

Characterization of artifacts and noise enhancement introduced by GRAPPA reconstructions

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Introduction: The g -factor map, defined for parallel imaging reconstructions using the SENSE algorithm [1], provides a spatial map of noise enhancement introduced by the SENSE matrix inversion. This map may be used to predict image reconstruction performance or the suitability of a particular receive coil array for accelerated imaging. However in some applications the GRAPPA technique [2] is advantageous due to the difficulty of accurately estimating the receive coil sensitivity profiles. Currently there is no consensus on an analogous formulation for a noise enhancement or “ g -factor” map for GRAPPA [3]. Here we review the two dominant sources of error—noise enhancement and image artifact—introduced by parallel imaging reconstruction, compare the noise enhancement between SENSE and GRAPPA, and introduce a method for characterizing image artifacts specifically for GRAPPA to aid in evaluating the performance and suitability of receive coil arrays for accelerated acquisitions.

Methods: The artifacts in GRAPPA reconstruction arise when the skipped lines of k -space, which are filled by linear combinations of collected lines, do not match the missing data. To quantify the ability of a particular GRAPPA kernel to replace the missing data, our GRAPPA artifact mapping method applies the kernel trained on a central subset of ACS lines to all lines in a fully sampled data set, and then compares the computed lines with the original lines, similar to a standard train-and-test validation. The difference between the two is then reconstructed and viewed in the image domain.

The effect of acceleration on SNR for GRAPPA reconstructions was investigated by computing the SNR images reconstructed from repeated measurements of an agar phantom, which was used both to avoid instabilities due to fluid motion and to eliminate contamination by physiological noise sources. The image SNR is calculated as the ratio of the time series mean to the standard deviation for each pixel in the image. The empirical GRAPPA g -factor was then calculated as the ratio of the resulting image SNR maps (normalized by the square root of the acceleration factor, R).

For all GRAPPA reconstructions, the ACS lines were used for GRAPPA kernel training only and were not included in the final reconstruction.

Results: Our artifact mapping method applied to human brain data, shown in Figure 1, produced images containing high-intensity, high-frequency content, such as the fat layer surrounding the skull, indicating that the GRAPPA kernel was unable to fill in missing k -space lines corresponding to higher spatial frequencies. This behavior is expected since the GRAPPA kernel is fit to the low-frequency ACS lines in the center of k -space in order to represent the smoothly spatially varying effect of the receive coil sensitivity profile modulation of the image domain data during acquisition.

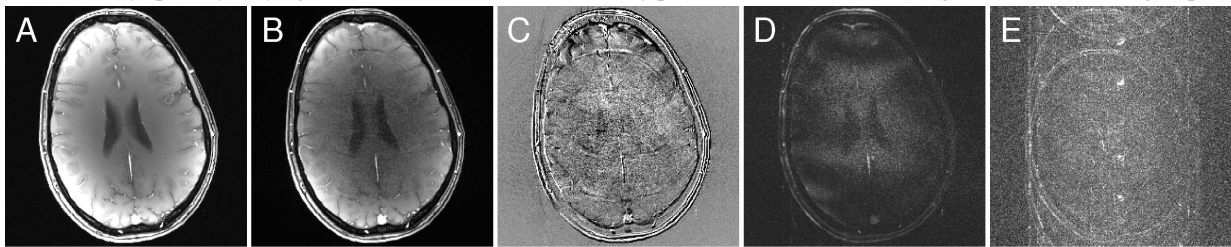


Figure 1: Image artifacts in GRAPPA reconstructions. (A) Fully sampled data collected with a 96-channel receive array. (B) GRAPPA reconstruction for $R = 6$ acceleration in the A-P direction. High-frequency artifacts, such as the fat layer surrounding the skull, alias into the center of the head. (C) Image domain residual, highlighting the aliasing artifacts caused by the replicated fat layer. (D) Artifact map, demonstrating high-frequency image features that are not captured by the kernel. (E) Artifact map with synthesized ghosting to highlight the effect of aliasing and the predicted artifact distribution in the GRAPPA reconstructed image.

The empirical GRAPPA and analytical SENSE noise enhancement are depicted in Figure 2, which show the percentage SNR compared to the reduced SNR expected due to undersampling (effectively $1/g$ in the SENSE case). In the SENSE $1/g$ maps the pattern of aliasing is apparent for each acceleration factor, and local jumps in g -factor follow the pattern of the replicates, whereas little correlation exists in the GRAPPA g -factor maps for lower accelerations. For $R=2$ the GRAPPA data show a boost in SNR in the periphery compared to what would be expected due to undersampling alone, while the SNR in center is reduced as expected. Thus the GRAPPA g -factor is not strictly greater than one, unlike its SENSE analog.

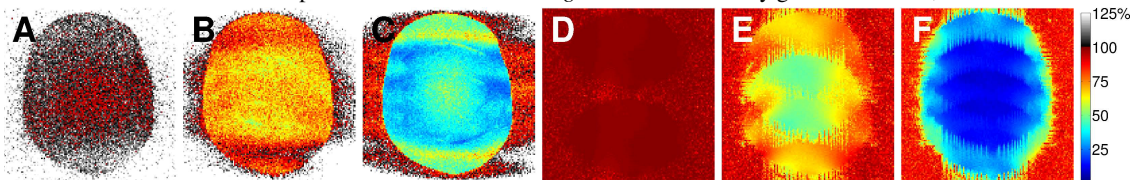


Figure 2: Comparison of noise enhancement in SENSE and GRAPPA. (A) Empirical GRAPPA accelerated SNR map (“ $1/g$ ”) collected with a 32-channel coil, reconstructed for $R = 2$, (B) $R = 4$, and (C) $R = 6$. (D) For comparison, the analytic SENSE noise enhancement ($1/g$) for $R = 2$, (E) $R = 4$, and (F) $R = 6$. In all maps, the color scale indicates SNR losses, whereas the gray scale indicates SNR gains. The SNR for some pixels in the GRAPPA reconstructions at low acceleration can be higher than what is expected due only to undersampling, which does not occur for SENSE.

Discussion: A recent proposal for an analytic GRAPPA g -factor was built upon the interpretation of the GRAPPA kernel as a convolution kernel that corresponds to the Fourier transform of the multiplicative filter given by the coil sensitivity weighting [4]. However, this analogy is confounded by the lack of shift invariance of the GRAPPA kernel as it is typically expressed (except for the special case where $R = 2$), and by the constraint that the kernel be asymmetric between the readout and phase encoding directions in standard Cartesian k -space sampling. While the derivation of an analytical GRAPPA g -factor poses many challenges, empirical SNR maps and their derived empirical g -factor maps provide both a valuable tool for understanding accelerated parallel imaging performance [5], as well as a standard GRAPPA g -factor that any analytical candidate should reproduce.

One drawback of our artifact mapping method is that GRAPPA performance is dependent upon image content and k -space sampling, thus the map needs to be regenerated for each acquisition. However, our GRAPPA artifact mapping method can be used to test the consistency of the GRAPPA kernel with ACS lines alone to measure the fitting error and estimate the reconstruction performance for a given accelerated image without requiring fully sampled k -space data. Understanding the errors inherent in both SENSE and GRAPPA methods will allow us to better exploit these powerful techniques, and can guide the design of new coil arrays adapted to maximize parallel imaging performance.

References: [1] Pruessmann *et al.* MRM, **42**:952, 1999; [2] Griswold *et al.* MRM, **47**:1202, 2002; [3] Griswold. *Parallel Imaging in Clinical MR Applications*, chap. 2, Springer, 2007; [4] Wang *et al.* Proc ISMRM, **13**:2428, 2005; [5] Robson *et al.* Proc ISMRM, **15**:1747, 2007.