Simultaneous Multi-slice MRI Reconstruction using LORAKS

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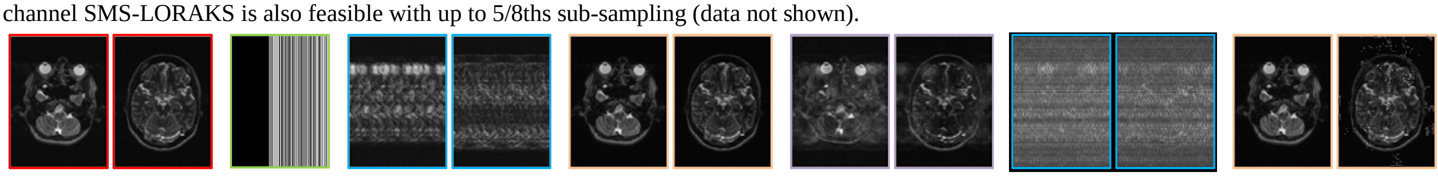
Introduction The combination of simultaneous multi-slice (SMS) acquisition with parallel imaging enables highly-accelerated MRI experiments [1,2]. However, most existing methods use highly structured k-space sampling, and require either prior knowledge of the coil sensitivity maps [1,2] or autocalibration data [3]. In this work, we propose a constrained reconstruction framework that works with traditional sampling schemes, but is flexible enough to also be used with calibrationless unstructured sampling patterns without any prior sensitivity information. The approach is also flexible enough that it can be used with single-channel data and/or random SMS encoding [4,5]. Our proposed approach specifically uses low-rank matrix modeling of local k-space neighborhoods (LORAKS) [6,7], a recent calibrationless MR image reconstruction framework that enables new k-space sampling trajectories for both single- and multi-channel data. Combining SMS with LORAKS leads to a framework we call SMS-LORAKS.

Methods

Data acquisition: Similar to existing SMS methods [1-3,5], we assume that multiple slices are excited simultaneously and Fourier encoded simultaneously, with measurements acquired using a phased array coil. The spatially-varying coil sensitivities provide information that can be used to help separate the signal from different slices. To make the separation of different slices even easier, spatially-selective RF pulses and/or imaging gradients can be used to change the phase relationships between the different slices for each individual phase encoding step (we refer to this as "slice encoding"). The slice encoding can either be performed in a structured way (as in Hadamard encoding) [1-3] or in a random way [4,5]. The information provided by the combination of coil sensitivities and slice encoding leads to data redundancies, which enables sub-sampling of k-space.

Reconstruction: We use the LORAKS framework [6,7] to reconstruct sub-sampled SMS data without coil sensitivity information and without autocalibration data. LORAKS is based on the assumptions that MR images frequently have limited spatial support and slowly-varying spatial image phase. These constraints result in linear dependence relationships that allow missing k-space data to be linearly predicted from neighboring k-space samples and/or k-space samples on the opposite half of k-space. In the absence of prior information about the linear dependencies, the relationships between neighboring k-space points can be imposed implicitly using low rank matrices. Specifically, linear dependence relationships imply that single-channel k-space data can be rearranged into structured matrices that must have low rank, and matrices with even better rank characteristics can be constructed in the presence of parallel imaging data [7]. The low-rank matrix structure can be enforced using regularization [6,7]. SMS-LORAKS reconstruction is achieved by minimizing the functional $\sum_{\ell=1}^{L} || \sum_{m=1}^{M} \mathbf{F}_m \mathbf{k}_{m\ell} - \mathbf{d}_\ell ||_{\ell_2}^2 + \lambda_C \sum_{m=1}^{M} J(\mathbf{C}_m) + \lambda_S \sum_{m=1}^{M} J(\mathbf{S}_m)$, where $\mathbf{k}_{m\ell}$ is the unknown (to be estimated) fully-sampled k-space data from the mth slice and the ℓth coil; $\mathbf{d}_\ell$ is the measured data from the ℓth coil; the $\mathbf{F}_m$ matrices describe the slice encoding, Fourier encoding, and Fourier sub-sampling operations for the mth slice; $\mathbf{C}_m$ and $\mathbf{S}_m$ are structured low-rank matrices formed from the k-space data from the mth slice (i.e., formed from the set of vectors $\mathbf{k}_{m1}, \mathbf{k}_{m2}, \ldots, \mathbf{k}_{mL}$ as described in the P-LORAKS method [7]); and $J(\cdot)$ is a regularization functional that encourages low-rank matrix structure. The matrix $\mathbf{C}_m$ is used to model support constraints for the mth slice, while the matrix $\mathbf{S}_m$ is used to model phase constraints for the mth slice. Note that the individual slices are being regularized independently, as we are not making any assumptions about inter-slice correlations. On the other hand, the reconstruction of the individual slices is coupled through the data fidelity terms, since each measured datapoint represents a combination of information from each of the different slices. The SMS-LORAKS optimization problem is solved using a majorize-minimize algorithm [6,7].

Results Due to space constraints, we only show a few results. Fig. 1 shows the results of applying SMS-LORAKS to retrospectively undersampled 12-channel 2-slice data with 3× acceleration, using a random calibrationless partial-Fourier k-space sampling scheme. SMS-LORAKS performs quite well, and we are unaware of any other method that could successfully reconstruct this kind of measured data. Note that the use of partial-Fourier undersampling allows the sampling density to be greater than it would have been if the same number of phase encodings were distributed over the full k-space grid. Joint total-variation reconstruction [8] is not nearly as successful. We also observe that there is not much difference in reconstruction quality between sub-sampled Hadamard slice encoding and sub-sampled random slice encoding. Other results demonstrate that single-channel SMS-LORAKS is also feasible with up to 5/8ths sub-sampling (data not shown).



(a) (b) (c) (d) (e) (f) (g)

Fig. 1. (a) Gold standard images. (b) Example random calibrationless partial-Fourier k-space sampling pattern. (c) Minimum norm least squares reconstruction (MNLS, which is like zero-padding but with phase compensation for slice encoding) of sub-sampled Hadamard SMS data. (d) **S**-based SMS LORAKS reconstruction of sub-sampled Hadamard SMS data. (e) Joint total-variation reconstruction [8] of sub-sampled Hadamard SMS data. (f) MNLS reconstruction of sub-sampled random SMS data. (g) **S**-based SMS LORAKS reconstruction of sub-sampled random SMS data.

Discussion and Conclusion In this work, we introduced a novel technique for accelerated SMS imaging. The flexible SMS-LORAKS approach can be used with both single- and multi-channel SMS data, with both structured and random slice encoding, and with both calibrationless and calibration-based sampling patterns. It is also easily combined with other regularization-based constraints. We expect this approach to be especially useful for SMS applications that require flexible k-space sampling and/or for which conventional sensitivity map estimation is challenging (e.g., due to motion or aliasing within the FOV).

References [1] F. Breuer et al., *Magn Reson Med*, 2005. [2] K. Setsompop et al., *Magn Recon Med*, 2012. [3] K. Zhu et al., *ISMRM*, 2012, p. 518. [4] J. Haldar, *IEEE TMI*, 2011. [5] K. Zhu et al., *ISMRM*, 2014, p. 4403. [6] J. Haldar, *IEEE TMI*, 2014. [7] J. Zhuo et al., *ISMRM*, 2014, p. 745. [8] C. Chen et al., *MICCAI*, 2013.