SENSE and GRAPPA Reconstruction of Multi-Shot Multi-Echo EPI Data

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Introduction. One of the most promising benefits of parallel imaging is that it can reduce distortions by shortening the read-out times of fast acquisition techniques such as EPI (1,2). The trade-off for this improvement is a drop in SNR due to imperfect receiver geometry (g-factor) and fewer measurements; there is also the potential for errors due to the more complicated reconstruction algorithms which rely on estimations of additional information about the receiver coils. This additional information is typically acquired either by a separate low-resolution scan or by incorporating a segment of k-space acquired at the Nyquist sampling rate directly into the sequence of interest; both of these techniques have limitations and disadvantages. We have recently developed a multi-shot multi-echo EPI pulse sequence to measure PERfusion with Multiple Echoes and Temporal Enhancement (PERMEATE), described elsewhere in this volume. This sequence allows for greater reconstruction flexibility: each shot can be treated as a separate under-sampled k-space acquisition and reconstructed using either GRAPPA (3) or SENSE (4) with an effective reduction factor, R, equal to the number of interleaves, N_i. By borrowing information from the other interleaves, it is possible to generate the auto-calibration signals (ACS) required for GRAPPA, or the full-FOV sensitivity maps required for SENSE (4). Additional flexibility is possible for acquisitions in which N_i is large enough so that various combinations of shots can be collated into k-space sets with $R < N_i$. In this work, we explore the differences between the implementation and performance of basic GRAPPA and SENSE reconstructions of PERMEATE data.

Materials and Methods. Images from a healthy volunteer were acquired using a 1.5 T scanner (GE Signa) with an 8-channel head array (MRI Devices). The PERMEATE pulse sequence was used with 96×96 resolution, 15 slices, 4 interleaves, 4 echoes (TE = 12.4, 27.4, 42.4, and 57.4 ms), TR = 1.2 s, and 20 time frames. Prior to GRAPPA or SENSE reconstruction, all 4 consecutive interleaves were assembled into one fully-sampled (R = 1) k-space and EPI correction was performed: phase correction using an entropy-minimization algorithm (described elsewhere in this volume) and regridding to account for ramp sampling. Two types of phase-encoding sub-samplings could then be extracted for each slice and echo: odd and even shots were combined for an effective R = 2, or each shot was treated separately for R = 4. GRAPPA was performed using a 5×4 kernel applied over the entire k_x range; the number of ACS lines used was 2. SENSE was performed using the typical unfolding method in which a least-squares solution is found for the R pixels that are aliased into the same location in each of acquired coil component images. The matrices that get inverted for each unfolding operation are comprised of data from coil sensitivity maps derived from the fully-sampled data. The methods used here are variations on those typically used to generate maps from a separate calibration scan. The full-FOV image can be obtained by taking the Fourier transform of the entire R = 1 k-space data or of a central subset (for a low-resolution estimate). In the latter case, cubic spline interpolation to the desired resolution is performed in the image domain. Each coil image is then smoothed by convolution with a square kernel and divided by the sum-of-squares image. One more refinement is the inclusion of a binary mask that can be used to limit the number of pixels known to contribute a given pixel in the aliased image and, hence, reduce noise contribution from areas outside the anatomy of interest.

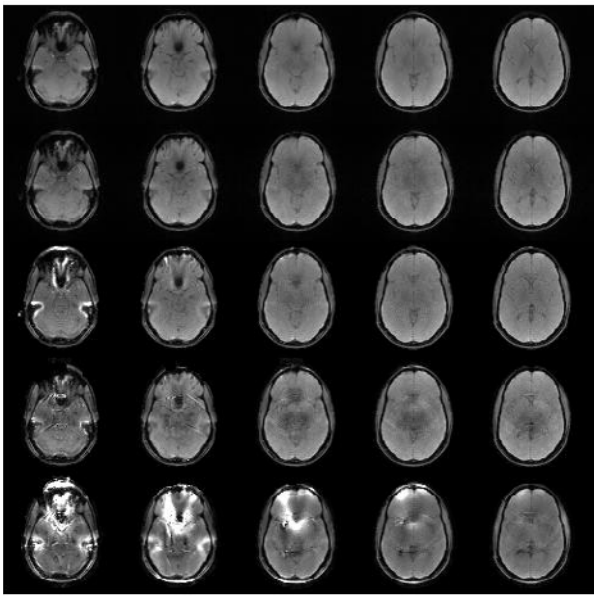

FIG 1. The first echo of 5 center slices (columns) from various reconstruction methods (rows). Row 1 (top) is the reconstruction of the fully-sampled data, R = 1. The lower 4 rows show the first shot of R = 4 reconstructions. Row 2 is GRAPPA; rows 3-5 are SENSE. In row 3, coil maps were made using the R = 1 k-space data and a 3×3 smoothing kernel. In row 4, the same smoothing was used, but maps were made using only the center 32×32 region of the R = 1 data then interpolating to 96×96 in the image domain. Row 5 is similar to row 3, but a 10×10 kernel was used.

Results and Discussion. Figure 1 shows examples of various R = 4 reconstructions (bottom 4 rows) with the R = 1 reconstruction show in the top row for comparison. The GRAPPA reconstruction performs well and, for the most part, can be treated as if it were a black-box operation. The initial results from the SENSE reconstruction (bottom row in Fig 1) seemed less promising. These were the results of a direct port of the algorithm being used for clinical scans in which the sensitivity maps were derived from a FGRE calibration scan. In this case, the fully-sampled images were smoothed with a 10×10 kernel to generate the maps. This method leaves considerable residual aliasing artifacts from poor coil sensitivity estimation at the edges of the head; also, there are regions of high signal pile-up in locations where the maps do a poor job of estimating the receiver phase. To improve this reconstruction, the next step (second-from-bottom row in Fig 1) was to use only a low-resolution estimate for the maps by extracting the center 32×32 region of the R = 1 data. This significantly reduced the regions of hyper-intensity but still left an undesirable amount of residual aliasing. One final alternative is shown in the center row of Fig 1; here, maps were made from the full k-space data and smoothed with a 3×3 kernel. While this appears to be the best of the SENSE reconstructions, especially in that there is essentially no residual aliasing, there is still more signal pile-up in regions of high susceptibility variation as compared to GRAPPA. One possible explanation for this is that the susceptibility drop-outs and distortions inherent in the EPI data used to make the coil maps have a strong influence in those regions.

Conclusions. We have presented both GRAPPA and SENSE reconstructions of multi-shot, multi-echo perfusion-weighted EPI data with an effective reduction factor of 4. Although both require no user input and are generally robust to the choice of acquisition parameters, we have shown here that a critical step for SENSE reconstruction is the method and parameters used for generating coil sensitivity maps. While GRAPPA reconstruction could be treated nearly as a black-box and demonstrates extremely robust and reliable performance in all cases treated here, the SENSE reconstruction required some refinement of the details involved in transforming the data from all shots into the optimum sensitivity maps.

References. (1) Bammer R, et al. MRM 2001;46:548. (2) Yang QX, et al. MRM 2004;52:1418. (3) Griswold MA, et al. MRM 2002;47:1202. (3) Pruessmann, et al. MRM 1999;42:952. (4) Skare et al. Workshop on Methods for Quantitative Diffusion MRI of Human Brain 2005:17.

Acknowledgements. NIH (1R01EB002771), The Center for Advanced MR Technology at Stanford (P41RR09784), The Lucas Foundation, The Oak Foundation. Thanks to MA Griswold for sharing the *opengrappa* Matlab code.