Compressed sensing with vascular phase contrast acquisition

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Introduction

Vascular imaging methods that do not require contrast agents have recently regained popularity due to the emergence of nephrogenic systemic fibrosis. Phase contrast imaging uses gradient waveforms that create phase modulation from flowing spins while leaving signal from static spins unchanged. Several echoes are collected with different combinations of flow-sensitizing gradients for each echo. The echoes are combined using either complex differences or phase differences to give images that are weighted by the flow velocity. The final images are usually further processed to give a maximum intensity projection (MIP) along one or several directions to visualize the vessels. The images look very sparse and invite acceleration using parallel imaging and compressed sensing. Multiple receive coils can enhance phase contrast imaging without acceleration (1). Acceleration from parallel imaging has also been incorporated into phase contrast processing (2). Compressed sensing (3) can be combined with parallel imaging using an image space (SENSE) approach (4). In this work, we explore image space compressed sensing to accelerate phase contrast acquisition.

Methods

A 3T commercial scanner (GE Healthcare, Waukesha, WI) and 8-channel head coil (Invivo, Gainesville, FL) were used to scan a volunteer with a 3D phase contrast pulse sequence (sagittal plane, 24cm field of view, 128 slices, 384x256 matrix). Four echoes were acquired with gradient moments given by (---,+--,-+-,--+) where the + or – sign refers to the sign of the first moment of the flow-sensitizing gradient on either the x, y or z axis. Full Nyquist sampling was used for acquisition and 2D undersampling was simulated by discarding ky and kz encoding points. Pseudorandom undersampling was used to enable compressed sensing, along with Nyquist sampling of the center of k-space to estimate coil sensitivities. Complex difference processing was used to calculate the flow images for each axis, e.g. for the x-axis, $m_x = \sqrt{|m_1|^2 + |m_2|^2 - 2|m_1||m_2|\cos\left[\angle(m_1 m_2^*)\right]}$ etc. where m_{echo} refers to the image for each flow moment combination (echo=1,2,3,4). The final flow image is given by $m_{flow} = \sqrt{m_x^2 + m_y^2 + m_z^2}$.

For compressed sensing the image must be compressible in the domain of some transform Ψ. Typically Ψ is a wavelet or gradient transform (total variation or TV). For image space combination of parallel imaging and compressed sensing, the image is reconstructed by minimizing an objective function $J(m) = \|Em - S\|_2^2 + \lambda\|\Psi m\|_1$ where E is the coil encoding operator that includes both the B1 receive field for each coil and the Fourier operator, m is the image, S is the k-space data, and the constant λ is adjusted to balance data fidelity and artifact reduction.

Even though the final phase contrast images are compressible, the intermediate echoes of each flow moment combination are not necessarily so. In addition to a sparsifying transform for each echo, we added a sparsifying transform of the final flow image, giving the objective function $J = \sum_{echo}\left[\|Em_{echo} - S_{echo}\|_2^2 + \lambda\|\Psi m_{echo}\|_1\right] + \lambda_{flow}\|\Psi m_{flow}\|_1$. This method gives a jointly optimized solution for all echoes if $\lambda_{flow} \neq 0$, otherwise it is equivalent to compressed sensing reconstruction of each image m_{echo} separately. Although only one sparsifying transform Ψ is shown here for simplicity, in practice two or more transforms are sometimes beneficial. For this work, both wavelet (2D Daubechies-4) and gradient transforms (2D nearest neighbor difference) were tested for Ψ. The conjugate gradient was used to find the minimum of J with a maximum of 16 iterations. The λ parameters were adjusted empirically.

Results

We found that the gradient transform was much more beneficial than the wavelet transform for Ψ and was therefore used exclusively. The k-space sampling pattern (ky by kz) for a typical 4-fold acceleration is shown in Fig. 1. The sagittal MIP for the unaccelerated case is shown in Fig. 2. The MIP for 4-fold acceleration with all λs set to zero (parallel imaging) is shown in Fig. 3. The MIP for 4-fold acceleration with empirically optimized λs is shown in Fig. 4. Almost all vessel visibility is maintained in the accelerated MIP images with optimal λs compared to the unaccelerated case. Including the flow regularizing term $\lambda_{flow}\|\Psi m_{flow}\|_1$ in the objective function was somewhat beneficial although most of the benefit was obtained from the sparsifying transform applied to each echo ($\|\Psi m_{echo}\|_1$ term)

Conclusions

Phase contrast flow imaging can be accelerated using a combination of image space parallel imaging and compressed sensing. The images are better than if parallel imaging were used alone. Most of the benefit is obtained by applying compressed sensing to each echo separately, however a small additional improvement results from using a sparsifying transform of the final flow image as well. This produces a jointly optimized solution for all echoes.

References

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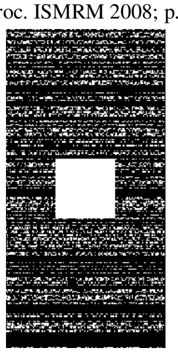

Figure 1. R = 4 k-Space sampling pattern

Figure 2. Unaccelerated

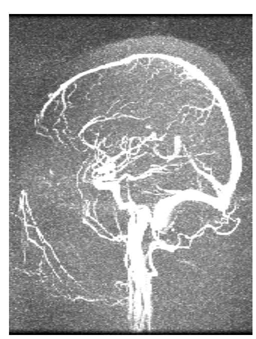

Figure 3. $\lambda = \lambda_{flow} = 0$

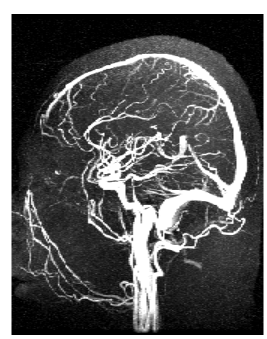

Figure 4. Optimized λ and λ_{flow}