A Subspace Approach to Accelerated HASTE Acquisition for Fetal Brain MRI

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Synopsis

Half-fourier Single-shot Turbo spin Echo (HASTE) acquisition is widely used in fetal MR imaging due to its T\textsubscript{2} contrast and motion robustness, but speed and T\textsubscript{2}-blurring remain a problem for fully sampled acquisitions. In the work, we describe a new reconstruction approach based on low-rank and subspace modeling of local k-space neighborhood to accelerate HASTE acquisition. The proposed approach decreases the echo-train length with improved image quality and noise robustness compared to conventional reconstruction. It is compatible with the vendor-provided acquisition. The effectiveness and utility of the proposed approach is evaluated with both retrospectively and prospectively undersampled fetal imaging data.

Introduction

Accelerated Half-fourier Single-shot Turbo spin Echo (HASTE) acquisition is widely used in fetal MRI\textsuperscript{1}, since it provides good T\textsubscript{2} contrast, and improves motion robustness. Conventional reconstruction approach accelerates HASTE acquisition with a hybrid half-Fourier\textsuperscript{2} and GRAPPA\textsuperscript{3} reconstruction. While widely used in clinical practice, it enables only a low to medium acceleration factor before severe noise amplification occurs. Recently, we introduced a low-rank model-based approach to accelerate HASTE\textsuperscript{4}, which utilizes the linear predictability of local k-space neighborhood associated with limited image support. The proposed approach provides better image quality and noise robustness, and is compatible with the standard HASTE acquisition scheme. In this abstract, we extend the early work to investigate an alternative low-rank model, which models slowly-varying image phase. To enhance the computational efficiency, we further incorporate a subspace constraint into the reconstruction process. We demonstrate the effectiveness of the proposed approach on both retrospectively undersampled data and prospectively-undersampled data.

Theory

Early work has shown that an approximately low-rank matrix can be constructed by collecting patches of k-space data, if the underlying image has a slow-varying image phase\textsuperscript{5}. Here we form such a data matrix, denoted as $S \in \mathbb{C}^{M \times N}$. Moreover, to account for correlation between multi-coil data\textsuperscript{6}, we further form the matrix $S^P = [S^1, S^2, \cdots, S^L] \in \mathbb{C}^{M \times LN}$. Here, by enforcing the low-rank property, i.e., $\text{rank}(S^P) \leq r$, we can formulate a matrix completion problem that enables reconstruction from sub-Nyquist data. Although directly solving the matrix completion problem often provides good accuracy, it often results in an expensive computational problem. To enhance the computational efficiency, we further introduce a null space constraint\textsuperscript{7}, which pre-estimates the null space of $S^P$ from the full-sampled calibration/training data. Figure 1 shows the singular value decays respectively from $S^P$ and the calibration data, which follow a very similar trend. More specifically, let the column of $V_s$ span the null space of $S^P$. Enforcing both the low-rank constraint and the subspace constraint, we can formulate the following image reconstruction problem:

$$\hat{z} = \arg\min_z \| P_s(\mathcal{T}(d) + \mathcal{T}^c(z))V_s \|_2^2$$

where $\mathcal{T}$ is the linear operator that maps the sampled k-space data into the complete k-space data vector, while filling unsampled k-space locations with zeros; $\mathcal{T}^c$ is the linear operator performing the complementary operation; and $P_s$ maps the complete k-space data to the data matrix $S^P$. Note that with the subspace constraint, the reconstruction problem reduces to a sparse linear least-squares problem, which can be efficiently solved by a number of numerical algorithms (e.g., the iterative LSQR algorithm).

Methods

We first evaluated the performance of the proposed approach with retrospectively-undersampled data. Here we compared the proposed approach with the conventional reconstruction. More specifically, under an IRB approved protocol, we performed the HASTE acquisition on one healthy pregnant woman at a 3T Siemens Skyra scanner, equipped with 20 coils. Here FOV = 360\,\times\,360 mm\textsuperscript{2}, slice thickness = 3.5 mm, and matrix size = 256\,\times\,512. We performed a half-Fourier acquisition covering the 5/8 of the k-space, and then performed a factor of 4 undersampling in the outer k-space. The data acquisition scheme is illustrated in Figure 2. With this acquisition scheme, the net acceleration factor is 3. We compared the proposed approach with the reference obtained from the fully-sampled data, and the conventional approach using the GRAPPA and half-Fourier
reconstruction. To evaluate the utility of the proposed approach, we further performed prospectively-undersampled HASTE acquisition of three imaging slices and reconstructed the data using the proposed approach.

**Results**

Figure 3 shows the results from the retrospectively-undersampled experiments. As can be seen, the proposed method provides improved image quality compared to the conventional reconstruction approach. In particular, it reduces the noise amplification, while well preserving the anatomical structure of the fetal brain. Figure 4 shows the results from the prospectively-undersampled experiments. As can be seen, the proposed approach consistently provides high-quality reconstructions for all the imaging slices.

**Conclusion**

In this abstract, we developed a new imaging approach to accelerate HASTE acquisition for fetal MRI. The proposed approach enforces the low-rank modeling of local k-space neighborhood, and further incorporates the subspace constraint to simplify the computational problem. We demonstrated the effectiveness of the proposed approach with both retrospectively-undersampled data and prospectively-undersampled data.

**Acknowledgements**

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**References**


**Figures**

![Figure 1: Singular values for the S matrix and the training matrix for estimating the null space.](Image link)
Figure 2: K-space sampling scheme for accelerated HASTE imaging. Here slightly more than half of k-space region is sampled, within which the central k-space is fully-sampled, while the other region is undersampled.

Figure 3: Reconstruction of the retrospectively-undersampled data at the net AF = 3.0. (a) Reference (Fully-sampled). (b) GRAPPA and Half-Fourier reconstruction. (c) Proposed method with the low-rank and subspace constraint. It is clear that the proposed method well preserves the anatomical structure, while effectively overcoming the noise contamination (as shown in the GRAPPA and Half-Fourier reconstruction).

Figure 4: Three imaging slices reconstructed using the proposed method for the prospectively-undersampled data at the net AF = 2.8.

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