Sequential Application of Parallel Imaging and Compressed Sensing

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Designing image acquisition and reconstruction methods to take advantage of both compressed sensing (CS) and parallel imaging (PI) is an area of growing importance in MRI. Existing approaches to this problem either use an iterative reconstruction process to simultaneously consider PI and CS constraints in order to generate a reconstructed image (1-5) or apply SENSE parallel imaging (6) as a separate stage following a compressed sensing stage (7). In this work, an alternative approach is proposed: applying parallel imaging and compressed sensing as separate stages in the reconstruction process, with parallel imaging being applied first. Separating the reconstruction into separate stages has the potential to reduce the computational burden of PI+CS reconstructions as well as to allow many existing parallel imaging techniques, such as GRAPPA (8) or ARC (9), to be used with compressed sensing without modification. The proposed method is described and an experiment is performed to demonstrate feasibility.

Theory The proposed approach is made possible by modifying the k-space sampling pattern to be "clustered incoherent". We define a clustered incoherent sampling pattern as 1) sampling k-space with enough density in some regions (clusters) to enable unacquired locations to be filled in using parallel imaging and 2) sampling k-space so that the pattern formed from the acquired locations plus the locations filled in via parallel imaging leads to incoherent aliasing in the sparsifying domain. An example clustered incoherent sampling pattern is illustrated in Fig 1. The entire sampling pattern is uniformly undersampled by a factor of 2 in both ky and kz, prohibiting its use with compressed sensing alone. However, by first applying parallel imaging, a sampling pattern is formed that is incoherent in the sparsifying domain and can be used with compressed sensing.

Methods Data was simulated by multiplying a high resolution (512x512 matrix) brain image with coil sensitivities for an 8-channel head coil and artificially down-sampling k-space, using the trajectory shown in Fig. 1a, thereby simulating a reformatted slice from a 2-D accelerated 3-D acquisition. Noise was added to the data and a separate low-resolution dataset was used for calibrating the parallel imaging stage. The reconstruction process is shown in Fig. 2. ARC parallel imaging, with external calibration, was used for the parallel image stage, filling in unacquired data as shown in Fig. 1c. Compressed sensing was then applied, independently to each coil dataset, using SparseMRI (10,11). A Daubechies-4 wavelet transform was used as the sparsifying transform. The net acceleration was 7.7, compared to a fully-sampled circular region.

Results Shown in Fig. 3, after the parallel imaging stage the coherent aliasing artifacts have been removed, but the image has a noisy appearance due to both the noise in the dataset as well as the incoherent aliasing artifacts from the remaining undersampling. The compressed sensing stage is able to remove much of the noisy appearance seen in the parallel imaging only reconstruction, although some loss in resolution and change in contrast is observed, compared to the unaccelerated reconstruction.

Discussion This study demonstrates the feasibility of the proposed approach to combine parallel imaging with compressed sensing. The proposed approach allows the use of non-iterative data-driven parallel imaging, which is recognized for its robust performance even in difficult imaging situations (12). It is expected that separating the PI and CS reconstruction into separate stages will lead to computational savings. The concept of clustered incoherent k-space sampling patterns was introduced and a simple radial-based example was used in our experiment. It remains to be seen if more optimal clustered incoherent sampling patterns can be designed and how well this sampling approach would work with other PI+CS reconstruction methods. While feasibility of the method has been demonstrated, further study is needed to see how the proposed approach compares to other methods for combining PI and CS acceleration.

References (1) Zhao et al., ISMRM 2008, p1478. (2) Wu et al., ISMRM 2008, p1480. (3) Marinelli et al., ISMRM 2008, p1484. (4) King, ISMRM 2008, p1488. (5) Liu et al., ISMRM 2008, p3154. (6) Pruessmann et al., 1999, MRM 42:952-62. (7) Liang et al., IEEE EMBS Conference 2008, p1667-70. (8) Griswold et al. 2002, MRM 47:1202-10. (9) Beatty et al., ISMRM 2007, p1749. (10) Lustig et al., 2007, MRM 58:1182-95. (11) Lustig, http://www.stanford.edu/~mlustig/SparseMRI.html. (12) Griswold et al. 2004, MRM 52:1118-2004.

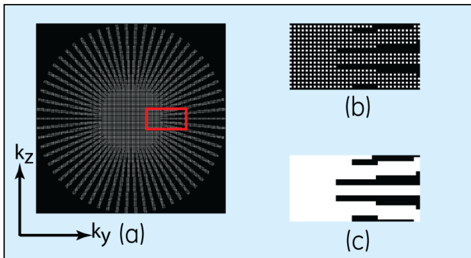

Figure 1: 'Clustered incoherent' sampling pattern. (a) Acquired sampling pattern. As shown in (b), within the spokes the data is accelerated with 2x2 acceleration in the (k_y, k_z) plane. (c) ARC parallel imaging is used to fill in the unacquired locations within in the central region and within the spokes. The result is then passed to the compressed sensing stage.

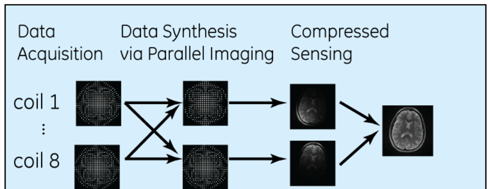

Figure 2: Reconstruction Stages
Multi-channel data is acquired using a clustered incoherent sampling pattern. Parallel imaging is used to fill in missing data within the clusters, resulting in a sampling pattern that gives incoherent aliasing artifacts in a sparsifying domain. Compressed sensing is then used to generate a final image.

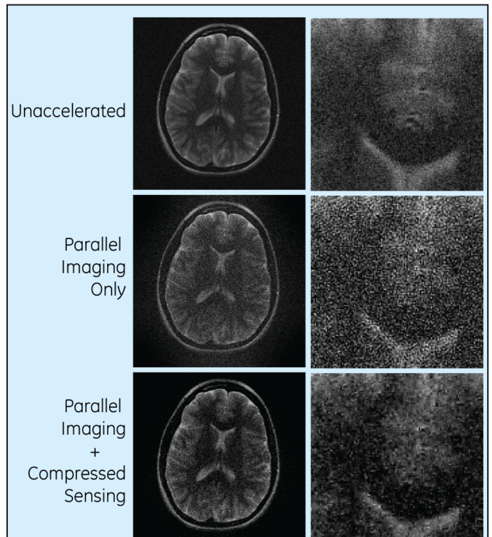

Figure 3: Reconstruction Results
Using parallel imaging to fill in the missing data in the spokes and central region of k-space removes the coherent aliasing artifacts due to the 2x2 uniform undersampling. The subsequent application of compressed sensing removes much of the noise and incoherent aliasing artifacts due to the unsampled gaps between spokes.