Imaging Near Metals with Phase Cycled SSFP

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Introduction Inhomogenous B_0 magnetic fields obscure MR image clarity near metals with geometric distortion, signal loss, and signal pile-up artifacts. Prevalent correction methods are incapable of complete artifact elimination, and require long scan times as they employ spin-echo (SE) sequence variants to maintain independence of T_2* effects [1,2]. Despite their standard classification as gradient echo sequences, balanced steady state free precession (bSSFP) sequences refocus magnetization to an extent comparable to SE sequences [3]. When combined with 3D imaging, bSSFP is optimal for imaging near metals. Scan time is short, and bSSFP's strong gradients generate high image resolution and minimal distortion, signal loss, and signal pile-up artifacts. 3D imaging has intrinsic distortion immunity along two dimensions of phase encoding, reduced signal loss through slab selection, and high SNR.

Unfortunately, bSSFP imaging suffers from signal nulls (banding artifacts) due to phase dispersion between RF pulses. Phase cycling can spatially shift the bands by incrementing the phase of successive RF pulses of the bSSFP pulse train by an angle $\Delta\theta$. Many methods combine images phase cycled at variable values of $\Delta\theta$ [4-6], but residual artifacts remain, especially in regions of high magnetic field inhomogeneity. A new Cross-Solution (XS) technique is proposed which derives an unbanded image from the magnetization expressions of four phase-cycled bSSFP images [7].

Fig. 1: Superimposed hip prosthesis is actually located within the Lego structure

Methods The imaging phantom consisted of a Zimmer™ (Warsaw, IN) ASTM F75 Cobalt-Chromium-Molybdenum alloy hip prosthesis encased in a Lego™ (Billund, Denmark) structure (Fig. 1), secured within a bottle of water using sponges. It was imaged within the body coil of a 1.5T Siemens Magnetom Avanto scanner using a 3D TrueFISP (bSSFP) pulse sequence. 52x3mm slices were acquired using flip angle: 41°, TR: 4.2ms, and TE: 2.1ms.

$$M = \frac{(x_1y_3 - x_3y_1)(I_2 - I_4) - (x_2y_4 - x_4y_2)(I_1 - I_3)}{x_1y_2 + x_2y_3 + x_3y_4 + x_4y_1 - x_1y_4 - x_4y_3 - x_3y_2 - x_2y_1} \quad (1)$$

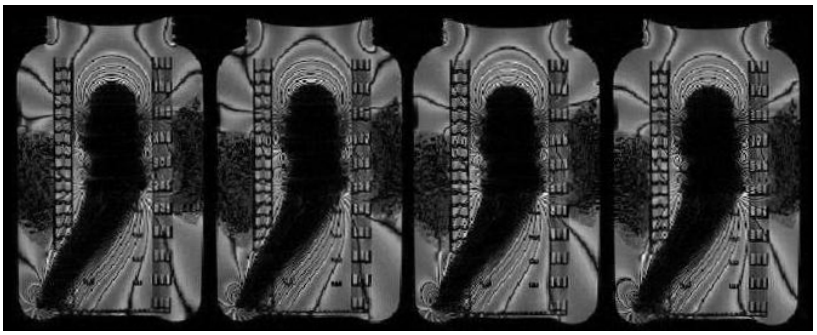

Fig. 2: 3D TrueFISP images with 0°, 90°, 180°, and 270° phase-cycling (left to right)

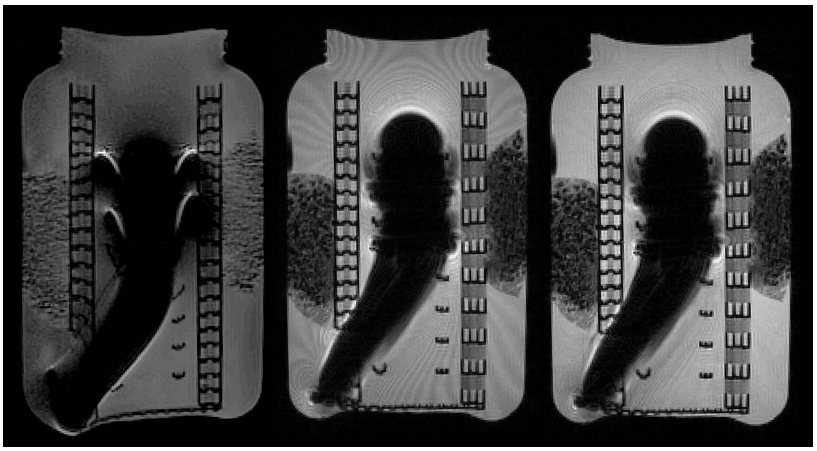

Fig. 3: 3D Turbo Spin Echo (SE) image

Fig. 4: 3D WC-SSFP reconstruction

Fig. 5: 3D XS-SSFP reconstruction

Complex phase cycled TrueFISP images were acquired with $\Delta\theta$ = 0°, 90°, 180°, and 270° for each image I_j, where j = 1,2,3, and 4 respectively (Fig. 2). Real components x_j and imaginary components y_j of each image I_j were input into Eq.(1) for calculation of the demodulated transverse magnetization M on a pixel-by-pixel basis. SNR was improved through a second pass solution, as in [8]. See [7] for further background and a novel geometric interpretation of the Cross-Solution.

Results Fig. 3 shows an SE image from the same location as the original TrueFISP images. Fig. 4 shows the reconstruction of the TrueFISP images using a p = 1 Weighted Combination bSSFP (WC-SSFP) [6] image combination algorithm. Fig. 5 depicts the image reconstructed using XS-SSFP. The frequency encoding gradient (FE) direction is vertical for Fig. 3-5. It is difficult to visually determine the FE direction in Fig. 4 & 5, since these images were acquired with strong bSSFP gradients which mitigate image distortion, signal loss, and signal pile-up relative to SE images. XS-SSFP adds the ability to eliminate banding artifacts, although some signal loss surrounding the implant still remains.

Discussion Total scan time was 2.5 minutes for the four 52-slice TrueFISP datasets. A smaller FOV would require even less scan time. XS-SSFP is also easy to implement: since $\Delta\theta$ may be altered directly in the scanner's protocol editor, TrueFISP sequence programming is unnecessary. Most importantly, XS-SSFP demodulates the signal completely, yielding band-free images. Future directions include testing the sequence at higher magnetic fields, and on metals with greater magnetic susceptibility. Other techniques such as 3D-PLACE [1] will be integrated with XS-SSFP in order to eliminate any residual image distortion.

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