Phase Constrained Parallel Imaging for Improved Fat Suppression in multi-echo LC SSFP

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INTRODUCTION

The Linear Combination SSFP (LC-SSFP) method that combines two steady-states with different passbands provides nice fat/water separation, even in voxels containing both fat and water. A dual half-echo acquisition with 3D PR trajectories [1] can provide efficient high-resolution spatial encoding while meeting the short TR requirement for LC-SSFP. However, because LC-SSFP is acquired using a center frequency between fat and water, signal loss is created by the phase incoherence between the two echoes. Unwanted bright fat signal is not fully suppressed in water images when the magnitudes of fat in two passes are different. With mixed voxels of fat and water are properly constrained to the water phase, the residual unwanted fat signal in water volume can be effectively removed. A self-calibrated multi-echo acquisition with radial trajectories using the conjugate gradient (SMART CG) can provide phase coherence between echoes and parallel imaging simultaneously [2]. In this work, we present improved SMART CG algorithm to provide parallel imaging, phase coherence, and improved fat/water separation in LC SSFP images acquired with dual half-echo 3D PR trajectories.

MATERIALS AND METHODS

SMART CG uses the conjugate gradient algorithm to solve a least square problem to minimize the undersampling artifact in non-Cartesian imaging [3]. SMART CG extends the coil sensitivities in [3] to combine information from the complex coil sensitivities and the off-resonance information crucial to LCSSFP in each echo. Termed virtual coil sensitivities, the sensitivity map from the εth echo and γth receiver ($\Phi vc_{\varepsilon,\gamma}$) can be represented by

$$\Phi vc_{\varepsilon,\gamma} = \Phi coil_{\gamma} + \Phi te_{\varepsilon} + \Phi lc_{f/w}$$

where $\Phi coil_{\gamma}$ is the phase of coil sensitivity from γth receiver, Φte_{ε} is the off-resonance phase from each echo based on its TE, and $\Phi lc_{f/w}$ is the phase difference of fat and water on the combination. For water volume the combination of Pass1 (0-0-0) - i*Pass2 (0-π-0) provides alignment of water signal and cancellation of fat signal. We can assume that $\Phi lc_{f/w}$ for both fat and water signals are the same as the phase difference on water signal between Pass1 and -i*Pass2 without any loss of water signals even though the phase difference on the fat signal is π. The virtual coil sensitivities are generated by taking the sum of magnitude of Pass1 and Pass2 and the phase of Pass1 where both fat and water signal have high enough signal to get proper phase estimates. The partial Fourier partial parallel imaging (PFPP) method with the phase constraint [4] can be used to minimize the objective function of

$$\|\boldsymbol{Em} - \boldsymbol{d}\|_2^2 + \lambda^2 \|\mathrm{Im}\{\boldsymbol{m}\}\|_2^2$$

where ***E*** is sensitivity encoding matrix containing all coil channels sensitivities, ***m*** is a vector of image space data, ***d*** is a vector of ordered echo data, λ is a scalar for the degree of phase constraint, and Im{***m***} is the imaginary part of ***m***

The combination of the passes in LCSSFP, acquired with different RF cycling and requiring a 90 shift of pass 2, is shown in Fig. 1 (a). When SMART CG applies the complex conjugate of the virtual coil sensitivities, the phase incoherence between the echo times due to the progression of the spins from TE1 to TE2 is removed. The phases of the two fat echo signals are also inverted and aligned by the multiplication of complex conjugate of virtual coil sensitivities (Fig. 1 (b)). The phase constraint previously suggested for exploiting the asymmetry of radial trajectories is also capable of removing residual fat signal in the combination depicted in Fig1 (c).

The volunteer study was conducted on a 3T GE Signa HDx scanner (GE Healthcare, Milwaukee, WI) with an eight-channel knee coil. Scan parameters were 3.6 ms TR, 0.3 ms TE_1, 2.6 ms TE_2, 15° flip angle, 15 cm FOV, 384^3 matrix size,.039 mm isotropic resolution, for a scan time of 4:30 minutes

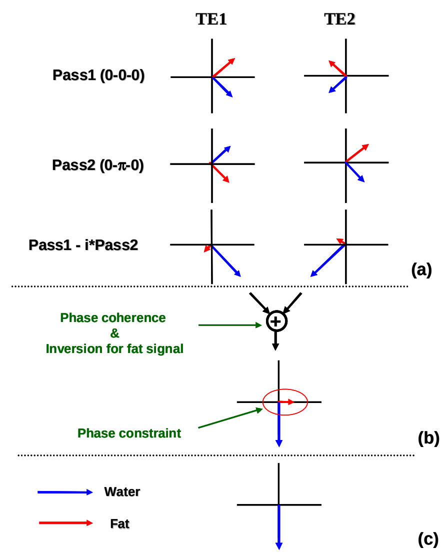

FIG. 1. Schematic illustration for combining signals at different echo times to suppress fat signal.

RESULTS AND DISCUSSION

The resulted images were compared with the images from conventional reconstruction[5]. 3 slices of isotropic resolution images were averaged through the planes. Fig. 2 shows that the proposed method provides excellent fat suppression and substantial improvement of image quality throughout the image volume.

The SMART CG algorithm was tailored to achieve superior performance based upon the phase sensitive nature of LCSSFP while providing the benefits of parallel imaging. Additionally the proposed phase constraint can effectively remove the residual unwanted fat signal that aligned on imaginary part of image and provide partial Fourier reconstruction simultaneously. The proposed phase constraint mechanism may also be utilized in Cartesian acquisition with PFPP imaging.

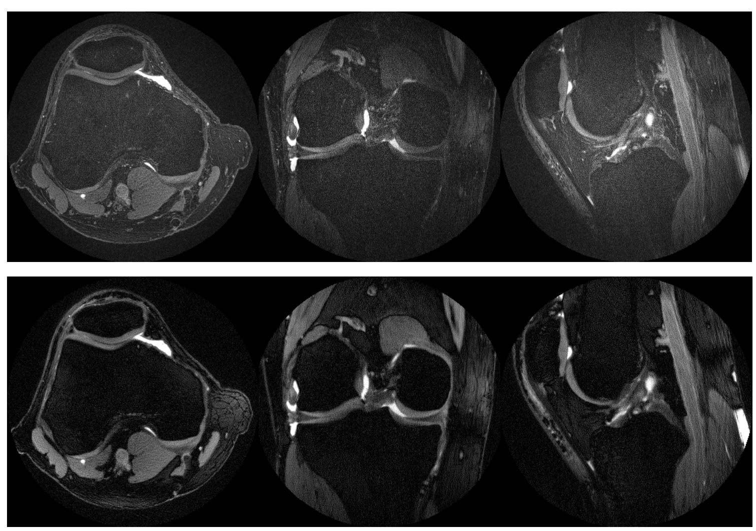

FIG. 2. Parallel imaging using SMART CG with phase constraint (bottom) creates significant improvement in SNR and fat suppression over conventional reconstruction(bottom)

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