

AUTO-CALIBRATED PARALLEL IMAGING USING A DISTORTION-OPTIMAL FILTER-BANK

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INTRODUCTION Most auto-calibrated parallel MRI (pMRI) methods, especially the popular GRAPPA method [1], perform image reconstruction by solving for missing k-space samples. Such methods, also known as k-space-based pMRI, utilize the redundancy in the multi-channel MR measurements to compensate for the R-fold subsampling ($R \geq 2$) relative to the Nyquist rate [2]. In essence, k-space-based methods solve the inverse problem of interpolating the acquired k-space data to the full Nyquist grid. As in any interpolation problem, constraints are typically introduced to ensure certain “consistency” conditions. In GRAPPA the consistency condition is matching of the reconstruction to the acquisition over a fully sampled region, typically located at the center of k-space, called the auto-calibrating scan (ACS) region. In this work, we focus on non-iterative Cartesian k-space-based auto-calibrated pMRI with minimal amount of ACS data. We present a new method that achieves artifact-free image reconstruction for high acceleration factors ($R=3$ 1D acceleration in the presented results) with few ACS lines ($\approx 5\%$ of phase-encodes). In-vivo results comparing the method to two alternative implementations of GRAPPA are provided.

THEORY Fig. 1 is a diagram for general k-space-based pMRI acquisition and reconstruction scheme. The pMR measurements consist of: (i) R-fold uniformly subsampled data from the N channel outputs; (ii) calibration data produced by the data truncation operator Π_{ACS} that removes all but the ACS phase encode lines. In the most general setting all pMR measurements are utilized in both the calibration process and the interpolation process (Fig. 1). The final outcome of the interpolation process is the fully encoded (interpolated) N-channel k-space data set, which is then combined after inverse FFT (e.g., using sum of squares) to form the final reconstructed image. The calibration scheme, indicated in all Figs. by the dashed lines, adjusts the coefficients in the interpolation kernel to optimize the output image and its consistency with the measured data. Fig. 2 depicts the detailed calibration diagram for GRAPPA, where the interpolation process involves the application of the GRAPPA weights to the R-fold subsampled data. The auto-calibration process (Fig. 2) measures the error between the measured ACS data and the corresponding k-space samples in the interpolated output; and adjusts (estimates) the coefficients of the interpolation kernel to minimize this error in the least-squares (LS) sense. Therefore, the only error measure considered in GRAPPA is consistency over the ACS region. Here, we propose an improved scheme (Fig. 3) that uses not only the data consistency (over the entire measured k-space) but also integrates a predicted measure of the aliasing distortion into the calibration process—hence employing a “total distortion” measure rather than just data consistency. The method uses a multi-input multi-output (MIMO) filter bank as its kernel and is dubbed ACSIOM (auto-calibrated sensitivity-encoded imaging using an interpolation-optimal MIMO filter bank).

METHODS All reconstruction experiments used MR data acquired on a 3T whole-body GE scanner (GE Healthcare, Waukesha, WI) from a healthy volunteer using an 8-channel head coil array (2D fast spoiled gradient echo, TR/TE: 300/10 ms, flip angle: 15, rbw: 16 KHz, FOV: 220 mm \times 220 mm, image matrix size: 256 \times 256). Figure 4(A) shows the sum-of-squares image for the fully encoded data. Multi-channel data was 3-fold subsampled ($R=3$) and all reconstructions were performed using 13 reference lines as ACS data—resulting in effective acceleration of $R_{eff}=2.7$. Reconstruction using two different versions of GRAPPA were performed wherein the size of the kernel was varied from 1 to 6 and the optimum size was chosen by visual inspection. Figs. 4(B) and 4(C) correspond to 1D GRAPPA reconstruction with x-varying (row-independent) calibration and reconstruction in the hybrid (x, k_y) space (kernel size: 2 blocks) [3-6]. Fig. 4(D) (and its error image 4(E)) show improved GRAPPA reconstructions using a 2D (k_x, k_y)-space kernel (see [6] and refs. therein), with an optimum size of 2 blocks. Finally, the reconstruction using the proposed ACSIOM technique is shown in Fig. 4(F), with its error image in panel G.

RESULTS The difference images in Fig. 4 suggest that the reconstruction error in both presented versions of GRAPPA is induced by aliasing and causes noticeable coherent distortions, thereby significantly reducing the diagnostic quality of the image. In contrast, the ACSIOM-reconstructed image in Fig. 4(F) only exhibits low-level noise-like error, while keeping the image free of any detectable distortion. The results presented in Fig. 4, therefore, demonstrate that the proposed method outperforms GRAPPA for these experiments.

CONCLUSIONS We presented a k-space-based self-calibrating pMRI reconstruction technique, dubbed ACSIOM, which estimates a GRAPPA-type interpolation kernel by jointly minimizing data inconsistency and aliasing distortion. In imaging scenarios where high effective acceleration is desired, the capability to reconstruct artifact-free images with minimal amount of ACS data is needed. In such cases, we have shown that ACSIOM outperforms two different implementations of GRAPPA. The results indicate that improved image quality, and thus greater scan time reductions compared to GRAPPA can be achieved.

REFERENCES [1] Griswold et al., MRM 47:1202-1210, 2002. [2] Griswold et al., NMR Biomed. 19:316-24, 2006. [3] Blaimer et al., Top Magn Reson Imaging 15:223-36, 2004. [4] Kholmovski et al., ISMRM (14), p. 285. [5] J. X. Ji, et al., Concepts Magn Reson B, 31B(1): 24-36, 2007. [6] Brau et al., MRM 59:382-95, 2008.

Acknowledgements Financial support: Beckman Inst., U. Illinois. Data set: Prof. J. X. Ji (Texas A&M U.)

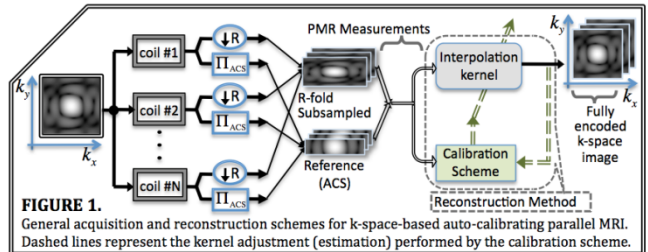


FIGURE 1. General acquisition and reconstruction schemes for k-space-based auto-calibrating parallel MRI. Dashed lines represent the kernel adjustment (estimation) performed by the calibration scheme.

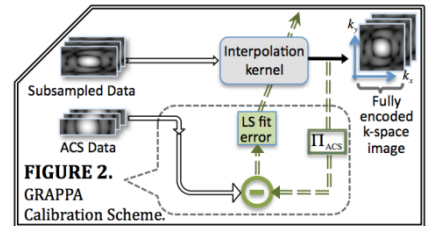


FIGURE 2. GRAPPA Calibration Scheme.

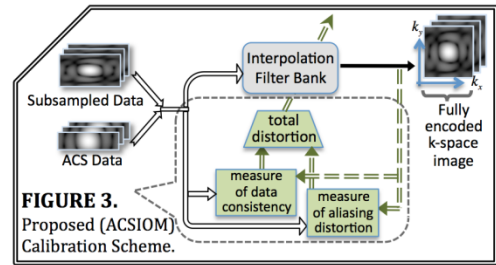


FIGURE 3. Proposed (ACSIOM) Calibration Scheme.

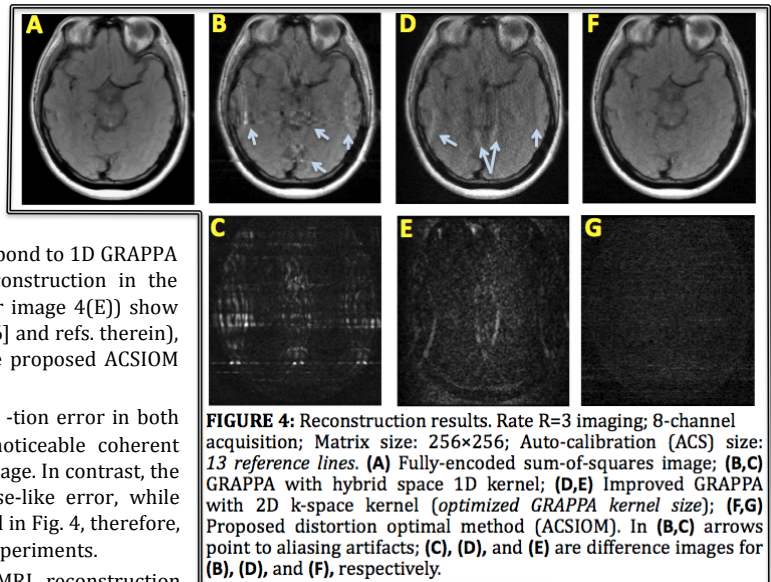


FIGURE 4: Reconstruction results. Rate $R=3$ imaging; 8-channel acquisition; Matrix size: 256 \times 256; Auto-calibration (ACS) size: 13 reference lines. (A) Fully-encoded sum-of-squares image; (B,C) GRAPPA with hybrid space 1D kernel; (D,E) Improved GRAPPA with 2D k-space kernel (optimized GRAPPA kernel size); (F,G) Proposed distortion optimal method (ACSIOM). In (B,C) arrows point to aliasing artifacts; (C), (D), and (E) are difference images for (B), (D), and (F), respectively.