Compressed Sensing in Metal Hip Imaging: Our Experience

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Introduction

For end stage hip disease, total hip arthroplasty (THA) has become an attractive management option for many patients [1, 2]. While THA offers excellent pain relief and helps a majority of patients to regain some portion of day to day mobility, it is not without complications. About 40% of patients who undergo THA report groin and thigh pain [3, 4]. Despite the development in implant design, fixation approaches, and bearing materials, most prostheses eventually fail [5]. Given this, there is an increasing demand for more accurate diagnosis and visualization prior to hip revision.

Recently, magnetic resonance imaging (MRI) has become the imaging modality of choice for most clinicians to image potential THA-related complications[1] [6, 7]. In one imaging session, MRI can provide useful information about periprosthetic fractures, and osteolysis, postoperative hematoma, disruption of the pseudocapsule, synovitis caused by polyethylene wear and adverse local tissue reactions, periprosthetic masses, bursitis, tendinopathy, and neurovascular compromise [8]. However, MRI near metal comes with a well-known challenge, the susceptibility induced blooming artifact. This artifact hinders image quality and consequently diagnostic accuracy.

Magnetic susceptibility refers to the extent by which a substance is magnetised when exposed to the magnetic field. Different substances exhibit various degrees of magnetic susceptibility when exposed to a static magnetic field [9, 10]. Metallic objects have higher magnetic susceptibility than biological tissues. This induces severe spin dephasing (incoherence) around metallic implants and causes signal drop out and a form of image distortion [11].

In practice, using high bandwidth (BW), thinner slices, smaller field of view, finer matrix and imaging at lower magnetic fields are all helpful protocol adaptions to reduce the metal-induced artifact. However, these changes to the MR sequence lead to reduced signal to noise ratio (SNR) and often increased specific absorption rate (SAR). Therefore, practitioners tend to scan for longer times to mitigate the adverse effects associated with reducing the metal-induced artifact.

syngo WARP is a Siemens Healthineers solution that offers techniques to reduce susceptibility-related distortions. *syngo* WARP comprises

- Turbo Spin Echo (TSE) sequence optimized for imaging in the presence of metal implants
- "View Angle Tilting" or VAT and
- "Slice Encoding for Metal Artifact Correction" or SEMAC[2].

When VAT is added to a turbo spin echo pulse sequence, an additional gradient is applied in the data readout step to correct the in-plane distortion. However, only correcting for the in-plane distortion is not enough. Hence, the SEMAC option has been introduced. SEMAC offers through-plane distortion correction, similar to 3D imaging, where additional phase-encoding steps are added in the third dimension. This provides information on how the slice profile is distorted, which is used later to correct the distortion during the image reconstruction stage. Therefore, the more additional phase-encoding steps, the richer the slice profile, which enhances the distortion correction process. However, while adding additional phase-encoding steps helps in improving the image quality, it requires longer scanning time and additional postprocessing [12, 13].

What is promising is that one can use VAT and SEMAC simultaneously. That is, concurrently correcting

[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 Healthineers.

[2]SEMAC is part of the Advanced WARP package

for in-plane and through-plane metal-induced distortions. However, unlike VAT, SEMAC impacts the scan time dramatically, making the addition of SEMAC to every sequence impractical in clinical settings. However, publications have shown a clear diagnostic benefit of SEMAC protocols for hip and knee joint replacements [14–16]. As a solution to this problem, we present our experience with a "Compressed Sensing" technique for metal hip imaging and its added benefit in improving image quality and reducing scan times.

Although it is beyond the scope of this work to discuss the technical aspects of the Compressed Sensing (CS) technique, briefly CS refers to the ability to reconstruct the image-forming signals with fewer measurements (or samples) than what was classically thought necessary. Therefore, Compressed Sensing is a method to accelerate the MRI procedure by collecting less data (i.e., undersampling *k*-space) while maintaining image quality [17, 18].

[3] *Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

Methods

43 patients with total hip arthroplasty (THA) were scanned on a 48-channel 1.5T MAGNETOM Aera system (Siemens Healthcare, Erlangen, Germany). In addition to their clinical imaging protocol (which includes "VAT only" WARP), we acquired additional SEMAC and Compressed Sensing-SEMAC (CS-SEMAC)[3] sequences. The latter being a prototype provided by Siemens Healthineers. All imaging was performed using the 18-channel body coil. Table 1 shows the imaging parameters of these three implemented sequences.

Aim

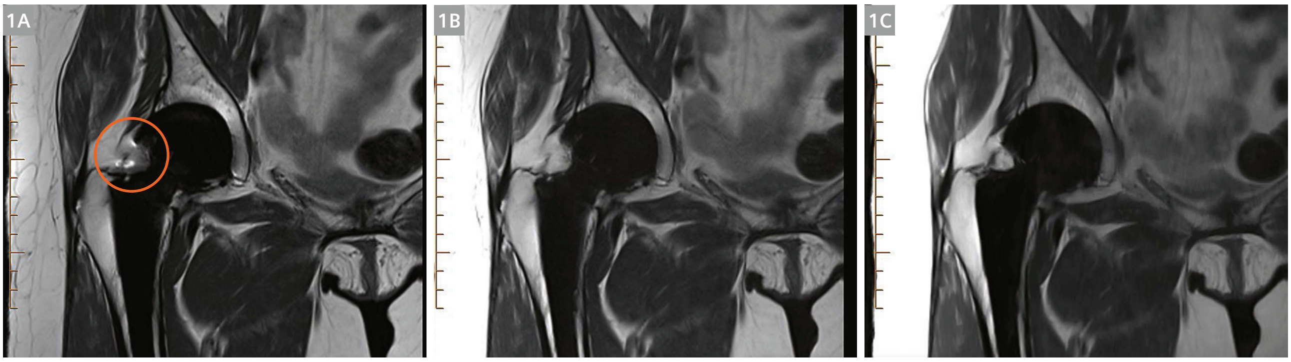
Combining VAT and SEMAC to achieve both in-plane and through-plane distortion correction is an attractive option; however, adopting such an approach is limited due to the long scan times. Leveraging Compressed Sensing (CS), we aim to explore whether CS-SEMAC[3] can offer improved image quality at reasonable imaging times.

Sequence	VAT only (default protocol)	VAT+SEMAC (12 PES)	VAT+CS-SEMAC (12 PES)	VAT+CS-SEMAC (20 PES)
Imaging plane	Coronal oblique	Coronal oblique	Coronal oblique	Coronal oblique
Image weight	Proton density	Proton density	Proton density	Proton density
Repetition time	2800 ms	2640 ms	3880 ms	3880 ms
Echo time	38 ms	32 ms	32 ms	32 ms
Field of view	240 mm	240 mm	240 mm	240 mm
Slice thickness	3.5 mm	3.5 mm	3.5 mm	3.5 mm
Matrix	320×256	320×256	320×256	320×256
Bandwidth	600 Hz	650 Hz	650 Hz	650 Hz
Flip angle	140	150	135	135
Averages	4	1	1	1
Turbo factor	15	14	21	21
GRAPPA	2	2	Off	Off
Compressed Sensing	Off	Off	On	On
VAT	**50%**	**100%**	**100%**	**100%**
SEMAC additional phase-encoding steps (PES)	**Off**	**12**	**12**	**20**
Echo spacing	7.56 ms	8.06 ms	8.06 ms	8.06 ms
Bandwidth	600 Hz/Px	650 Hz/Px	650 Hz/Px	650 Hz/Px
Scan time (minutes)	**03:20**	**06:50**	**02:50**	**04:25**

Table 1: Imaging parameters
VAT = View Angle Tilting; **SEMAC** = Slice Encoding for Metal Artifact Correction;
PES = Phase-encoding steps; **GRAPPA** = GeneRalized Autocalibrating Partially Parallel Acquisitions

Findings and discussion

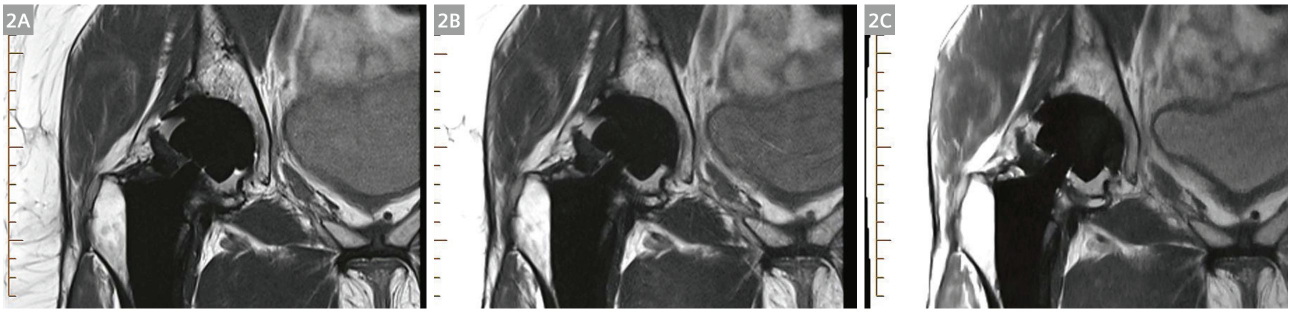
VAT-only versus SEMAC:



Sequence	Cor PD VAT-only (product)	Cor PD VAT+SEMAC (product)	Cor PD VAT+CS-WARP (WIP)
Quality	Image quality degraded by pile-up artifact (circled in orange).	Artifact reduced.	Artifact markedly reduced.
Time	03:20 min	06:50 min	02:50 min
Overall rating	Still suffers an artifact.	Good artifact reduction, but infeasibly long.	Reduced artifact and short scan time.

1 A 61-year-old female with right total hip arthroplasty (THA). The implant-associated artifact is relatively benign (i.e., relatively subtle susceptibility artifact). However, the VAT-only image (**1A**) shows signal "pile up" caused by the signal aggregation (circled in orange). While the use of the SEMAC sequence (**1B**) was helpful in reducing the "pile up" artifact significantly, the imaging time was unacceptably long in a busy clinical setting. The application of Compressed Sensing (**1C**) resulted in reduced artifact, excellent image quality, and shorter scan time.

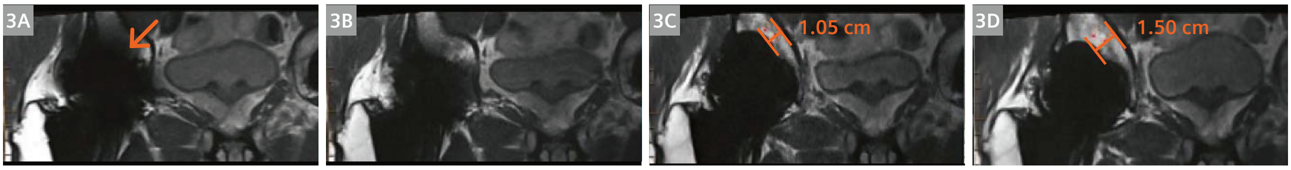
SEMAC "with motion" versus CS-SEMAC:



Sequence	Cor PD VAT-only (product)	Cor PD VAT+SEMAC (product)	Cor PD VAT+CS-WARP (WIP)
Quality	Image quality degraded by susceptibility artifact.	Susceptibility artifact with image blurring (due to patient movement).	Mild susceptibility artifact, without patient movement.
Time	03:20 min	06:50 min	02:50 min
Overall rating	Still suffers an artifact.	Patient was in pain and moved during this long scan. We decided not to repeat this scan.	Relative to the VAT-only scan, not only did we achieve better artifact reduction, but we saved 4 minutes by avoiding repeating the long VAT+SEMAC blurry scan.

2 40-year-old female with right total hip arthroplasty (THA). The patient was referred to MRI with right hip pain. The VAT-only image (**2A**) shows a minimal amount of metal-induced artifact in relation to the case in Figure 1. Image (**2B**), took nearly 7 minutes to acquire. Unfortunately the patient moved during this long scan, resulting in motion-degraded images. The Compressed Sensing VAT+SEMAC scan (**2C**) took just 02:50 minutes to collect and was better tolerated by the patient. This case shows the advantage of using Compressed Sensing in accelerating the scan while maintaining and improving image quality. This is especially important in cases where patients are uncomfortable and cannot remain still.

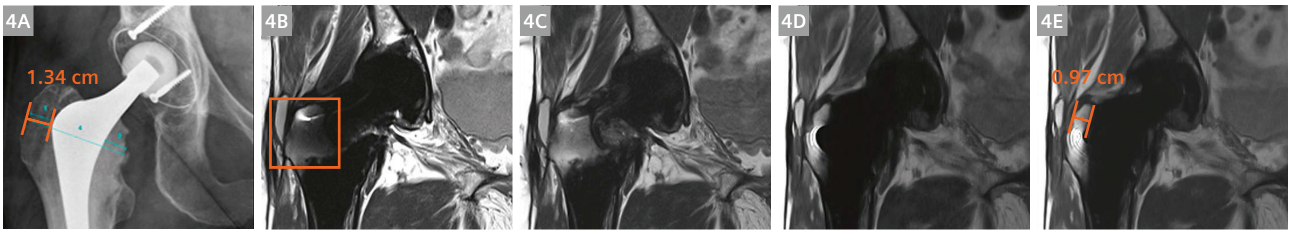
SEMAC versus CS-SEMAC:



Sequence	Cor PD VAT-only (product)	Cor PD VAT+SEMAC (product)	Cor PD VAT+CS-WARP-12 (WIP)	Cor PD VAT+CS-WARP -20 (WIP)
Quality	Severe susceptibility artifact.	Susceptibility artifact reduced.	Susceptibility artifact reduced, with recovery of pubic bone detail.	Susceptibility artifact reduced, with excellent pubic bone recovery.
Time	03:20 min	06:50 min	02:50 min	04:25 min
Overall rating	Still suffers an artifact.	Despite the artifact reduction, it is still infeasibly long.	Reduced artifact and short scan time.	The gain in near-metal visibility outweighs the 1.75 min extra time added, in our opinion.

3 59-year-old male with right cementless metal-on-metal total hip arthroplasty (THA). The patient enjoyed 8 years of excellent functional outcome after the THA. He was referred to MRI with right groin pain and clunking sensation. The implant-associated artifact is severe. Using the pubic bone as a reference (orange arrow), on the VAT-only image (**3A**), it is difficult to visualize the pubic bone due to the artifact impact on the image. On the VAT+SEMAC image (**3B**), despite the long scan time, only a slight improvement has taken place and the bone detail suffers significant distortion. Implementing CS-SEMAC with 12 phase-encoding steps (**3C**), the bone morphology normalises. Finally, using the CS-SEMAC sequence, we increased phase-encoding steps from 12 to 20 (**3D**); this resulted in a marked improvement in visualisation of the anatomy. When we compared CS-SEMAC-12 to CS-SEMAC-20 images, we achieved 70% morphology recovery (1.05 cm to 1.50 cm). In our opinion, the gain in image quality afforded by the CS-SEMAC-20 sequence outweighs the additional scan time (02:50 min to 04:25 min).

SEMAC versus CS-SEMAC:



Sequence	Hip Radiograph	Cor PD VAT-only (product)	Cor PD SEMAC (product)	Cor PD VAT+CS-WARP -12 (WIP)	Cor PD VAT+CS-WARP-20 (WIP)
Quality	The greater trochanter measures 1.34 cm.	Severe distortion of the greater trochanter (orange square).	Susceptibility artifact reduced, but the image still suffers an artificial bone distortion similar to the image in 4B.	Greater trochanter image quality improved, it measured 0.86 cm.	Further image quality improvement, with reduced artifact. The greater trochanter measured 0.97 cm.
Time		03:20 min	06:50 min	02:50 min	04:25 min
Overall rating		Still suffers an artifact with misleading greater trochanter measurement – induced by the artifact.	Still suffers an artifact with misleading greater trochanter measurement – induced by the artifact.	The addition of CS-SEMAC allowed for better artifact reduction and more realistic structural measurement around the implant.	Artifact reduction is shown to be directly associated with the number of phase encoding steps in the Compressed Sensing technique.

4 67-year-old female with right total hip arthroplasty (THA). The patient had two dislocations and was referred to MRI to rule out abductor dysfunction. While both the VAT-only and VAT+SEMAC scans (**4B & 4C**) were degraded by geometric distortion and susceptibility artifact, the Compressed Sensing scans (**4D & 4E**) demonstrated a great ability to reduce these artifacts. This resulted in marked improvement in periprosthetic image quality, with mild residual inherent artifact. In the CS-SEMAC scan, despite the increase in the scan time after increasing the number of phase encoding steps from 12 to 20, the gain in the image quality was clinically significant.

Conclusion

Imaging near metals is largely "implant" dependant – some implants induce significantly detrimental artifacts while others result in relatively minor distortion. The recent improvement in imaging techniques such as VAT and SEMAC allowed imaging professionals to correct for both in-plane and through-plane metal-induced artifacts, with a corresponding improvement in diagnostic accuracy. However, acquiring images with VAT and SEMAC combined prolongs the imaging time, which is impractical in many clinical settings.

In this work, we demonstrated the utility of Compressed Sensing (CS) SEMAC technique not only in reducing the scan time, but also in improving image quality. Artifact severity was inversely associated with the number of the phase-encoding steps performed in the Compressed Sensing approach – that is, increasing phase encoding steps reduced artifact severity, but at the expense of increased scan time.

The only challenge we have experienced during our usage of the CS WIP package was the image reconstruction time. While data acquisition is remarkably short, it took a few minutes for the images to reconstruct (on our scanner at least). The reconstruction time is proportional to the number of phase-encoding steps. This has changed completely with the product implementation, where optimized algorithms are exploiting the power of a reconstruction system specifically designed for CS calculations. In conclusion, we are impressed with the image quality and scan times achievable with the CS-SEMAC technique.

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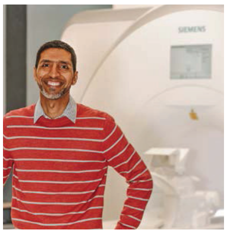

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