Characterization of autocalibration methods for accelerated EPI reconstructions using GRAPPA

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Target audience: Clinicians/researchers using accelerated echo planar imaging, especially in high-field or high-resolution applications.

Purpose: Accelerated parallel imaging greatly benefits echo planar imaging (EPI) acquisitions by helping to reduce geometric distortion and T_2/T_2^* blurring, and techniques such as SENSE and GRAPPA require calibration data to train the algorithm parameters. For EPI reconstructed with GRAPPA, this training data is typically a segmented EPI acquisition with echo-spacing matched to the subsequent accelerated image data. It has been recently demonstrated that mismatch between the calibration data and the accelerated EPI acquisitions can have a dramatic impact on image quality, and in particular phase errors across the segments can cause severe SNR loss and ghosting/aliasing artifacts[1,2]. Several methods have been developed to circumvent this issue. The FLASH-based ACS approach[2,3] acquires autocalibration (ACS) data of higher quality than the typical EPI-based ACS data and has been shown to substantially improve image SNR; this data differs from the accelerated EPI in terms of susceptibility-induced geometric distortion and phase errors across positive and negative readout lines and across segments. The FLEET-ACS approach[1] utilizes a multi-shot EPI acquisition in which all segments within a slice are acquired consecutively within a short time interval, reducing phase errors between segments caused by *dynamic* B_0 changes driven by, e.g., respiration or bulk motion. These data still retain the *static* phase errors due to eddy currents which result in Nyquist ghosting in the ACS data. However, it has been shown that the FLEET ACS reconstructions can provide GRAPPA reconstructions with identical SNR improvements, and also provides reduced residual aliasing compared to the FLASH ACS method especially in areas near susceptibility gradients. Here we attempt to isolate the key discrepancy between these two approaches, and to do so utilize two new techniques for acquiring ACS data. The GESTE method[4] is an EPI ghost correction strategy whereby two copies of the k-space data are acquired with reversed readout polarity. This data is then *coherently* combed to cancel static phase errors. GESTE provides images that are ghost-free, like FLASH, and like FLEET is distortion-matched to the accelerated EPI data. By comparing the results of GESTE with FLEET and FLASH we may determine the impact of complete Nyquist ghost removal in the ACS data on the GRAPPA reconstructions. A novel, combined **FLEET-GESTE** approach is also evaluated, which removes both static and dynamic phase errors. To further investigate the impact of Nyquist phase errors, we applied a **dual-kernel GRAPPA** approach (similar to an approach proposed for slice-GRAPPA[5]) in which two independent kernels are trained to the ACS data and applied to the accelerated data—which was designed to be robust to systematic phase shifts between positive and negative readouts and thus fits a kernel that respects the phase errors rather than removing them. We find that this dual-kernel approach when used with conventional segmented EPI can outperform both the reconstruction based on FLASH ACS data as well as that based on the FLEET-GESTE ACS data in terms of aliasing removal, suggesting that static phase corrections in the ACS data are not necessary, and in fact may *introduce* reconstruction errors when similar phase correction methods are not also applied to the accelerated imaging data itself.

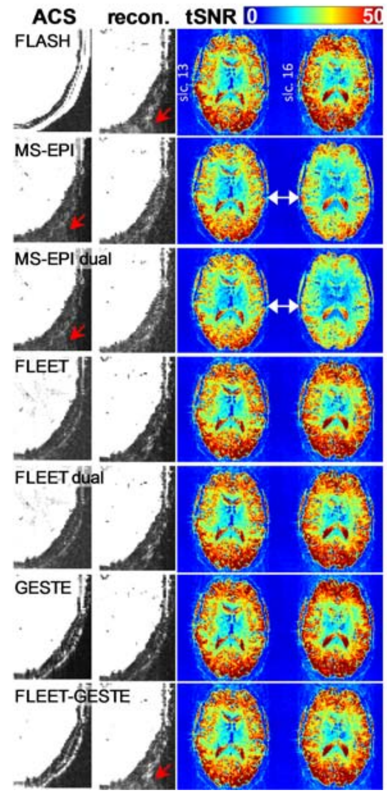

Fig. 1: ACS data, image reconstructions (windowed to highlight ghosts) and tSNR maps. Areas with strong aliasing/ghosting indicated with red arrows.

Methods: Three volunteers (having given informed consent) were scanned on a Siemens 7 T whole-body scanner (Siemens Healthcare, Erlangen, Germany) using a custom-built 32-channel receive array and birdcage transmit coil. A single BOLD-weighted EPI protocol was used with each ACS calibration scheme tested, consisting of the following parameter values: 1.5×1.5 mm^2 voxel size, (192×192 mm^2 FOV, 128 matrix), 37 1.5-mm thick slices with TR=2.0 s, TE=25 ms, flip=75°, no p.F., BW=1776 Hz/pix, nominal echo spacing 0.67 ms, and 75 measurements with R=3 acceleration. For each ACS acquisition, the maximum number of reference lines was acquired (i.e., 126). The GESTE method[4] for acquiring segmented EPI was combined with a FLEET acquisition[1] by first acquiring all segments in a given slice with the conventional readout polarity then immediately acquiring all segments a second time with the reversed readout polarity. For the FLASH reference scan, the ACS acquisition parameters were: TE=3.2 ms, flip=5°, BW=1000 Hz/pix. For the FLEET-based reference scans, the ACS acquisition parameters were: flip=10° with 5 "dummy" preparation pulses. All images were reconstructed offline in MATLAB using a conventional GRAPPA fitting and EPI reconstruction, and the reconstruction algorithms applied to the acquired data differed only in the preparation of the ACS. Time-series SNR (tSNR) was evaluated as the ratio of the time-series mean with the time-series standard deviation after motion correction and linear detrending.

Results: A total of 15 reconstruction methods were evaluated; results from the 7 most informative are shown in Fig. 1. The GESTE/FLEET-GESTE ACS data are virtually free of ghosting artifacts, as expected. The tSNR is comparable across all techniques with the exception of the conventional multi-shot EPI. (Note the abrupt change in tSNR seen across odd and even slices in the data reconstructed with conventional ACS data, as reported previously[1], indicated by white arrows.) Despite the low ghost levels in the ACS data, the residual aliasing is consistently highest in the FLASH and FLEET-GESTE reconstructions.

Discussion & Conclusion: The combination of FLEET with GESTE provides ACS data free of static and dynamic artifacts, yet residual aliasing is observed in the reconstructions, although GESTE and FLEET alone produce similarly artifact-free images. While the results here indicate that the ACS acquisition must match the accelerated data, it is well-known that the GRAPPA technique is robust to some differences between ACS and image data, such as tissue contrast[3,6], and both FLEET and FLASH exhibit slightly different image contrast than the accelerated acquisitions. These experiments suggest that the ideal ACS data must match the accelerated EPI data in terms of phase errors and geometric distortion to provide the highest quality GRAPPA reconstructions.

References: [1] Polimeni *et al.* (2013) *ISMRM* p.2646. [2] Talagala *et al.* (2013) *ISMRM* p.2658. [3] Griswold *et al.* (2006) *NMR in Biomed* **19**:316. [4] Hoge *et al.* (2010) *MRM* **64**:1781. [5] Setsompop *et al.* (2012) *NeuroImage* **63**:569. [6] Breuer *et al.* (2004) *ESMRMB* p.398.

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