Highly Efficient Respiratory Motion Compensated Free-Breathing Coronary MRA Using Golden-step Cartesian Acquisition

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INTRODUCTION: Respiratory motion remains a major challenge in free-breathing whole-heart coronary MR angiography (CMRA). Diaphragmatic navigators are commonly used for respiratory motion compensation in CMRA but lead to prolonged scan times since only a fraction of the acquired data is used for image reconstruction (20-50%). To overcome this problem methods based on navigator image registration have been recently introduced to achieve 100% scan efficiency [1-3]. These methods usually use additionally acquired 2D or 3D low-resolution images to correct and image-average undersampled respiratory-resolved images at a reference breathing position. Here we propose a new 3D image registration based motion correction approach that achieves 100% scan efficiency by estimating the motion from the data itself and correcting the acquired data directly in the k-space reconstruction. For this, image-based registration of high-resolution undersampled reconstructed image data is performed using a golden-step spiral-like Cartesian acquisition (CASPR), similar to [4]. CASPR ensures quasi-uniform k-space sampling for any breathing position and respiratory window size, independently of the breathing pattern. Motion parameters are estimated from undersampled respiratory resolved images reconstructed with iterative SENSE [5] and 3D motion correction is performed directly in the reconstruction using a multiple-coils generalized matrix formulation method [6]. This approach was tested on healthy subjects and compared against a conventional diaphragmatic navigator acquisition.

METHOD: *a) Data acquisition*: Data is acquired using a golden-step spiral-like 3D Cartesian trajectory (CASPR). CASPR samples the phase encoding plane following approximate spiral interleaves on the Cartesian grid. The angular step between two consecutive spiral interleaves is given by the golden ratio φ = 0.618 (Fig.1a). This trajectory ensures quasi-uniform k-space sampling at any breathing position and for any respiratory window, independently of the breathing pattern.

b) Motion estimation: The acquired data is retrospectively assigned to N respiratory bins according to their position in the respiratory cycle (given by a diaphragmatic navigator signal). Iterative SENSE is performed to reconstruct *N* undersampled respiratory resolved images, which are registered to a common respiratory position to yield 3D motion parameters $\mathbf{T}_t$ (Fig1.b).

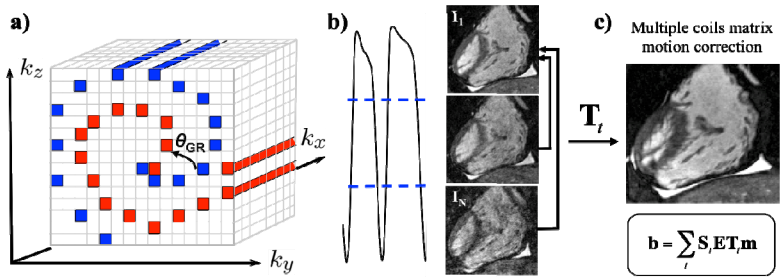

Fig.1: a) Golden-step spiral-like Cartesian trajectory, b) N respiratory-resolved undersampled images I_i are reconstructed using iterative SENSE and registered to a common respiratory position, c) Estimated 3D motion parameters T are incorporated directly in the reconstruction of k-space data using a matrix description of general motion correction.

c) Motion corrected reconstruction: The estimated 3D motion parameters $\mathbf{T}_t$ (t = 1,…,N) are incorporated directly in the reconstruction using a matrix description of general motion correction [5]. Considering **m** as the motion-free object, the motion corrupted k-space data **b** is given by $\mathbf{b} = \Sigma_t \mathbf{S}_t\mathbf{E}\mathbf{T}_t\,\mathbf{m}$ where **E** the encoding matrix, consisting of coil sensitivities and Fourier transform, and $\mathbf{S}_t$ is the sampling operator at the t^{th} respiratory position with $\Sigma_t \mathbf{S}_t$ resulting in a non-overlapping fully sampled k-space. This formulation is solved iteratively using a conjugate gradient method.

In-vivo experiments were performed on four healthy subjects on a 1.5T Philips scanner using a 32-channel receiver coil. 3D segmented balanced-SSFP CASPR acquisitions were performed under free breathing without gating window. Relevant scan parameters include: FOV = 288x288x120mm, resolution = 1x1x2 mm, TR/TE/flip angle = 4.5ms/2.2ms/70°, T2 preparation pulse (TE = 40ms), fat saturation prepulse (SPIR), subject specific mid-diastolic trigger delay, acquisition window ~ 100ms, 1 spiral-like interleaf per R-R interval. Five undersampled respiratory resolved images were retrospectively reconstructed for each volunteer (undersampling factors ~ 3-8 depending of respiratory position and breathing pattern). These images were registered to the end-exhale position using an affine motion model in a region of interest around the heart. An 8mm navigator-gated acquisition was performed at end-exhale with the same trajectory and identical imaging parameters for comparison purposes.

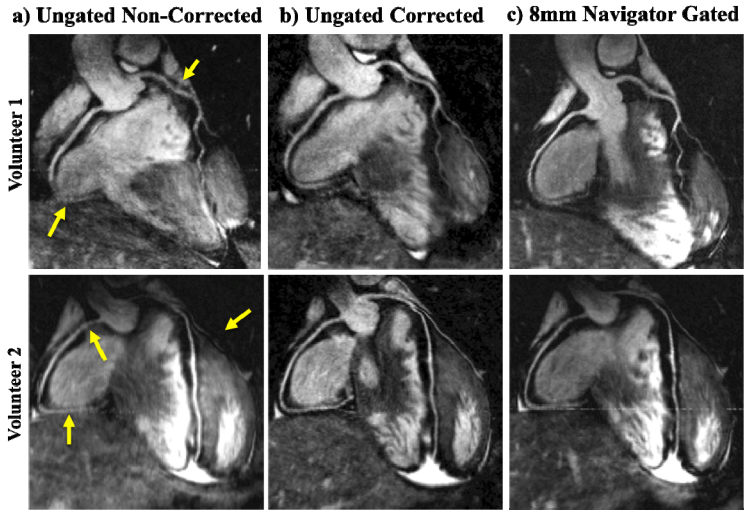

Fig.2: a) Ungated non motion corrected images, b) Proposed motion corrected reconstruction, c) Navigator gated reference.

RESULTS: Reformatted images with the proposed approach are shown in Fig.2 for two healthy volunteers (b). The ungated non-corrected (a) and navigator-gated (c) acquisitions are also included. Motion blurring is observed in the non-corrected images (arrows). The proposed approach achieves similar image quality to the reference navigator-gated scan. The average navigator efficiency for the gated scan was 60% ±12%, compared to 100% for the proposed approach.

CONCLUSIONS: We have demonstrated the feasibility of the proposed approach to perform respiratory motion correction directly in the k-space reconstruction by estimating the 3D motion from the same acquired data. This approach achieves 100% scan efficiency and image quality comparable to that of an 8mm navigator-gated longer scan time acquisition. The use of a Cartesian acquisition allows adequate signal to noise ratio and computationally efficient reconstruction.

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