Nyquist Ghosting Correction For Simultaneous Multislice Echo Planar Imaging

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Purpose: In simultaneous multislice (SMS) echo planar imaging (EPI), the ghosting artifacts are usually corrected using either the measured eddy current effects from one slice location (single-slice correction) or the effects averaged over all simultaneous slices (slice-averaged correction). These methods cannot accurately correct each individual slice since the eddy current effects vary in the slice direction [1]. Here we propose a matrix-decoding ghosting correction for SMS EPI, which suppresses the ghosting artifacts in each individual slice to the same level as in standard single-slice EPI.

Methods: EPI eddy current effects are well represented by perturbations in the 0th and 1st-order magnetic field, corresponding to a k_x shift and phase modulation of echoes. Nyquist ghosting artifacts occur due to alternating eddy current effects for odd and even echoes. These k-space echo variations correspond to a linear phase ramp weighting along x (Fig. 1). In standard single-slice EPI (Fig. 1a), this phase weighting can be written as $\theta(x, k_y(n)) = a(n)x+b(n)$, where n is the echo index. In SMS EPI, data is acquired in 3D k-space with k_x fully sampled and the k_y-k_z plane undersampled [2]. The linear phase weighting can be written as $\theta(x, k_y(n), k_z(n), z) = a(n, z)x+b(n, z)$, where z is the slice index. θ can be estimated from a reference scan with all phase encoding gradients turned off [3]. The first step of the matrix-decoding ghosting correction is to conduct an inverse FFT along k_x to transform the 3D k-space data into x-k_y-k_z space. Two scenarios are then considered.

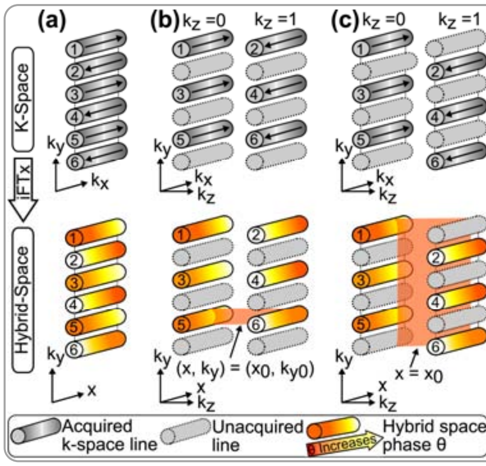

Fig. 1. Eddy current effects introduce echo shift and alternating phase modulation to EPI k-space data(upper row), which correspond to linear phase ramp weighting along x(lower row). Numbers on the acquired lines represent echo indices. (a) Standard single-slice EPI; (b) SMS EPI with fully sampled k_z and uniformly under-sampled k_y; (c) Blipped-CAIPI SMS EPI.

Scenario 1: k_z is fully sampled. This includes both rectilinearly undersampled (Fig. 1b) and fully sampled SMS EPI. In this case, each acquired point (x_0, k_{y0}) in the x-k_y plane corresponds to N_s acquired points along k_z, where N_s is the number of simultaneous slices. The measured signal in the x-k_y-k_z space is

$$s(x_0, k_{y0}, k_z) = \sum_z m_1(x_0, k_{y0}, z)\, exp(-i2\pi k_z z/N_s)\, exp(i\theta(x_0, k_{y0}, k_z, z)).$$

m_1 is the signal in x-k_y-z space and θ is the eddy current induced phase. m_1 is the only unknown in the signal equation and can be found by inverting the known encoding matrix. After finding m_1 for each acquired point on the x-k_y plane, either a SENSE [4] or a GRAPPA [5] reconstruction can be conducted to recover any missing k_y lines.

Scenario 2: Arbitrary k_y-k_z sampling pattern, including patterns both with and without fully sampled k_z. This includes the blipped-CAIPI acquisition (Fig. 1c) [6]. In the x-k_y-k_z space, each point x_0 along x corresponds to an undersampled k_y-k_z plane. The measured signal in the x-k_y-k_z space is

$$s(x_0, k_y, k_z, c)=\sum_y\sum_z m(x_0, y, z)\, S_c(x_0, y, z)\, exp(-i2\pi(k_y y/N_y+k_z z/N_s))\, exp(i\theta(x_0, k_y, k_z, z)),$$

where c is the coil index, N_y is the matrix size in y, m is the magnetization of the simultaneous slices, S_c is the receive sensitivity of the c^{th} coil, and θ is the eddy current induced phase. m is the only unknown in the signal equation and can be found using the pseudoinverse of the known encoding matrix. By finding m for each point in x, the ghosting artifacts in the individual slices are accurately corrected while a SENSE reconstruction is conducted.

Results: Fig. 2 displays two simultaneous slices in a SMS EPI acquisition. A region of interest (ROI) containing the residual ghosting artifacts in the background is picked for each image. The signal variance in each ROI is calculated and then normalized by the ROI variance in the first image. A smaller value of the normalized variance (numbers in Fig. 2) indicates lower energy in the residual ghosting. Fig. 3 compares the performance of three ghosting correction methods in a whole-brain acquisition.

Discussion: The matrix decoding method achieves comparable eddy current correction for SMS acquisitions as for single-slice acquisitions. This method outperforms either slice-averaged or single-slice reference correction method.

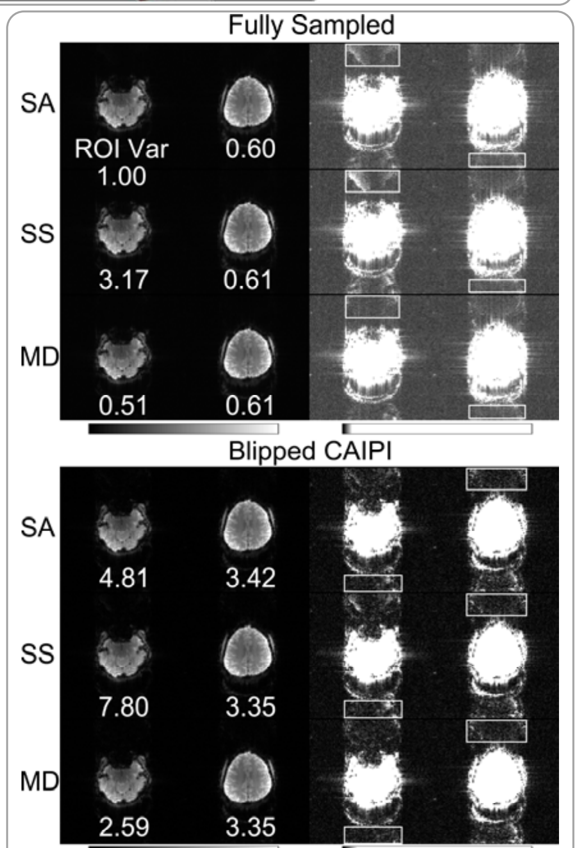

Fig. 2. Each row displays two simultaneous slices acquired at 3T, and the same images windowed down to show the ghosting and background noise. Each data set is processed three times, with the ghosting artifacts corrected by the slice-averaged (SA), the single-slice (SS) and the proposed matrix-decoding (MD) correction, respectively. Numbers show the normalized signal variances in the ghosting ROIs (rectangles). k_x, k_y and k_z are all fully sampled in the fully sampled data set. The blipped-CAIPI data are reconstructed by SENSE. The SS method performs well only on the 2nd slice because it uses the eddy current effects at the 2nd slice.

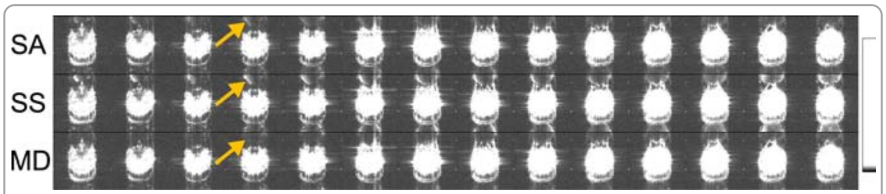

Fig. 3. 14 windowed down images out of 27 slices from the 1st band in a fully sampled simultaneous two-slice data set acquired at 3T. The data set is processed 3 times with the slice-averaged (SA), the single-slice (SS), and the matrix-decoding (MD) ghosting correction, respectively. Regions containing residual ghosting (arrows point to examples of such regions) exhibit the lowest signal with MD correction.

References: 1. Setsompop K. et al. Neuroimage. 2012; 63:569-580. 2. Zhu K. et al. ISMRM. 2012:p.518; 2013:p.125. 3. Bruder H. et al. MRM. 1992; 23:311-323. 4. Pruessmann KP. et al. MRM. 1999; 42:952-962. 5. Griswold MA. et al. MRM. 2002; 47:1202-1210. 6. Setsompop K. et al. MRM. 2012; 67:1210-1224.