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Improved spatial resolution for Looping Star fMRI using UNFOLD

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Synopsis

Keywords: New Trajectories & Spatial Encoding Methods, fMRI Acquisition

Motivation: Looping Star is a silent fMRI pulse sequence that is often highly undersampled in k-space at high spatial resolution.

Goal(s): This work aims to improve spatial resolution by increasing coverage of k-space over time.

Approach: We propose to use a cycle of 10 spherical sampling patterns with UNFOLD post-processing to reduce aliasing artifacts.

Results: Our methods significantly reduced spatial artifacts and improved fMRI activation t-scores.

Impact: The results of this work will improve spatial resolution Looping Star fMRI studies with high undersampling rates.

Introduction

Looping Star is a T2*-weighted pulse sequence with minimal acoustic noise for BOLD fMRI, making it ideal for noise-sensitive subjects and minimizing signal contamination from auditory confounds [1,2]. However, its spherical k-space acquisition is often undersampled, especially at higher spatial resolutions, necessitating specialized k-t reconstruction to address aliasing artifacts. Previous work [3] showed that alternating between two sampling patterns with UNFOLD-based temporal filtering [4] reduces aliasing in Looping Star data. Here, we extend this approach by using 10 unique sampling patterns, further reducing sampling artifacts with UNFOLD filtering.

Methods

Pulse sequence: Figure 1 shows the Looping Star pulse sequence, which is optimized for low acoustic noise, making it suitable for noise-sensitive fMRI tasks. This sequence produces 23 overlapping echoes by burst RF pulses that are dephased and refocused using sinusoidal gradients. To achieve spherical k-space coverage, the initial Looping Star plane is rotated with 3D golden angles. Gradient parameters and sampling criteria were set to achieve a 3D field of view of 22 cm and matrix size of 90.
Reconstruction: Using the multi-echo signal model for Looping Star acquisitions [5], we reconstructed the image time series using CG-SENSE with a spatial roughness penalty. We then applied UNFOLD temporal filtering as post-processing, using a temporal notch filter designed from frequency peaks in the average block cycle (Figure 2). Finally, fMRI activation t-scores were calculated by fitting a general linear model to the reconstructed data.
Experimental setup: For this study, fMRI participants watched a flashing checkerboard animation (20s on, 20s off) and performed a finger-tapping task while viewing the checkerboard. Each 20s block was sampled with 10 unique kspace volumes consisting of 35 planes as shown in Figure 3. For fully Nyquist-sampled data at this matrix size (M = 90), approximately $\pi(M/2)^2$ spokes would be required per volume. However, since UNFOLD enables data sharing across multiple unique volumes, increasing the number of unique volumes from 2 to 10 effectively reduces the undersampling factor from approximately 5.5 to 1.1.

Results

De-aliasing with UNFOLD: Figure 4 shows that UNFOLD significantly reduces the aliasing artifacts in each frame of the reconstruction.
fMRI activation maps: Figure 5 shows higher activation t-scores in the motor and visual cortex and less false positives when UNFOLD post-processing is used.

Conclusion

The proposed study demonstrated that using a cycle of 10 volumetric sampling patterns with UNFOLD filtering significantly reduces the aliasing artifacts in Looping Star fMRI data. Effective use requires that care is taken so that undersampling artifact frequencies do not overlap with task frequencies.

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Figures

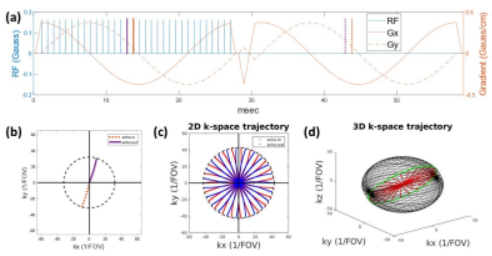

Figure 1: (a) Looping Star pulse sequence diagram. Echoes are formed by a series of burst pulses that are dephased and later refocused by low-slew sinusoidal gradients; (b) illustration of overlapping echo-in (orange) and echo-out (purple); (c) 2D k-space trajectory with all combined echoes; (d) 3D spherical k-space trajectory after rotating the initial plane.

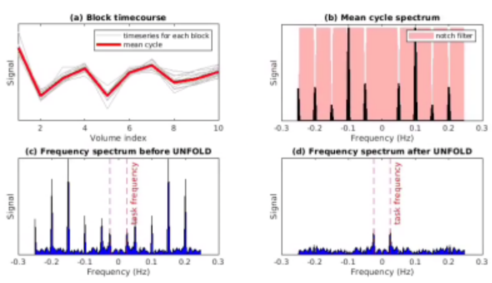

Figure 2: (a) Time course for a selected voxel for each block. A mean block cycle is determined by computing the mean time course over each block; (b) Spectrum of the mean cycle is plotted and the frequency peaks are used to design a notch filter that zeros out the peaks corresponding to aliasing; (c) Frequency spectrum of a selected voxel. Task frequency is marked at 0.025 Hz (40s period). Peaks can be seen at aliasing frequencies; (d) Frequency spectrum of a selected voxel after notch filtering. Task frequency peaks are preserved, but aliasing peaks are filtered out.

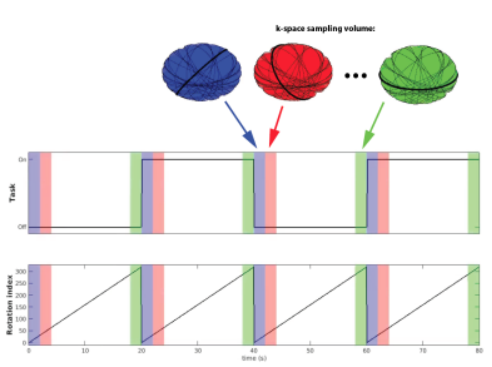

Figure 3: Illustration of volumetric sampling patterns within each fMRI activation block. Each block is sampled with 10 unique kspace volumes, each consisting of 35 looping star planes before being repeated for the next block.

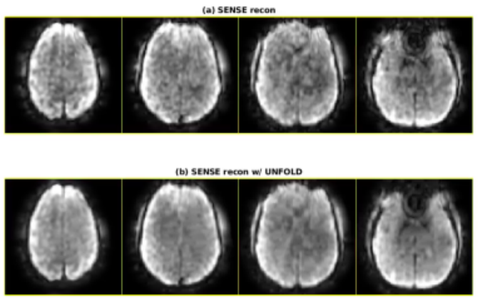

Figure 4: Selected axial slices for a single time point (a) frame-wise SENSE reconstruction (without UNFOLD); (b) SENSE reconstruction followed by $10\times$ UNFOLD filtering; Images have less undersampling artifacts when UNFOLD filtering is performed.

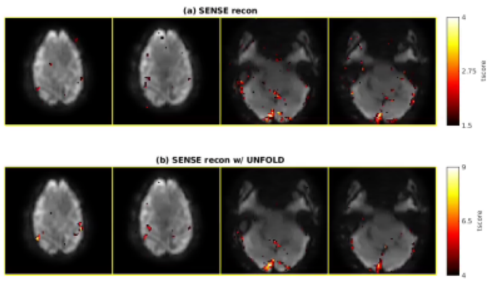

Figure 5: fMRI activation t-scores in selected axial slices near motor and visual cortices; (a) SENSE reconstruction (without UNFOLD); (b) SENSE reconstruction with UNFOLD filtering. Due to undersampling artifacts in (a), which obscure activation signals and lower t-scores, a reduced threshold was used to reveal patterns. Despite this, (b) shows greater significance in motor and visual cortices with fewer false positives, as UNFOLD filtering reduces aliasing, enhancing true activation signals.

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