A New Binning Approach for 3D Motion Corrected Self-Navigated Whole-Heart Coronary MRA Using Independent Component Analysis of Individual Coils

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Introduction: Despite significant progress in navigator technology, respiratory motion correction remains a major challenge in coronary magnetic resonance angiography (MRA). In response to this challenge, *one-dimensional* self-navigation (SN) techniques have been developed that extract respiratory-induced motion of the heart directly from the imaging data themselves. SN approaches have shown similar image quality when compared to conventional diaphragmatic navigator gated (NAV) acquisitions, while affording 100% scan efficiency and improved ease-of-use[1]. To account for *three-dimensional* motion of the heart, *image-based* SN approaches that exploit 3D radial trajectories have recently been introduced[2]. These methods produce aliased sub-images for each respiratory phase by combining (binning) data segments from different cardiac cycles (interleaves). From such sub-images, 3D motion parameters are estimated and used for motion correction during final image reconstruction. To bin interleaves in different respiratory phases, the NAV signal[3] or the superior inferior (SI) displacement obtained from 1D-SN[2] have demonstrated to be effective. However, the use of NAV requires additional planning and expertise, and 1D-SN still depends on the tracking of the ventricular blood-pool on a 1D projection image. Unfortunately, this projection does not only integrate the signal from the heart, but also that from surrounding anatomical structures in the field-of-view (FOV)[4]. This unwanted background signal remains one of the major barriers for accurate respiratory motion tracking of the heart. To remove this barrier, we propose the following 2-step approach to take 1D-SN to 3D-SN. First, we extract the respiratory signal from independent component analysis (ICA) [5] of the k-space center amplitude in all receiver coils and use it for binning and subsequent 3D sub-image generation. Second, we use an atlas-based segmentation of the heart for image-based motion detection without background contribution. In 11 healthy adult human subjects, the performance of this 3D-SN methodology was then quantitatively ascertained in comparison to conventional 1D-SN coronary MRA[4].

Materials and Methods: The proposed 3D-SN technique employs a 3D radial trajectory with an interleaved spiral phyllotaxis pattern[6], adapted to SN with an additional SI readout at the beginning of each interleave[4]. A golden-angle increment is also used to rotate the spiral pattern from one interleave to the next (Fig.1A). To obtain a respiratory signal, the amplitude of the k-space center, obtained from the SI readout, is recorded for all interleaves and for all receiver coils (Fig.1A,B). These individual traces are then processed with ICA[5] to extract the fluctuations related to respiration (Fig.1C). While this unit-less signal cannot directly be used for displacement measurements and correction, it can still be exploited to bin data for 3D sub-image reconstruction. The histogram of this signal is then sorted into 15 bins (Fig.1D). Uniform k-space coverage for each bin is promoted by the golden-angle phyllotaxis pattern. After discarding poorly populated bins (<15 interleaves), 3D sub-images from 10-11 respiratory phases can be reconstructed and used for final image reconstruction (Fig.1D). For motion detection, each undersampled sub-image (Fig.1E) is registered to the reference sub-image that is extracted from the most populated bin. However, prior to registration, an automated atlas-based segmentation[7] is performed on this reference sub-image to automatically locate the heart within the FOV. As a result, a binary mask of the heart is applied to the reference sub-image (Fig.1F). This is followed by a registration that aligns the remaining sub-images with the reference by means of a 3D affine transformation. Subsequently, all these transformed sub-images are combined to produce the final 3D motion-corrected dataset (Fig.1G). Free-breathing self-navigated whole-heart coronary MRA was performed in 11 healthy adult volunteers with ECG triggering on a 1.5T clinical MRI scanner (MAGNETOM Aera, Siemens AG, Healthcare Sector, Erlangen, Germany) with a total of 30 receiver coils. The acquisition window (~100ms) was placed in mid diastole. The protocol parameters of the 3D radial[6], non slice-selective, T2-prepared, fat-saturated, bSSFP imaging sequence included: FOV $(220\text{mm})^3$, voxel size $(1.15\text{mm})^3$, 12320 radial readouts acquired in 385 heartbeats. Each dataset was reconstructed offline in MATLAB with both the above-described 3D-SN algorithm and with a previously described[4] 1D-SN approach. Quantitative image analysis was then performed on all 1D and 3D self-navigated images using the Soap-Bubble tool[8]. For comparison, proximal, mid and distal coronary segments were visualized, and analyzed for vessel length, average vessel diameter and vessel sharpness (%VS). The number of visible vessel segments (AHA classification) was counted. For statistical analysis, a paired two-tailed Student's *t*-test was used and $p<0.05$ was considered statistically significant.

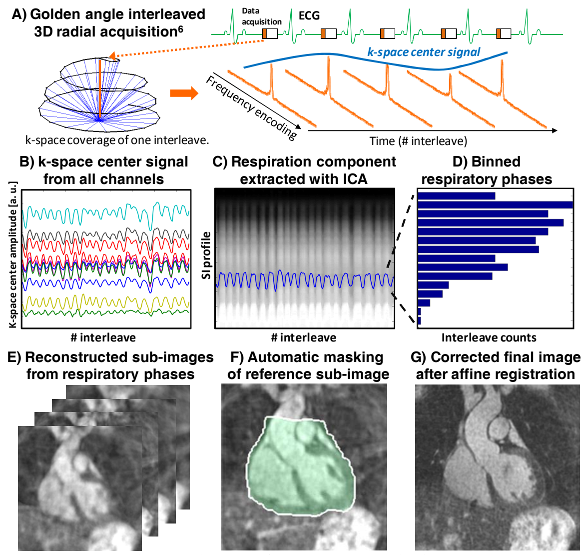

Figure 1 – Fundamental steps of the 3D-SN method. *The k-space center amplitude is obtained at the beginning of each interleave and for all channels (A,B). From such signals a component related to respiration is extracted via ICA[5] (C) and directly used to bin data in sub-images from different respiratory phases (D,E), without the need for tracking of the heart. An automatic atlas-based segmentation[7] of the heart is then used to align the sub-images at the level of the heart with affine registration (F). Combination of all registered sub-images provides a motion corrected, final image (G).*

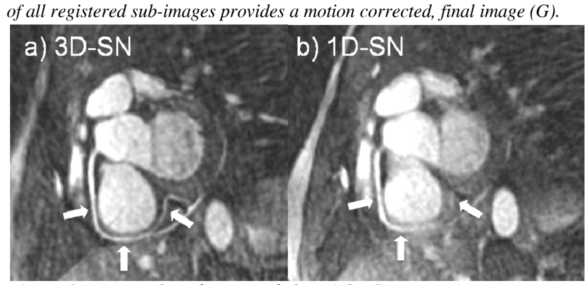

Figure 2 – Example reformats of the Right Coronary Artery. *Improved overall depiction of the distal parts of the RCA can be observed on the 3D-SN image, when compared to a 1D-SN reconstruction (arrows).*

Results: In a representative coronary MR image (Fig.2) after motion correction, an improved visual delineation of the right coronary artery (RCA) is obtained with 3D-SN (Fig.2A) when compared to the 1D-SN (Fig.2B). Note that the data were reconstructed from one and the same dataset. Consistent with these visual findings, the %VS is significantly improved with 3D-SN in the mid and distal RCA and in the left main coronary artery (LM) (Tab.1). With 3D-SN, a trend for higher %VS was observed for all other coronary segments, although this did not reach statistical significance. A total of 82/88 coronary segments were visualized by 3D-SN, whereas the 1D-SN technique allowed visualization of 76/88 segments. Vessel length and average diameter did not show significant differences among the two techniques.

Discussion and Conclusion: We have developed and tested a new SN approach that enables 3D motion correction for free-breathing coronary MRA. This method uses independent component analysis of fluctuations of the k-space center amplitude in all receiver coils to distinguish respiratory phases. A respiratory signal is therefore directly obtained from the imaging data, while obviating the need for additional navigator signals or motion tracking of the heart on projection images. The proposed 3D-SN significantly improved %VS and overall vessel visualization compared to the 1D-SN in healthy adult subjects.

Method:	*1D SN*	*3D SN*	*1D SN*	*3D SN*	*1D SN*	*3D SN*	*1D SN*	*3D SN*
Segment:	**LM**		**RCA prox**		**RCA mid**		**RCA dist**	
Visualized	11/11	11/11	11/11	11/11	11/11	11/11	11/11	11/11
Sharpness	44.2 ± 8.3	50.2 ± 10.1*	47.5 ± 15.9	53.8 ± 12.9	48.8 ± 10.6	53.5 ± 11.2*	29.2 ± 11.5	38.8 ± 9.7*
Diameter	3.8 ± 0.7	3.7 ± 0.5	3.1 ± 0.3	3.2 ± 0.3	2.9 ± 0.2	2.9 ± 0.2	2.8 ± 0.4	2.8 ± 0.6
Length	1.3 ± 0.3	1.5 ± 0.3	2.8 ± 0.7	2.5 ± 0.5	3.2 ± 0.9	3.1 ± 0.7	3.7 ± 1.0	3.2 ± 1.1
Segment:	**LCX**		**LAD prox**		**LAD mid**		**LAD dist**	
Visualized	7/11	8/11	10/11	11/11	9/11	11/11	6/11	8/11
Sharpness	42.4 ± 11.2	44.0 ± 6.9	39.4 ± 7.6	42.8 ± 9.9	37.0 ± 7.6	39.7 ± 10.0	41.7 ± 9.0	41.3 ± 8.6
Diameter	3.4 ± 0.2	3.3 ± 0.3	3.1 ± 0.2	3.3 ± 0.5	3.1 ± 0.3	3.4 ± 0.4	3.5 ± 0.4	3.4 ± 0.3
Length	2.3 ± 0.9	2.7 ± 1.6	2.6 ± 1.3	2.2 ± 0.8	2.9 ± 1.1	2.8 ± 0.8	4.2 ± 1.4	3.8 ± 1.3

Table 1 – Quantitative analysis of coronary artery segments. *LM, left circumflex (LCX), RCA and left anterior descending (LAD) segments were analyzed and compared for 3D-SN and 1D-SN. (*) indicates statistical significance of the Student's t-test (p<0.05).*

References: 1. Stehning MRM 2005;54,2:276 **2.** Pang MRM 2013 in press **3.** Bhat MRM 2010;65:1269 **4.** Piccini MRM 2012;68(2):571 **5.** Hyvärinen IEEE-TNN-1999;10(3),626 **6.** Piccini MRM 2011;66(4):1049 **7.** Chefd'hotel Proc. IEEE-ISBI-2002 pp.753 **8.** Etienne MRM 2002;48,4:658.