

Focused navigation (fNAV) for cardiac and respiratory motion-compensated free-running 3D whole-heart coronary MRA

Giulia MC Rossi¹, Nemanja Masala¹, Jessica AM Bastiaansen¹, Aurelien Bustin^{1,2}, Jérôme Yerly^{1,3}, John Heerfordt^{1,4}, Davide Piccini^{1,4}, Matthias Stuber^{1,3}, and Christopher W Roy¹

¹Department of Radiology, Lausanne University Hospital (CHUV) and University of Lausanne (UNIL), Lausanne, Switzerland, ²LIRYC (Electrophysiology and Heart Modeling Institute), Bordeaux, France, ³CIBM Center for Biomedical Imaging, Lausanne, Switzerland, ⁴Advanced Clinical Imaging Technology (ACIT), Siemens Healthcare AG, Lausanne, Switzerland

Synopsis

A novel method for reconstructing motion-compensated 3D CMRA images from free-running data is proposed. We extend the use of a recent method for non-rigid respiratory motion correction called focused navigation (fNAV) to also encompass cardiac motion compensation that accounts for beat-to-beat heart-rate variability. Our combined fNAV approach is compared to the previously established cardiac and respiratory motion-resolved 5D imaging *in vivo* and is shown to provide overall similar image quality and comparable right coronary artery visualizations to 5D imaging in significantly shorter reconstruction times.

Introduction

Coronary Magnetic Resonance Angiography (CMRA) requires robust compensation of both cardiac and respiratory motion. The free-running framework¹⁻² allows for cardiac and respiratory motion-resolved 5D imaging, where an end-expiratory mid-diastolic motion state can be retrospectively identified to effectively “freeze” motion for coronary visualization. However, unresolved intra-bin motion, heart-rate variability, and undersampling artifacts may still degrade the image quality. Recently, an auto-focusing technique (fNAV)³ was proposed for intra-acquisition non-rigid correction of respiratory motion in 3D radial ECG-triggered CMRA acquisitions. Using fNAV, high quality visualizations of the coronary arteries can be obtained by combining data from the entire respiratory cycle. Still, prospectively triggered images can suffer from incorrect resting phase calculation or heart-rate variability.

In this work, we developed a novel method for whole-heart CMRA that extends and integrates the fNAV approach with a previously published free-running¹⁻² uninterrupted bSSFP acquisition using LIBRE water excitation pulses⁴⁻⁶. We test the hypothesis that, a) by using fNAV to correct for non-rigid respiratory motion and b) by integrating a subject-specific auto-focusing strategy for retrospective cardiac soft-gating, we can obtain high-quality images of coronary arteries accounting for heart-rate variability without the need for prospective calibration scans⁷ or long compressed sensing (CS) reconstructions. We quantitatively compare our approach to the previously established cardiac and respiratory motion-resolved 5D imaging *in vivo*.

Methods

Acquisition. CMRA data were acquired in 19 healthy volunteers (age: 23-38 y; 10 male) with written informed consent on 1.5T clinical scanners (MAGNETOM Aera and MAGNETOM Sola, Siemens Healthcare, Erlangen, Germany) with a previously described prototype free-running acquisition⁷ while simultaneously recording the ECG signal.

Reconstruction. For each volunteer, two reconstruction approaches were compared. First, 5D images were reconstructed using CS as previously reported^{1-2,6} and a 3D volume corresponding to a manually identified quiescent cardiac phase at end-expiration was selected. In the second approach, a quiescent 3D volume was obtained by correcting an automatically selected subset of quiescent cardiac data for respiratory motion using fNAV (Fig.1), according to the following steps:

1. Respiratory motion amplitudes are estimated with fNAV³ and are used for *rigid* correction of respiratory motion in k-space.
2. Quiescent cardiac data selection and soft-gating is performed by extending the auto-focusing concept to the cardiac motion model presented in [7]. Based on the ECG time stamp, for each heart-beat i , the trigger delay (Td) is computed as:

$$Td(i) = k_0 \cdot T_{RR,AVG}(i) + (1 - k_0) \cdot k_1 \cdot \log(10 \cdot (T_{RR,AVG}(i) + k_2))$$

where, to account for heart-rate variability, the R-R interval is computed for each heart-beat based on the average of the five preceding heart-beats. A window of empirically determined fixed width (w) starting from Td is considered to be quiescent and corresponding readouts are weighted by a Gaussian function centered at $Td(i)+w/2$. Here, k_0 replaces an offset value traditionally determined through calibration scans⁷, while k_1 and k_2 are related to the duration of the systolic and diastolic portions of the cardiac cycle and are age and gender dependent. In our approach, the three coefficients are considered subject-specific and are iteratively estimated by evaluating the image gradient entropy of intermediate images obtained with respiratory motion correction from (1) and the current cardiac soft-gating.

3. Final *non-rigid* respiratory motion correction of the cardiac soft-gated data from (2) is performed using fNAV³.

Quality assessment. For both methods, reconstruction times were recorded for comparison. Curved reformats of the right coronary artery (RCA) were obtained from the resulting 3D images and visually compared. Quantitative comparison of image quality was performed via evaluation of RCA percentage vessel sharpness (%VS) and visible length using Soap-Bubble⁸ and the blood-to-myocardium contrast ratio (CR) measurements using 3DSlicer⁹. Statistical significance was evaluated using paired t-tests. RCA detection rates were compared for the two methods.

Results

Overall, fNAV reconstructions were significantly faster than 5D reconstructions (39±6 minutes vs 479±88 minutes, $p < 10^{-13}$), while achieving comparable image quality (Fig.2). Reformats of the RCA were also similar; however, the fNAV approach provided improved visual vessel conspicuity at specific locations (Fig.3). Quantitative comparisons revealed improved CR with fNAV ($p < 10^{-4}$), comparable visible RCA length, equal RCA detection rates and no statistically significant difference in %VS (Table1).

Discussion and Conclusion

Using our fNAV approach, we were able to correct free-running whole-heart CMRA data for non-rigid respiratory motion and by extending the auto-focusing concept to retrospective cardiac soft-gating, we were able to provide subject-specific compensation of cardiac motion that accounts for heart-rate variability. This combined approach produced high-quality CMRA images that were comparable to previously established 5D image reconstructions of the same data, but with a much shorter reconstruction time. In the current work, we used fNAV to produce static 3D volumes in contrast to the dynamic 5D image reconstructions. In principle, dynamic data could be generated by the fNAV method by shifting the cardiac soft-gating window, and provided enough data remain in our temporal footprint during peak motion. Furthermore, in patient populations where un-resolved intra-bin respiratory motion and heart-rate irregularities may be further amplified and degrade image quality of 5D imaging, our approach may be particularly beneficial, but this remains to be studied. Finally, if sufficient SNR gain could be achieved whilst preserving %VS, the increased amount of signal could be traded for higher resolution or abbreviated scan times, potentially improving the current clinical utility of 3D radial CMRA.

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Figures

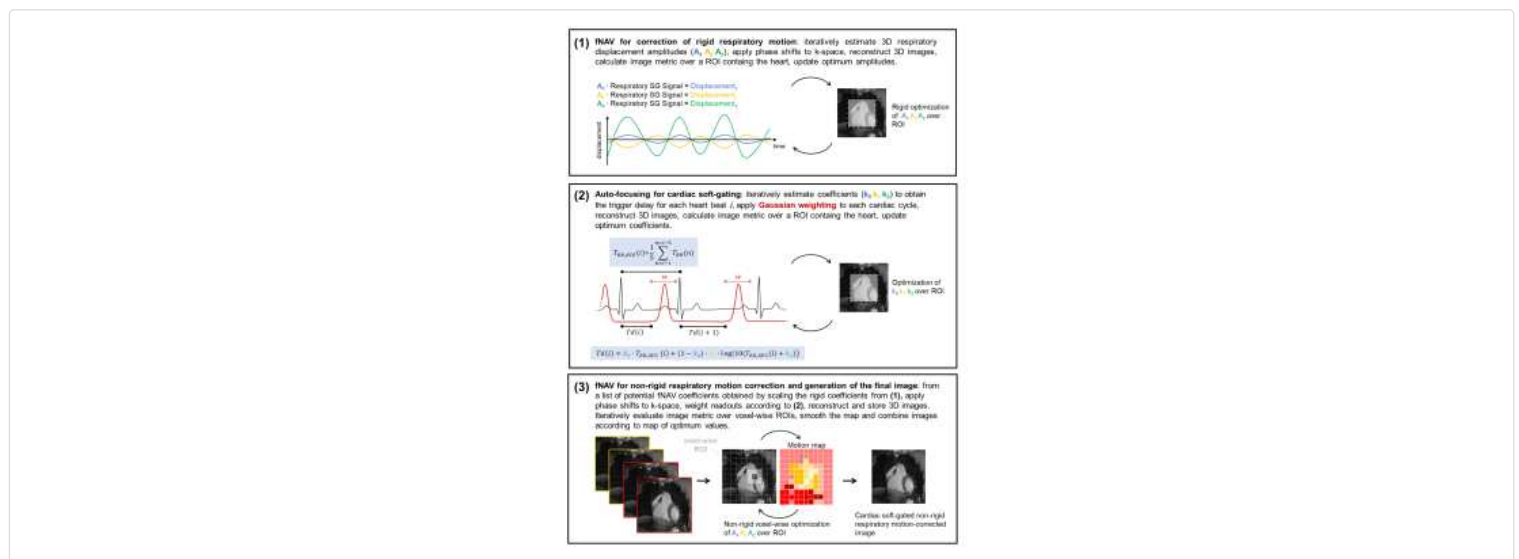


Figure 1. Overview of the 3-step auto-focusing framework for reconstructing cardiac and respiratory motion-compensated 3D whole-heart CMRA images from free-running data.

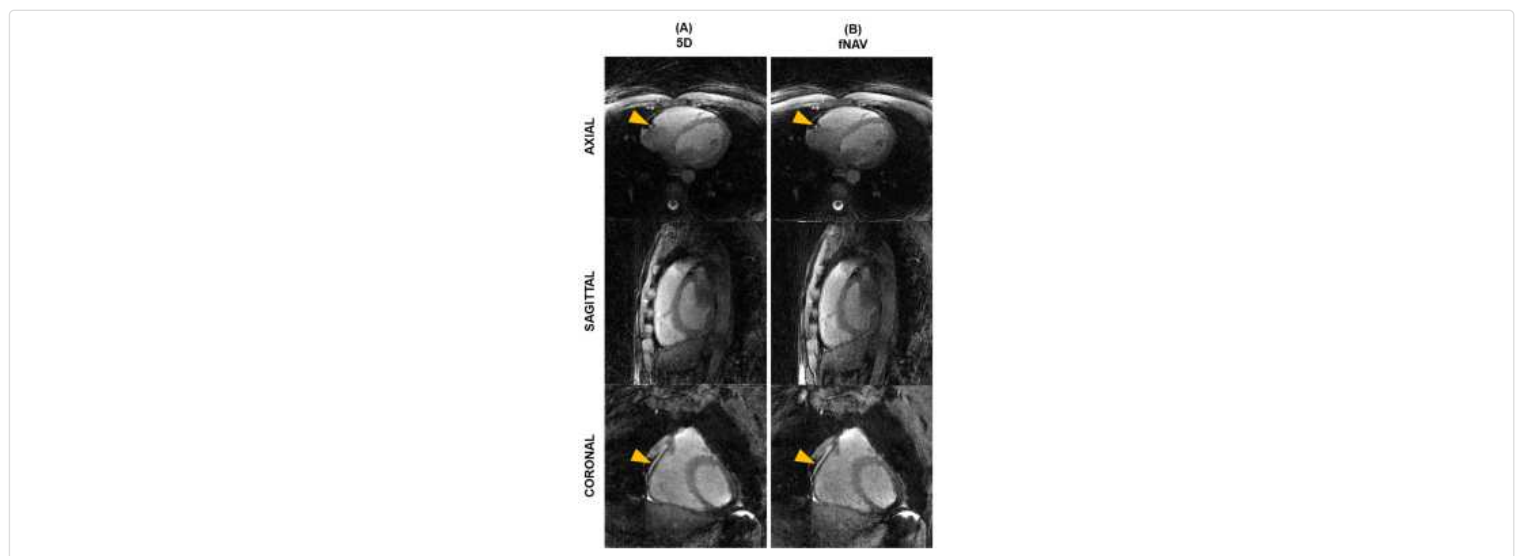


Figure 2. Qualitative comparison between 5D and fNAV-based reconstructions. Representative images in axial, sagittal, and coronal orientations are shown for a mid-diastolic end-expiration phase in the reference 5D reconstruction (A) and for the proposed fNAV reconstruction (B). Yellow arrows indicate locations where a portion of the right coronary artery is visible.

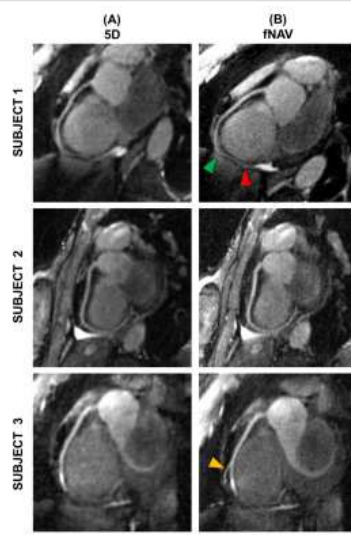


Figure 3. Reformatted images of the right coronary artery (RCA). Reformatted images of the RCA obtained with Soap-Bubble are shown for three representative volunteers for the reference 5D reconstruction (A) and for the proposed fNAV-based reconstruction (B). Arrows indicate RCA branches (yellow) or segments (green: beginning of the segment, red: end of the segment) for which the fNAV-based reconstruction approach allowed for improved detail visibility.

	5D	fNAV	p-value
Reconstruction time (min)	39 ± 6	479 ± 88	<10 ⁻¹³
CR blood-myocardium	1.67 ± 0.56	1.85 ± 0.66	<10 ⁻⁴
RCA detection rate	18/19	18/19	-
RCA Vessel length (cm)	7.72 ± 3.04	8.18 ± 2.48	0.37
RCA %VS (first 4 cm)	48.86 ± 10.19	48.24 ± 12.54	0.65
RCA %VS (full length)	46.57 ± 10.03	45.29 ± 11.27	0.31

Table 1. Quantitative comparison between 5D and fNAV-based reconstructions. CR, contrast ratio; RCA, right coronary artery; VS, vessel sharpness. Data are presented as mean ± SD, except for detection rates. RCA was considered detected if >2cm were visible. Differences in reconstruction time and blood-myocardium CR were statistically significant at a 0.05 significance level (paired t-test).