HYPR-L0: A Hybrid Technique for CE MRA with Extreme Data Undersampling Factors

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Introduction.

Many clinical applications, most notably contrast-enhanced (CE) time-resolved angiographic imaging, would benefit from volumetric coverage with high spatial and temporal resolution to capture the rapid passage of contrast material. For many applications such as intracranial examinations, these requirements necessitate data undersampling by as much as 40-100 times in 2D. Image reconstruction from such highly undersampled data poses a challenging problem even for recently introduced techniques created for accelerated imaging. Indeed, the acceleration from parallel MRI and k-t BLAST/SENSE [1] is limited by SNR losses and the ability to learn temporal behavior from low resolution training images. HYPR reconstruction allows much higher undersampling factors due to inclusion of a composite image that improves SNR and spatial resolution [2]. However, at extreme accelerations HYPR images may suffer from cross talk between vessels with different time courses due to very low spatial resolution and SNR of the low resolution images used in the reconstruction. We propose a synergistic approach that utilizes independent acceleration mechanisms of parallel MRI, novel compressed sensing (CS) approach, and HYPR to achieve the needed acceleration, spatial resolution and high SNR.

Theory and Methods

Algorithms of the HYPR family produce images by constraining the reconstruction process by a temporally averaged composite image. In HYPR LR [3], individual images are obtained by multiplying the composite image by a weighting image formed as a ratio of low resolution versions of the time frame and composite images. However, at extreme acceleration, HYPR images may suffer from spatial mixing of temporal information due to in-plane smoothing. In our algorithm, we propose to substitute the low resolution images with the corresponding images obtained from a constrained reconstruction using information about vessel edge locations in the composite image. This is accomplished by solving the following problem:

$$\min_{\mathbf{f}}\left(\left\|\mathbf{Ef}-\mathbf{s}\right\|_2^2+\lambda\left\|\mathbf{W}^{1/2}\,\mathbf{Df}\right\|_2^2\right)$$

where **E** is the encoding matrix containing coil sensitivity values and Fourier terms, **s** is the acquired *k*-space data, **D** is image gradient operation, and **W** is a diagonal matrix whose entries are equal to 0 for edge pixels and 1 otherwise. A standard edge detection algorithm may be used to determine matrix **W** from the composite image. It may be shown that if all edges in the image are known and accounted for by **W**, the above equation corresponds to the following CS formulation:

$$\min_{\mathbf{f}}\left(\left\|\mathbf{Ef}-\mathbf{s}\right\|_2^2+\lambda\left\|\mathbf{Df}\right\|_0\right)$$

where the zero subscript denotes l_0 norm. It should be noted that direct solution of the l_0 minimization problem is not feasible because of its combinatorial complexity. Since this reconstruction respects image edges and relies on a powerful sparsifying l_0 semi-norm, the reconstructed time frames depict more temporal dynamics accurately. However, while l_0 minimization allows restoration of temporal behavior in a more complete fashion than HYPR-LR, reconstructed images exhibit blocky artifacts at extreme undersampling factors. We correct this problem, typical to CS algorithms, by applying post-processing similar to HYPR LR reconstruction. Thus, the final formula for HYPR-l_0 images is $(T_0/C_0)\times C$, where C is the composite image and T_0 and C_0 are l_0-minimization solution for the time frame and identically undersampled composite images.

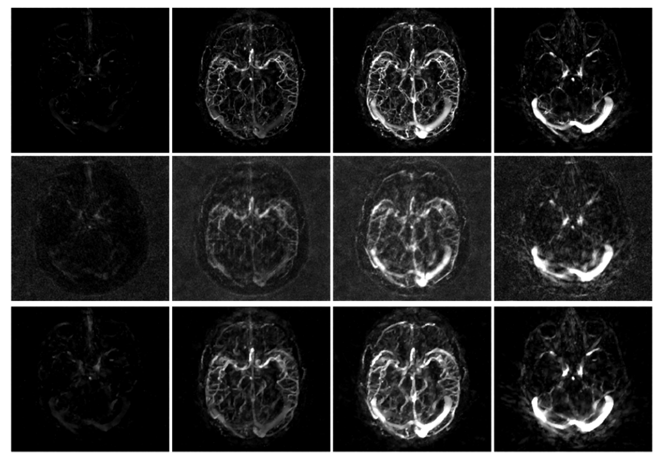

Figure 1. Reconstruction results of 4 time frames from 10 projections each using HYPR-l_0 (top), iterative SENSE (middle), and l_0 minimization (bottom) algorithms.

Results

We applied the developed algorithm to in vivo CE cranial exams in healthy volunteers. Following informed consent, the data were collected on a 3T GE scanner with an 8-channel head coil using hybrid 3D radial (in-plane)/Cartesian (through-plane) acquisition timed to the gadolinium contrast injection. The total of 768 projections was collected during the 80 second scan for each of the 16 slices. A temporally averaged image was obtained from all the data acquired during the passage of contrast and used as the composite image in both l_0 and HYPR reconstructions. In the first exam, we reconstructed individual 1 s time frame images from 10 projections each using several different techniques. Fig. 1 compares reconstruction results of 4 time frames using HYPR-l_0 (top row), iterative SENSE (middle row), and l_0 minimization (bottom row) algorithms. With an acceleration factor of 40, the last two techniques suffer from resolution loss and SNR loss (for SENSE only). At the same time, HYPR-l_0 algorithm demonstrates correct temporal behavior while maintaining high spatial resolution and SNR. At the extreme acceleration factor of 40, HYPR LR exhibits cross-talk between venous and arterial signals. In the second exam, the number of projections per time frame was reduced to 5 in order to increase temporal resolution. At the acceleration factor of 80, images reconstructed with iterative SENSE algorithm (not shown) have prohibitively high noise level that prevents from discerning the vasculature. Both HYPR-l_0 and l_0 minimization algorithms furnish images that illustrate the gradual passage of the contrast material as shown in the top and bottom rows of Fig.2, respectively. However, images reconstructed by l_0 minimization exhibit lower SNR and loss of spatial resolution, while HYPR-l_0 images have clinically acceptable quality.

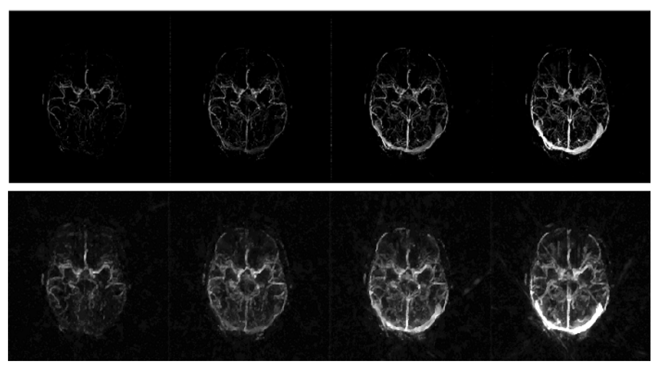

Figure 2. Reconstruction of consecutive time frames from 5 projections each using HYPR-l_0 (top) and l_0 minimization (bottom) algorithms.

Conclusions

Our results suggest that the combination of parallel MRI, a novel l_0 minimization implemented through utilization of prior information about vessel edges and HYPR algorithm is a promising technique that can provide images with high spatial resolution and SNR for extreme acceleration factors (up to 80), at which other methods fail due to exceptionally high level of undersampling. The ability of the algorithm to reconstruct time series of images with high temporal and spatial resolution holds potential to make it useful in clinical applications that still lack the necessary high frame rate, such as evaluation and medical management of patients with arterial-venous malformations. The proposed method is flexible in its ability to use other sources of prior information, such as a high quality composite image acquired in a separate non-time-resolved phase contrast or time-of-flight exam.

References

1. Tsao J *et al*, MRM 50:1031-1042. 2. Mistretta CA *et al*, MRM 55:30. 3. Johnson KM *et al,* MRM 59:456.