High Spatial and Temporal Resolution Dynamic Contrast-Enhanced Magnetic Resonance Angiography (CE-MRA) using Compressed Sensing with Magnitude Image Subtraction

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Target audience: MR scientists working with compressed sensing as well as clinicians interested in accelerated dynamic contrast-enhanced MRI.

Purpose: We propose a compressed sensing (CS) technique based on magnitude image subtraction for high spatial and temporal resolution dynamic contrast-enhanced MR angiography (CE-MRA) and DCE-MRI in general. Our goal is to develop a technique for acquiring five to six 12-fold-accelerated dynamic CE-MRA volumes within a single breath-hold that have similar spatial resolution with the current state-of-the-art of CE-MRA while providing higher temporal resolution than the current clinical standard dynamic CE-MRA TWIST[1,2] sequence. In a breath-held dynamic CE-MRA acquisition, the subtraction of a pre-contrast mask to all post-contrast frames promotes sparsity of the resulting difference images. This "subtraction sparsity" using direct k-space complex subtraction has previously been shown to benefit parallel imaging[3,4] as well as compressed sensing[5] but suffers from SNR loss based on our experience. We propose a novel CS algorithm for dynamic CE-MRA that integrates *magnitude subtraction* into the reconstruction to avoid direct complex subtraction while taking advantages of the "subtraction sparsity" for CS reconstruction.

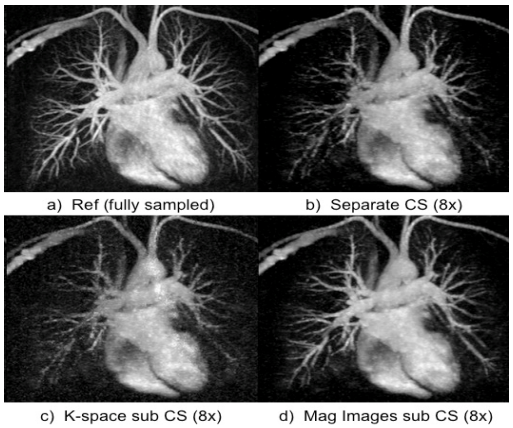

Figure 1: Thin MIP chest CE-MRA (zoomed, same windowing level). The proposed magnitude subtraction CS (d) reconstructs excellent image quality, close to reference (a) from highly under-sampled data while subtracted images from independent CS reconstruction (b) of each volume suffers from image degradation. Image quality is inferior using k-space subtraction CS reconstruction (c) due to significant SNR loss.

Methods: Our reconstruction technique uses a single iterative split-Bregman[6] minimization of the following two equations where I_1 and I_2 are two successive temporal frames we are solving for.

$$(I_1, I_2) = argmin \left\{ \begin{matrix} \|U_1\mathcal{F}(I_1) - K_1\|_2^2 + \lambda TV(I_1) + \mu \left| |I_2|e^{i\phi_1} - I_1 \right|_1 \\ \|U_2\mathcal{F}(I_2) - K_2\|_2^2 + \lambda TV(I_2) + \mu \left| I_2 - |I_1|e^{i\phi_2} \right|_1 \end{matrix} \right\}$$

In each equation, the first term is data fidelity term, the second is the total variation of each individual volume and the third term is our proposed L1 norm of the pixel-wise magnitude subtracted image, i.e. $\left| |I_2| - |I_1| \right|_1 = \left| |I_2|e^{i\phi_1} - I_1 \right|_1 = \left| I_2 - |I_1|e^{i\phi_2} \right|_1$.

Retrospective study: A full-sampled Cartesian 3D GRE sequence was used for the CE-MRA acquisitions on 6 volunteers with a resolution of 1x1x1.3-2.2 mm^3. Datasets were retrospectively subsampled and different strategies of reconstruction were quantitatively and qualitatively evaluated: a) magnitude subtraction of the original k-space images; b) separate independent CS reconstructions (IDCS); c) k-space complex subtraction CS reconstruction (KDCS); d) magnitude subtraction CS reconstruction (MDCS). Prospective study: A sequence was implemented that is capable of prospectively acquiring under-sampled 3D dynamic CE-MRA data according to pre-defined sampling mask every 5.9s at 1x1x2.0 mm^3 resolution. The net acceleration from random subsampling was set to 12.5-fold, enabling the acquisition of 6 volumes within a single breath-hold on 2 volunteers.

Results: The proposed novel magnitude-subtraction CS reconstructs images with accurate details (Fig. 1) compared to independent CS and less noise than complex-subtraction CS. At 10-fold acceleration, RMSE was lower for MDCS (20.36 %) compared to IDCS (28.93%, p<0.05) and KDCS (25.15%, p=0.07) and qualitative scores confirmed the superiority of MDCS images (2.59±0.51) to KDCS (1±0, p<0.01) and IDCS (1.75±0.45, p<0.05) images. K-space subtraction suffers very poor images quality due to the SNR loss from complex subtraction. Independent CS reconstruction has significantly lower images quality while our magnitude subtraction CS images were considered "good" for all subsampling rates tested (6X-10X).

Based on our developed prospective CS dynamic CE-MRA sequence and our magnitude-subtraction based reconstruction algorithm, high quality dynamic CE-MRA is feasible even at 12.5X acceleration as shown in Fig. 2.

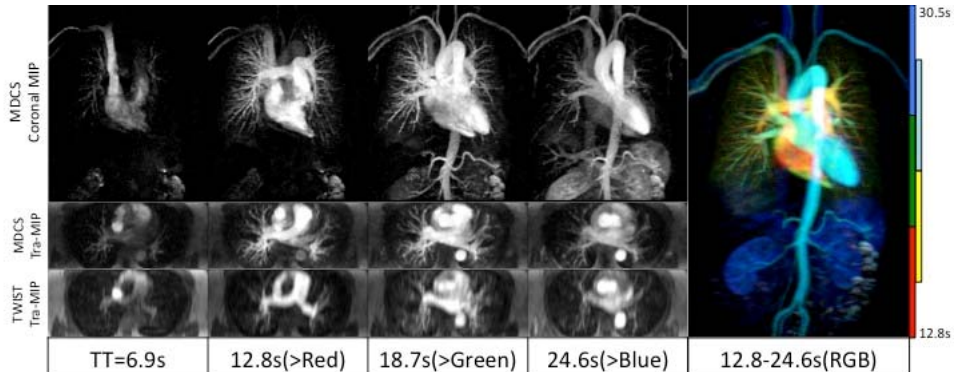

Figure 2: The high image quality of a prospectively subsampled (12.5-fold) dynamic high-resolution CS-CE-MRA allows obtaining both the hemodynamics and fine anatomical details (1x1x2 mm^3). No view sharing or parallel imaging was used. Thin MIP are reconstructed in coronal planes (10cm thick) and transverse planes (6cm thick). Comparing with TWIST, our sequence shows improved spatial resolution in the slice direction (2mm instead of 6mm) and shorter temporal footprint of each frame (5.9s vs. ~10s). The color-combined MIP (Right) provides both high-resolution vascular structure and dynamic information, where color indicates post-injection time.

Discussion: Although the proposed technique was developed only in the context of dynamic CE-MRA, it is also applicable to DCE-MRI for quantitative tissue perfusion imaging. The shorter temporal footprint enabled by our sequence may be useful for applications where arterial to venous transit time is short, such as imaging of the pulmonary vasculature. Several extensions of our algorithm remain to be explored, such as combining parallel imaging or view-sharing. The concept of magnitude subtraction can also be extended to various non-contrast MRA applications.

Conclusion: The proposed technique enables has the potential to benefit dynamic CE-MRA and DCE-MRI clinical practice.

References: 1. Lim et al. *AJNR* 2008, 1847-1854; 2. Nael et al. *AJR* 2009, 1731-1738; 3. Koktzoglou et al. *MRM*. 2010;64(6):1843–1848; 4 Storey et al. *MRM*. 2012;65:1391–1400; 5. Trzasko et al. *MRM* 2011;66(4):1019–1032; 6. Goldstein et al. *SIAM JIS*. 2009;2:323.