Wave-CS: Combining wave encoding and compressed sensing

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Intro: Practical parallel imaging acceleration rates at a given field strength are ultimately limited by the interplay of two factors: the k-space sampling pattern and the receive coil geometry. In the case of 3D imaging, distributing under-sampling in multiple acquisition dimensions typically provides improved parallel imaging performance. Wave-CAIPI encoding [1] pushed this concept farther by effectively distributing under-sampling in the read dimension (k_x) as well, but critically, without requiring non-Cartesian reconstruction approaches and full 3D sampling strategies. As the read line is acquired, WAVE encoding in Wave-CAIPI modulates the phase/slice gradients such that the read trajectory corkscrews through k-space, sampling additional spatial frequencies. Because of the nature of the Wave-CAIPI approach, a simple computational step can "undo" the additional gradient encoding, allowing the use of traditional reconstruction techniques. Bilgic et al [1] demonstrated that such an approach leads to significant performance improvements in SENSE reconstructions versus regular Cartesian sampling.

Purpose: In this work, we investigate the combination of WAVE encoding with compressed-sensing (CS) via random phase/slice under sampling patterns and sparsity prior reconstruction [2], which we termed Wave-CS. It is hypothesized that the additional encoding and the aliasing generated in the read direction from WAVE should provide similar benefits to CS-SENSE as it did with for the Cartesian SENSE case [1].

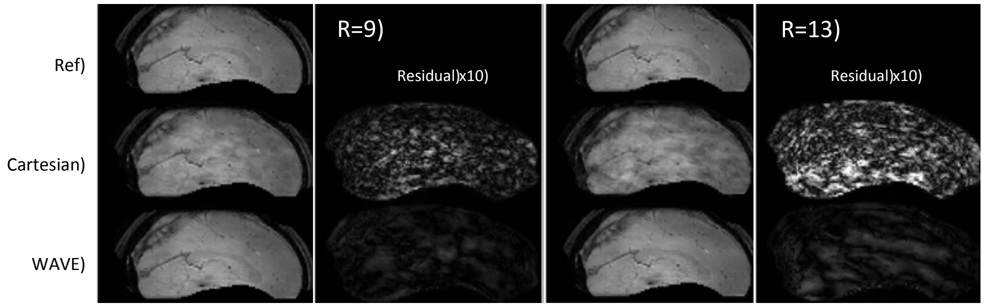

Figure 1: CS Reconstructions of regular Cartesian and Wave- encoded sampling for reduction factors 9 and 13.

Methods: A fully sampled T_2^*-weighted gradient echo acquisition was acquired on a Siemens scanner at 3T using a 32-channel head receive array with the following parameters: FOV: 224x220x120mm, voxel size: 1x1x2mm, TR/TE=26/13.3ms, BW=70Hz/px, Tacq=5 mins and 42s..Poisson-disk distributed random sampled patterns for phase/slice encode locations were generated at two target under-sampling factors of R=9 and R=13 and the center 4x4 of each pattern was densely sampled (actual under sampling rates of 8.93 and 13.3). Data were retrospectively under-sampled with these patterns. Data with and without WAVE encoding (with Wave gradient amp=6mT/m, slew=50mT/m/ms, 7 sinusoidal cycles/readout and 5x read oversampling) were generated and reconstructed. An efficient reconstruction supporting WAVE encoding was developed leveraging the BART toolkit [3]. Reconstruction follows the typical 3D iterative CS-SENSE approach with an L_1 penalty to enforce sparsity in the wavelet transform of the image estimate. The FISTA algorithm [4] was used to solve the L1 constrained reconstruction problem. For WAVE encoding, a modification is required, because the additional phase modulation means one cannot naively apply the regular Fourier transform. Instead, every instance of the 3D-FFT is replaced by an operator chain that performs a partial FT in phase/slice, followed by WAVE de-modulation[1], followed by a FT in read. With such modification, Wave-CS reconstruction can be performed using fast FFT, without the need for time-consuming gridding. To assess image quality, magnitude images were reconstructed and differenced with a fully sampled reconstruction. For additional visualization of imaging performance phase data is also displayed. Phase data were post-processed with Laplacian unwrapping [5] and SHARP filtering[6].

Results: Overall, WAVE encoding improved CS image reconstruction performance, as demonstrated in Fig 1, highlighting the markedly reduced reconstruction error and lower residuals. As compared to gradient echo reconstructions, the additional WAVE encoding reduced reconstruction residuals by approximately 37.5% and 68% for R=9 and R=13, respectively. Acquisition time for R=9 and R=13 data would have been 38s and 26s, which should enable very rapid T_2^*-weighted GRE imaging. Computation time for similar iterative solver convergence levels for the Wave-CS reconstruction was roughly six times that of the regular Cartesian sampling, due to the additional encoding step and the significant extra data size in the oversampled read dimension. Axial magnitude and phase images for the R=13 data (Figure 2) visualize additional differences, where the traditional GRE-CS is almost unusable for phase imaging due to the unrecoverable signal.

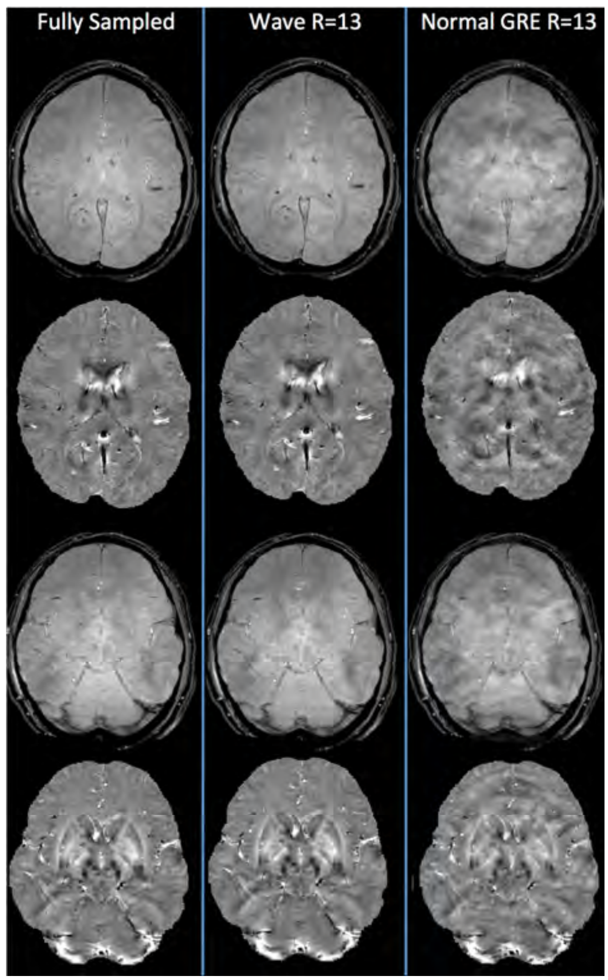

Figure 2: Reconstructions at R=13 displaying two axial slices magnitude and phase pairs. Phase has been processed to remove background fields (see text).

Conclusion: In this preliminary work, WAVE encoding approaches appear beneficial for compressed-sensing based imaging, likely due to a combination of a) distributing under-sampling more effectively and b) sampling additional spatial frequencies. Continuing work will address prospective under-sampling and higher resolution acquisitions.

References: 1. Bilgic B. et al. MRM 2014 (epub: Jul 1. doi: 10.1002/mrm.25347)
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