Minimization of Respiratory Motion Artifacts for Whole-Heart Coronary MRI: A Combination of Self-navigation and Weighted Compressed Sensing Reconstruction

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INTRODUCTION – In recent years, respiratory self-navigation techniques were introduced in the field of free-breathing, whole-heart coronary imaging [1, 2]. Radial trajectories intrinsically provide information about the respiratory offset and are insensitive to artifacts due to motion during data acquisition. In contrast, Cartesian sampling is superior to radial trajectories in terms of signal to noise ratio (SNR) [3] and is less sensitive to hardware parameters of the MR scanner, e.g. gradient delays [4]. Furthermore, in the context of iterative reconstruction, gridding of the radial spokes is the most time-consuming factor. In the present work, we propose the application of respiratory self-navigation on an incoherent, undersampled Cartesian trajectory. As self-navigation can be used to compensate for the effects of respiratory motion along the superior-inferior (SI) direction, the effects of motion perpendicular to this direction, such as chest wall motion, remain uncompensated and cause motion artifacts. Hence, iterative reconstruction was combined with a weighted data fidelity term, based on the information derived from the self-navigation, to suppress these artifacts in image reconstruction. In-vivo experiments were performed on four healthy volunteers and compared to navigator-gated acquisitions featuring identical acquisition and reconstruction.

MATERIALS and METHODS – Incoherent Cartesian sampling in the kx-ky phase encoding plane was obtained by the spiral phyllotaxis pattern [5]. ECG triggering to end-diastolic phase was applied to minimize cardiac motion during data acquisition. An additional SI-projection was placed at the beginning of each interleave for self-navigation [6]. To utilize the self-navigation properties to correct for 1D respiratory motion along SI direction, data was acquired in a sagittal 3D slice orientation.

The maximum value of the respiratory signal derived from self-navigation was used to determine the position of end-expiration for each volunteer. As most of the acquisitions are performed in such respiratory phase, this position was chosen as reference. The effects of motion increase with the respiratory offset with respect to the reference. Therefore, read-outs were weighted according to this distance, using a Gaussian kernel centered at the reference position and with $\sigma = 2.0$. The weighting factor W was directly introduced into the data fidelity term of the cost function of the iterative, total variation (TV) regularized, CS-SENSE algorithm:

$$\min_x \sum_i \left\| W(AC_i\mathbf{x} - \mathbf{y}_i) \right\|_2^2 + \lambda \left| \mathbf{x} \right|_{TV},$$

Here, x represents the desired image and A is the Fourier transform. The coil sensitivity and measured k-space data of the i-th channel are denoted by C_i and y_i, respectively. Image reconstruction was fully integrated into the scanner software architecture.

In-vivo experiments were performed on four healthy volunteers on a 1.5T clinical MRI scanner (MAGNETOM Aera, Siemens AG, Healthcare Sector, Erlangen, Germany). A volume-selective, T2 prepared, fat saturated, ECG-gated (triggered to end-diastolic phase), balanced SSFP sequence was performed with the following parameters: TR/TE 4.0/2.0 ms, $\alpha = 90°$, FOV 270x270x150 mm^3, matrix 256x256x144, voxel-size 1.05 mm^3 and a receiver bandwidth of 849 Hz/Px. The total of 5580 readouts resulted in an undersampling ratio of 14% compared to fully sampled acquisition. Reference lines in k-space center with a matrix of 20x30 were used to estimate coil sensitivity. Signal was received using an 18 channel body matrix coil anterior and 8 elements of the spine matrix coil posterior. The proposed method was compared to a navigator-gated acquisition with an acceptance window of 5 mm placed in end-inspiration, identical sampling pattern, and iterative reconstruction. To specifically evaluate the effects of motion suppression, the proposed method was compared to images with respiratory motion correction featuring self-navigation only. Image quality was quantitatively measured by the sharpness of the RCAs as described in [7].

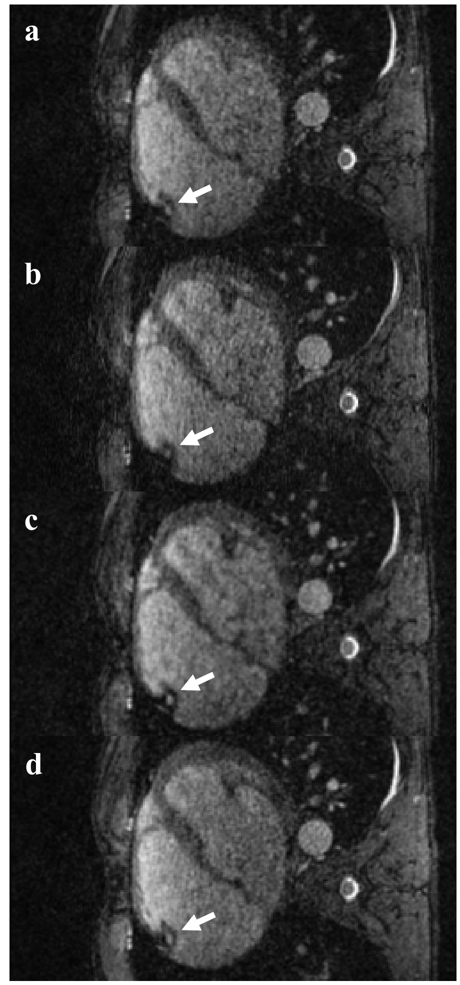

Figure 1: Axial images of the RCA representing the input data (a) without correction, (b) with correction based on the SI projection, and (c) in combination with respiratory motion minimization using a weighted data fidelity term. (d) Navigator gated data is acquired for reference.

RESULTS and DISCUSSION – Self-navigated as well as navigator-gated acquisition was successful in all volunteers. Figure 1 shows an example of reconstructed images for (a) no motion correction, (b) with correction using the SI projection only, (c) with the proposed method, and (d) a navigator-gated protocol for reference. An averaged amplitude of 8.3±1.3 mm was measured in the respiratory signal of the self-navigation. The acquisition time was decreased from 7.9±1.0 min, using navigator gating, to 2.7±0.2 min with self-navigation. Visual inspection of both self-navigated and navigator-gated datasets resulted in a overall comparable image quality. The average vessel sharpness of the RCA was 0.31±0.07 for the navigator-gated acquisition, 0.30±0.04 for the self-navigated and 0.32±0.05 for the proposed method. Images reconstructed using the uncorrected data suffer from motion artifacts, which also affect the sharpness of the coronary vessels (RCA: 0.28±0.03). While 1D respiratory motion correction was able to reduce these artifacts, the effects of motion perpendicular to the SI projection remained uncorrected. Even though, the use of a weighting factor results in an increased undersampling, the proposed method could minimize residual motion artifacts without visible loss of image quality. The improvement in vessel sharpness even with respect to the navigator-gated approach can be explained by the width of the Gaussian kernel, which was smaller than the navigator's acceptance window.

CONCLUSIONS – The presented combination of respiratory motion correction and motion suppression in image reconstruction was able to improve image quality. However, image quality remains a trade-off between undersampling ratio and artifacts due to residual respiratory motion. Further improvements could be obtained by reconstructing different respiratory phases with the proposed method. The resulting images could be combined with affine registration to obtain the final image.

REFERENCES – [1] Stehning, C. et al., MRM, 51:476-480, (2005); [2] Piccini D. et al, Proc. 19th ISMRM, p. 1259, (2011); [3] Pipe, J. et al., MRM, 34:170-178, (1995) [4] Block, T. et al, Proc. 19th ISMRM, p. 2816, (2011); [5] Vogel, H. et al., Mathematical Biosciences, 44:179-189 [6] Piccini, D. et al, MRM, in press, (2011); [7] Li, D. et al., Radiology, 219:270-277, (2001)

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