Feasibility of Free-Breathing Whole Heart Coronary MRA in Less Than 3 Minutes Using Combination of Compressed Sensing, Parallel Imaging and A 3D Radial Phyllotaxis Trajectory

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Target Audience: Scientists, researchers and clinicians who have interest in rapid free-breathing whole heart coronary MRA with isotropic spatial resolution.

Introduction: Coronary MR Angiography (MRA) is a non-invasive tool for evaluating coronary artery disease and congenital heart disease. Balanced steady state free precession (b-SSFP) imaging, which offers high blood-background contrast, allows non-contrast coronary MRA for potential clinical use. However, due to the smaller vessel diameter and motion from both heart and respiration, visualization of the coronary arteries in MRI requires high spatial resolution and signal to noise ratio, good robustness against physiological motion and practical total examination time. Parallel imaging with Cartesian trajectories has been applied for coronary MRA in a single breath-hold implemented with promising image quality [1, 2], but the prolonged breath-hold duration is not feasible for practical clinical use and thus free-breathing coronary MRA is desirable. In this context, 3D radial imaging is most interesting because it allows high degrees of undersampling of k-space in three dimensions, and may thus enable higher acceleration factors and acquisition efficiency [3, 4]. Recently, an innovative self-navigated "koosh ball" 3D radial trajectory based on a spiral phyllotaxis pattern was proposed [5], which allows for uniform distribution of the radial readouts, acquisition efficiency and a high degree of incoherence as is required in compressed sensing (CS), Meanwhile, this trajectory also enables flexible undersampling pattern and easy incorporates of respiratory motion correction in order to achieve 100% acquisition efficiency [6]. However, the relative long scan time (6-9 minutes) still limits clinical application. Therefore, in this study, we aim to combine CS and parallel imaging techniques (Sparse-SENSE) [7, 8] with the 3D radial phyllotaxis trajectory in order to achieve whole heart 3D coronary MRA with high isotropic spatial resolution in less than 3 minutes.

Methods and Materials: Free-breathing cardiac imaging was performed in 10 healthy volunteers on a 1.5 T whole-body MRI scanner (Avanto, Siemens) equipped with a 12 element body coil array. An ECG triggered, T2-prepared and fat-saturated sequence with balanced SSFP readout was implemented with the following parameters: TR/TE=3.0/1.51ms, FOV=220 mm^3, readout sampling =192, flip angle=90°, bandwidth=898 Hz/Pixel. 32 radial spokes were acquired in each heartbeat (HB) and a total of 12064 spokes were acquired in 377 HBs, corresponding to an overall undersampling ratio of 20.8% when compared to the Nyquist sampling requirement. Reconstruction using all the data from 377 HBs was performed using 3D non-uniform fast Fourier transform (NUFFT) with matrix size of 192x192x192 and isotropic spatial resolution of 1.15 mm^3. A respiratory motion correction framework was performed in radial k-space before reconstruction, as described in [6]. Datasets with higher accelerations (233, 144 and 89 HBs) were also generated by retrospectively discarding subsets of the acquired radial spokes. All the four datasets (377,233,144 and 89 HBs) were further reconstructed using both conjugate gradient SENSE (CG-SENSE) [9] and Sparse-SENSE. The reconstructions were implemented by minimizing the following cost function: $d=\text{argmin}_d \{\|E\cdot d-m\|_2 + \lambda\|W\cdot d\|_1\}$, where E is the multi-coil 3D NUFFT operator incorporating the coil sensitivities, d is the image to be reconstructed and m is the acquired radial k-space. For CG-SENSE reconstruction, λ was set to 0 so that the l_1 regularization term was disabled. For Sparse-SENSE reconstruction, λ was empirically selected and W was chosen to be a 3D wavelet transform. Coil sensitivity maps were generated using low resolution images reconstructed from the central part of 3D radial k-space. All the reconstructions were performed in MATLAB (MathWorks, MA).

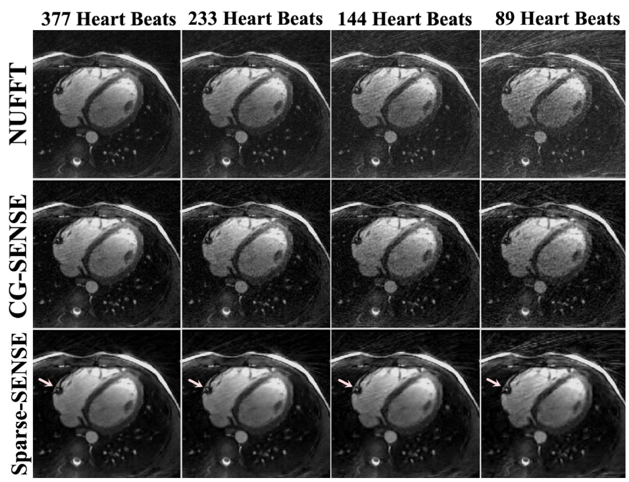

Fig 1. Results reconstructed in 1 of the 10 volunteers using three different reconstruction methods. From top to bottom: NUFFT, CG-SENSE, Sparse-SENSE; from left to right: 377HB, 233HB, 144HB,

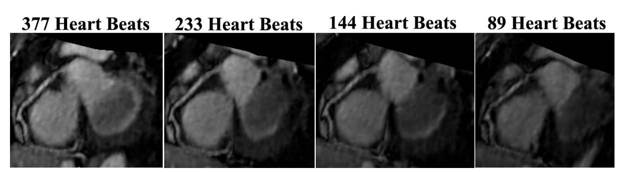

Fig 2. Reformatted left Coronary arterial tree using Sparse-SENSE. From left to right: 377HB, 233HB, 144HB, 89HB.

Results: Figure 1 shows an example of the reconstructed datasets where improvements in the overall image quality and, in particular, in the cross-section of the right coronary artery (RCA) from NUFFT to Sparse-SENSE is clearly seen. When compared to result of 377 HBs, highly accelerated NUFFT results shows more incoherent artifact despite of the decreased acquisition durations. While all three reconstructions yielded comparable image qualities in high sampling densities, both iterative reconstruction techniques provided superior image quality when compared to the NUFFT results in lower sampling densities,. However, sharper edges and less streaking artifacts can be observed on images reconstructed with the Sparse-SENSE algorithm, when compared to the CG-SENSE algorithm. Figure 2 shows an example of multi-planar reformat of the RCA using the Sparse-SENSE reconstructed results. While the image quality is still comparable to the reference (377 HBs) when using the 144HBs datasets, the 89HBs dataset shows compromised image quality.

Conclusion: This work demonstrated that free-breathing whole heart and isotropic coronary MRA is feasible in approximately 2-3 minutes (144HBs) by using the proposed Sparse-SENSE reconstruction in combination with the 3D radial phyllotaxis trajectory. The qualitative image quality was shown to be comparable to that obtained with a standard 7 minute respiratory self-navigated acquisition and conventional gridding reconstruction. Further evaluation, including assessment of clinical efficacy in a patient cohort with cardiac disease is ongoing.

References: [1] Niendorf T, et. al. MRM 2006;56:167–176. [2] Jian Xu, et. al. JMRI 38:180–188(2013).[3] Himanshu Bhat,et. al. MRM 65:1269–1277 (2011).[4] Seunghoon Nam,et. al MRM 69:91–102 (2013).[5] Davide Piccini et. al MRM 66:1049–1056 [6]Piccini D, et al, MRM 2012; 68:571-579.[7] Otazo R et al MRM 2010. [8] Liu et al. ISMRM 2008, 3154.[9]Pruessmann KP,et.al,MRM 2001 Oct;46(4):638-51 .