GHOST-CORRECTING SENSE RECONSTRUCTION FOR MULTI-BAND EPI

Franciszek Hennel[1], Aline Seuwen[1], Constantin von Deuster[1], and Klaas P. Pruessmann[1]
[1]*Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland*

PURPOSE: Separation of simultaneously excited slices by SENSE[1] may be hindered by the N/2-ghost problem when it is applied to multi-band EPI. The phase correction needed for the ghost removal is often slice-dependent, which makes it applicable only after the separation of slice signals. On the other hand, the SENSE separation requires ghost-free images to assign coil sensitivity to pixels. Recently Zhu et al.[2] have proposed to incorporate the slice-dependent phase correction in the equations linking the k-space data with the image. Their reconstruction requires solving N_{coils} x N_y linear equations for N_yxN_z unknowns for each readout position (N_z= n. of slices, N_y = n. of pixels in phase encoding direction). Our goal was to reduce the problem complexity by posing it in the image domain.

METHODS: We make the common assumption that the phase error in EPI oscillates between two opposite values for even and odd echoes, and split the data in two arrays: one containing only the even echoes and the remaining ones replaced by zeros, and another with odd echoes and zeros. These arrays are reconstructed giving two sets of images:

$$\rho_{nxy}^{e} = \frac{1}{2}\sum_{z}\left[\rho_{xyz}C_{nxyz}e^{i\theta(x,y,z)} + \rho_{xyz}^{(1)}C_{nyz}^{(1)}e^{i\theta^{(1)}(x,y,z)}\right], \qquad \rho_{nxy}^{o} = \frac{1}{2}\sum_{z}\left[\rho_{xyz}C_{nxyz}e^{-i\theta(x,y,z)} - \rho_{xyz}^{(1)}C_{nxyz}^{(1)}e^{-i\theta^{(1)}(x,y,z)}\right]$$

where *n* enumerates array coils, *x/y* image pixels in read and phase direction, and z the simultaneously excited slices; ρ is the image we want to reconstruct, *C* the coil sensitivity, and θ the phase error caused by eddy currents (typically, a linear function of x). The index $^{(1)}$ symbolizes a cyclical shift in the phase direction by half the matrix size. These images are doubly folded: they contain 'collapsed' slices and replicas shifted by half FOV in the y direction. For each x and for each y in the first half of the image, we have $2N_{coils}$ linear equations (even/odd-reconstructions of pixel x,y for each coil) for $2N_{slices}$ unknowns (contribution of each slice to this pixel and to its counterpart in the other half of the image). Provided there are more coils than slices, the system of equations can be solved in the least-squares sense. Compared to the method proposed in ref. 2, the size of the system matrix is reduced by $N_y/2$ in each dimension. Taking into account that the least-squares solution has complexity $O\left(N_{\text{equations}} \times N_{\text{unknowns}}^2\right)$ and needs to be calculated $N_y/2$ times, we reduce the computation time by a factor of $N_y^2/4$.

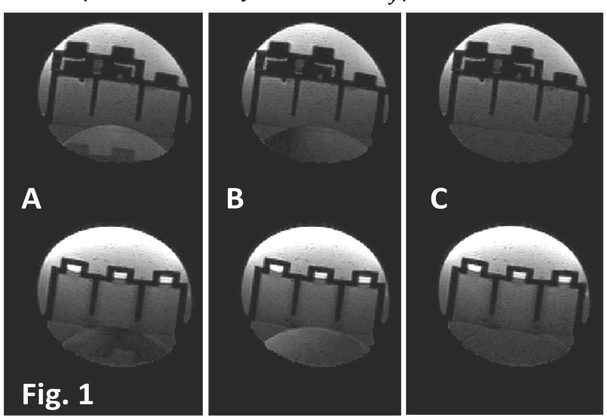

Fig. 1

EPI with 2-band excitation was applied on 7T and 9.4T pre-clinical MRI systems (Bruker BioSpec) with 2x2 channels receiver arrays (room temperature at 7T and cryogenically cooled at 9.4T) to acquire phantom and mouse brain images. In an additional reference scan the same slices were measured independently with the array and with a volume coil to derive coil sensitivities. The reference scan was repeated without the phase encoding blips to measure $\theta(x,z)$ (dependence on y was not taken into account). Reconstructions were done by least-squares-solution of the above equations and, for comparison, by standard multi-band SENSE[1] starting from folded images obtained with the ghost correction adjusted to one of the slices or to the slice average. To test the method's robustness the difference in the phase error between slices in the phantom experiment was enhanced by modification of gradient cross-preemphasis (23 deg difference reached in the zero order term).

RESULTS: **Figure 1** shows results of the phantom experiment at 7T: **A** - the two slices separated by standard SENSE with the ghost correction adapted to the lower one; **B** - the same strategy adapted to upper slice; **C** - separation with the proposed method. **Figure 2** shows mouse brain images measured at 9.4T: **A** - standard SENSE with average ghost correction; **B** - separation by the proposed method.

DISCUSSSION: When the EPI ghost correction parameters differ between slices, standard multi-band SENSE does not allow a proper slice separation. With the correction adapted to one of the slices, the uncorrected slice appears with the N/2 ghost, which is expected, and alone would not be a problem (one could target this slice in another run). Unfortunately, the "corrected" slice keeps an admixture from the other slice's ghost. That is because the SENSE separation in the ghost region was attempted based on the true coil sensitivity, and not the shifted one of the ghost. Using the average ghost correction only mitigates the problem (ghosts remain on both slices, see arrows). Including the slice-dependent ghost correction in the encoding equations for the even- and odd echo-based images separates the slices correctly and removes the N/2 ghost from both of them (Figs. 1C and 2B). The price for this improvement is a slight increase of computation time related to the separation of even and odd k-space lines and doubling the size of the encoding matrix. This task, however, is still much simpler than the direct fit to the k-space signal as proposed in ref. 2. Compared to the GRAPPA multiband reconstruction, which can also feature a slice-dependent ghost correction[3], our method keeps the advantage of being object-independent, and should thus better tolerate motion and intensity changes in dynamic studies.

CONCLUSION: Slice-dependent ghost correction can be easily included in the image-domain SENSE reconstruction of multi-band EPI leading to improved image quality.

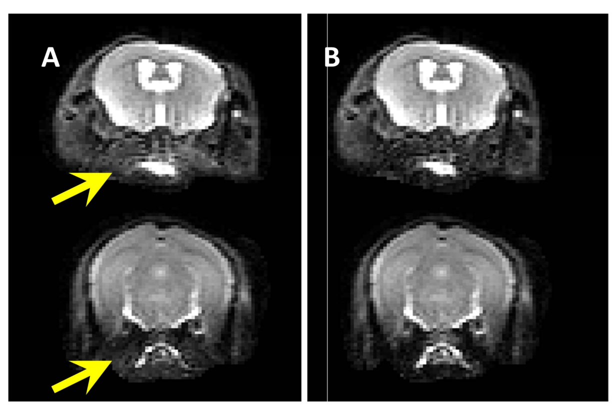

Fig. 2

REFERENCES:

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2. Zhu K et al. (2014) *Proc Int Soc Mag Reson Med* 22, 647.
3. Setsompop K. et al. (2012) *Neuroimage* 63 569-580.