Free-Breathing Whole-Heart Coronary MRI: An Image-based Motion Compensation Integrated into Compressed-Sensing Reconstruction

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INTRODUCTION – Respiratory motion compensation has been an active field of research in whole-heart coronary magnetic resonance angiography (CMRA) for many years. Most recently, non-rigid registration was integrated into iterative reconstruction [1] and promising initial results were demonstrated for whole-heart CMRA in [2, 3]. These methods, however, use 2-D navigators to estimate the motion pattern. A compressed sensing (CS) method which was introduced last year seems to be a promising alternative [4]. This method features a motion-compensated reconstruction after binning of the input data, utilizing the principle of self-navigation [5, 6]. Whereas only a subset of the acquired data was reconstructed in a weighted fashion in the original version, this method was now extended to integrate non-rigid registration and, thus, taking more of the acquired data into account. In-vivo experiments were performed on seven healthy volunteers and the resulting image quality was compared to the result of the weighted CS reconstruction and a navigator-gated reference scan.

MATERIALS and METHODS – In the current work, free breathing whole-heart coronary MRI featuring 3D volume-selective, incoherent Cartesian sampling was performed in the sagittal orientation. As a first step of the image reconstruction, binning of the input data was performed as described in [4]. Next, not only the first but all bins featuring a net acceleration of less than 10.0 were reconstructed iteratively using the weighted CS. After this, a motion model was estimated from the resulting volumes using non-rigid symmetric diffeomorphic image registration [7]. Finally, this enabled the reconstruction of input data also from other respiratory phases by minimizing the cost function incorporating the motion model with a quasi-Newton optimizer and fast pixel-wise operations [1]:

$$\arg\min_{\mathbf{x}} \sum_j \sum_i \left\| \mathbf{M}_j \mathbf{F} \mathbf{C}_i \mathbf{U}_j \mathbf{x} - \mathbf{y}_{i,j} \right\|_2^2 + \lambda \left| \mathbf{x} \right|_{TV} .$$

Here, $\mathbf{U}_j$ represents the deformation field to model the motion during the acquisition of data $\mathbf{y}_{i,j}$ with the sampling pattern $\mathbf{M}_j$ for all respiratory phases j to reconstruct the motion-free image $\mathbf{x}$ with the Fourier transform $\mathbf{F}$ and the estimated coil sensitivities $\mathbf{C}_i$ for the i-th coil.

In-vivo experiments were performed on a 1.5 T clinical MR scanner (MAGNETOM Aera, Siemens AG, Healthcare Sector, Erlangen, Germany) on 7 healthy volunteers with T2-prepared, fat-saturated, ECG-gated, balanced-SSFP imaging: TR/TE 4.0/2.0 ms, $\alpha = 90°$, FOV 270×270×150 mm^3, matrix 256×256×144, voxel-size 1.05 mm^3 and a receiver bandwidth of 849 Hz/Px. Signal reception was performed using an 18-channel body array coil and 8 elements of a spine array coil. The data acquisition was segmented over 398 heartbeats. Within each heartbeat one SI-projection was acquired prior to 30 readouts used for imaging. The proposed method was compared to a navigator-gated acquisition with 254 segments of 30 readouts and an acceptance window of 5 mm placed in end-exspiration. The datasets were reformatted using CoronaViz (work-in-progress software, Siemens Corporate Research, Princeton, NJ, USA). For evaluation, image quality was quantitatively measured by computing vessel sharpness of the RCA as described by [8].

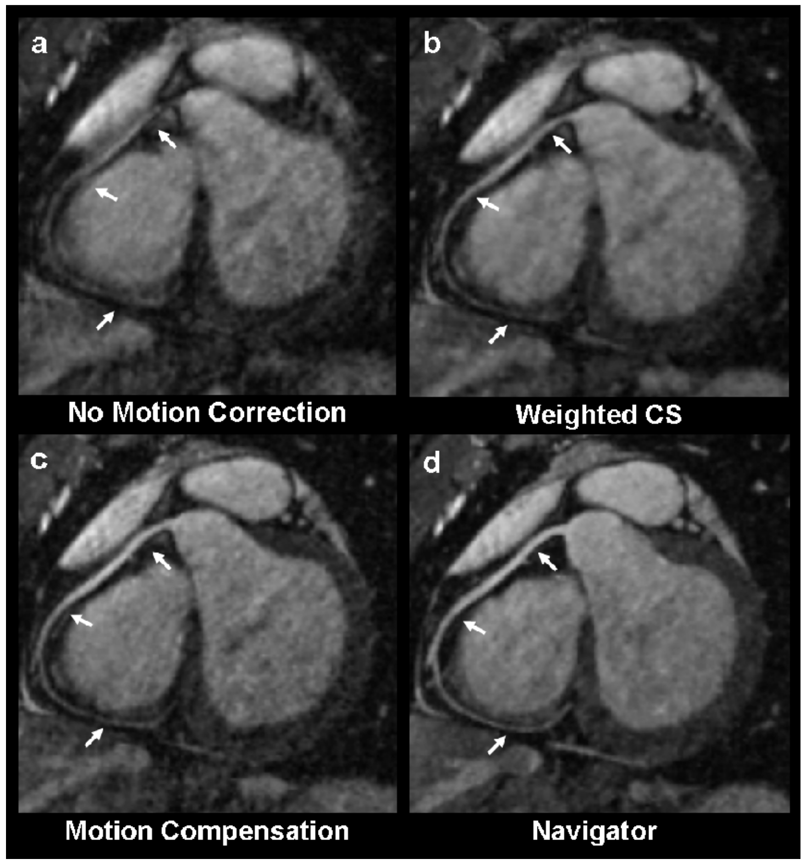

Figure 1: Reformatted images of the RCA reconstructed with (a) no motion correction, (b) weighted CS reconstruction to one respiratory phase, (c) motion-compensated reconstruction incorporating the motion model and (d) of a navigator-gated reference.

RESULTS and DISCUSSION – Navigator-gated as well as self-navigating acquisitions finished successfully for all volunteers. The average navigator acceptance rate of 0.40±0.11 prolonged the acquisition time to 9.2±2.3 min, which was reduced with the proposed method to 6.3±1.0 min. Figure 1 shows the reconstructed images of one volunteer with (a) no motion correction, (b) with weighted CS reconstruction, (c) with the proposed method, and (d) a navigator-gated reference. The reconstructed images without motion compensation suffered from artifacts due to respiration, which also affected the sharpness of the right coronary vessels (0.56±0.07). Weighting the reconstruction to one respiratory phase minimized the artifacts due to motion, which improved the average vessel sharpness to 0.68±0.10. In the proposed method, data from other respiratory phases were incorporated into image reconstruction by utilizing the motion model, thus reducing the degree of k-space undersampling. This led to a further improvement of vessel sharpness to 0.72±0.07. The results of the proposed method were comparable to the navigator gated reference (0.71±0.17). However, the new method involves time-consuming computations, which would benefit from optimization and GPU implementations to meet current clinical needs.

CONCLUSIONS – The proposed reconstruction method was shown to compensate for k-space undersampling and minimizes respiratory motion artifacts by incorporating data from other respiratory phases into image reconstruction. The required motion model is derived by a weighted CS reconstruction for individual respiratory phases of the acquired data of the actual scan and, thus, requires no acquisition of navigator echoes or other additional data.

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