Improved Compressed Sensing Reconstruction for Equidistant K-Space by Sampling Decomposition and Its Application in Parallel MR Imaging

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INTRODUCTION

Compressed Sensing (CS) is of significant interest for fast MR imaging because it can be used with k-space sub-sampling and parallel imaging [1,2]. Although implementations were made to combine CS with parallel imaging, the incoherent sampling requirement is a bottleneck for implementation because most k-space sampling in parallel imaging is coherent. Thus, a direct plug-in of CS to parallel imaging, especially in the case of equidistant k-space sampling, is not feasible. We propose a simple method to eliminate this problem and illustrate the idea using GRAPPA reconstruction [3]. A perceptual difference model (Case-PDM) was used to quantitatively evaluate image quality [4] in experiments.

METHODS

Given a coherent parallel imaging k-space data, we break the coherence through applying random masks to decompose the data along phase encoding (PE) into multiple incoherent subsets. Sampling within each subset is randomized. All k-space sampled data were utilized. CS reconstruction [5] was applied on each subset to recover a full k-space data. Finally, all CS reconstructed full k-space datasets were aggregated to produce the final, aliasing reduced, k-space data. To combine with GRAPPA, we use the full k-space reconstruction from the previous step to calibrate the GRAPPA complex weights. (We call this method "*CS+GRAPPA*" hereafter). Both phantom and in vivo parallel MR cardiac data were used.

RESULTS

Coherent aliasing artifact due to equidistant under-sampling cannot be reduced by CS without decomposition, but can be significantly reduced by CS with just 2 decompositions (Fig. 1c). More decompositions further reduce aliasing artifacts (Fig. 1d) at the expense of computation time. *CS+GRAPPA* significantly improved image quality as compared to the standard method for the same high-speed (reduction factor = 8) imaging condition by both visual inspection and PDM score (Fig. 2). *CS+GRAPPA* can work with much higher reduction factors and fewer ACS lines that are not feasible for the standard method (Fig. 2). Alternatively, comparable image quality can be achieved with many fewer data samples.

DISCUSSION

We conclude that CS can be applied to equidistant k-space sampling by the proposed method and that the sampling scheme can be applied to CS in parallel MR imaging. The proposed method significantly reduced coherent aliasing artifact using just 2 decompositions. By sequentially combining with our method, GRAPPA imaging can be significantly improved in image quality and sped up with fewer k-space samples, and potentially even no ACS lines. A great application opportunity is in dynamic MR imaging, particularly, cardiac imaging, where reduction factors could be very high. The computational cost of our method should not be a limitation for its application due to development of fast CS algorithms, parallelization of the CS processes, and GPU acceleration. The results could be further improved through using edge detection guided reconstruction [6].

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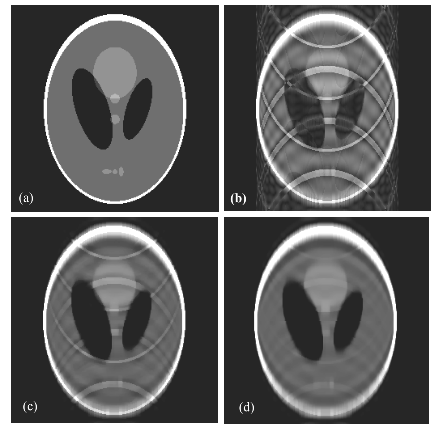

Fig. 1. (a) is a reference image for the numerical phantom. For the same equidistantly subsampled variable density k-space data, (b) was from zero-padding and it suffers serious coherent aliasing artifact. (c) was reconstructed by CS with 2 decompositions. Coherent aliasing artifact was significantly reduced. (d) was reconstructed by CS with 6 decompositions. The aliasing artifact was greatly reduced.

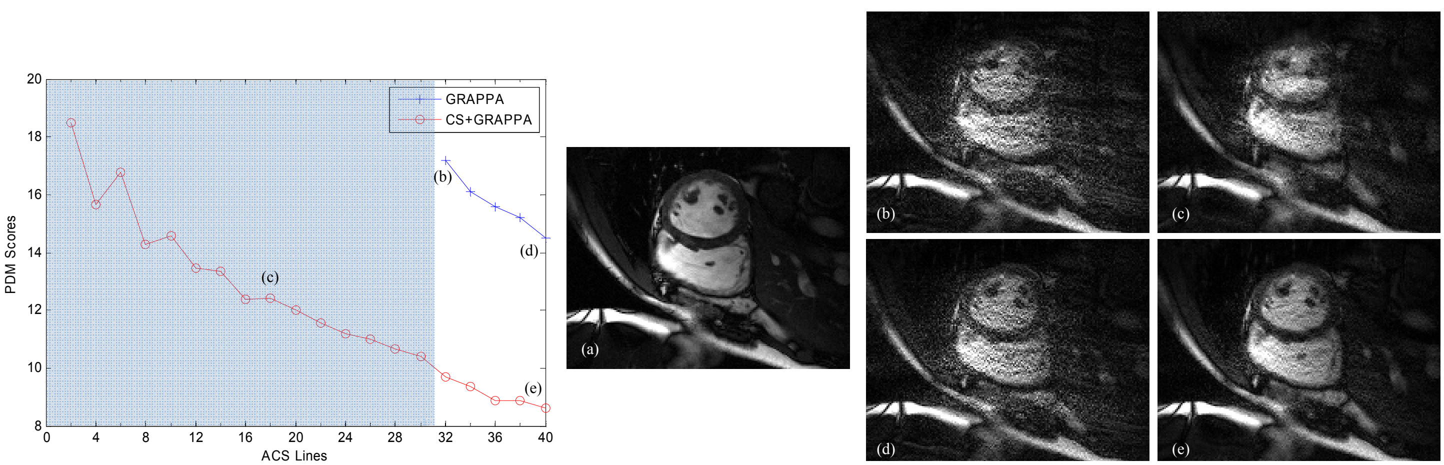

Fig. 2. A plot demonstrating PDM evaluations for GRAPPA and *CS+GRAPPA* reconstructions for sub-sampled 8-channel data with a high reduction factor of 8 and different ACS sizes. *CS+GRAPPA* produced significantly better image quality (with lower PDM score) than GRAPPA with even much less ACS lines which is not feasible for standard method (shaded area in the plot). (a) is a reference from full k-space. (b) was reconstructed by GRAPPA with 32 ACS lines and (c) was by *CS+GRAPPA* with 16 ACS lines. Although (c) used only half of ACS lines as (b) needed, its image quality is significantly better than (b). (d) and (e) were by GRAPPA and *CS+GRAPPA* respectively with 40 ACS lines. Image quality was significantly improved by *CS+GRAPPA* as compared to standard method.