Rapid Free-Breathing Dynamic Contrast-Enhanced MRI Using Motion-Resolved Compressed Sensing

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Target Audience: Scientists and clinicians who are interested in rapid dynamic contrast-enhanced MRI

Introduction: Respiratory motion remains a major challenge in abdominal MRI. Conventional approaches that make use of a navigator or respiratory bellows to acquire data at specific motion states (e.g., end-expiration) significantly reduce imaging efficiency. Radial sampling is an alternative method for free-breathing imaging due to its significantly lower sensitivity to motion than Cartesian sampling schemes [1]. However, the intrinsic motion averaging effects associated with radial sampling can still introduce blurring and streaking artifacts. Instead of correcting for respiratory motion, e.g., by integrating a registration framework [2], the self-navigation properties of radial imaging can be exploited to sort the acquired data into multiple undersampled motion states, and compressed sensing reconstruction that exploits sparsity along the new respiratory motion dimension can be used to reconstruct unaliased images in each motion states [3]. Successful application of this idea has been demonstrated for cardiac MRI with separated cardiac and respiratory motion dimensions [4]. **The purpose of this work** is to translate this concept into free-breathing dynamic contrast-enhanced (DCE)-MRI. The proposed method, called XD-GRASP (eXtra-Dimensional Golden-Angle RAdial Sparse Parallel MRI), is demonstrated for free-breathing abdominal imaging using two different 3D golden-angle (GA) radial sampling schemes.

Methods: (a) ***Sampling Schemes, Motion Detection and Data Sorting:*** Fig 1 shows two types of 3D GA radial sampling schemes that are based on stack-of-stars (top) and spiral phyllotaxis (bottom) [5] patterns. Respiratory motion signals were obtained from the projection profiles of the entire imaging volume (red lines), which can be computed by performing a 1D partition-direction FFT on the series of central points (kx=ky=0) in the stack-of-stars trajectory or on the self-navigation spokes (red lines in Fig 1 bottom) in the spiral phyllotaxis trajectory. Principal component analysis was performed along the concatenated z+coil dimension [6] (Fig 2a) to determine the most common signal variation mode among all the coil elements and the principal component with the highest peak in the frequency range of 0.1-0.5Hz was selected as the respiratory motion signal (Fig 2b). The envelope of the detected signal (Fig 2c) was estimated using spline data fitting and then subtracted in order to separate respiratory motion from contrast enhancement (Fig 2d). Fig 2e&f plot two examples of the detected respiratory motion signal for normal breathing (e) and heavy breathing (f). Given the motion signal, respiratory motion can be resolved by sorting each contrast-enhanced phase into multiple undersampled respiratory states.

(b) ***Data Acquisition and Image Reconstruction:*** IRB approved abdominal DCE-MRI was performed on 7 volunteers and 1 patient using a 3D stack-of-stars GA radial GRE sequence on a 3T scanner (MAGNETOM Verio, Siemens). Imaging parameters included: TR/TE=3.52/1.41 ms, FOV=360x360x240 mm^3, spatial resolution=1.4x1.4x3 mm^3, number of slices=80 with 60% slice reduction and 6/8 partial Fourier along the slice dimension. 600 spokes were continuously acquired in each partition for a total scan time of ~95 seconds. Abdominal DCE-MRI was also performed on 1 volunteer using a prototype 3D phyllotaxis GA radial GRE sequence on a 1.5T scanner (MAGNETOM Avanto Siemens). Imaging parameters included: TR/TE=3.6/1.34ms, FOV=$(350mm)^3$, spatial resolution=$(1.8mm)^3$. 32732 spokes were continuously acquired for a total scan time of ~2 min. For comparison, GRASP reconstruction [7] (without respiratory sorting) was first performed on a time-series of undersampled contrast-enhancement phases with temporal resolution of ~10-12 seconds. In XD-GRASP reconstruction, each contrast-enhancement phase was further sorted into 4 respiratory states, generating a 5D undersampled dataset (x-y-z-contrast-respiration) and the reconstruction was performed by solving the optimization problem

$$\boldsymbol{d} = \min_{\boldsymbol{d}} \|\boldsymbol{F}\cdot\boldsymbol{C}\cdot\boldsymbol{d}-\boldsymbol{m}\|_2^2 + \lambda_1\|\boldsymbol{S}_1\cdot\boldsymbol{d}\|_1 + \lambda_2\|\boldsymbol{S}_2\cdot\boldsymbol{d}\|_1$$

where $\boldsymbol{F}$ is the NUFFT operator [8], $\boldsymbol{C}$ represents the coil sensitivity maps, $\boldsymbol{d}$ is the 5D image set to be reconstructed, and $\boldsymbol{m}$ is the corresponding radial k-space data. $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ are the sparsifying transforms (finite differences to minimize total variation) applied along the contrast-enhancement and respiratory-state dimensions with regularization parameter $\boldsymbol{\lambda_1}$ and $\boldsymbol{\lambda_2}$, respectively**.**

(c) ***Image Quality Assessment:*** For each subject, one pre-contrast phase, one early later arterial enhancement phase, one later arterial enhancement phase, and one portal venous enhancement phase were selected from both GRASP and XD-GRASP (end-expiratory state) reconstructions and all the images were pooled for blinded evaluation. A radiologist scored the overall image quality, liver edge sharpness and hepatic vessels clarity in each image on a 1-5 (non-diagnostic to excellent) scale. The reported scores represent mean ± standard deviation, and a paired student's t-test was used for statistical analysis, where $P < 0.05$ suggested statistically significance.

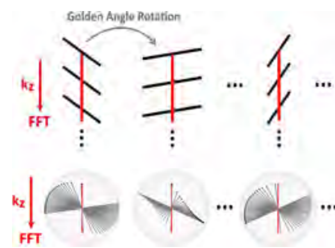

Fig. 1: 3D stack-of-stars (top) and spiral phyllotaxis (bottom) golden-angle radial sampling schemes. Red lines indicate the projections in each sampling point computed for self-navigation.

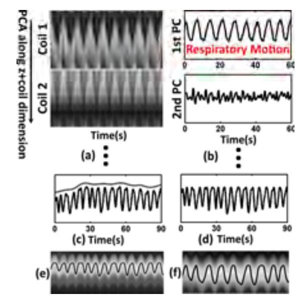

Fig. 2: Respiratory motion detection scheme in free-breathing DCE-MRI.

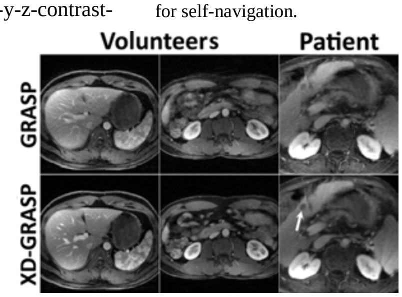

Fig. 3: Comparison of GRASP and XD-GRASP (expiratory-state only) in volunteers and patient.

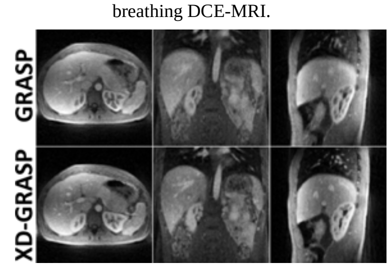

Fig. 4: Comparison of GRASP and XD-GRASP (expiratory-state only) in three orientations with isotropic spatial resolution.

	Overall IQ	Liver Edge Sharpness	Vessel Clarity
GRASP	**3.29±0.66**	**3.71±0.46**	**3.32±0.55**
XD-GRASP	**4.04±0.79**	**4.00±0.67**	**3.75±0.65**
***P* Value**	**0.000014**	**0.0297**	**0.0079**

Table 1: Clinical reader's scores in all the 9 subjects comparing GRASP reconstruction v.s. XD-GRASP reconstruction (end-expiration only) in overall image quality (IQ), the liver edge sharpness and hepatic vessel clarity. The scores were averaged over 4 different contrast-enhanced phases. P<0.05 suggests significantly improvement. 1-5: non-diagnostic to excellent.

Results: Fig 3 shows representative portal venous contrast-enhanced phases in two of the volunteers and in the patient, comparing GRASP and XD-GRASP (end-expiration state). The reduction of respiratory motion blurring in XD-GRASP improves the vessel-tissue contrast, the delineation of small bowel, and the depiction of a suspected small tumor in the patient (white arrow). Fig 4 shows the results using 3D radial phyllotaxis sampling, which enables whole-abdomen coverage with isotropic spatial resolution. Similar improvement in image quality and vessel delineation can be seen in XD-GRASP for this sampling trajectory as well. The scores in Table 1 also demonstrate that XD-GRASP systemically outperformed GRASP in different contrast-enhancement phases. Table 1 summarizes the reader scores, in which the improvement in overall image quality, the sharpness of liver edge and hepatic vessel clarity were all statistically significant.

Discussion: XD-GRASP represents a new and effective way to handle respiratory motion in free-breathing DCE-MRI. Instead of correcting for respiratory motion using error-prone registration steps or a specific motion model, an extra respiratory motion-state dimension is reconstructed using compressed sensing to exploit the sparsity along the new dimension. XD-GRASP significantly reduces motion-induced blurring and allows separation of respiratory motion from contrast-enhancement in DCE-MRI without the use of explicit motion models. The idea of XD-GRASP has also been previously demonstrated in Cartesian sampling that employs butterfly navigators for respiratory motion detection in pediatric MRI [9]. However, Cartesian sampling does not share the advantages of motion robustness and incoherence and the capacity for flexible continuous sampling that are inherent to radial imaging.

Funding: NIH P41 EB017183. **References:** [1] Glovr GH et al. MRM 1992;28(2) :275-89. [2] Chen et al. ISMRM 2013; 601. [3] Feng et al. ISMRM 2013; 606. [4] Feng et al. ISMRM 2014; 3928. [5] Piccini et al. MRM 2011;66(4):1049-56. [6] Pang et al. MRM 2014;72(5):1208-17. [7] Feng et al. MRM 2014;72(3):707-17. [8] Fessler. IEEE T-SP 2003;51(2):560-74. [9] Cheng et al. ISMRM 2014; 330.