

Comprehensive CG-SENSE reconstruction of SMS-EPI

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Synopsis

A 2D CG-SENSE framework is proposed aiming at an integrated treatment of the main error sources in SMS-EPI reconstruction. Our pipeline jointly estimates the sensitivity profiles, Nyquist ghosting parameters, and image to be unfolded. In addition, an artifact-SNR tradeoff is established at a pixel level. Assessment by a phantom experiment has shown that all the main functionalities of the method do help diminish reconstruction artifacts. Stable results have been obtained when applying the framework in a large cohort of motion corrupted fMRI and DWI neonatal studies.

Purpose

Simultaneous multislice (SMS) or multiband (MB) techniques¹ allow the acceleration of echo planar imaging (EPI) by the simultaneous acquisition of different slices that are subsequently unfolded using a receiver-coil array. Together with signal to noise ratio (SNR) benefits, SMS allows for efficient acceleration in EPI due to relatively short sampling/acquisition time ratio. 2D sensitivity encoding (SENSE) can be used to unfold MB images² and, particularly, by conceiving the sampled information as a subsampled 2D phase-encoded (PE) \mathbf{k} -space³, a flexible problem formulation is available by conjugate gradient (CG) SENSE⁴. However, unfolding of MB-EPI is prone to residual leakage, which has been reported both for SENSE⁵ and generalized autocalibrating partially parallel acquisitions (GRAPPA)⁶ techniques. In this paper we propose a step towards an integrated treatment of the error sources in MB-EPI reconstructions within a 2D CG-SENSE framework.

Theory and Methods

The reconstruction is based on the iterative estimation of the sensitivity profiles, ghosting parameters, and unfolded image using the pipeline depicted in Fig. 1. First, a conventional reference scan initializes the sensitivities and a singleband (SB) dataset is used to update the sensitivities in the EPI distorted space. For this, SB and MB readouts are matched and the SB reconstruction is adopted as the body coil and the SB measurements as the surface coils^{7,8}. Then, CG-SENSE reconstruction is formulated as:

$$(\mathbf{x}^*, \boldsymbol{\theta}^*) = \underset{\mathbf{x}, \boldsymbol{\theta}}{\operatorname{argmin}} \|\mathbf{B}\mathbf{P}(\boldsymbol{\theta})\mathcal{F}\mathbf{S}\mathbf{x} - \mathbf{P}_0^H \mathbf{y}\|_2^2 + \boldsymbol{\lambda}^T \|\mathbf{W}\boldsymbol{\theta}\|_2^2,$$

with \mathbf{x} the image to be reconstructed, $\boldsymbol{\theta} = \boldsymbol{\theta}_{i,r}$ the Nyquist ghosting parameters, using a slice (r) dependent linear ($i = \{0, 1\}$) phase shift in the readout direction, \mathbf{B} the MB encoding matrix, $\mathbf{P}(\boldsymbol{\theta})$ accounting for ghosting, \mathcal{F} the discrete Fourier transform in the PE direction (encompassing in-plane downsampling), \mathbf{S} the coil sensitivity matrix, \mathbf{P}_0^H the ghosting parameters from the calibration data⁹, \mathbf{y} the measured data, and \mathbf{W} promoting second order smoothness in the slice direction as regulated by $\boldsymbol{\lambda}$. The algorithm alternates between data-based ghosting estimation (using the Newton's method) and estimation of the underlying image (using CG). Despite iterative refinements, residual sensitivity errors or inconsistencies due to motion may still degrade the reconstruction. To cope with this, an extension of the minimal artifact factor (MAF) SENSE method¹⁰ has been introduced. An optimal balance between artifacts and SNR is achieved at each location by (iteratively) estimating the \mathbf{g} -factor penalty introduced by the MAF reconstruction at that location and weighting the artifact matrix¹⁰ accordingly.

The pertinence of the main reconstruction components is visually assessed by a phantom experiment of a spin-echo EPI acquisition. Its parameters are summarized in Fig. 2. The proposed reconstruction method is also applied to both functional (fMRI) (MB factor **9**)¹¹ and diffusion weighted (DWI) (MB factor **4**)¹² datasets within the developing Human Connectome Project (dHCP).

Results

In Fig. 3 we compare four CG-SENSE reconstruction settings in the coronal view (for which the folded dimensions are in plane). In Fig. 3a, a standard CG-SENSE is performed using the original FFE reference. Inconsistencies between the space in which sensitivities are estimated and distorted EPI space provoke different sources of error, such as distorted areas appearing folded or residual ghosting. In Fig. 3b, the SB-based reference estimation is introduced. Now, Nyquist ghosting is likely to be the leading source of folding. In Fig. 3c, the ghosting estimation is included with a noticeable reduction of artifacts. Finally, in Fig. 3d, MAF-SENSE leakage reduction is incorporated, which effectively limits the remaining artifacts with a minor hit in SNR with respect to the optimal SNR of Fig. 3c.

In Fig. 4 we include an example of the SMS-EPI fMRI unfolding from the dHCP cohort (where **143** fMRI and **131** DWI cases have been reconstructed so far). In these highly accelerated datasets, motion occurring between the reference and the data acquisitions may break reconstruction assumptions. However, we have observed our results to be relatively insensitive to motion. Similar conclusions can be established from the DWI reconstructions in Fig. 5; despite large distortions, no perceptible folding is observed. However, in the DWI case, strong distortions and motion are in some cases generating significant leakage, which we expect to reduce with further refinements of SNR balanced MAF-SENSE.

Conclusions

We have presented a comprehensive framework for the SMS-EPI reconstruction that, by alternating between the estimation of the sensitivities, ghosting, and unfolded volumes, accounts for distortion and motion induced errors in sensitivity estimation and slice dependent ghosting. The introduced refinements have proven to reduce the leakage artifacts in a phantom experiment and stable results have been obtained when applying the pipeline to motion corrupted SMS-EPI fMRI and DWI datasets. Future work will study the incorporation of prior information to inform the alternating optimization involved in the formulation.

Acknowledgements

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References

1. Barth, M, Breuer, F, Koopmans, et al. Simultaneous multislice (SMS) imaging techniques. *Magn Reson Med*. 2015; in press.
2. Zahneisen, B, Ernst, T, and Poser, BA. SENSE and simultaneous multislice imaging. *Magn Reson Med*. 2015;74(5):1356-1362.
3. Zhu, K, Dougherty, RF, Takahashi, AM, et al. Nyquist ghosting correction for simultaneous multislice

echo planar imaging. ISMRM. 2014;647.

4. Pruessmann, KP, Weiger, M, Börnert, P, et al. Advances in sensitivity encoding with arbitrary k -space trajectories. Magn Reson Med. 2001;46(4):638-651.

5. Hennel, F, Buehrer, M, von Deuster, C, et al. SENSE reconstruction for multiband EPI including slice-dependent $N/2$ ghost correction. Magn Reson Med. 2015; in press.

6. Cauley, SF, Polimeni, JR, Bhat, H, et al. Interslice leakage artifact reduction technique for simultaneous multislice acquisitions. Magn Reson Med. 2014;72(1):93-102.

7. Ying, L, and Sheng, J. Joint image reconstruction and sensitivity estimation in SENSE (JSENSE). Magn Reson Med. 2007;57(6):1196-1202.

8. Allison, MJ, Ramani, S, and Fessler, JA. Accelerated regularized estimation of MR coil sensitivities using augmented Lagrangian methods. IEEE Trans Med Imag. 2013;32(3):556-564.

9. Ahn, CB, Cho, ZH. New phase correction method in NMR imaging based on autocorrelation and histogram analysis. IEEE Trans Med Imag. 1987;6(1):32-36.

10. Peeters, JM, and Fuderer, M. SENSE with improved tolerance to inaccuracies in coil sensitivity maps, Magn Reson Med. 2013;69(6):1665-1669.

11. Price, AN, Cordero-Grande, L, Malik, SJ, et al. Accelerated neonatal fMRI using multiband EPI. ISMRM. 2015;3911.

12. Hutter, J, Tournier, JD, Hughes, EJ, et al. Optimized multi-shell HARDI acquisition with alternating phase encoding directions for neonatal dMRI. ISMRM. 2015;3640.

Figures

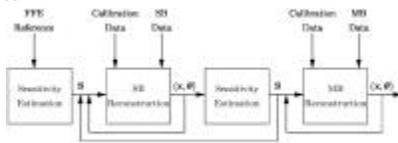


Fig. 1. Reconstruction pipeline. First, sensitivities are estimated from a separate scan. Then, SB data is used as a new reference to estimate the sensitivities in the EPI distorted space. This procedure is repeated until convergence. Finally, reconstruction alternates between data unfolding and estimation of ghosting parameters for each slice.

Resolution (mm ²)	Slice distance (mm)	# coils	PE
1.5 x 1.5 x 3	1.5	32	LR
MR factor	PE shift	SENSE factor	Partial Fourier
4	1/2	1.2	5/8
FOV (mm ²)	T ₁ (ms)	T ₂ (ms)	α(°)
150 x 150 x 97.5	3000	96	90

Fig. 2. Parameters of the phantom sequence used for validation.

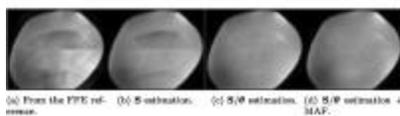
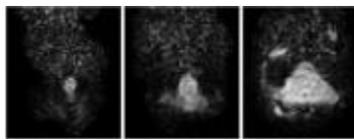


Fig. 3. Incremental refinement of reconstructions when incorporating the main functionalities of our proposal.



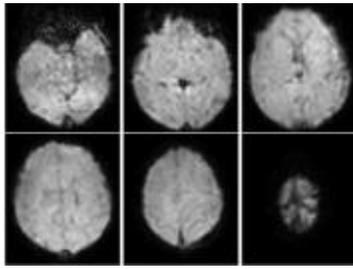


Fig. 4. Reconstruction of a MB 9 resting-state fMRI dataset. Unfolded slices shown were acquired within a single SMS EPI readout.

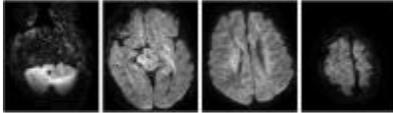


Fig. 5. Reconstruction of a MB 4 / SENSE 1.2 neonatal DWI dataset ($b = 1000 \text{ mm}^2/\text{s}^2$). Unfolded slices shown were acquired within a single SMS EPI readout.