High Spatial and Temporal Resolution 2D Real Time and 3D Whole-Heart Cardiac Cine MRI Using Compressed Sensing and Parallel Imaging with Golden Angle Radial Trajectory

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Introduction: 2D real-time cine imaging is valuable for imaging myocardial function in patients with impaired breath-hold capacity [1]. 3D whole-heart cine imaging, on the other hand, can provide higher SNR and contiguous volumetric coverage, at the expense of being more susceptible to cardiac and respiratory motion. Fast imaging is required to meet the spatial and temporal requirements for both 2D real-time and 3D whole-heart cine imaging. Compressed sensing (CS) [2] is a recently developed technique for accelerating imaging acquisition in MRI and is particularly appealing for cardiac cine imaging, due to the presence of spatial and temporal correlations in the image series which enable sparse representations. Higher accelerations can be obtained by combining CS and parallel imaging (PI) and, 8-fold accelerated real-time cine imaging using k-t SPARSE-SENSE [3] was demonstrated before [4-5]. Radial trajectory is an alternative acquisition scheme, which is less sensitive to motion-related artifacts and offers higher incoherence than Cartesian trajectories [6]. Moreover, radial acquisitions using golden angle (GA) approach enable continuous data acquisition and retrospective reconstruction with arbitrary temporal resolution. In this work, we propose to highly accelerate both 2D real-time and 3D whole-heart cine imaging using a combination of compressed sensing and parallel imaging with golden angle radial trajectory (k-t RASPS: RAdial SParse-Sense) to achieve high spatial and temporal resolution.

Methods: ***Continuous Cardiac Cine Acquisition:*** The benefit of using a GA radial trajectory is that one does not need to predefine cardiac phases during the acquisition, as is done conventionally. Instead, by grouping together specific number of adjacent spokes into one cardiac phase, continuous spokes can be acquired, allowing for generation of dynamic images with arbitrary temporal resolution. Fig 1a illustrates an example of 2D cardiac cine acquisition without ECG gating. Here, n continuous spokes are acquired to cover a full cardiac cycle, and groups of 8 adjacent spokes are used to form a dynamic cine series. This acquisition scheme can also be extended to a 3D stack of stars trajectory by repeating the GA radial acquisition for multiple partitions, as shown in Fig 1b. Note that the acquisition of each partition in 3D is the same as in 2D, except for the inclusion of ECG.

K-t RASPS: K-t RASPS reconstruction is developed by incorporating a gridding operator (NUFFT [7]) into k-t SPARSE-SENSE, as minimization of $||R^{-1}E\bullet x-y||_2+\lambda||T\bullet x||_1$, where R is a gridding operator that interpolates the Fourier data onto spokes, y is the undersampled k-space data, x is the image to be reconstructed, T is the sparsifying transform, and E is an operator incorporating Fourier transformation together with multiplication by coil sensitivities, which were calculated using the image regridded from all the acquired radial spokes.

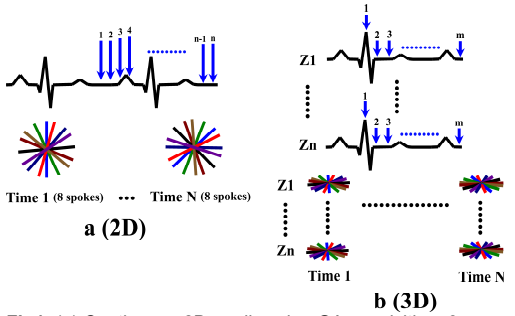

Fig1. (a) Continuous 2D cardiac cine GA acquisition; 8 adjacent spokes are grouped together in one phase (b) Extension into 3D stack of stars GA trajectory

Cardiac Cine Imaging: Imaging was performed in a 1.5T whole-body MRI scanner (Siemens, Avanto) equipped with a 12-element body matrix coil array. Both 2D and 3D (stack of stars) radial SSFP pulse sequences with GA radial trajectory were implemented in the scanner. For 2D imaging, one healthy volunteer was scanned during free breathing without ECG gating. Three acquisitions with base resolutions 128, 192 and 256 were performed in both short axis (SAX) and long axis (LAX) views. 500 continuous spokes were acquired in each acquisition and the total acquisition times were 2.1s, 2.3s and 2.5s respectively, including a 1s dummy scan for reaching steady state. FOV=400x400, BW=1502 Hz/pixel. Slice thickness=10mm, FA=70°. Please see table 1 for other imaging parameters. For 3D imaging, the same volunteer was scanned under breath hold, with ECG gating in SAX plane. The base resolution was 192 and 40 partitions were prescribed to cover the entire left ventricle. 320 continuous spokes were acquired in each partition within one heart beat and the total acquisition time was 30 heartbeats (6/8 partial Fourier used in slice direction). FOV and BW is the same as that in 2D. Slice thickness=2.8mm, FA=50°, TR/TE=2.8/1.4ms. K-space data were regridded into a volume with size 192x192x30. Reconstruction was implemented using customized software developed in MATLAB (MathWorks, MA), using a non-linear conjugate gradient algorithm and a total variation along temporal direction was chosen as the sparsifying transform. For the 2D datasets, three reconstructions were performed by grouping 13, 8 and 5 adjacent spokes together in one cardiac phase, resulting in three different temporal resolutions (table 1). For the 3D dataset, 8 adjacent spokes were grouped together in one cardiac phase (acquisition window 22.4 ms), and reconstruction was performed slice by slice.

Results: Fig 2 shows representative 2D images of end-systole from both SAX and LAX for base resolutions 128, 192 and 256. 13, 8 and 5 adjacent spokes were grouped together (from top to bottom) in one cardiac phase to form a dynamic series with 3 different temporal resolutions (Table 1). Fig 3 shows representative images from the 3D dataset at end-systole and end-diastole, from the apex (top), mid (middle) and base (bottom) slices, with acquisition window 22.4 ms

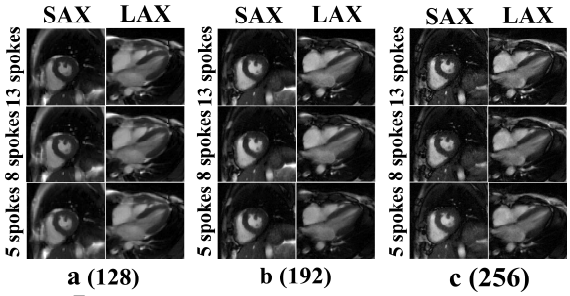

Fig 2. End-systolic images with base resolution 128 (a), 192 (b) and 256(c). 13, 8 and 5 adjacent spokes were grouped into one cardiac phase to reconstruct image sets with different temporal resolutions.

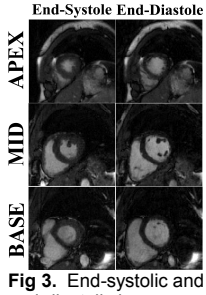

Fig 3. End-systolic and end-diastolic images from apex, mid and base slices in 3D data set

Discussion: This study demonstrates that k-t RASPS, which is a combination of CS, PI and GA radial trajectory, is capable of performing highly accelerated 2D real-time and 3D whole heart cardiac cine imaging with high spatio-temporal resolution and adequate image quality. It also provides flexibility in reconstruction with arbitrary temporal resolution. K-t RASPS may be useful for other applications, such as imaging valve. Future work includes quantitative evaluation of the technique in terms of image quality and evaluation of the accuracy of volume and ejection fraction calculations.

Grant Sponsor: NIH R01-EB000447.

Reference: [1]. Kellman, P et al.; MRM V. 62, pp. 1557 (2009). [2]. Lustig M, et al. MRM 2007;58:1182-1195. [3]. Otazo R et al. MRM 2010; 64:767-776. [4] Feng L, et al. ISMRM 2010; 3602. [5] Feng L, et al. ISMRM 2011; 748. [6] Uecker M, et al. NMR Biomed 23: 986-994, doi:10.1002/nbm. [7] Fessler. IEEE T-SP 2003 51(2):560-74.

Table 1. Relevant imaging parameters for 2D real time cine imaging.

Base Resolution	TR/TE (ms)	Matrix Size	Temporal Resolution (ms)		
			13 spokes	8 spokes	5 spokes
128	2.2 /1.1	128 x 128	28.6	17.6	11
192	2.6 /1.3	192 x 192	33.8	20.8	13
256	3.0 /1.5	256 x 256	39	24	15