Self-Calibrated Multi-Echo Sequences: Use of Conjugate Gradient Method with Radial Trajectories to Remove Phase Cancellation

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INTRODUCTION

Pulse sequences that acquire gradient echoes such as GRASS (FISP), CE-FAST, SPGR (FLASH), and GRASE are widely used due to their acquisition speed. However, there are limitations on accelerating the scan by using multiple echoes per excitation. One particular problem is how to combine data from different echo times without signal dropouts due to phase cancellation between the echoes. Intrinsically radial imaging can easily produce phase estimates whose resolution grows with the number of sampled projections and do not need separate acquisitions. Simple phase correction by using phase estimates obtained from a single echo within a single coil, however, is not optimal as the dataset is undersampled. The Conjugate gradient (CG) method could be used to correct phase variations for both fully and undersampled cases with proper phase estimates [1]. In this work, we present a method to acquire multiple echoes per excitation and remove artifacts due to off-resonance using the CG method. Our result demonstrates substantial image quality improvement.

MATERIALS AND METHODS

A 3DPR CE-FAST sequence was implemented to acquire four different radial lines per excitation. Spoiler gradients located immediately after the RF pulses were used to remove the unwanted M^+ signal (Fig. 1 (a)). Acquired *k*-space data was divided into 4 subsets based on the echo times (Fig. 1 (b)). For each γ^{th} receiver of *Nc*, low resolution images were extracted from the fully sampled central part of *k*-space of each ε^{th} echo subset, resulting in a total of 4x*Nc* virtual coil channel sensitivities $\boldsymbol{S}_{\varepsilon,\gamma}$. The coil channels were used to build a system of linear equations similar to a generalized sensitivity encoding equation [1, 2]:

$$\boldsymbol{d} = \boldsymbol{E}\boldsymbol{m}$$

where $\boldsymbol{d}$ is a vector of ordered echo data, $\boldsymbol{E}$ is sensitivity encoding matrix containing all coil channels sensitivities $\boldsymbol{S}_{N\varepsilon,N\gamma}$, and $\boldsymbol{m}$ is a vector of image space data. The system was solved iteratively with CG implemented similarly to Ref. [2].

The volunteer studies were conducted on a 3T GE Signa HDx scanner (GE Healthcare, Milwaukee, WI) with an eight-channel phased array head coil. A 24 cm spherical FOV was imaged with a readout matrix equivalent to 128*128*128. *k*-Space data was fully sampled, however every other acquisition was skipped to show the feasibility of our method with undersampled acquisitions. With the undersampling factor of 2, a total of 32 phase estimates were generated, each with the resolution of 16*16*16.

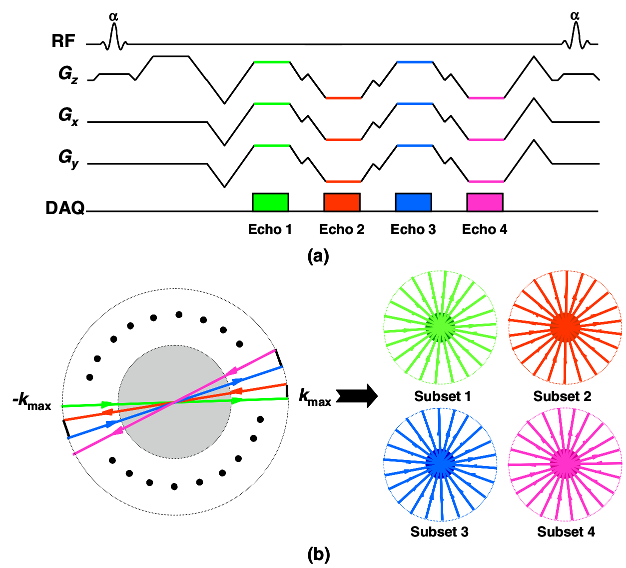

FIG. 1. Pulse sequence diagram for acquiring four echoes per CE-FAST excitation (a). Radially acquired k-space is divided into 4 subspaces based on the echo times, individually regridded, and encoded in the CG algorithm with the sensitivity estimates ($\boldsymbol{S}_{\varepsilon,\gamma}$) derived from the shaded oversampled regions.

RESULTS AND DISCUSSION

All echoes were regridded onto *k*-space and the sum of square method used to combine images from all channels in Fig. 2 (a). The same process was used in Fig. 2 (b) with the undersampled dataset. Fig. 2 (c) shows the effectiveness of the applied CG phase correction method for removing artifacts due to off-resonance when using the undersampled dataset form Fig. 2 (b). After 6 iterations with the CG method, artifacts due to off-resonance near the sinus cavity and in the brain stem are removed.

When multi-channel data is available, the proposed CG method is similar to the non-Cartesian SENSE reconstruction [2] and possible streaking artifact shown in undersampled scans could also be removed simultaneously with signal dropouts.

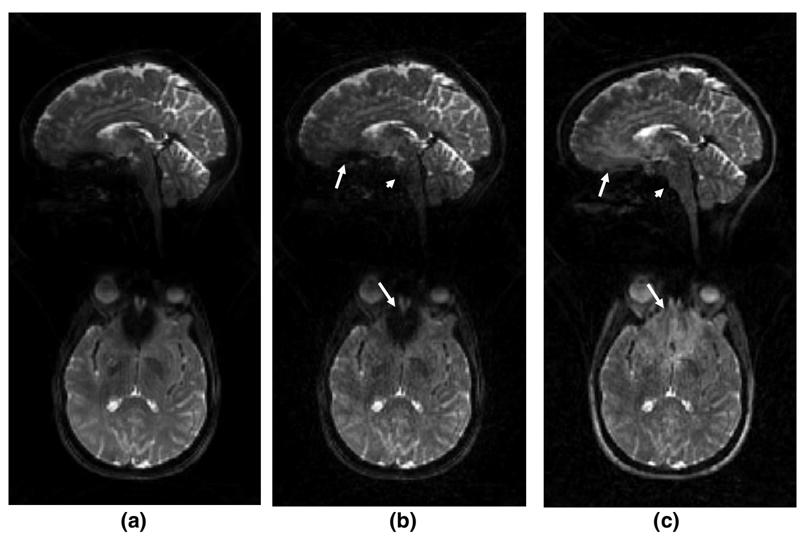

FIG. 2. Sagittal (upper row) and oblique axial (lower row) reformatted images with fully sampled data using conventional method with fully sampled data (a) and with a half of acquired data (b). The results of the CG algorithm using the undersampled data in Fig 2 (b) are shown in (c). Susceptibility artifacts near the sinus cavity (arrows) and in the brain stem (arrowheads) are completely removed.

CONCLUSIONS

The suggested CG method for combining multiple echoes with radial acquisitions provides significant reduction of susceptibility artifacts. We have demonstrated the method on four-full echo CE-FAST acquisition in 3D. However, the benefit can apply to other combinations of multi-echo radial acquisition schemes and gradient echo pulse sequences.

ACKNOWLEDGMENT

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