Improved free-running self-navigated 4D whole-heart MRI through combination of compressed sensing and parallel imaging.

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Target Audience: Basic and clinical researchers interested in cardiovascular and coronary imaging.

Purpose: Free-running self-navigated 4D radial whole-heart imaging techniques have recently been developed [1,2] to take advantage of the whole cardiac cycle in order to allow for 3D coronary artery visualization at any given cardiac phase, as well as to evaluate cardiac function, from one single free-breathing scan. These techniques rely on golden-angle radial acquisitions to homogeneously distribute the acquired lines in k-space over time, and to allow the lines to be re-arranged after the scan in order to reconstruct different volumes for each cardiac phase. This approach allows the reconstruction window to be chosen a posteriori in the cardiac cycle, therefore minimizing the planning needed at the scanner. However, the final images inevitably suffer from streaking artifacts due to radial undersampling and from the suboptimal uniformity of the k-space sampling in individual cine frames. Such artifacts limit the minimum number of k-space lines that can be used per volume, thus affecting the maximal achievable temporal resolution. The goal of the project is to overcome this drawback by applying a novel reconstruction framework that combines dynamic compressed sensing and parallel imaging to remove the streaking artifacts in the 4D datasets. First results with the proposed technique are presented.

Methods: The protocol was approved by the local ethics committee and all healthy adult volunteers (n=9) provided written informed consent. Data were acquired on a 1.5 T system (MAGNETOM Aera, Siemens Healthcare, Erlangen, Germany) with 30 coil elements used for signal reception. A prototype free-running self-navigated 4D radial whole-heart balanced steady-state free precession (bSSFP) acquisition [1] was acquired continuously during free breathing and with a scan time of 14:17 min. Sequence parameters included: TR/TE=3.1/1.56ms, FoV=$(220mm)^3$, voxel size=$(1.15mm)^3$, matrix size=192^3, radiofrequency (RF) excitation angle=90°, data segments=5'749, lines per segment=22, total acquired lines=126'478. Each data segment was preceded by CHESS fat saturation. Self-navigation [3] was then applied to compensate for respiratory motion in each individual 3D cine frame. A first reconstruction was performed with standard gridding, and the acquired lines were regrouped in 3D cine frames of 100ms duration, every 20 ms, with view sharing of 80%, as described in [1]. Each of these frames was composed of ~12'000 lines. In a second reconstruction, instead, all the lines were sorted into twenty 3D cine frames evenly distributed throughout the average R-R interval, without view sharing. A reconstruction framework that combines compressed sensing and parallel imaging (CS+PI) for radial trajectories [4] was employed to solve the following optimization problem: $\boldsymbol{d} = \boldsymbol{min_d} \|\boldsymbol{F} \cdot \boldsymbol{C} \cdot \boldsymbol{d} - \boldsymbol{m}\|_2^2 + \boldsymbol{\lambda}\, \|\boldsymbol{S} \cdot \boldsymbol{d}\|_1$ where $\boldsymbol{F}$ is the 3D radial NUFFT operator implemented on a graphical processor unit (GPU) [5], $\boldsymbol{C}$ represents the coil sensitivity maps, $\boldsymbol{d}$ refers to the 4D dynamic images to be reconstructed, and $\boldsymbol{m}$ relates to the corresponding resorted multi-coil radial k-space data. $\boldsymbol{S}$ is the sparsifying transform (finite differences to minimize total variation) applied along the dynamic dimension with regularization parameter $\boldsymbol{\lambda}$, which was empirically selected in one representative dataset and then applied to all other datasets. A tailored version of a non-linear conjugate gradient algorithm was used to solve the optimization, and the average reconstruction time in Matlab (The Mathworks) was ~3.5 hours for each dataset. From the two 4D reconstructions (without and with CS+PI), coronaries were reformatted [6] and compared. For gold-standard comparison of the coronary vessel sharpness (VS) with the 4D CS+PI datasets [6], a conventional, ECG-triggered mid-diastolic 3D self-navigated whole-heart scan with T_2 preparation [7] was also acquired with imaging parameters very similar to those mentioned above. End-systolic and end-diastolic cardiac phases were also extracted from the 4D CS+PI datasets, and manual segmentation was performed to compute end-systolic (ESV), end-diastolic (EDV) volumes and ejection fraction (EF=(EDV-ESV)/EDV). For gold-standard comparison, a stack of bSSFP 2D cine images covering the entire left ventricle was acquired in a short axis orientation in multiple breath-holds (FOV=300x171mm^2, voxel size=1.17x1.17x8mm^3). From these short-axis images, volumes were calculated using the Simpson's rule, and ESV, EDV and EF were then measured using Argus VF software (Siemens Medical Systems). These results were subsequently compared to those obtained from the 4D CS+PI image analysis. All comparisons where done with a paired Student's t-test with a P-value <0.05 considered statistically significant.

Results and Discussions: The proposed compressed sensing and parallel imaging (CS+PI) framework allows for a significant reduction of the streaking artifacts in the 4D images compared to the gridding-only approach (Figure 1) thus increasing the overall image quality. The number of lines used for each cardiac cine frame was 5'868±368, which is two times lower than that needed for the simple gridding reconstruction (13'150±2'458 lines). On average, the temporal resolution obtained with the proposed CS+PI method was 43.5±8 ms without view sharing, i.e. two times higher than that of the gridding reconstruction (100ms). The lower amount of required lines in each 3D cine frame that leads to an increased temporal resolution may help to reduce motion artifacts and increase the cardiac motion quantification. Furthermore, this may also be exploited to reduce scanning time for this 4D approach. The coronary arteries could be successfully visualized from the 4D CS+PI datasets in spite of the significantly lower number of lines used for the reconstruction compared to the regular gridding (Figure 2). The measured VS obtained from the CS+PI reconstructed images was in line with that obtained from the ECG-triggered images (Right coronary artery VS: 43.8±11.4% and 40.8±15.2% respectively, P=0.48; Left anterior descending artery VS: 43.4±9.4% and 40.9±10.7% respectively, P=0.39). Furthermore, EDV, ESV and EF obtained from the $4D_{CS+PI}$ datasets were consistent with the measures obtained from the 2D images (EDV_{CS+PI}=146±35ml, EDV_{2D}=148±36ml, P=0.65; ESV_{CS+PI}=58±20ml, ESV_{2D}=55±19ml, P=0.38; EF_{CS+PI}=61±6%, EF_{2D}=63±5%, P=0.16).

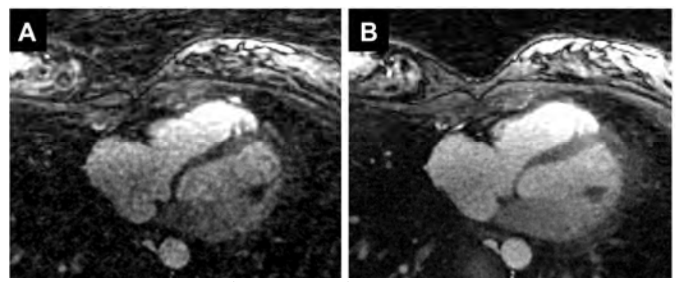

Figure 1: *Comparison of a 3D cine frame reconstructed with (**A**) regular gridding with ~12'000 lines and a 100ms temporal resolution, and (**B**) with the CS+PI framework with ~6'300 lines and 43ms temporal resolution, which results in a reduction of the streaking artifacts throughout the image.*

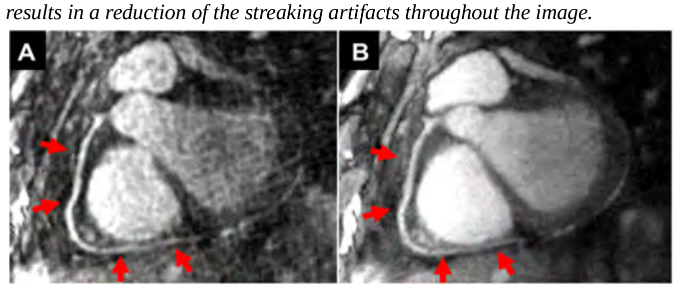

Figure 2: *Right coronary artery (arrows) reformatted from a diastolic 3D cine frame reconstructed with: (**A**) regular gridding (lines ~12'000; temporal resolution = 100ms) and (**B**): the proposed CS+PI method (lines ~6'300; temporal resolution = 43ms). A reduction of streaking artifacts can be observed in **B** when compared to **A**.*

Conclusions: A reconstruction framework that combines compressed sensing and parallel imaging has been integrated with a free-running self-navigated 4D radial whole-heart imaging technique. Initial results demonstrate that the proposed technique reduces the streaking artifacts and therefore increases the temporal resolution and the overall image quality when compared to the standard gridding reconstruction. Finally quantitative vessel sharpness and left ventricular function parameters are in line with those of the gold standard approaches.

References: ***1.*** *Coppo et al. MRM 2014, in press;* ***2.*** *Pang et al. MRM 2014,72:1208;* ***3.*** *Piccini et al. MRM. 2012, 68:571;* ***4.*** *Feng et al. MRM 2014,72:707;* ***5.*** *Knoll et al. ISMRM 2014; p 4297;* ***6.*** *Etienne et al. MRM 2002, 48:658* ***7.*** *Piccini et al. Radiology 2014, 270:378.*