

2D-SENSE-GRAPPA For Fast, Ghosting-Robust Reconstruction of In-Plane and Slice Accelerated Blipped-CAIPI-EPI

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Purpose

Simultaneous multislice imaging (SMS) in EPI using blipped-CAIPI¹ is hindered by:

- 1) *EPI N/2 ghosting artefacts*. These cannot be corrected before un-aliasing the SMS slices because the ghosting varies per slice due to spatial variation of the eddy current effects. Ghosting mimics the effects of the CAIPI operation, the problem being most pronounced when using a CAIPI factor of FOV/2 as shown in Fig 1.
- 2) *Reconstruction times*. In long time-series (fMRI/DTI) the calculation times become unwieldy when using high acceleration factors. The current standard method to reconstruct SMS-CAIPI-EPI data is Slice-GRAPPA¹ that uses two steps: first the slices are un-aliased and then a conventional GRAPPA reconstruction is performed along the phase dimension. We propose a one-step reconstruction within the SENSE-GRAPPA³ framework to reduce the computational cost while being robust against N/2 ghosting artefacts.

Background

A Slice-GRAPPA solution to N/2 ghosting interfering with CAIPI was proposed² that uses reference data for slice un-aliasing that have identical ghosting levels (i.e. using the same readout module for the reference data, which is very common in fMRI/DTI SMS data acquisition). Ghosting robustness is achieved by training kernels for the odd and even phase encode lines separately. Applying these kernels to the odd and even SMS lines will un-alias the slices correctly, each with their own ghosting intact which then can be corrected for post-hoc using standard, single-slice methods.

Slice-GRAPPA itself was invented as a solution to the idea that CAIPI and SENSE-GRAPPA would be incompatible: in SENSE-GRAPPA the reference slices are concatenated in the phase dimension, but the CAIPI operation introduces discontinuities at the edges where the slices meet and the reconstruction kernel cannot cope with these. However, it was noted earlier⁴ that SENSE-GRAPPA works just as well when concatenating along the read axis to avoid interference from CAIPI. The advantage of simultaneous reconstruction of in-plane and SMS acceleration offered by the original SENSE-GRAPPA method can be retained by simply changing the kernel from 1D to 2D.

Methods

We used data obtained with a standard diffusion imaging protocol (3T, 96 matrix size, 2 mm isotropic) to simulate SMS data in order to assess the reconstruction methods' performances with a known underlying truth. Three slices of the b=0 image were taken with 16 mm slice spacing. SMS data were simulated after 2-fold in-plane undersampling, applying CAIPI FOV/2 shift and introducing artificial slice-dependent ghosting by shifting the odd k-space lines by [-1, -0.5 and +1] k-space units. We tested three reconstruction algorithms, each in two variants (ordinary and using odd-even kernels):

- 1) The two-step Slice-GRAPPA method¹. Slices are un-aliased with a 5x5 kernel, followed by a 5x4 in-plane grappa reconstruction.
- 2) A SENSE-GRAPPA³ implementation that also uses two steps (i.e. no computational advantage) for comparison with Slice-GRAPPA. Both kernels were 5x4.
- 3) One-step 2D-SENSE-GRAPPA. Kernel size was 6x6. In-plane acceleration is slightly problematic due to the requirement of ghosting in the reference data but it can be solved by treating the reference data appropriately according to Fig. 2. Like Slice-GRAPPA, 2D-SENSE-GRAPPA thus also needs prior knowledge on ghosting.

The kernel sizes varied slightly due to requirements of the implementations w.r.t. even and odd sizes in specific dimensions. Note that the 6x6 kernel is not as unfair as it may seem at first glance: Slice-GRAPPA uses a 5x5 kernel to estimate 2 missing values (SMSfactor -1) and subsequently uses 5x4 points to reconstruct 1 missing in-plane value. 2D-SENSE-GRAPPA needs to estimate 5 missing values simultaneously (3x2 -1) using only 36 points (see Discussion).

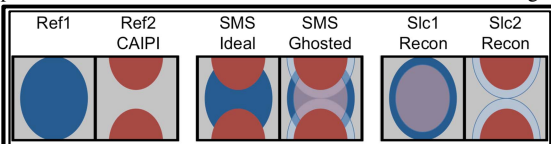


Fig 1. Ghosting and CAIPI=2. The ghost of slice 1 matches the sensitivity profile of slice 2 after CAIPI much better than its own, causing the ghosted signal to be assigned to the wrong slice. Post-hoc ghost correction is no longer possible.

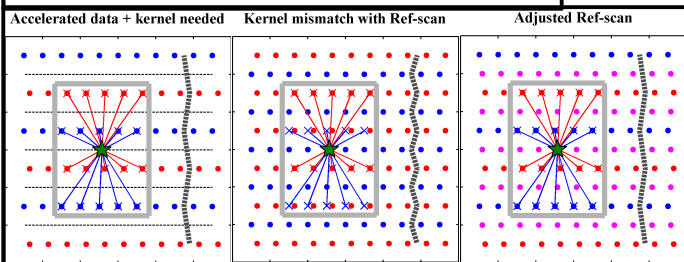


Fig 2. Ghosting & 2-fold GRAPPA. The kernel needed for the aliased data (left) clearly does not match the (non-segmented) reference data (mid). Its N/2 effect has twice the frequency. Removing the ghost and re-introducing it with the correct frequency fixes this (right). This allows GRAPPA recon. in the presence of ghosting.

Discussion

The results show that all methods perform similar, the odd-even ones dealing well with the ghosting whereas the ordinary kernels fail (note that all images in Fig 3. are after post-hoc ghost correction by shifting the odd-lines back as soon as the slices are separated). The root-sum-of-squares error (RSSE) inside the brain is much lower for the odd-even methods. Slight differences between the three methods are present but these are in part attributable to differences in kernel sizes which will be further investigated. The main message is that the images qualitatively convey is that similar ghosting robustness and reconstruction fidelity can be obtained with 2D-SENSE-GRAPPA compared to the current standard Slice-GRAPPA method, which means we can potentially reduce reconstruction times 'for free'.

References: [1] Setsompop *MRM* 2012; [2] Setsompop *Neuroimage* 2012; [3] Blaimer *JMRI* 2006; [4] Moeller *ISMRM* 2014. **Acknowledgements:** WT100092MA

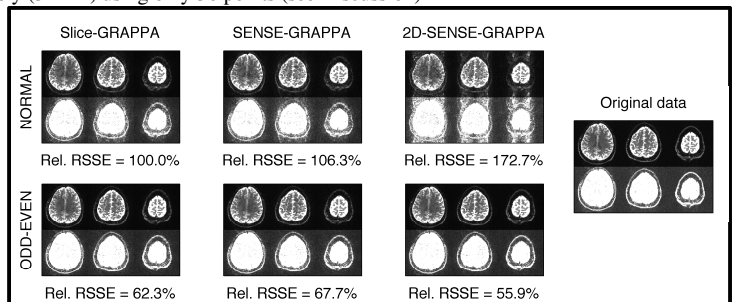


Fig 3. Results of the simulated ghosted SMS reconstructions shown on normal scale and with restricted window to visualise ghosting better. RSSE error measures are calculated inside the brain w.r.t the original data and expressed relative to the RSSE of normal Slice-GRAPPA (top-left).

The 'normal' variants clearly cannot cope with ghosting whereas the odd-even ones can. The minor RSSE differences could possibly be explained due to slight variations in kernel sizes.