Five-Dimensional Cardiac and Respiratory Motion-Resolved Whole-Heart MRI

Li Feng[1], Simone Coppo[2], Davide Piccini[2,3], Ruth P Lim[4], Matthias Stuber[2], Daniel K Sodickson[1], and Ricardo Otazo[1]

[1]Center for Advanced Imaging Innovation and Research (CAI2R), Department of Radiology, New York University School of Medicine, New York, NY, United States, [2]Department of Radiology, University Hospital (CHUV) and University of Lausanne (UNIL) / Center for Biomedical Imaging (CIBM), Lausanne, Switzerland, [3]Advanced Clinical Imaging Technology, Siemens Healthcare IM BM PI, Lausanne, Switzerland, [4]Department of Radiology, Austin Health and The University of Melbourne, Melbourne, Victoria, Australia

Target Audience: Scientists and clinicians who have interest in rapid and continuous whole-heart MRI

Introduction: 3D whole-heart MRI allows a multifaceted assessment of the cardiovascular system and is particularly attractive due to the high SNR, large spatial coverage, and simplified data acquisition. However, sensitivity to motion, particularly respiratory motion, remains one of the major challenges in this field. Various approaches have been proposed to enable 3D free-breathing cardiac imaging by retrospectively coregistering images at different respiratory states in order to achieve nearly 100% imaging efficiency [1-3]. Recently, self-navigated 4D cardiac MRI methods have also been proposed for simultaneous visualization of cardiac function and cardiac motion-resolved coronary arteries [4-5], in which respiratory motion was corrected using either displacement-based or affine transform-based registrations. These motion correction schemes, however, require the use of specific motion models, which may be insufficient to account for the complex 3D movement of the heart during respiration, especially for patients with pronounced respiration or irregular respiratory patterns. Compressed sensing has become a powerful approach for fast cardiac imaging [6]; and in addition to enabling increased acquisition speed, it has recently been shown that sparsity can also be used to resolve respiratory motion by reconstructing an extra motion-state dimension [7-8]. This technique, called XD-GRASP (eXtra-Dimensional Golden-angle RAdial Sparse Parallel MRI), aims to combine the self-navigation properties of radial sampling and the acceleration capability of compressed sensing. **The purpose of this work** is to describe and test a 5D (x-y-z-cardiac-respiration) cardiac and respiratory motion-resolved whole-heart imaging framework using XD-GRASP.

Methods: (a) ***Data Acquisition and Motion Detection*:** IRB-approved cardiac imaging was performed in 9 healthy volunteers during free-breathing and without ECG triggering on a 1.5T clinical scanner (MAGNETOM Aera, Siemens). K-space data were continuously acquired using a prototype 3D radial b-SSFP sequence [4] with golden-angle rotation scheme based on the spiral phyllotaxis pattern [9]. Imaging parameters included: TR/TE=3.1/1.56ms, FOV=$(220mm)^3$, matrix size=192^3, voxel size= $(1.15mm)^3$ and flip angle=90^o. A total of 126478 spokes were acquired in each subject in 14 minutes and 17 seconds, including 5749 golden-angle interleaves. Each interleave started with a spoke oriented along the superior-inferior (SI) direction for self-navigation and was preceded by CHESS fat saturation. Cardiac motion signal was obtained retrospectively from the ECG trace and respiratory motion signal was estimated from the SI spokes, using the principal component analysis approach proposed in [5].

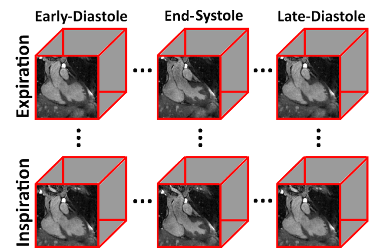

Fig. 1: 5-dimensional data sorting with one cardiac motion dimension (20 cardiac phases) and one respiratory motion-state dimension (4 respiratory states).

(b) ***Data Sorting and Image Reconstruction*:** The continuously acquired golden-angle radial datasets were first sorted into 20 cardiac phases (temporal resolution of ~40-50ms) without any view sharing using the cardiac signal and each cardiac phase was further sorted into 4 respiratory motion states spanning from end-expiration to end-inspiration using the estimated respiratory motion signal, thus generating a 5D image set (x-y-z-cardiac-respiratory), as shown in Fig 1. XD-GRASP reconstruction was performed by solving

$$d = \min_{d} \|F \cdot C \cdot d - m\|_2^2 + \lambda_1 \|S_1 \cdot d\|_1 + \lambda_2 \|S_2 \cdot d\|_1$$

where $\boldsymbol{F}$ is the NUFFT operator, $\boldsymbol{C}$ represents the coil sensitivity maps, $\boldsymbol{d}$ is the 5D image set to be reconstructed (size=192x192x192x20x4), and $\boldsymbol{m}$ is the corresponding multicoil radial k-space data. $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ are the sparsifying transforms (finite differences to minimize total variation) applied along the cardiac and respiratory motion dimensions, respectively, with regularization parameter $\boldsymbol{\lambda_1}$ and $\boldsymbol{\lambda_2}$, which were empirically selected. In order to speed up the reconstruction, the NUFFT operator was implemented using parallel computing on GPUs [10], and was called in the main reconstruction program implemented in MATLAB. For comparison, 4D reconstruction with respiratory motion correction (MC) [3-4] was also performed on all the datasets, in which 20 cardiac phases were generated without any view sharing (size=192x192x192x20) and were reconstructed using compressed sensing that exploits sparsity along the cardiac dimension using a total variation constraint [6].

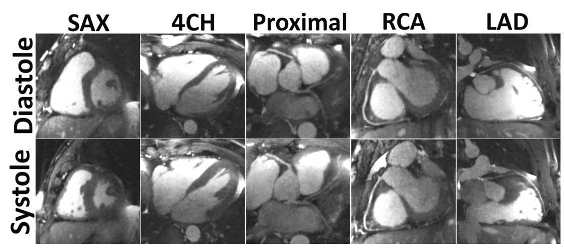

Fig. 2: End-expiratory myocardial wall (SAX and 4CH), proximal coronary arteries, right coronary artery (RCA) and left anterior descending coronary artery (LAD) in diastolic (top) and systolic (bottom) phases. All the images are reformatted from a single continuous data acquisition with 5D XD-GRASP reconstruction.

(c) ***Image Quality Assessment*:** One end-systolic and one mid-diastolic frame were manually selected from each subject (in both the 4D reconstruction and the end-expiratory state of the 5D reconstruction) and all the images were randomized for blinded evaluation. A radiologist scored the visualization/sharpness of myocardium, the proximal segment of right coronary artery (RCA), left main coronary artery and left anterior descending coronary artery (LAD) 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 statistical significance.

Results: Fig 2 shows the ventricular chambers and the coronary arteries at end-expiration in one representative volunteer, in both systolic (top) and diastolic (bottom) phases, derived from the 5D XD-GRASP reconstruction. Good delineation of both myocardial wall and coronary arteries was obtained without using any explicit respiratory motion correction algorithm. Fig 3 shows the results from another volunteer who had an irregular respiratory pattern during data acquisition. In this case, 5D XD-GRASP reconstructions exhibited less motional blurring and achieved better visualization of both myocardial wall and RCA (red arrows) than 4D reconstruction with MC. Table 1 summarizes the reader's scores. The improvement in myocardial wall sharpness, RCA and left main coronary using 5D XD-GRASP was statistically significant (P<0.05, Table 1). Although scores were also slightly higher for the LAD using 5D XD-GRASP, the improvement was not significant (P>0.05).

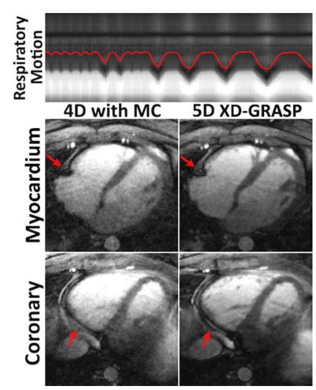

Fig. 3: 5D XD-GRASP reconstruction achieved reduced blurring, improved sharpness and better visualization of myocardium and the RCA compared with 4D reconstruction with respiratory motion correction (MC) in one representative volunteer with irregular respiratory pattern.

	Myocardium	RCA	Left Main	LAD
5D (Exp)	3.78±0.73	3.44±1.20	3.22±1.17	2.28±0.57
4D	3.06±0.94	2.83±1.34	2.61±1.20	2.00±0.69
P Value	0.0032	0.012	0.023	0.14

Table 1: Clinical reader's scores for comparison of 5D XD-GRASP reconstruction (end-expiration only) v.s. 4D reconstruction with motion correction in myocardial wall sharpness and visualization/sharpness of RCA, left main coronary artery and LAD. P<0.05 suggests significantly improvement. 1-5: non-diastolic to excellent.

Discussion: This work describes and tests a framework that allows continuous cardiac and respiratory motion-resolved whole-heart imaging. Instead of removing or correcting for respiratory motion, 5D images are reconstructed containing separated cardiac and respiratory motion dimensions. The method enables high isotropic spatial resolution and high temporal resolution for the assessment of myocardial function in arbitrary orientations and the visualization of coronary arteries at a particular cardiac phase and respiratory motion-state.

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