Chemical Shift Correction in Bipolar Multi-Echo Sequences for Water and Fat Separation

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Introduction: The main disadvantage of water and fat separation methods based on chemical-shift induced phase, such as multi-point Dixon methods, is long scan time and suboptimal SNR efficiency. To improve imaging efficiency and reduce motion induced artifacts, multi-echo sequences [1] have been developed to acquire images at different echo times in a single repetition interval (TR). In this case the echo-spacing ΔTE depends on spatial resolution and readout bandwidth; hence ΔTE can be long even at a medium bandwidth, which leads to less robust field map estimation [1]. Both improved imaging efficiency and more robust field map estimation can be achieved by acquiring data using a "bipolar multi-echo" sequence (Fig. 1). After time reversal of the second echo, the alternating readout polarity results in misalignment between even and odd echoes due to gradient delays and eddy currents that need to be corrected for [2]. More importantly, the chemical-shift induced misregistration between water and fat exists in opposite readout directions between even and odd echoes. In this work we demonstrate a method that effectively eliminates such chemical-shift induced artifacts in separated water/fat images.

Method: Assume field maps are smoothly varying; we have the following simplified signal model for the bipolar multi-echo sequence:

$$I_n(x,y) = \begin{cases} (W(x,y)+F(x+\Delta x_{cs},y))e^{j2\pi\psi(x,y)TE_n}, \forall n=1,3 \\ (W(x,y)+F(x-\Delta x_{cs},y))e^{j2\pi\psi(x,y)TE_n}, \forall n=2 \end{cases} \quad \text{where} \quad \begin{matrix} W:\text{water} \\ F:\text{fat} \\ \psi:\text{field map} \end{matrix}$$

and $\Delta x_{cs} = \Delta f_{cs} / BW_{pixel}$, $\Delta f_{cs} \approx -210\text{Hz at }1.5\text{T}$. The relative fat signal shift $\pm\Delta x_{cs}$ prevents direct application of existing water and fat separation methods. Consider a conservative imaging case with bandwidth ±41kHz (BW_{pixel}=320Hz/pixel for a 256x256 matrix), $\pm\Delta x_{cs}$ gives 1.3 pixels shift for fat signal between even and odd echoes. Fig.2 (a) shows the water image of a knee obtained using an existing water and fat separation method [3], where the artifacts are identified by arrows.

To handle such difficulties, we propose a method consisting of two steps:

1) *Field map estimation using low-resolution image data*: This step exploits the fact that field maps are smoothly varying and the fat signal shift $\pm\Delta x_{cs}$ can be neglected at low resolution. We obtain low-resolution images by low-pass filtering the k-space data along the readout direction. Subsequently from the low-resolution image data a field map is estimated [4].

2) *Water and fat separation using field map corrected k-space data*: After demodulating the field map, the field map corrected image data is transformed back to k-space. The k-space samples $S_n(k_x,k_y)$ of three echoes become

$$\begin{pmatrix} S_1(k_x,k_y) \\ S_2(k_x,k_y) \\ S_3(k_x,k_y) \end{pmatrix} = \begin{pmatrix} 1 & e^{j2\pi\Delta f_{cs}t_1(k_x,k_y)} \\ 1 & e^{j2\pi\Delta f_{cs}t_2(k_x,k_y)} \\ 1 & e^{j2\pi\Delta f_{cs}t_3(k_x,k_y)} \end{pmatrix} \begin{pmatrix} S_W(k_x,k_y) \\ S_F(k_x,k_y) \end{pmatrix}, \quad \begin{matrix} S_W:\text{k-space water sample} \\ S_F:\text{k-space fat sample} \end{matrix}$$

where $t_n(k_x,k_y)$ is the acquisition time of a k-space sample at (k_x,k_y) for the n^th echo. Fig. 1 shows one example of k-space sampling pattern, in which $S_{1,2,3}(k_x,k_y)$ are marked with ▤ symbols. The water and fat separation in k-space is done by solving pseudo-inverse of the above equation for S_W and S_F, hence eliminating the phase factor of k-space fat samples due to the chemical shift Δf_{cs}. The separated water and fat images are the Fourier transforms of S_W and S_F, respectively.

Results: The sequence was implemented on a GE 1.5T scanner. Scans were performed on both a fat/water phantom and human subjects. Fig. 2,3,4 (a) shows the water/fat separation results using the existing separation method, where the chemical-shift induced artifacts are identified with arrows. As can be seen from Fig. 2,3,4 (b), the proposed method successfully separates fat from water and eliminates the chemical shift induced artifacts.

Discussion: Bipolar multi-echo sequences offer many advantages such as high SNR efficiency, reduced echo-spacing compared to multi-echo sequences, and reduced motion induced artifacts. We proposed a method that resolves the associated opposite fat/water signal shifts in even and odd echoes by using a robust field map estimation followed by a least-squares water and fat separation in k-space.. Currently the correction of field inhomogeneity induced spatial misregistration is under investigation. In short, the proposed method enables bipolar multi-echo sequences to achieve fast and efficient scanning with robust water and fat separation.

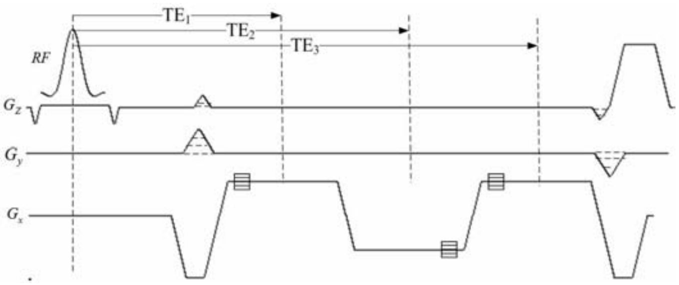
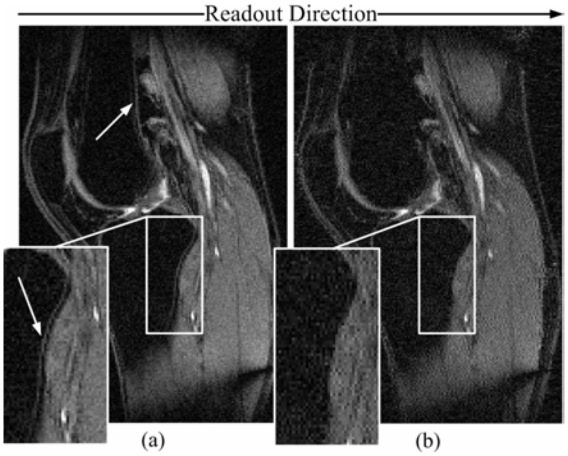


Fig.1: Diagram of a bipolar multi-echo sequence. The time instances when $S_n(k_x,k_y)$ (n=1,2,3) are sampled are marked with ▤ symbols.



Imaging parameters:
A knee study at 1.5T with
TR: 13ms
TE:3.8, 7, 10.2ms
256×256 matrix
flip 30° and
BW ±41kHz .

Fig.2: Chemical-shift induced artifacts are identified with boxes in the water image (a) obtained using an existing separation method. (b) shows the water image obtained using the proposed method, which eliminates the artifacts.

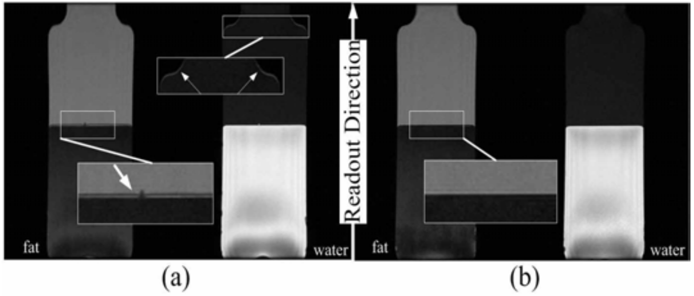


Fig. 3: A phantom study at 1.5T with the same imaging parameters as the study shown in Fig. 2. The artifacts (boxes) present in (a) are eliminated in (b).

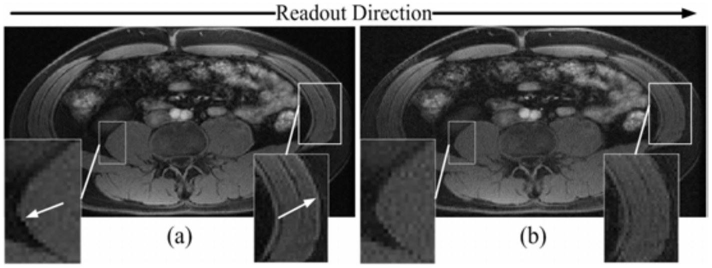


Fig. 4: An abdomen study at 1.5T with the same imaging parameters as the study shown in Fig. 2, except 256×144 matrix. The artifacts (left box: signal null; right box: "piling-up") at interfaces between the muscle water signal and adjacent retroperitoneal and/or body wall fat signal in (a) are eliminated in (b).

References: 1. Wieben O., *et al.* ISMRM, 2005. 3. Wong E.C., ISMRM, 1992. 3. Reeder S., et al. MRM2004 51(1):123-30. 4. Yu H., *et al.* MRM2005 54(3):1032-1039.

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