Undersampled simultaneous multi-slice readout-segmented EPI diffusion acquisition with a patch-based low rank constraint

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Introduction: Diffusion imaging offers a promising way to probe brain microstructure for different neurological disorders including stroke. Single shot echo-planar imaging is the most commonly used readout scheme for diffusion imaging. However, long echo spacing times associated with the single shot EPI readout can cause blurring and distortions in images and can also limit the desirable high spatial resolution. Readout Segmented EPI acquisitions (RS-EPI) can reduce these distortions and allow for higher spatial resolution by using shorter echo spacing times [1]. This approach however increases scan time due to long diffusion preparation times for each segment. Scan time increases almost proportionally to the number of readout segments which can be a limiting factor for diffusion acquisitions with a large number of directions as well as higher order diffusion acquisitions like diffusion spectrum imaging and high angular resolution imaging. Simultaneous multi-slice (SMS) imaging with blipped CAIPI [2] can speed up single shot EPI [2,3]. SMS was recently used in conjunction with RS-EPI [4-6] where two slices were simultaneously excited for each readout segmented acquisition leading to twice the slice coverage or effectively a factor of two scan time reduction. In order to reduce echo time (TE) an in-plane undersampling of R=2 was also used for each shot with an in-plane GRAPPA and a slice GRAPPA reconstruction [4,6]. To further speed up RS-EPI here we combine the SMS approach with k-space undersampling constrained reconstructions that exploit correlations across diffusion directions. We use a patch-based low rank regularizer [7] for SMS reconstructions to reduce undersampling artifacts.

Methods: Fully sampled RS-EPI diffusion MRI data was obtained on a Siemens 3T Verio scanner using a 32-channel head coil in stroke patients with IRB approval and informed consent. One b=0 and twenty diffusion weighted images with a b-value of 2000 s/mm^2 were acquired with a TR=3.5 secs, TE=100 msec, number of shots=7, number of slices=16 with a slice thickness of 2.1 mm, and pixel size=2.1 x 2.1 mm^2. The total acquisition time was 9 minutes. SMS RS-EPI data with a slice acceleration factor of three was simulated from the standard RS-EPI data by phase modulating the segments of k-space with 0, 2π/3, 4π/3 for the three slices respectively and adding them together. Undersampling of the generated SMS data was then performed to mimic a variable density random pattern by skipping lines within each shot as well as skipping shots entirely. Figure 1 shows the undersampling scheme with a net R=3 for a seven shot readout segmented acquisition for three different diffusion encoding directions. Skipping shots is important to have actual time gains with k-space undersampling. For the undersampling scheme we also ensured that the time to the center of k-space was the same for different directions. Reconstruction from the undersampled SMS data was performed by iteratively minimizing the expression in (1).

$$\min_{\forall I_j}\left(\sum_{i=1}^{nc}\left\|\left(\sum_{j=1}^{nsl}\emptyset_j\left(FS_{ij}I_j\right)\right)-d_i\right\|_2^2+\alpha\sum_{j=1}^{nsl}PLR\left(I_j\right)\right) \quad (1)$$

In (1) d_i is the undersampled k-space SMS data for coil i, I_j is the image estimate for slice j from all coils, S_{ij} is the coil sensitivity for coil i and slice j, F computes the Fourier transform at the sampled locations in k-space, $\emptyset_j$ is the phase modulation for slice j, nsl is the number of slices simultaneously excited, nc is the number of coils. PLR is the patch-based low rank regularizing operator that is applied on each slice separately [6] and α is the weighting factor for the constraint. Square patches are extracted and Casorati matrices are formed in which each column represents a patch from a diffusion direction. In the above reconstruction, fidelity is preserved to the acquired SMS data and the patch based regularizer helps mitigate the undersampling artifacts. After reconstruction, eddy current correction was done in FSL [8]. Mean Diffusivity (MD), Fractional Anisotropy (FA) and color FA maps were computed using Camino [9].

Results: Figure 2 shows a raw diffusion weighted image, MD, FA and color FA maps for SMS data with a slice acceleration factor of 3 that also has R=3 in-plane k-space undersampling. Reconstructed images from the proposed framework match closely with fully sampled non SMS RS-EPI images. Corresponding absolute difference images, scaled by a factor of five and shown on the same greyscale range as the corresponding original images, have little structure. The framework here translates to a net scan time reduction factor of ~4.2 (2.2 minutes from 9 minutes), 3x from SMS and 1.4x from k-space undersampling (as most of the time gains are from skipping the shots).

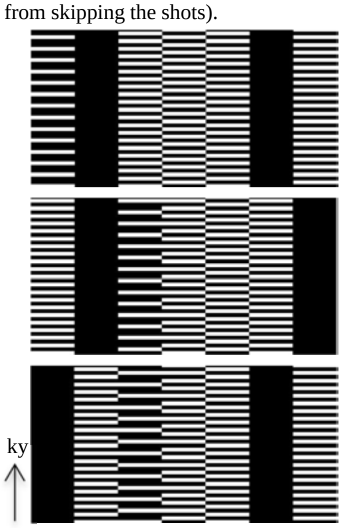

Figure 1: *R=3 k-space undersampling pattern for three different diffusion directions (top, middle, bottom). White represents sampled data. Two shots are skipped entirely for each direction.*

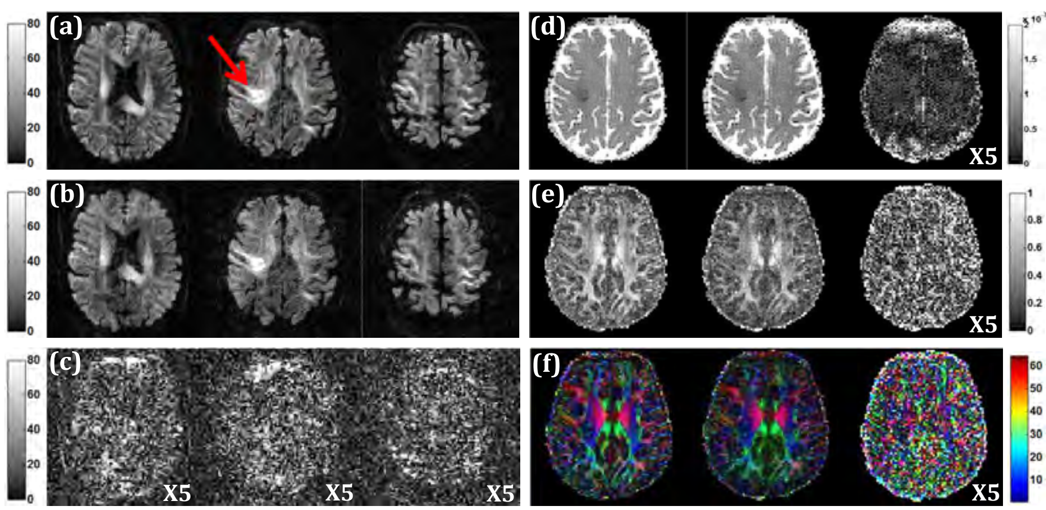

Figure 2: ***(a)*** *One diffusion weighted image for the three slices from fully sampled non-SMS RS-EPI acquisition. Arrow points to stroke region.* ***(b)*** *Corresponding three reconstructed slices from SMS=3 and R=3 k-space data.* ***(c)*** *Corresponding scaled absolute difference images.* ***(d)*** *MD maps for the stroke slice; left: truth, middle: recon, right: scaled difference* ***(e)*** *FA maps for the stroke slice; left: truth, middle: recon, right: scaled difference* ***(f)*** *color FA maps for the stroke slice; left: truth, middle: recon, right: The scaled color difference image obtained by subtracting each of the RGB components.*

Conclusions: Regularized SMS reconstruction with a patch-based low rank constraint is promising for speeding up RS-EPI diffusion acquisitions.

References: [1] Porter DA et al, 62:468-475, MRM 2009. **[2]** Setsompop K et al, 67:1210-24, MRM 2012. **[3]** Moeller S et al, 63:1144-53, MRM 2010. **[4]** Frost R et al, #116, ISMRM 2012. **[5]** Holdsworth SJ et al, #2061, ISMRM 2013. **[6]** Frost et al, epub, MRM 2014. **[7]** Adluru et al #1562 ISMRM 2014. **[8]** http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/ **[9]** http://cmic.cs.ucl.ac.uk/camino/