Phase Correction in Bipolar Multi-Echo Water-Fat Separation for Off-Isocenter Imaging

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Introduction: Traditional three point Dixon techniques [1,2] acquire one echo per TR, which leads to prolonged scan times. To achieve better SNR efficiency and reduced motion artifact levels, bipolar multi-echo sequences [3,4] have been proposed to acquiring multiple echoes with alternating readout gradients. However, the alternating readout polarity leads to a phase discrepancy between even and odd echoes, and imaging artifacts induced by field-inhomogeneity and chemical shift, which can cause failure of water-fat separation. Imaging artifacts are well addressed by shifting the up-sampled image based on estimated field-map (image warping), and k-space water-fat separation as suggested in [4]. Although various techniques [3-5] have been developed for linear phase correction in bipolar sequences before field-map estimation, the application for off-isocenter imaging is further complicated by timing differences between acquisition and frequency-offset waveforms, which can lead to a large constant phase error between echoes of opposite polarity. This work uses a reference scan [6,7] to corrects both constant and linear phase errors, so that accurate water-fat separation could be achieved at any scan location, including off-isocenter.

Methods: The reference scan acquires data with the phase encoding gradients off, and is repeated twice with the opposite readout polarities, as shown in Fig.2. The reference scan provides the following signal modeling at the nth echo: (n= 1,2,3)

Baseline1 $S_{n,1}(x) = S_n(x) \cdot e^{j\phi_0} \cdot e^{j\alpha_n x}$ (1)

Baseline2 $S_{n,2}(x) = S_n(x) \cdot e^{-j\phi_0} \cdot e^{-j\alpha_n x}$ (2),

where $S_n(x)$ includes phase variations from coils and echo time, $e^{j\phi_0}$ is the constant phase, and $e^{j\alpha_n x}$ is the linear phase, both arising from eddy currents and timing delays between acquisition, gradients and frequency offset waveforms. Although the constant phase error, denoted by ϕ_0, is negligibly small in isocenter imaging, it is often substantial in off-isocenter imaging, and should be removed throughout the baseline projections. As described in Fig.2, for phase correction, the phase difference between (1) and (2) is formed as $(S_{n,1}(x) \cdot S_{n,2}(x)^*)$ for the nth echo, yielding the phase equation, $\theta(x) = 2\phi_0 + 2\alpha_n x$ (3). Next, phase unwrapping is executed after a masking operation that excludes the region with intensity less than 10 percent of baseline signals. Finally, linear phase and constant phase in equation (3) can be estimated by polynomial fitting. Each echo of the image is phase-corrected by multiplying by the phase $-\theta(x)/2$ on each echo. Phase corrected data are then used for field-map esitmation, followed by image warping and k-space water-fat separation.
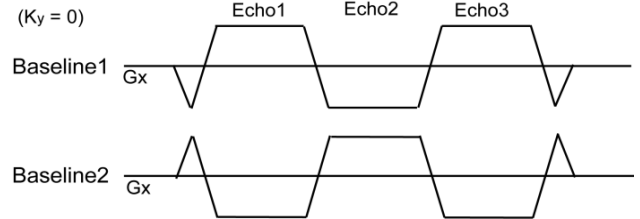
  In vivo data were acquired using 1.5T GE scanner, with a 3D SPGR 3-pt bipolar multi-echo sequence: BW=$\pm$83.3 kHz, TE=1.4, 3.0, 4.6 ms, FOV 40 x 30 cm^2. All data pass through the same additional processing for field-map estimation and corrections of imaging artifacts. For off-isocenter imaging, data were acquired just 2 cm off-isocenter in the readout direction with the same FOV.

Results: Fig.3 shows water, fat, and fat fractional images without and with phase corrections on both on- and off-isocenter abdominal imaging. Without phase corrections, phase errors cause failure of water-fat separation, as displayed in the top row in Fig.3. The second row in Fig.3 exhibits that the proposed method performs well in correcting phase errors for the on-isocenter imaging, where linear phase errors were nearly equivalent to $\pm 2\pi/3$ across the FOV, and constant phase errors in three echoes were negligibly small. To validate the performance in off-isocenter imaging, this proposed method was compared with the phase correction suggested in [4], which only accounts for the linear phase error. As can be seen in the third and fourth rows of Fig.3, the proposed method shows better correction of phase errors, hence yielding more uniform and consistent water-fat separation. Here, estimated linear phase errors were almost analogous to those in on-isocenter imaging, whereas constant phase errors, ± 1.9 radians for the three echoes, were much greater than constant phase errors in on-isocenter imaging.

Discussion: We demonstrate that the correction of linear and constant phase errors in bipolar multi-echo sequences can be achieved throughout simple reference scan and baseline projections. Importantly, this proposed method can be applied for phase correction in off-isocenter imaging, hence greatly improving water-fat separation. Higher order phase errors that can be induced by eddy currents or concomitant field errors were assumed to be sufficiently small to be neglected. The reference scan can be well combined with parallel imaging techniques, such as GRAPPA.

Conclusion Correction of both linear and constant phase errors through the use of simple reference scan significantly enhances the robustness of bipolar multi-echo water-fat separation at any scan location.
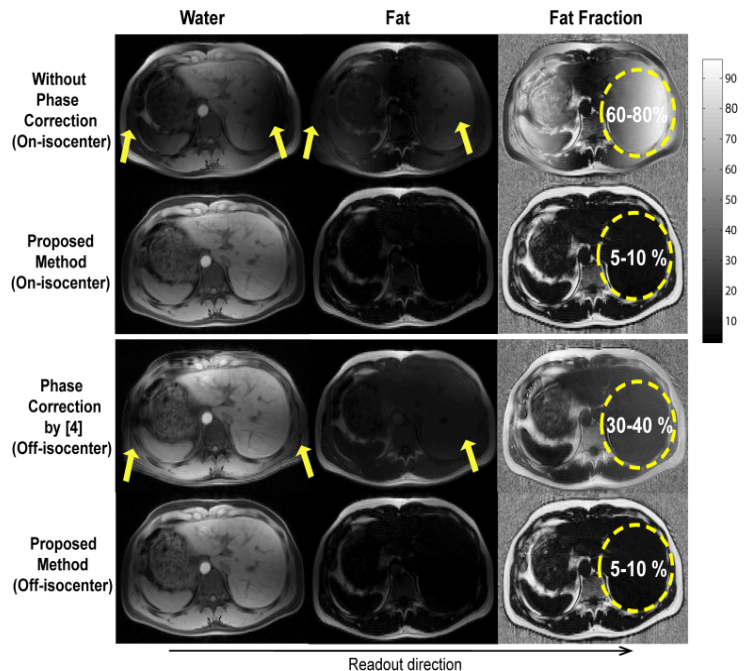

Fig. 1 Reference scan used in this study for two baseline projections with opposite polarity where phase encoding gradient is off.
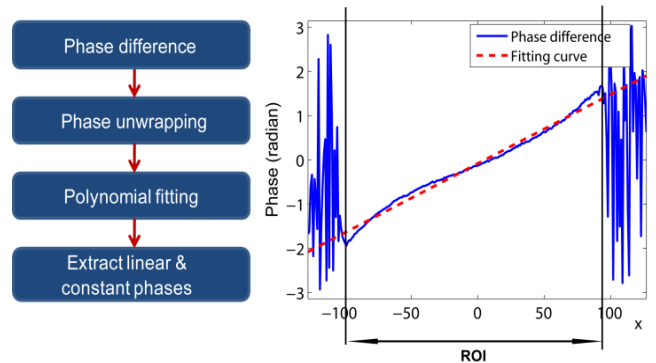
Fig. 2 The process of estimating linear and constant phase errors from the phase difference.

Fig. 3 Water, fat and fat fractional image with/without phase correction in both on- and off-isocenter imaging. Arrows indicate failure of water-fat separation. Numbers in dotted rounds represent the fat fraction inside those areas. Proposed method with linear and constant phase error corrections serves uniform water-fat separation in both on/off-isocenter.

References [1] Glover et al, MRM 1991;18:371-383   [2] Reeder et al, MRM 2005;54;636-644   [3] Ma, MRM 2004;52:415-419   [4] Lu et al MRM 2008; 60;198-209   [5] Yu et al, ISMRM 2008; 16: 648   [6] Wong et al, SMRM 1992;4514   [7] Maier et al, US patent 1992; #5, 151,656