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 imaging 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