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FULL PAPER

Reducing metallic artefacts in post-operative spinal imaging: slice encoding for metal artefact correction with dual-source parallel radiofrequency excitation MRI at 3.0 T

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Objective: To compare the effects of metal artefacts and acquisition time among slice encoding for metal artefact correction (SEMAC), SEMAC with dual-source parallel radiofrequency (SEMAC-DSPRF) transmission and fast spin echo (FSE) images using 3.0-T MRI.

Methods: The signal-to-noise ratio (SNR) was calculated in a phantom study using a pedicle screw. A total of 16 patients who underwent spinal surgery using pedicle screws were included in the clinical study. T_1 weighted FSE, SEMAC and SEMAC-DSPRF images were obtained. Four imaging findings (visibility of the dural sac, neural foramina, bone-implant interface and overall artefacts) were evaluated by using five-point scales independently by two observers. The mean scan time was recorded.

Results: The mean SNR was 71.2, 25.7 and 28.4 for FSE, SEMAC and SEMAC-DSPRF images, respectively. FSE

images were ranked lower than SEMAC and SEMAC-DSPRF images, and ranking of SEMAC and SEMAC-DSPRF images did not differ statistically for all four imaging findings. The mean scan time was 9 min 51 s and 6 min 31 s for SEMAC and SEMAC-DSPRF images, respectively.

Conclusion: SEMAC can reduce metallic artefacts and improve the visualisation of anatomical structures around metal implants. An additional DSPRF technique can reduce the acquisition time of SEMAC images without the loss of SNR and image quality.

Advances in knowledge: This study demonstrates that the use of the DSPRF transmission technique can reduce the acquisition time of SEMAC images without loss of image quality in patients with metal implants.

Metal implants are commonly used in surgical procedures to fixate fractures, replace damaged joints or immobilise joints. However, many kinds of local complications associated with metal implants can occur. They include mechanical aseptic loosening, prosthetic or periprosthetic fracture, dislocation, superficial and deep infections, heterotopic bone formation and osteolysis. Such complications are a common source of patient morbidity and often necessitate revision surgery.

MRI is a commonly used imaging modality for musculoskeletal imaging because of its good, soft-tissue contrast. However, metal artefacts limit the usefulness of MRI for evaluation of disease in the presence of metal. Artefacts on MR images obtained in patients with metallic implants are produced by large differences between the magnetic properties of human tissues and those of the implanted metals. Differences in the magnetic susceptibilities of adjacent tissues and implants create local magnetic field inhomogeneities, altering the phase and frequency of local spins [1,2].

Much less severe artefacts are produced by implants made of titanium alloy than ferromagnetic implants made of stainless steel. In addition, metal artefacts may generally be decreased either by choosing a small voxel size, using a short echo time (T_E) or short interecho interval, or by increasing the sampling bandwidth [3]. Recently, the three-dimensional MRI technique, slice encoding for metal artefact correction (SEMAC), was developed [4]. The SEMAC technique corrects metal artefacts via robust encoding of each excited slice against metal-induced field inhomogeneities. The robust encoding is achieved by extending a view angle tilting spin echo sequence with additional z-phase encoding [5]. Several studies have demonstrated that SEMAC effectively eliminated metal artefacts [4–7]. However, a higher z-phase encoding resolution requires more z-phase encoding steps to maintain the same z-phase encoding the field of view (FOV), which leads to a longer scan time [5].

Recently, parallel radiofrequency (RF) transmission technology was commercialised. Parallel transmission describes

the use of multiple RF transmit coils that project multiple, independent RF transmit signals. It can reduce dielectric resonance effects at high field strengths and enable control of the RF distribution to optimise RF deposition [8]. As a result, parallel transmission can reduce the required RF power, *i.e.* the specific energy absorption rate (SAR). In addition, parallel transmission can be used to shorten the duration of spatially selective RF pulses, *i.e.* image acquisition time, or to increase their spatial resolution definition while maintaining the pulse duration [8].

Although SEMAC can reduce metal artefacts, long acquisition times may be a problem in its clinical application. If parallel RF transmission is combined with SEMAC to reduce acquisition time, clinical application of SEMAC could become more practicable.

The purpose of this study is to compare the metal artefacts and acquisition time among SEMAC, SEMAC with dual-source parallel RF (DSPRF) transmission and fast spin echo (FSE) images with 3.0-T MRI.

MATERIALS AND METHODS

Phantom study

A phantom study was performed by using a titanium alloy pedicle screw (8.0×45.0 mm) that is currently used for treatment at our institution. The phantom was constructed as a box (20×14×6 cm, cuboid in shape) with eight test tubes (diameter, 1.5 cm; length, 5.0 cm) containing diluted gadolinium

solution (Dotarem®; Guerbet Laboratories, Aulnay sous Bois, France; concentration, 0.004 mmol ml⁻¹). The screw was fixed in the centre of the box parallel to the bottom plate of the box. The box was filled with distilled water (Figure 1).

Clinical study

Our institutional review board approved this study. 16 consecutive patients (3 males and 13 females; age range, 41–76 years) who underwent spinal surgery using titanium alloy pedicle screws and had been scheduled for spinal MRI were enrolled. Patients who had any instrument using other metallic components were excluded.

MRI

MRI was performed with a clinical 32-channel whole-body 3.0-T MRI system (Achieva 3.0 T TX; Philips Healthcare, Best, Netherlands) equipped with DSPRF excitation and transmission technology and a 15-channel spinal coil for both the phantom study and the clinical study. MRI studies consisted of T_1 weighted FSE images, T_1 weighted SEMAC images and T_1 weighted SEMAC-DSPRF images in the phantom study. MR images were obtained parallel to the bottom of the box in the phantom study. For the clinical study, axial and sagittal conventional FSE images (pre-contrast T_1 weighted, pre-contrast T_2 weighted and post-contrast T_1 weighted images), post-contrast axial T_1 weighted SEMAC images and post-contrast axial T_1 weighted SEMAC-DSPRF images were acquired. The parameters of MRI for both the phantom study and the clinical study are summarised in Table 1.

Figure 1. Phantom study. (a) Photograph, (b) fast spin echo image, (c) slice encoding for metal artefact correction (SEMAC) image and (d) SEMAC-dual source parallel radiofrequency excitation image. The phantom study was carried out using a box consisting of eight tubes filled with diluted gadolinium solution (concentration, 0.004 mmol ml⁻¹). The screw was located in the centre of the box. The box was filled with distilled water. The signal-to-noise ratio of the fast spin echo images was higher than those of SEMAC and SEMAC-dual source parallel radiofrequency excitation images.

Table 1. MRI parameters

	Phantom study			Clinical study ^a		
	<i>T</i> ₁ weighted FSE	SEMAC	SEMAC-DSPRF	<i>T</i> ₁ weighted FSE	SEMAC	SEMAC-DSPRF
<i>T</i> _R (ms)	700	700	700	540	700	700
<i>T</i> _E (ms)	18	15	15	10	12	12
ETL	6	7	7	6	7	7
Bandwidth (Hz per pixel)	890	793	793	804	798	798
FOV (cm)	25	25	25	22	25	25
Section thickness (mm)	4	4	4	4	4	4
Image matrix	512×512	400×400	400×400	640×640	400×400	400×400
Number of signals acquired	3	1	1	3	1	1
Frequency encoding direction	R to L	R to L	R to L	AP	AP	AP
Imaging time (min:s)	3:06	12:53	8:36	3:24	9:51	6:1

AP, anteroposterior; DSPRF, dual-source parallel radiofrequency; ETL, echo train length; FOV, field of view; FSE, fast spin echo; L, left; R, right; SEMAC, slice encoding for metal artefact correction; *T*_E, echo time; *T*_R, repetition time.

^aAll the sequences are axial images.

ANALYSIS OF MR DATA

Phantom study

The image showing the middle of the screw was chosen to draw regions of interest (ROIs). ROIs were placed over four test tubes in the phantom. The size of the ROIs was 100 mm², which was the same in all images. The signal-to-noise ratio (SNR) was calculated by dividing the signal intensity from the ROIs that were placed over the test tubes by the mean background signal intensity, which was measured from the ROIs in artefact-free areas.

Metal artefacts were also compared between the three images. The central axial images were chosen for measurement of metal artefacts. The length of the short axis of the pedicle screw, including metal artefacts, was measured at the level of the mid-body. The number of section slices that were affected by metal artefacts was counted.

Clinical study

A musculoskeletal radiologist (with 8 years of experience in the interpretation of spinal MRI) and a senior resident assessed the quality of all images independently. The axial FSE images, the SEMAC images and the SEMAC-DSPRF images were evaluated in a random order. The readers were blinded to the scores of the corresponding previous images. A picture archiving and communication system (Centricity 2.0™; General Electric Medical Systems, Milwaukee, WI) was used. To minimise the learning bias, patients' information and the imaging parameters were hidden. There was a 3-week interval between the blinded interpretations.

Four imaging findings—visibility of the dural sac, visibility of the neural foramina, visibility of the bone–implant interface and

overall artefacts—were assessed with five-point scales. With the cross-reference function, axial images that were obtained at the level of the centre of the pedicle screws were selected for evaluation of visibility of the dural sac, visibility of the bone–implant interface and overall artefacts. Axial images just below the pedicles were selected for evaluation of visibility of the neural foramina. (a) The visibility of the dural sac was graded based on the following criteria [9]: Grade 0, no visible quadrant of the dural sac; Grade 1, one visible quadrant; Grade 2, two visible quadrants; Grade 3, three visible quadrants; and Grade 4, whole dural sac visible. (b) The visibility of the neural foramina was graded based on the following criteria: Grade 0, no visibility; Grade 1, only one of the bilateral neural foramina inferior to the screw was partially visible; Grade 2, bilateral neural foramina inferior to the screw were partially visible or one neural foramen was completely visible; Grade 3, one neural foramen was partially visible and one neural foramen was completely visible; and Grade 4, bilateral neural foramina were completely visible. (c) The visibility of the bone–implant interface was graded based on the following criteria: Grade 0, impossible to evaluate the bone–implant interface; Grade 1, it was possible to evaluate only one side; Grade 2, it was possible to evaluate two sides; Grade 3, it was possible to evaluate three sides; and Grade 4, it was possible to evaluate whole bone–implant interfaces. (d) The overall artefact was graded based on the following criteria [9]: Grade 0, no artefact-free quadrant; Grade 1, one artefact-free quadrant; Grade 2, two artefact-free quadrants; Grade 3, three artefact-free quadrants; and Grade 4, free of artefacts.

STATISTICAL ANALYSIS

Interobserver agreement for the four categories of imaging findings was assessed by means of weighted kappa values. The

kappa value was interpreted as follows: slight, <0.20 ; fair, $0.21-0.40$; moderate, $0.41-0.60$; substantial, $0.61-0.80$; and almost perfect, $0.81-1.00$ [10]. The Friedman two-way analysis of variance test was used to compare the mean individual grade scored by the two observers for T_1 weighted FSE images, SEMAC images and SEMAC-DSPRF images. Statistical analyses were performed with PASW® statistical software (v. 18.0; SPSS, Inc., Chicago, IL). A two-sided p -value of <0.05 was considered to be statistically significant.

RESULTS

Phantom study

The SEMAC images and the SEMAC-DSPRF images showed improvement in reducing the metal artefacts compared with the FSE images. The original short-axis diameter of the screw was 8 mm. The short-axis lengths of the pedicular screw, including metal artefacts, were 27.0 mm, 18.8 mm and 20.0 mm for FSE images, SEMAC images and SEMAC-DSPRF images, respectively (Figure 2). Both the upper and lower five section slices were affected by metal artefacts on FSE images, and both the upper and lower three section slices were affected by metal artefacts on both SEMAC images and SEMAC-DSPRF images. The mean SNR was 71.2, 25.7 and 28.4, and the scan time was 3 min 6 s, 12 min 53 s and 8 min 36 s for FSE images, SEMAC

images and SEMAC-DSPRF images, respectively. With the DSPRF transmission technique, image acquisition time decreased by 35%.

Clinical study

No patients underwent additional spinal surgery after MRI. In Table 2, a ranking of the three sequences (T_1 weighted FSE images, T_1 weighted SEMAC images and T_1 weighted SEMAC-DSPRF images) using the results of the Friedman test is shown. FSE images were ranked lower than SEMAC images and SEMAC-DSPRF images for all four imaging findings ($p<0.001$) (Figure 3). Interobserver agreement was fair or moderate for all four imaging findings (Table 2).

The mean scan time was 3 min 38 s for the T_1 weighted FSE images. The mean scan time was 9 min 51 s (range 8 min 51 s–13 min 2 s) and 6 min 31 s (range 4 min 21 s–8 min 51 s) for the SEMAC images and SEMAC-DSPRF images, respectively. To acquire 23 sections (coverage length of spine 23×4 mm), the scan time was 9 min 46 s and 6 min 31 s for the SEMAC images and SEMAC-DSPRF images, respectively. However, the upper four sections and the lower four sections were not suitable for image interpretation because the signal intensity was too low.

Figure 2. A 75-year-old female who underwent transforaminal lumbar interbody fusion and percutaneous transpedicle screw fixation 3 years ago. On (a) the fast spin echo image, about 50% of the dural sac is visible, and the bone-implant interface is not evaluable in all interfaces owing to metal artefact. On (b) slice encoding for metal artefact correction (SEMAC) and (c) SEMAC-dual source parallel radiofrequency (DSPRF) excitation images, both the dural sac and the bone-implant interface are clearly visible. Scores for visibility of the dural sac, visibility of the bone-implant interface and overall artefacts were 2, 0, 0 for the fast spin echo image and 4, 4, 4 for the SEMAC and SEMAC-DSPRF excitation images, respectively.

Table 2. Ranking of fast spin echo (FSE), slice encoding for metal artefact correction (SEMAC) and SEMAC-dual source parallel radiofrequency (DSPRF) with the results of the Friedman test

		FSE	SEMAC	SEMAC-DSPRF
Dural sac	Observer 1	1.57	2.17	2.27
	Observer 2	1.62	2.23	2.15
	kappa-value	0.453	0.441	0.546
Neural foramen	Observer 1	1.30	2.37	2.33
	Observer 2	1.13	2.40	2.47
	kappa-value	0.516	0.447	0.355
Bone-implant interface	Observer 1	1.38	2.45	2.17
	Observer 2	1.42	2.42	2.17
	kappa-value	0.325	0.350	0.389
Overall artefact	Observer 1	1.42	2.35	2.23
	Observer 2	1.12	2.38	2.50
	kappa-value	0.575	0.505	0.562

As a result, 15 effective sections were acquired. With the DSPRF transmission technique, image acquisition time decreased by 34%.

Figure 3. A 66-year-old male who underwent posterior lumbar interbody fusion with a metal interbody spacer and transpedicle screw fixation 8 years ago. On (a) the fast spin echo image, bilateral neural foramens are not visible owing to the metal artefact. On (b) slice encoding for metal artefact correction (SEMAC) images and (c) SEMAC-dual source parallel radiofrequency (DSPRF) excitation images, bilateral neural foramens are clearly visible. Scores for visibility of the neural foramen was 0, 4 and 4 for the fast spin echo, SEMAC and SEMAC-DSPRF excitation images, respectively.

DISCUSSION

In our study, we demonstrated that the metal artefacts were decreased and the visibility of anatomical structures such as the dural sac, neural foramen and bone-implant interface in the post-operative spine was improved by using the SEMAC technique. The main purpose of MRI after spinal surgery is to evaluate the post-operative complications, such as haematomas, infection, aseptic loosening and osteonecrosis, and whether there is any disease recurrence. Therefore, our results are meaningful because improved visibility of anatomical structures may enable better evaluation of the post-operative spine. In addition, the DSPRF transmission technique combined with the SEMAC technique reduced image acquisition time by 35% without loss of SNR and image quality. This result is important because reduced imaging time may minimise discomfort in patients who have undergone spinal surgery.

In DSPRF transmission mode, the RF pulses have higher peak B_1 values, so the fat saturation, excitation and refocusing pulses take less time, which lowers the SAR since the SAR is a time-averaged result. In addition, in DSPRF transmission mode, a different SAR model is applied that assumes better control over the local SAR. This assumption is justified because of the optimisation of the B_1 field from the calibration data for adaptive shimming. The SAR model for conventional quadrature RF transmission is very conservative in the permitted energy transmission because of the possibility that local SAR peaks, or hotspots, will exceed safety limits. The optimisation of the B_1

shimming can reduce these local peaks in deposited energy. Once the SAR is lower, a shorter repetition time (T_R) is possible, and the number of slices within a T_R can be increased, so that the 15 slices divide into two packages of 8 and 7 slices, rather than having to be split into three packages of five slices. This is the mechanism by which DSPRF transmission mode can reduce the scan time.

Except for simple modifications to pulse parameters, several imaging techniques, such as single-point imaging [11], projection reconstruction acquisitions [12], pre-polarised MRI [13] and view angle tilting [14], have been developed to reduce the metal artefact in MRI. However, they are not widely used in clinical practice because they have several limitations [7]. On the other hand, two novel techniques, multi-acquisition variable-resonance imaging combination [15–17] and SEMAC have shown great potential in enabling clinical imaging near metal implants in previous studies. However, they also have problems that need to be resolved. One of them is the relatively long acquisition time. Separately, a recent study demonstrated that the DSPRF excitation technique accelerated MRI at 3.0 T [18]. To our knowledge, our study is the first to combine the two techniques of SEMAC and DSPRF.

Our study showed that the SEMAC technique reduced metal artefacts. However, SEMAC images have lower spatial resolution than conventional FSE images. FSE images provide greater detail of soft tissues away from the metal, such as of back muscles. Therefore, we do not think that the SEMAC technique can replace

the use of FSE sequences, but it can give additional information in the assessment of spinal surgery with metallic implants, especially of anatomical structures or diseases adjacent to metallic implants.

Our study has several limitations. First, it was impossible to blind the observers to the type of image being assessed because of the marked difference in the image quality between the FSE images and the SEMAC images with or without the DSPRF transmission technique. Second, our scoring methods to evaluate the visibility of anatomical structures are rather subjective. However, we calculated interobserver agreement to overcome this problem, and the results revealed moderate or substantial agreement. Third, we did not evaluate pathological conditions owing to the small study population. Therefore, it remains unclear whether the SEMAC technique can improve the diagnosis of diseases under clinical circumstances or not. Fourth, we did not correlate the imaging findings with surgical findings, because none of the included patients underwent further surgery after MRI. Finally, we used a 3-T MRI system because the DSPRF transmission technique is commercialised for only a 3-T MRI system.

CONCLUSION

SEMAC can reduce metallic artefacts and improve the visualisation of anatomical structures around metal implants. With the addition of the DSPRF transmission technique, the acquisition time of SEMAC images without loss of SNR and image quality can be reduced.

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