

Low Rank SENSE: A Robust Reconstruction Method for ms-EPI based high spatial resolution DWI

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Purpose To improve the spatial resolution of diffusion weighted imaging (DWI), multi-shot EPI (ms-EPI) has been proposed. Due to the high sensitivity to motion, different shots of ms-EPI may have inconsistent phase, which result in aliasing artifacts in the reconstructed image [1, 2]. To remove the impact of phase differences, parallel imaging, such as SENSE [3], is conventionally used to generate individual images for each shot. The magnitude average of these images is used as the final reconstruction. This method may result in clinically unacceptable image when the number of shots is high. The image will be corrupted by the g-factor and aliasing artifacts due to high acceleration factors, which is equal to the number of shots. However, more number of shots is expected for higher spatial resolution and/or lower geometry distortion, especially for high field system [2]. The goal of this work is to provide a reconstruction algorithm for ms-EPI, which can robustly deliver high image quality even when the number of shots is as high as 8 with an 8-channel RF coil.

Methods Unlike previous methods for ms-EPI phase correction [1,2], the ms-EPI is treated as accelerated dynamic imaging in this work. Each single shot corresponds to one static image. Hence the acceleration factor of the dynamic image set is the number of shots. A unique property of this dynamic image set is that these images have the same magnitude [1], but possibly different phase. Therefore, the rank of the image set is low. Low-rank property has been successfully used for the reconstruction of highly accelerated dynamic imaging [4,5]. Therefore, we propose to use low rank property to solve this accelerated dynamic imaging problem for ms-EPI. The mathematical model of the proposed method can be written as $E(I_s) = \sum_{s=1}^{s=N_s} \|F I_s - k_s\|_2^2 + \gamma \text{rank}(I_s)$ (1). s is the count of shot; I_s is the image of shot s ; F is the encoding operator; k_s is the acquired data for shot s ; $\text{rank}(\ast)$ is the rank calculation operator; γ is a non-negative parameter to balance these 2 terms. Since number of signal averages (NSA) for the acquisition of DWI is often larger than 1 to improve the SNR, s can include both number of shots and number of average. When multi-channel data is used, the first data fidelity term is the SENSE term. The second term is the low-rank regularization term, which forces the low rank property of the images corresponding to multi-shots of the same subject. Hence, the model is actually low rank regularized SENSE. If there is no motion at all, then all of these images should be exactly same and the rank is one. If there is only occasional relatively large scale motion, the rank is still low. In these scenarios, the model is theoretically sound. The model will fail when there is continuous random motion. Ideally, the final reconstruction is the registered average of I_s . This method is called Low-rank SENSE.

To evaluate the performance of low-rank SENSE, 10 sets of high resolution DTI images were acquired on a Philips 3T Achieva system with an 8-ch head coil (Invivo Corp., Gainesville, U.S.A). A multi-shot spin echo EPI sequence ($b = 800 \text{ s/mm}^2$, number of average = 3 or 4, number of directions (nDir) = 6, 10 or 15, FOV = 230mm^2 , in-plane spatial resolution = 0.8 mm^2 , slice thickness 4mm, partial Fourier ratio = 0.6, FA = 90° , TR = 2.8s, and TE = 70ms) was used for data acquisition. Number of shots 4, 6 and 8 were used in the experiment. In the results, a simplified numerical implementation using variable splitting [6] for model (1) was used for the reconstruction: rank = 1 was enforced for the magnitude of I_s . The simplified version is theoretically correct when there is no large scale motion.

Results Fig. 1 shows the comparison of the reconstruction with and without using the low rank regularization. A 6-shot data set (NSA = 3, nDir = 10) was used in this example. The first row of Fig. 1 shows that ms-EPI resulted in serious artifacts without taking care of the phase variation. The conventional SENSE average scheme resulted in serious artifacts due to the high acceleration factor 6 with a 8-channel coil (second row). With low-rank regularization, the image quality was dramatically improved (third row). Fig. 2 shows the FA map comparison for data sets with number of shots 4, 6, and 8. With the increase of number of shots, the advantage of using low-rank regularization becomes more obvious. Even for number of shots 8, low-rank SENSE can still result in clinically acceptable FA map.

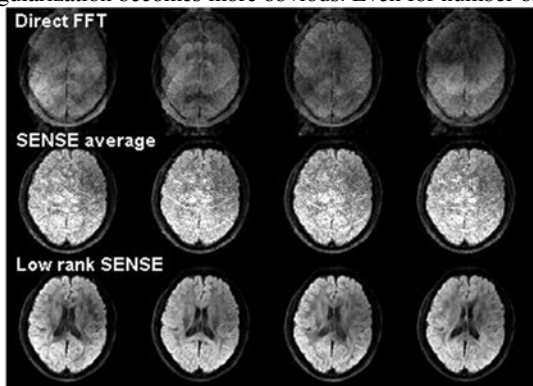


Fig. 1. Reconstructions of a 6-shot data set. The 3 rows are by direct FFT, SENSE average and Low-rank ms-EPI respectively. The columns are for different gradient directions.

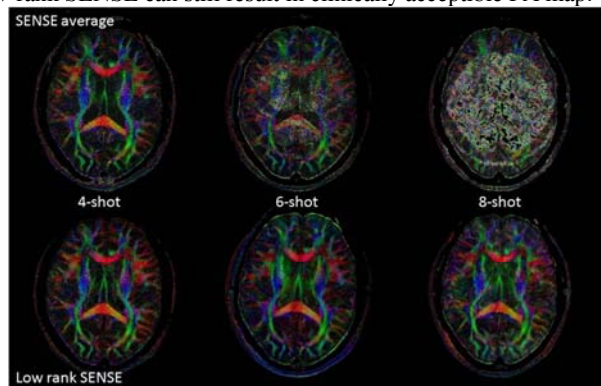


Fig. 2. Comparison of FA map. The two rows are for SENSE average and low-rank SENSE separately. The three columns are for 4 (NSA = 4, nDir = 6), 6 (NSA = 3, nDir = 10), and 8 (NSA = 4, nDir = 6) shots data.

Discussion Conventionally, SENSE is used to reconstruct individual images for each shot in ms-EPI DWI. The strong correlation among the shots that they share the same magnitude is unfortunately not used in the shot-wise reconstruction. In the proposed method, low rank property is used as a tool to take advantage of the correlation. Theoretically, this model (1) can also handle occasional large scale inter-shot motion, which will be tested in the future. MUSE [1] and IRIS [2] also cleverly use the same magnitude property with prior phase information. However, MUSE [1] did not show any results for data sets with number of shots higher than 4. The reason might be that the initial SENSE reconstruction in MUSE has difficulty to provide reasonable phase information when the acceleration factor is high. Compared to the proposed method, IRIS [2] needs extra navigator information.

Conclusion The image quality can be dramatically improved by using low-rank regularization in the reconstruction of ms-EPI, especially when the number of shots is high.

References : [1] Chen, N-k, et. al. NeuroImage 2013;72:41-47 [2] Jeong, H-k., et. al. MRM 2013; 69:793-802 [3] Pruessmann K.P., et. al. MRM 1999;42:952-962. [4] Zhao, B., et. al. IEEE ISBI; 2010. p 996-999 [5] Lingala, S. G., et. al. IEEE TMI 2011;30:1042-1054 [6] Huang, F., et. al. MRM, 2010; 64(4):1078-1088