Automated RF Spike Noise Removal with Compressed Sensing

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INTRODUCTION Radio frequency (RF) spike noise (1) in MRI is defined as bursts of high amplitude corruptions in the Fourier domain (*k*-space) that cause Moiré patterns in the reconstructed image. Traditional spike correction techniques include zeroing the corrupted k-space samples or replacing them using interpolation. Compressive sensing (CS; 2) outperforms zero-filling and interpolation in partial Fourier reconstructions where a significant fraction of *k*-space was not acquired, so it is reasonable that CS will outperform traditional spike correction techniques when only a very small fraction of *k*-space has been corrupted.

MATERIALS AND METHODS For automatic detection of spikes, *k*-space is searched for indivudal samples that have the largest effect on the anisotropic total variation (TV) of the spatial domain image. To do this, each point of the full, acquired *k*-space data set b was in turn zeroed, leading to a corresponding image S^j:

$$S^j = F^{-1} M_j b,$$

where F^{-1} is the inverse discrete Fourier transform, and M_j is the identity matrix with the *j*-th element set to zero. The TV of each image S^j was defined as

$$\mathrm{TV}(S^j) = \sum_x \sum_y \left(\left| S^j_{xy} - S^j_{x,y+1} \right| + \left| S^j_{xy} - S^j_{x+1,y} \right| \right).$$

The TV values were then sorted from smallest to largest, and the n *k*-space locations that when zeroed created the images with the smallest TV were then discarded to create a very slightly subsampled (~99.9%) data set b_n and associated sampling mask M_n. Images cleaned of spikes were then reconstructed using an unconstrained TV-regularized CS reconstruction of the form

$$I_{\mathrm{clean}} = \arg\min_x \mathrm{TV}(x) + \frac{\lambda}{2} \left\| M_n F x - b_n \right\|_2^2,$$

where F is the discrete Fourier transform and λ a scalar weight.

RESULTS Figure 1 shows a phantom experiment with five simulated spikes in a noiseless phantom. All five spikes were correctly located (images 1b,c) and removed with CS (1f,i), while zeroing or interpolating left residual Moiré patterns on the images (1d,e,g,h). Normalized mean square error in the magnitude image was ~10^{-3} for zeroing and interpolating and ~10^{-5} for the proposed TV-constrained method. Figure 2 shows a gradient echo data set acquired with a faulty cable within the scanner bore and corrupted by spike artifacts. The image is significantly cleaned with the new method with the number of removed spikes (*n*) equal to 5 and becomes mostly clear with $n = 20$.

DISCUSSION Beside the effect on the image TV, inconsistencies across multi-channel or dynamic data could be added to the spike detection algorithm to increase detection reliability. Also, the number of spikes detected and replaced could be variable with a thresholding criterion setting the upper limit. As with any algorithm, the added time and complexity must be weighed against image quality gains. This method has the advantage of being both automated and more accurate than zero-filling or interpolation approaches for spike compensation.

REFERENCES [1] Chavez et al.; Magn Reson Med 2009;62,510. [2] Lustig et al.; Magn Reson Med 2007;58,1182.
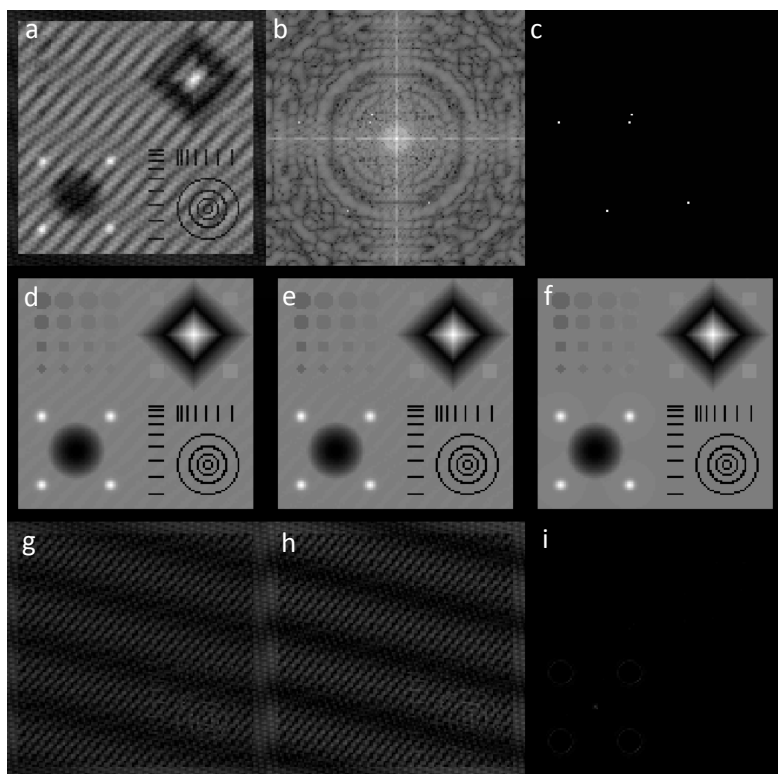
Fig. 1 – Noise-free phantom example corrupted by 5 spikes. The original corrupted image (a) and log *k*-space (b) lead to the automatically generated mask with $n = 5$ (c), which correctly locates the 5 inserted spikes. Comparison between replacement of spikes by zeros (d), *k*-space linearly interpolated data (e), and CS (f) shows the superiority of the CS approach. The bottom row shows the % difference between corresponding corrected images on the middle row and the ground truth (not shown). CS (i) eliminated the Moiré pattern in (g) and (h).
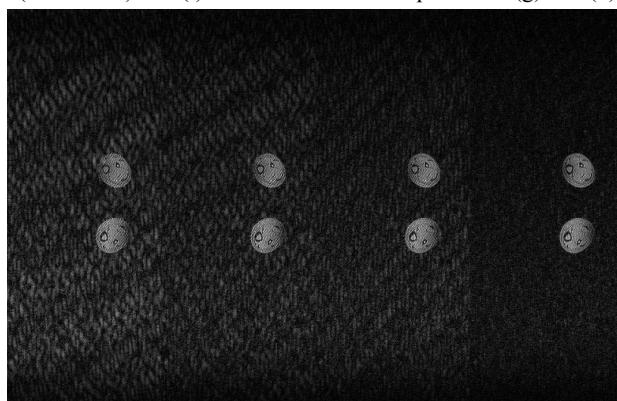

Fig. 2 – Example images corrupted by RF spike noise in a gradient echo scan of the lower legs. The leftmost image is the original data that has been corrupted by a faulty cable, creating an unknown number of spikes. The remaining images from left to right have had 5, 10, and 20 data points automatically replaced by the proposed CS technique.