may cause significant artifacts. The physical property behind this effect is called 'magnetic susceptibility' and unfortunately, the magnetic susceptibility of metal is much higher than that of tissue. Resulting distortions of the magnetic field can reach out far beyond the metal surface and affect the diagnostic quality of the surrounding anatomical structures.

This does not mean, however, that a patient with a metal implant cannot be helped diagnostically with MRI; it means that we must dig deeper into the MR toolkit to produce the best possible diagnostic MRI (Fig. 1).

Determining the type of artifact

The course of action is, in part, dictated by the type and extent of artifact. In some cases, the signal piles up to produce a very bright signal on the MR image. In other instances, signal is lost and only a large, dark area can be seen. There is also signal displacement, where a voxel is shifted from one place to a different location. The signal may be shifted within the imaged slice along the frequency encoding direction (but not along the phase encoding direction!), the so called in-plane distortion. It may be also dislocated with respect to the selected slice position, i.e. the displayed signal originates from a different spatial position than the expected image plane, what is called through-plane distortion [2]. Commonly applied spectral fat suppression techniques are also extremely susceptible to resonance frequency variations. Combating the issues created by insufficient fat suppression is critical to the diagnostic process.

[1] *The MRI restrictions (if any) of the metal implant must be considered prior to patient undergoing MRI exam. MR imaging of patients with metallic implants brings specific risks. However, certain implants are approved by the governing regulatory bodies to be MR conditionally safe. For such implants, the previously mentioned warning may not be applicable. Please contact the implant manufacturer for the specific conditional information. The conditions for MR safety are the responsibility of the implant manufacturer, not of Siemens.*



Drill fragment (Stainless steel)	Total knee arthroplasty (Titanium)	Metal artifacts may extend far beyond the actual metal object	Massive metal implant imaged with a STIR SEMAC sequence

Figure 1: How do metal artifacts arise?
The degree of artifact around the implant[1] is not only induced by its size, but also by the metal composition. **(1A, C)** Objects made of stainless steel, even when very small in size, induce a substantially augmented local magnetic field. Therefore, a conventional coronal STIR sequence without metal artifact optimization exhibits extensive artifacts induced by a broken off drill fragment (arrow) in a patient with anterior cruciate ligament (ACL) reconstruction. **(1B, D)** Titanium implants in general induce less distortions, however, in particular large structures require dedicated metal artifact reduction techniques to enable a diagnostic image quality.
Image reproduced with permission from [1], © Georg Thieme Verlag KG.

Reducing metal artifacts

A simple, yet effective technique to reduce metal artifacts is to increase the bandwidth of the sequence. The bandwidth describes a property of the imaging sequence, linking the applied magnetic field gradients to the frequency spectrum required for encoding the image. In short, a high bandwidth applied to both signal excitation and signal reception turns the sequence less sensitive to distortions of the static magnetic field.
A recent study from Johns Hopkins Hospital [3] analyzing the effect of increased receiver bandwidth on imaging of ankle arthroplasty confirmed that this renders substantially improved images (Fig. 2). High bandwidth does come with some disadvantages: An increased readout dth decreases the signal to noise ratio (SNR). Furthermore, the specific absorption rate (SAR) is higher when using a high excitation bandwidth. As a consequence, high bandwidth protocols tend to exhibit longer scan times. To a certain degree, this may be compensated by longer echo train length when applying turbo spin echo sequences. However, it should be noted that long echo trains may cause an additional degradation of image quality around implants [3]. Other basic steps to improve MRI diagnostic quality are to:

1. Use thin sections, a small voxel size, and small field of view (FOV);
2. Perform the exam at a field strength of 1.5T rather than 3T, as the severity of the artifacts is in most cases directly proportional to the field strength;
3. Use turbo spin echo sequences rather than gradient or 3D sequences; and,
4. Set the frequency encoding gradient parallel to the long axis of the prosthesis/implant.

These and other techniques are an integral part of *syngo* WARP, providing a comprehensive set of sequence optimizations for metal implant imaging.

The problem with fat saturation

Fat saturated sequences are some of the most important sequences in any musculoskeletal MR imaging protocol, with the ability to visualize e.g. the anatomical distribution of fluid collections, bone marrow edema, and soft tissue edema. However, the presence of large or multiple metal artifacts often impedes fat saturation techniques and may result in a non-diagnostic image. Standard spectral fat saturation is based on different resonance frequencies of water and fat; when metal is present, the fat peak shifts to a different frequency and keeps the RF pulse from suppressing the signal from fat tissue. However, there is a technique that allows us to tackle this issue: short-tau inversion recovery (STIR).

Capitalizing on the different relaxation times of water and fat, first a 180-degree pulse inverts the longitudinal magnetization. Fat has a much shorter T1 relaxation time than water, so when during signal relaxation the fat is at a magnetization of zero, the excitation pulse only affects the water molecules and not the fat molecules, and this technique results in a more stable fat saturation in the presence of metal. Even better results are achieved by combining STIR with high bandwidth, but this still would not be sufficient for clinical use [4].

The *syngo* WARP STIR sequence employs a dedicated bandwidth matching for each RF pulse within the sequence, which is critical for robust STIR contrast around metal implants while still covering a large anatomical field of view (Fig. 3). Further improvements can be achieved by adding the View-Angle Tilting technique (VAT), another feature of the *syngo* WARP toolkit. VAT applies an additional compensation gradient which effectively cancels the in-plane displacement (Fig. 4). This technique allows to visualize periprosthetic tissues with only little residual artifacts, and with reasonable acquisition times.

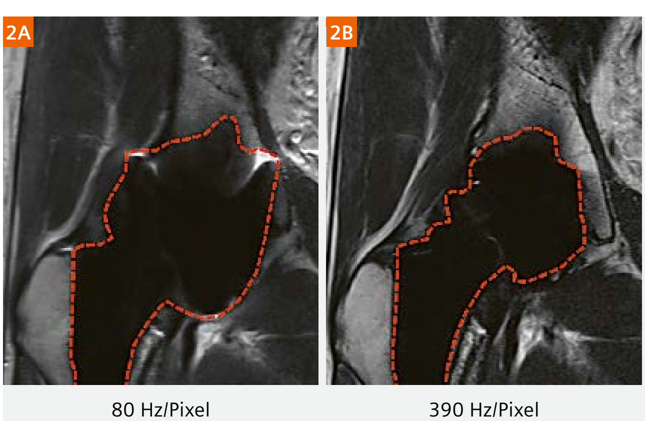


Figure 2: Increasing the receiver bandwidth
A simple but very effective step for reducing metal artifacts is increasing the receiver bandwidth, as shown in a 76-year-old patient with total hip arthroplasty. **(2A)** Coronal T2-weighted turbo-spin echo sequence with a standard receiver bandwidth of 80 Hz/Pixel shows large artifacts around the acetabular component. **(2B)** When the same sequence is repeated with an increased receiver bandwidth of 390 Hz/Pixel the artifacts around the acetabular component are substantially smaller.

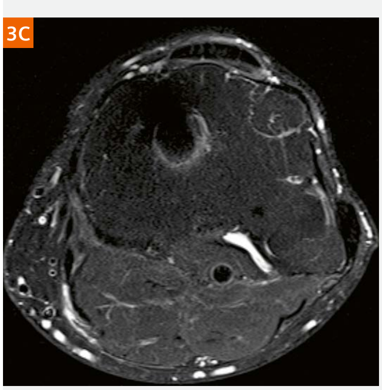
Dealing with severe metal artifacts

For some implants it may be not sufficient to apply sequences with high bandwidth as described above. Typically structures composed of stainless steel or hardened surfaces frequently containing CoCr alloys are very difficult to handle.

In these cases an excessive distortion of the slice profile is the dominating factor, requiring a more powerful tool, which is able to correct for signal dislocated in through-plane direction.

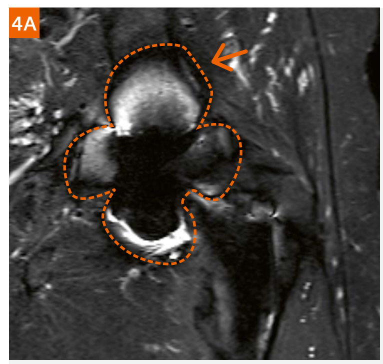
A break-through in this field was achieved with the invention of the SEMAC (slice encoding for metal artifact correction) method [5] that has meanwhile been applied successfully in clinical imaging for several years [2]. The SEMAC technique employs the through-plane distortion correction to significantly reduce what can be called the "Potato Chip Effect". When you visualize the warped artifacts that occur because of through-plane distortion, the imaged plane looks like a potato chip, with distortions affecting several adjacent image planes. Image reconstruction using SEMAC substantially mitigates these distortions, allowing the radiologist to appreciate areas of osteolysis and other conditions that are obscured when imaging is performed without through-plane distortion correction (Fig. 5).

Spectral fat saturation



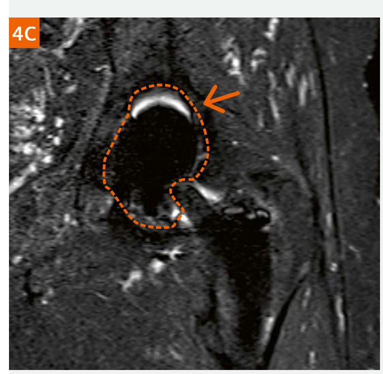
STIR WARP

Figure 3: Two types of fat saturation
Anterior cruciate ligament (ACL) reconstruction in a 69-year-old patient. **(3A)** Radiograph of the left knee showing large Ligamys screw in the tibial head. **(3B)** Axial intermediate-weighted turbo-spin echo sequence with spectral fat saturation and increased bandwidth shows complete fail of the spectral fat saturation at the level of the tibial head. **(3C)** Axial STIR WARP sequence with optimized inversion pulse shows stable and homogeneous fat saturation of the whole image.



Standard STIR hiBW

STIR WARP



STIR WARP + VAT

Figure 4: STIR WARP and View-angle Tilting (VAT)
Different methods for metal artifact reduction in a 66-year-old patient with total hip arthroplasty (THA). **(4A)** The standard coronal STIR sequence with increased receiver bandwidth (hiBW) often allows for a basic diagnostic image quality, but suffers from many areals with failed fat saturation (arrow). **(4B)** STIR WARP with an optimized inversion pulse is much more stable for reduction of metal artifacts, with a smaller area of insufficient fat saturation. **(4C)** An additional compensation gradient shifts the view-angle during the readout, and this view-angle displacement cancels the in-plane displacement, resulting in an even better reduction of metal artifacts.

New horizons: Compressed Sensing SEMAC[2]

SEMAC depends on numerous slice encoding steps to gain the most benefit, requiring considerable additional scan time and thus poses some challenges, both to the time scheduling of a busy practice and also with respect to patient comfort.

In recent years a new technique emerged, known as Compressed Sensing (CS). It has opened new perspectives to accelerate the MR acquisition process in various fields and can now also be applied to SEMAC (Figs. 10, 11). The CS-SEMAC[2] technique is facilitated by the inherent sparsity of the acquired SEMAC data, since the actual distortions make up for just a small fraction of the acquired signal. Compressed Sensing SEMAC applies 8-fold undersampling of *k*-space in combination with an iterative reconstruction algorithm. As a result, images with very comparable diagnostic quality can be created from e.g. a six minute CS-SEMAC scan that would otherwise take approximately twelve minutes even with parallel imaging acceleration.

The number of recommended slice encoding steps for CS-SEMAC according to a recent study was 19 for STIR and T1-weighted images, and 11 slice encoding steps for T2-weighted images [6]. A study on knee implants by Fritz et al. [7] found that CS-SEMAC allows the acquisition of accelerated MR imaging with acquisition times of less than 5 minutes.

[2]*The product is still under development and not commercially available yet. It is not for sale in the US. Its future availability cannot be ensured.*

The plan in action

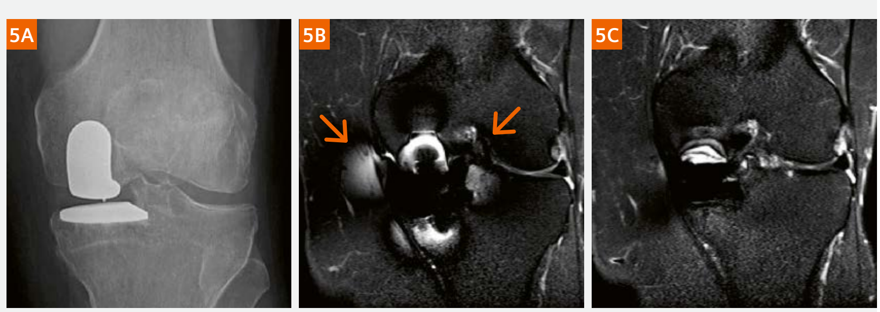
A sample protocol for hip prosthesis

At Balgrist University Hospital a protocol with a mix of techniques is in use for scanning hip implants: The first two sequences cover the whole prosthesis. A coronal STIR CS-SEMAC sequence gives the best visibility of the bone-metal-interface with an acquisition time of approximately six minutes. Additionally, a transverse STIR WARP sequence is acquired, allowing the coverage of a large field of view in less than 4 minutes. The second part of the protocol is focused on the joint and the periarticular muscles with turbo-spin echo sequences that feature a high receiver bandwidth, allowing to visualize soft tissue pathology with sequences that only require acquisition times of 2–3 minutes.

What is the clinical impact?

In patients with residual pain after total arthroplasty, soft-tissue related complications are the most common problem, followed by aseptic loosening and infection. Soft-tissue related complications include e.g., damaged or detached external rotator tendons and scarred abductor tendons with associated muscle atrophy and fatty muscle degeneration (Fig. 6).

One place where MRI can be of significant help is in differentiating between osteolysis and diffuse osteopenia next to the implant: While in conventional radiographs and computed tomography (CT) this can be difficult or even impossible, MR imaging allows the accurate differentiation between these two entities (Fig. 7). In patients with suspected infection the extent of the infected areas can be determined using STIR WARP or CS-SEMAC (Fig. 8). Naturally, aspiration is still required to determine the pathogen. Other complications can also be visualized such as the hypointense masses seen in metal-on-metal hip implants called pseudotumors (Fig. 9).



STIR hiBW STIR SEMAC

Figure 5: Unicompartmental knee arthroplasty
This 58-year-old male with unicompartmental knee arthroplasty underwent MRI to evaluate those parts of the knee joint that were not replaced. **(5A)** Radiograph of the left knee shows prosthesis components in the medial compartment. **(5B)** In the standard coronal STIR sequence optimized with high receiver bandwidth (hiBW) both the collateral ligament and the intercondylar notch are obscured (arrows). **(5C)** STIR SEMAC (slice encoding for metal artifact correction) and its reduction of through-plane metal artifacts improves the visualization of the collateral ligament and the intercondylar notch.

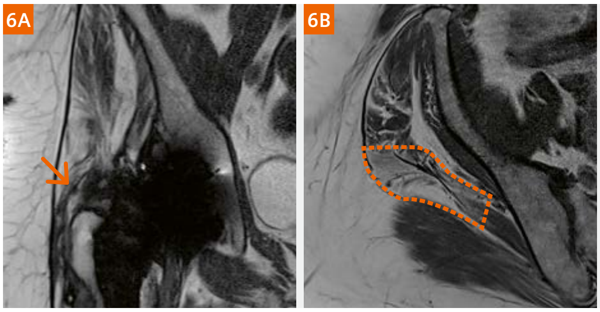


Figure 6: Abductor insufficiency
61-year-old female patient with pain and unsteady gait after total hip arthroplasty (THA), and positive Trendelenburg sign at clinical examination. **(6A, B)** At MR imaging improved with high receiver bandwidth a rupture of the gluteus medius tendon (arrow) and fatty degeneration of the respective part of the gluteus medius muscle (outlined areas) are depicted on a coronal T2-weighted and axial T1-weighted sequence.

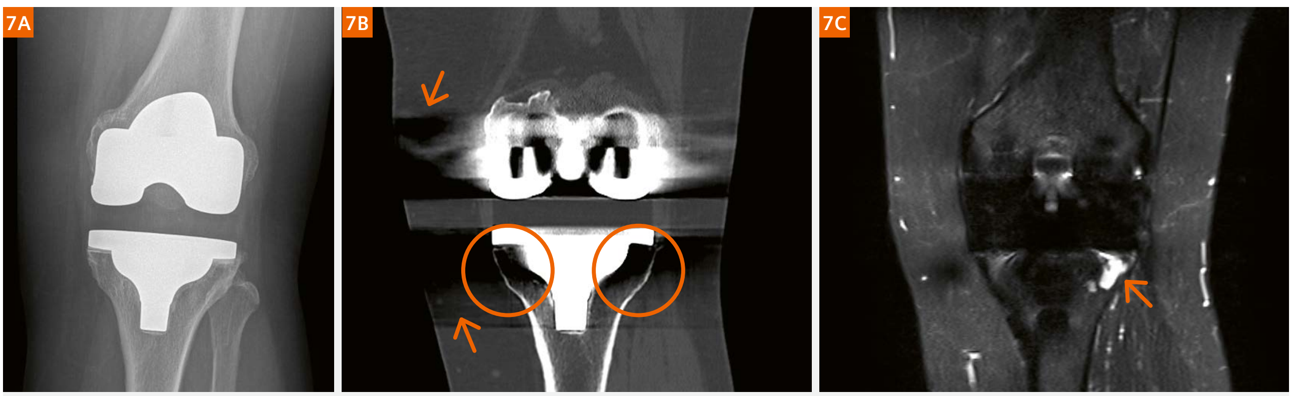


Figure 7: Osteolysis vs. Osteopenia
Painful total knee arthroplasty (TKA) in a 57-year-old female patient. **(7A)** Radiograph of the left knee is unremarkable. **(7B)** At computed tomography (CT) suspected areas of osteolysis are visible next to the tibial component (circles), however this region is partially masked by beam hardening artifacts (arrows). **(7C)** At MR imaging an osteolysis (arrow) is detected on a coronal STIR SEMAC sequence only on one side of the tibial component, but not on the other side.

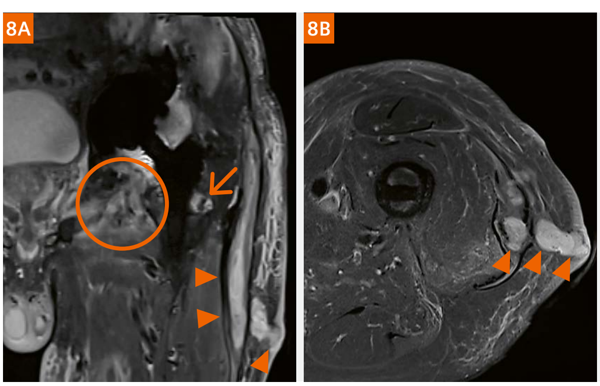
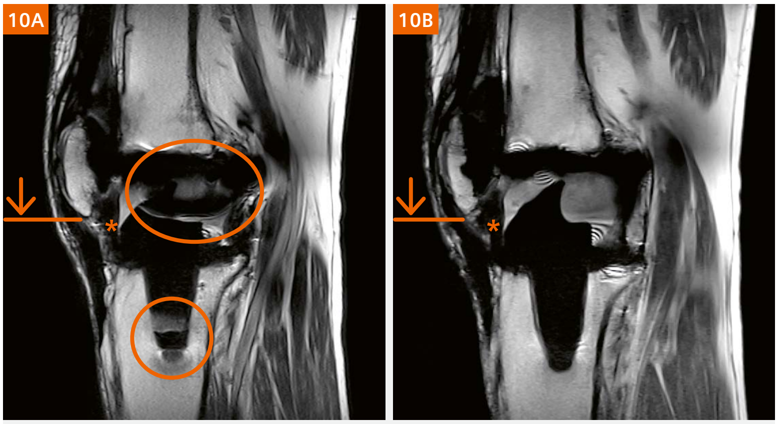


Figure 8: Infection
70-year-old patient with infected total hip arthroplasty. **(8A)** Coronal CS-SEMAC STIR sequence shows extensive soft tissue edema adjacent to the left hip joint, e.g. in the adductor region (circle), periprosthetic osteolysis (arrow) and soft tissue abscesses (arrowheads) with a cutaneous fistula. **(8B)** Soft tissue abscesses (arrowheads) and cutaneous fistula depicted on axial STIR WARP image at the level of the femoral shaft.

Figure 9: Metal-on-metal hip
42-year-old female patient with pseudotumors after short-stem metal-on-metal prosthesis. **(9A, B)** Coronal STIR SEMAC sequence shows intraosseous hypointense mass (circle) that is connected to a paratrochanteric soft tissue mass (circle) with similar morphology. **(9C)** The pseudotumors show finger-like extensions (circles) into the soft tissues that are visible on the axial T1-weighted turbo-spin echo sequence with high receiver bandwidth.



SEMAC CS-SEMAC

Figure 10: Compressed sensing SEMAC of total knee arthroplasty
Patella baja (low lying patella) due to arthrofibrosis in a 61-year-old patient with total knee arthroplasty (TKA). **(10A)** Sagittal intermediate-weighted image of the left knee with SEMAC [11 slice encoding steps, acquisition time 4:50 min] shows low lying patella (line and arrow) due to arthrofibrosis (asterisk), but residual through-plane artifacts at the level of the joint and the tip of the tibial peg (circles). **(10B)** Sagittal intermediate-weighted compressed sensing (CS) SEMAC image [15 slice encoding steps, acquisition time 4:22 min] is free of through plane artifacts and even faster than the standard SEMAC sequence.

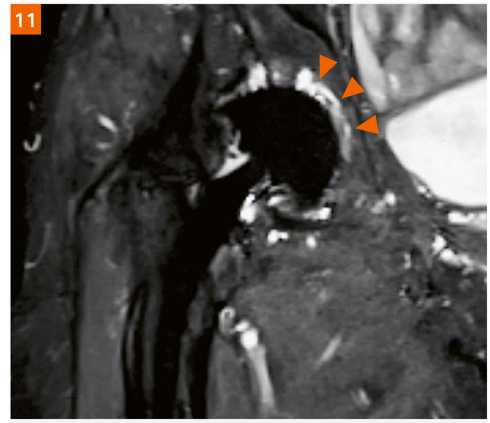


Figure 11: Compressed sensing SEMAC of total hip arthroplasty
Periprosthetic osteolysis (arrowheads) in a 66-year-old patient with painful total hip arthroplasty of the right hip. The compressed sensing (CS) SEMAC STIR sequence was acquired with 19 slice encoding steps, allowing for complete removal of through-plane artifacts and stable fat saturation with an acquisition time of 6:19 min.

Conclusion

Imaging joint replacements can be successfully done in clinical MRI if distortion from metal artifacts are reduced. In our experience, the quality of the MR images can be significantly improved using the following steps:

1. Increase the receiver bandwidth of the sequences. This simple and effective technique delivers improved diagnostic quality right away.
2. Use STIR instead of spectral fat saturation to gain a good overview of the pathology.
3. Acquire and utilize the advanced techniques such as *syngo* WARP and CS-SEMAC.

These reliable techniques will render a much clearer and, therefore, much more diagnostically powerful MR image. Not only does this make the MR suite a more valuable resource for the diagnosing physicians, but it also gives the patients the chance of better outcomes.

Contact

Reto Sutter, M.D.
Deputy Head of Radiology
University Hospital Balgrist
Forchstrasse 340
8008 Zürich
Switzerland
Tel.: +41 44 386 33 13
reto.sutter@balgrist.ch

References

1 Sutter R, Dietrich T. Reduction of metal artefacts in musculoskeletal imaging. Radiologie up2date 2016; 16(02): 127-144.
2 Sutter R, Ulbrich EJ, Jellus V, Nittka M, Pfirrmann CW. Reduction of metal artifacts in patients with total hip arthroplasty with slice-encoding metal artifact correction and view-angle tilting MR imaging. Radiology. 2012;265(1):204-14.
3 Kumar NM, de Cesar Netto C, Schon LC, Fritz J. Metal Artifact Reduction Magnetic Resonance Imaging Around Arthroplasty Implants: The Negative Effect of Long Echo Trains on the Implant-Related Artifact. Invest Radiol. 2017;52(5):310-316.
4 Ulbrich EJ, Sutter R, Aguiar RF, Nittka M, Pfirrmann CW. STIR sequence with increased receiver bandwidth of the inversion pulse for reduction of metallic artifacts. AJR Am J Roentgenol. 2012;199(6):W735-42.
5 Lu W, Pauly KB, Gold GE, Pauly JM, Hargreaves BA. SEMAC: Slice Encoding for Metal Artifact Correction in MRI. Magn Reson Med. 2009;62(1):66-76.
6 Jungmann PM, Bensler S, Zingg P, Fritz B, Pfirrmann CW, Sutter R. Improved Visualization of Juxtaprosthetic Tissue Using Metal Artifact Reduction Magnetic Resonance Imaging: Experimental and Clinical Optimization of Compressed Sensing SEMAC. Invest Radiol 2018; epub before print. http://doi.org/10.1097/RLI.0000000000000504
7 Fritz J, Ahlawat S, Demehri S, Thawait GK, Raithel E, Gilson WD, Nittka M. Compressed Sensing SEMAC: 8-fold Accelerated High Resolution Metal Artifact Reduction MRI of Cobalt-Chromium Knee Arthroplasty Implants. Invest Radiol. 2016;51(10):666-76.

Further reading

Jungmann PM, Agten CA, Pfirrmann CW, Sutter R. Advances in MRI Around Metal. JMRI.2017;46(4):972-991.