k-Space Based Multicoil Phase Correction and Reconstruction for Multishot Diffusion Weighted Imaging

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Introduction: Motion sensitivity induced by strong diffusion encoding gradients used in diffusion weighted imaging (DWI) can cause severe phase variations in image space. Multishot EPI has the potential to provide high resolution DW images, but is susceptible to ghosting artifacts due to such intershot phase variations. Conventional correction methods measure the intershot phase errors with a low resolution image and subtract the phase error from each shot [1]. This effectively convolves k-space with a kernel that is equivalent to the Fourier transform of the conjugate of the phase error. While this is effective for regions of k-space sampled at the Nyquist rate, multishot acquisitions have undersampled outer regions of k-space that cannot be perfectly corrected with this method. Applying a conventional parallel imaging (PI) method such as SENSE or GRAPPA could potentially exacerbate the resulting artifacts. Recently, an iterative conjugate gradient (CG) algorithm [2] based on Generalized SENSE reconstruction [3] has applied parallel imaging reconstruction concepts to combined multicoil phase correction and reconstruction for DWI. However, k- and hybrid-space based PI reconstructions [4, 5] have demonstrated robustness against aliasing artifacts [6], which would be advantageous for multishot diffusion acquisitions when coil sensitivity maps are difficult to generate. Here we present a novel k-space based correction of intershot perturbations and compare it with the CG image-based approach.

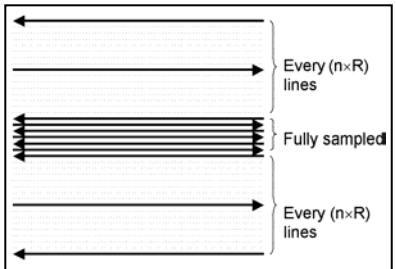

Figure 1. Variable Density EPI

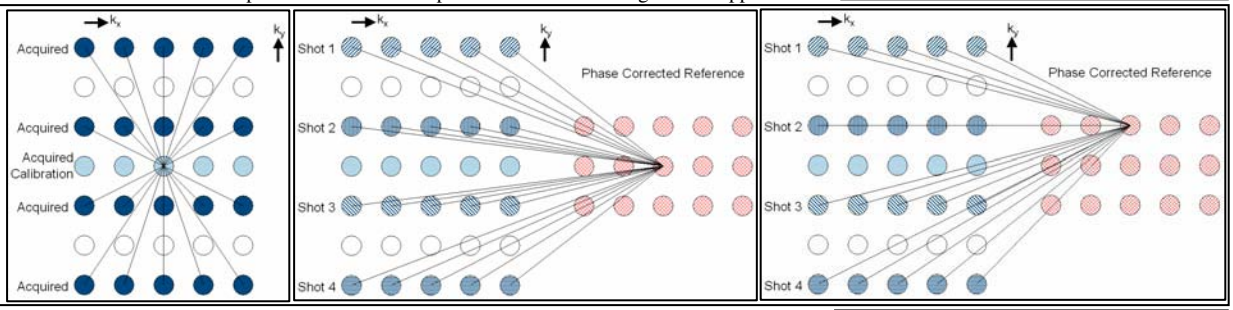

Figure 2. Multicoil k-space correction method. a) For PI, acquired cal lines provide target points. b) For shot to shot phase correction, a corrected reference serves as target. c) Acquired lines are also resynthesized.

Methods: A multishot DW EPI pulse sequence was designed to fully sample the center 1/8 of k-space at the Nyquist rate for each shot. Echo train shifting of the undersampled outer portions was applied to reduce discontinuities from T2* magnitude scaling and phase evolution of off-resonance spins. For PI, the outer portions were undersampled further by a reduction factor R=2 to reduce ETL. Volunteer images were acquired with this sequence on a clinical 1.5T whole body scanner (GE Signa Excite, GE Healthcare Technologies, Waukesha, WI). Imaging parameters were: TR = 3000 ms, TE = 120 ms, BW = +/- 100 kHz, FOV = 24 cm, matrix = 128x128, slice thickness = 5 mm, b = 0 and 500, diffusion weighting directions = 3, number of shots = 4, peripheral cardiac gating active. For all acquisitions, sampling was restricted to the readout gradient plateaus to simplify image reconstruction.

All multishot image reconstructions were performed offline (Sun Microsystems, Santa Clara, CA) using Matlab (Version 7, The Mathworks, Inc., Natick, MA). Using the central portions of k-space, data acquired without diffusion weighting gradients were used to generate self-calibrated sensitivity maps [7], and phase error maps for each shot were generated by multicoil combination of phase differences between data acquired with and without diffusion weighting gradients. The CG method was then applied to the acquired data using the calculated sensitivity and phase error maps.

The same raw data were also reconstructed with a two-part correction algorithm. First, phase error along the readout direction was estimated for each shot by summing the magnitude weighted phase error along the phase encoding direction, and each k-space line acquired in the corresponding shot was corrected for this error. Second, the k-space correction algorithm was applied on this partially corrected data. Phase correction was integrated with PI reconstruction, so all lines were synthesized. Phase corrected autocalibration data were created by subtracting the low resolution phase error from each shot, and this data were averaged over all shots to produce a fully corrected low resolution reference. During the training phase, coil weights were computed to fit blocks measuring four ky lines by five kx points to target points on the phase corrected reference. Since lines were interleaved by shot in the accelerated regions of k-space, data in the block was likewise filled with lines from the various shots from the autocalibration region. Unacquired lines may lie in one of four possible positions in relation to the shots, and separate reconstruction kernels were generated for each position. Unique reconstruction kernels were also generated for lines acquired in each of the four shots, but with an asymmetric block as shown in figure 2c. The eight kernels covered the full rotation of line positions in the outer parts of k-space, such that every eighth line in the outer part of k-space was synthesized with the same kernel. The central part of k-space was filled by the phase corrected reference data. After this reconstruction was applied for all coils, the resulting coil images were combined with a sum of squares.

Results: In-vivo images are shown in figure 3. Very little ghosting artifact was observed in images reconstructed with either the CG method or k-space based method. Background artifacts in the k-space based method were mainly localized along the phase encoding direction relative to the anatomy, while artifacts in the CG method were spread throughout the image. In general, any ghosting was incoherent, resembling noise.

Discussion: A k-space based algorithm performs excellent correction and reconstruction of intershot perturbations from multishot DW EPI by synthesizing k-space data at each point in the reconstruction matrix. Ideally the block size should cover the k-space spread caused by the phase error. Hence, the use of larger blocks could potentially improve phase correction, and may be essential for higher b-values or areas with greater potential motion. Both algorithms assume that the center of k-space provides an accurate low-resolution representation of the true image, and proper even-odd line phase corrections for EPI must be applied to the data before the described reconstruction to eliminate potential errors from underlying N/2 ghosting.

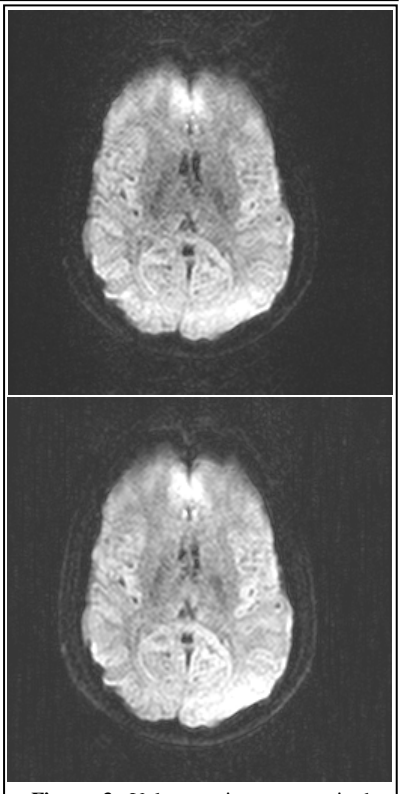

Figure 3. Volunteer images acquired with VD-EPI and reconstructed using a) the k-space based algorithm and b) the CG algorithm. Window levels are adjusted to display some of the background noise and artifacts.

References: 1. Miller K et al, MRM 50:343-353. 2. Liu C et al, MRM 54:1412-1422. 3. Pruessmann KP et al, MRM 46:638-651. 4. Griswold MA et al, MRM 47:1202-1210. 5. Brau AC et al, Proc 14th ISMRM (2006), p2462. 6. Beatty PJ et al, Proc 14th ISMRM (2006), p2467. 7. McKenzie CA et al, 47:529-538.