Phase Correction for 3D Fast Spin Echo Imaging With Compressed Sensing

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Introduction: Fast spin echo (RARE, FSE, or TSE) (1) imaging plays a central role in clinical imaging. 3D FSE (2) is gaining interests in the field these days due to its improved spatial coverage and the ability to reformate images into arbitrary plane. FSE sequences rely on CPMG condition during imaging. Eddy current and other factors, however, can introduce phase error in FSE sequences, which causes the violation to CPMG condition and result in image artifacts. Such phase error is more sever when imaging at off isocenter. Consequently, phase correction is critical for FSE imaging at off isocenter. The existing phase correction method (3) works well for 2D FSE, which assumes a linear phase error along readout direction. However, to extend this approach to 3DFSE, we may need assume a linear phase error along both readout and slice direction (4-5), which may not always be the case. Data acquisition with phase cycling (6) can be used to address this problem at the cost of doubled scan time. In this work, we investigated compressed sensing acceleration of data acquisition for 3DFSE phase correction using phase cycling.

Theory and Method: In FSE sequences, the spins at each echo can be categorized into two groups based on the parity of the times their phase has been inverted. The CPMG condition causes constructive interference between these two groups of spins, whereas the violation of it causes destructive interference. Phase cycling methods (7) can be used to realign the phase of these spins when the CPMG condition is violated. Based on this principle, we collect both CPMG and CP data sets and then combine them in reconstruction to correct phase error artifacts. The approach we developed is robust at the presence of non-linear term of phase error, however, with cost of doubled scan time. To reduce scan time, we accelerate data acquisition using EPIRIT (7) and then integrate it with phase correction to correct both phase error and aliasing artifacts (Fig 1). Both CPMG and CP data can suffer from signal loss due to phase error, which can result in suboptimal reconstruction if we apply ESPIRIT directly on each of them. In the proposed method, we apply phase correction to the two calibration data sets from CPMG and CP to generate an artifact-free composite calibration data set. This calibration data is then used to estimate sensitivity maps based on eigenvector computations. The under-sampled k-space data for both CPMG and CP were synthesized by enforcing signal sparsity in wavelet coefficients and sensitivity iteratively, as described in ESPIRIT (7). The reconstructed CPMG and CP data sets are combined using phase correction algorithm to form a final image.

The in vivo data sets were collected from a Discovery MR750 3T scanner (GE Healthcare, Waukesha, WI) using a trans-receive 8-channel knee coil (Invivo Inc., Gainesville, FL). The imaging parameters include: TR/TE 800/14.4ms, FOV 20×16cm, 136 slices with 1mm thickness, ETL 45, BW ±62.5kHz, image matrix 256×206. For evaluation purpose, we collected fully sampled data and then under-sampled it in k-space to emulate data acquisition with different acceleration factors. The under-sampled data were reconstructed using the proposed method and also a conventional data driven parallel imaging method (8). For parallel imaging and ESPIRIT, we used typical Cartesian under-sampling and Poisson disc under-sampling pattern (9), respectively.

Results and Discussion: Figure 2 and 3 show the in vivo results. Note the visible shading artifacts (solid arrows) on 3DFSE images. Both conventional parallel imaging and the proposed method achieved good image quality at 4X acceleration. At 6X acceleration, the conventional parallel imaging produced visible aliasing artifacts (dashed arrows), whereas the images from the proposed method show much reduced artifacts level. The two acquisition approach used for phase correction does increase SNR compared to single 3DFSE acquisition. Such SNR gain can be used to further reduce scan time by adjusting pulse sequence parameters. Other than EPSIRIT, other recon methods can also be used in the proposed method for 3DFSE phase correction.

Conclusion: 3D FSE imaging can be challenging at off-isocenter due to the risk of violation of CPMG condition. We demonstrated that phase cycling methods can be combined with accelerated data acquisition to achieve robust 3DFSE imaging without significant increase of scan time.

Reference: 1. Hennig et al MRM 1986 p823 2. Busse et al MRM 2008 p640 3. Hinks et al US patent 6,160,397 4. Granlund et al ISMRM 2012 p3382 5. Granlund et al ISMRM 2011 p2822 6. Zur et al JMR 1987 p212 p212 7. Lai et al, ISMRM, 2010, p345 8. Brau et al, MRM 2008, p382 9. Lustig et al, ISMRM, 2009, p334

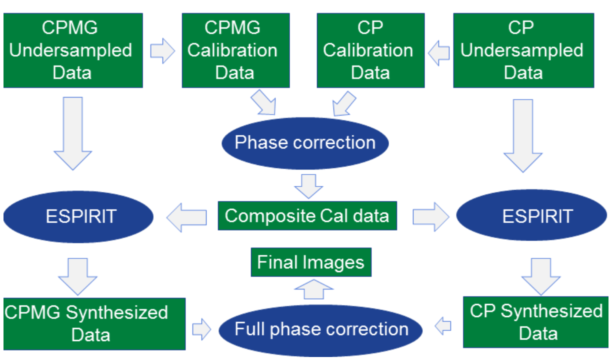

Figure 1: The proposed recon algorithm.

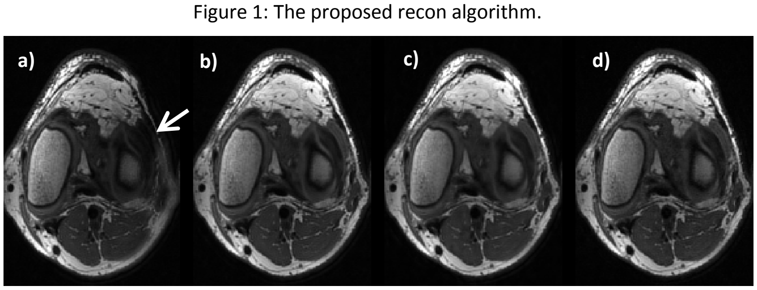

Figure 2: a) fully sampled 3DFSE. White arrow indicates phase error artifacts. b) CPMG+CP acquisition for phase correction with doubled scan time. c) Proposed method, and d) conventional parallel imaging at 4X acceleration.

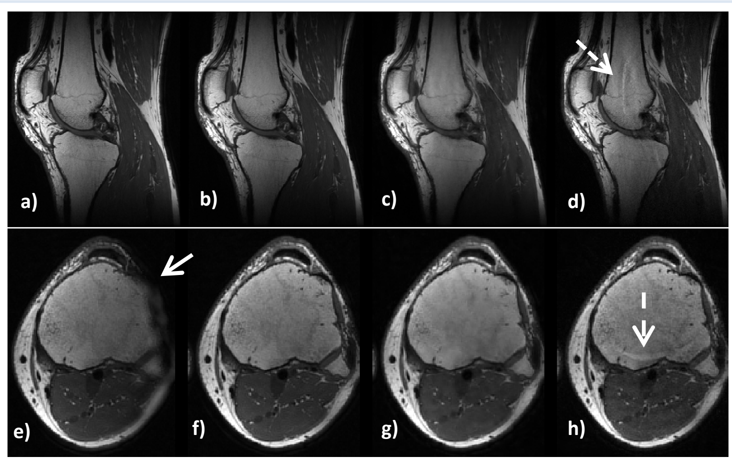

Figure 3: a,e) fully sampled 3DFSE. White arrow indicates phase error artifacts. b,f) CPMG+CP acquisition for phase correction with doubled scan time. c,g) Proposed method at 6X acceleration, and d,h) conventional parallel imaging at 6X acceleration. Note residual aliasing.