Fast 3D DCE-MRI with Sparsity and Low-Rank enhanced SPIRiT (SLR-SPIRiT)

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Purpose: Dynamic contrast enhanced (DCE) MRI is commonly used to detect and characterize lesions. For 3D DCE MRI, a trade-off between spatial and temporal resolution is often necessary. In this work, a method named Sparsity and Low-Rank enhanced SPIRiT (SLR-SPIRiT) is developed and implemented. SLR-SPIRiT combines L_1-SPIRiT[1] with a locally low-rank constraint[2] that exploits the data redundancy in dynamic image series. We then assess the feasibility of the resulting joint parallel imaging and compressed sensing (sparsity and low-rank) method to achieve high spatial-temporal resolution for 3D DCE MRI in a pediatric setting, where anatomical structures are small and contrast kinetics are fast.

Methods: L_1-SPIRiT is a compressed sensing parallel imaging reconstruction method[1]. It can achieve high acceleration when acquiring a single image. In DCE MRI, the dynamic image series is low-rank[3-5]: dynamic images can be reformatted into a Casorati matrix (every column in the matrix representing a single image at one time point), which is low-rank. Undersampled dynamic series can be reconstructed by a matrix completion method that minimizes the rank of the Casorati matrix subject to a data consistency constraint. A dynamic image series has even lower rank when partitioned into small image blocks[2] (i.e. locally low rank). SLR-SPIRiT exploits both the sparsity and low rank properties of dynamic images series. Assume x_t is a vector of images from all coils at time point t, y_t is a vector of acquired k-space data from all coils at time point t, x is a vector of images from all coils at all T time points, x_b is a vector of images in image block b from all coils at all time points, G_t is a SPIRiT kernel in the image domain at time point t, F is a Fourier transform operator, D_t is the under-sampling operator for time point t, Ψ is a sparsifying transform operator applied to images from all coils and time points, and C is a operator that reformats x_b into its Casorati matrix. The problem of image reconstruction can be formulated as:

$$\text{minimize}_x \ \text{Joint}L_1(\Psi x) + \mu(\Sigma_b||Cx_b||_*), \ \text{subject to: } D_tFx_t = y_t,\ G_tx_t = x_t,\ t=1,2,\ldots,T$$

where $||A||_*$ denotes the nuclear norm of matrix A and μ is a weighting constant (empirically chosen). G_t is calculated at each time point from the autocalibrating signals (ACS) in center k-space. A projection onto convex sets (POCS) method is used to solve this problem. In each POCS iteration, the following operations are performed: (1) soft-threshold the singular values of the Casorati matrix in every image block (locally low-rank); (2) soft-threshold the joint Ψ-transformed data (joint sparsity[1]); (3) apply SPIRiT in the image domain; (4) update the reconstruction with the acquired data. For 3D Cartesian acquisition, an inverse Fourier transform is performed on the acquired data in the readout direction. SLR-SPIRiT is carried out separately at each spatial location in the readout direction.

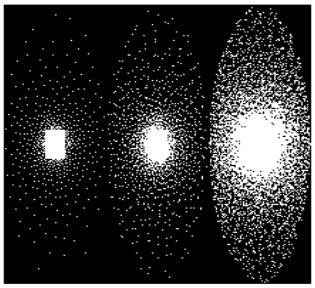

Fig.1 Left to right: sampling pattern of t=1, combination of t=1-3 and combination of t=1-20. Actual acceleration factor is 19.7, 10.2 and 3.2 respectively.

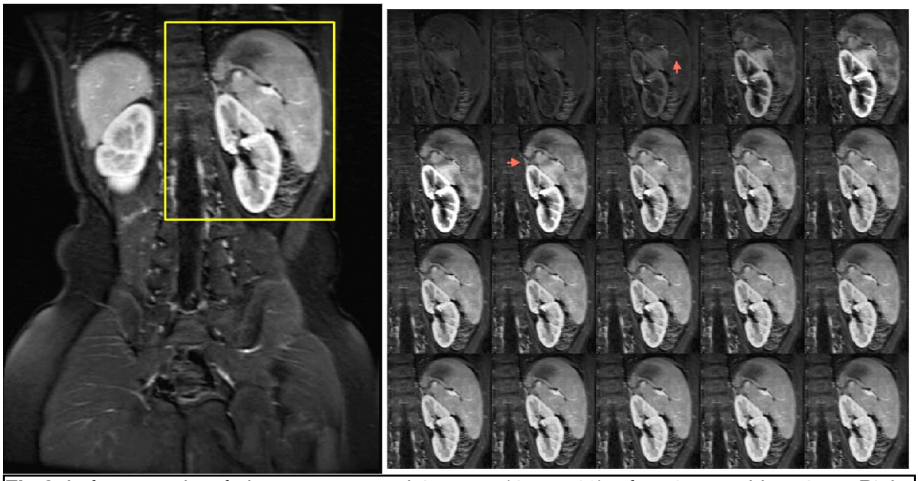

Fig.2 Left: example of the reconstructed images (time #12) of a 4-year-old patient. Right: zoomed cropped region to show that fine structures (arrows: small vessels and adrenal gland) were resolved. Rapid regional perfusion pattern in the spleen as well as progressive renal cortical to medullary enhancement evidence the high temporal resolution.

Results: With IRB approval and informed consent, a 4-year-old patient was scanned during suspended respiration and upon injection of single dose gadolinium using a fat suppressed 3D SPGR sequence on a 3T GE MR750 scanner with a 32-channel cardiac coil and the following parameters: TR/TE(partial echo) 3.4/0.9ms, flip angle = 15°, matrix=280x230x72, FOV=30x24x14 cm^3. 20-phase DCE data with different variable density Poisson-disc sampling (ACS=24x14) at each phase were acquired. The sampling pattern is shown in Fig. 1. The total acceleration for each phase was 19.7 to achieve a temporal resolution of 3 seconds. Coil compression[6] was used before SLR-SPIRiT reconstruction to reduce computation time. A representative slice is shown in Fig. 2 and selected contrast uptake curves are shown in Fig. 3. Fine abdominal structures were resolved at a high spatial resolution (1x1x2 mm^3). The contrast uptake dynamics (liver, spleen, kidney, etc) were also captured with the high temporal resolution. Together, this demonstrates feasibility of depicting small rapidly enhancing structures in a small child with rapid hemodynamics.

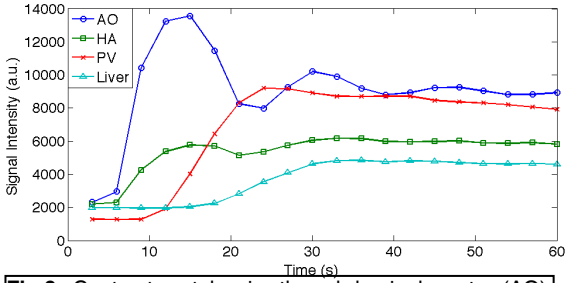

Fig.3 Contrast uptake in the abdominal aorta (AO), hepatic artery (HA), portal vein (PV) and liver. Signal intensity is in arbitrary unit (a.u.).

Discussion: The contrast uptake has very sharp changes at the beginning of the enhancement. To avoid inaccurate contrast enhancement dynamics, the SPIRiT kernel was calculated separately in each phase in the proposed SLR-SPIRiT.

Conclusion: SLR-SPIRiT combines parallel imaging and compressed sensing (sparsity and low-rank). Highly accelerated data (R≈20) have been reconstructed with good image quality. The proposed method can achieve a very high spatial-temporal resolution desired in 3D DCE MRI.

References: [1]. Lustig M, *et al*. Magn Reson Med 2010; 64:457-471 [2]. Trzasko J, *et al*. ISMRM 2011, p4371; [3]. Liang ZP. ISBI 2007; 988-991 [4]. Lingala S, *et al*. IEEE Trans Med Imag 2011; 30:1042-1054 [5]. Pedersen, *et al*. Magn Reson Med 2009; 62:706-716 [6]. Zhang T, *et al.* Magn Reson Med 2012: early view.