Respiratory Displacement-Dependent Weighting of the Center of K-Space for Improved Image Quality in Self-Navigated Golden Angle 3D Radial Whole-heart Coronary MRA

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Target. Basic scientists and clinicians interested in free-breathing 3D whole-heart MRA and motion compensation.

Introduction. Whole-heart coronary MRA is usually performed during free-breathing using a segmented k-space imaging sequence in which a navigator is commonly placed at the lung-liver interface to gate the acquisition to a specific respiratory phase [1]. In order to avoid navigator localization, to improve scan efficiency and to measure respiratory displacements directly at the level of the heart, respiratory self-navigated (SN) methods [2] have recently been introduced. While 100% scan efficiency has been reported, 1D superior-inferior (SI) motion correction [3] is performed over a large range of respiratory displacements and outliers in the respiratory position as frequently occurring in patients may still adversely affect image quality. Here, 1D motion correction is not sufficient, and reconstruction algorithms that account for 3D displacement, rotation, and deformation of the heart may be necessary to further improve image quality [4]. Alternatively, and owing to the unique characteristics of the spiral phyllotaxis arrangement of a 3D radial trajectory [5], we hypothesize here that a KWIC-like [6] respiratory SI-displacement-dependent weighting of central k-space positions improves image quality when compared to more conventional SN approaches.

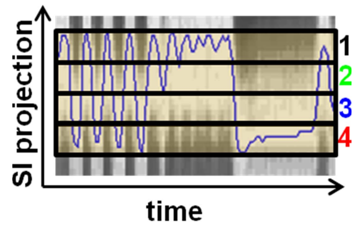

***Figure 1:** Detection of the heart using SI projections (blue line) during deep and shallow breathing and breath-hold. Bins 1-4 are used for binning of the k-space profiles obtained from different respiratory positions of the heart.*

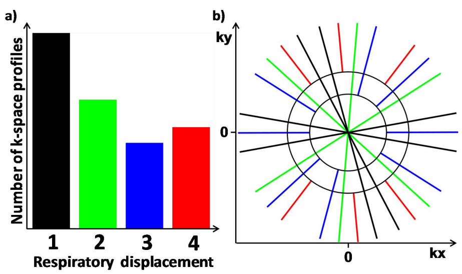

***Figure 2:** a) Histogram of the respiratory displacement measurements modulus. The black bin is the position of reference. Black and green bins contain data-segments which contribute to the center of k-space; b) schematic of respiratory SI-displacement-dependent weighting of the k-space center at the level kz=0. Profile colors match the bin colors of the histogram. Blue and red profiles are attributed a 0 weight within their individual Nyquist radii since they were obtained during large respiratory SI displacements of the heart.*

Methods. To test the above hypothesis, we designed a coached breathing pattern that aims at mimicking respiratory irregularities as frequently occurring in patients and which consists of the following subsections: deep breathing, shallow breathing, breath holds, coughing fits, leg crossing and free breathing (Fig 1). The data were acquired during this coached breathing in n=7 healthy adult volunteers after written consent was obtained with a prototype b-SSFP ECG-triggered self-navigated 3D radial sequence implementing a spiral phyllotaxis pattern [5] and T2Prep to enhance contrast. An SI projection is obtained at the beginning of each acquired data-segment and is used to detect and correct for 1D respiratory displacement of the heart [3]. One of the main characteristics of the spiral phyllotaxis pattern is that k-space is sampled uniformly over time, as each data segment is always automatically rotated by the golden-angle (137.51°) with respect to the previous one. Moreover, since 3D radial imaging oversamples k-space center, a limited amount of central k-space data can be discarded without a major detrimental effect on image quality. Acquisition was performed on a 1.5T clinical MR system (MAGNETOM Aera, Siemens AG, Healthcare sector, Erlangen, Germany). Acquisition parameters: TE/TR=1.56/3.1 ms, FOV=$(220mm)^3$, matrix=$(192)^3$ pixels, pixel size=$(1.1mm)^3$, T2 preparation=40ms, radio frequency excitation angle=115°, data-segments=623, radial views per data-segment=31 (19,313 radial views in total). As an SI-displacement-dependent weighting scheme, we defined the individual weight of a radial readout by first binning the k-space profiles according to the modulus of the respiratory displacement measured by the 1D SN algorithm (Fig 1&2.a). Secondly, we positioned a data acceptance window of 3.3mm width at the end-expiratory level as extracted from the histogram (Fig. 2.a). This corresponds to the first two bins of the histogram as shown in Fig 2.a (1st bin: end expiration; 2nd bin: ± 1.1 mm). Within such a small window, linear 1D motion correction has shown to be sufficient [7]. Consequently, the data contained in these two bins were assigned the weight 1 along their entire length of the readout in k-space, such that they fully contribute to the reconstructed image (black and green k-space profiles in Fig 2.b). In contrast, for the outer bins, a value of 0 was attributed to the central part in k-space, limited by a bin-specific radius calculated to fulfill the Nyquist criterion: $radius_{bin\,X} = \sqrt{\frac{2}{\pi}\sum_{i=0}^{X} histogram(i)}$, where X being the bin to be included (blue and red k-space profiles in Fig 2.b). Beyond this radius, the weight 1 is assigned to these profiles. The density compensation was adapted accordingly. In summary, and using this approach, data that are acquired during a respiratory position distant from the reference contribute less in terms of contrast to the final image, thus minimizing the effects of unsuppressed three-dimensional motion. Images were reconstructed from the same datasets using both this new algorithm and the conventional self-navigation approach for comparison. Both reconstruction approaches were implemented in Matlab (The Mathworks, Natick, MA, USA). The quantitative end-points for comparison were obtained using Soapbubble [8] and included vessel sharpness measured in the proximal right coronary artery and CNR analyses. Statistical comparisons were made using a paired two-tailed Student's t-test where $p<0.05$ was considered statistically significant.

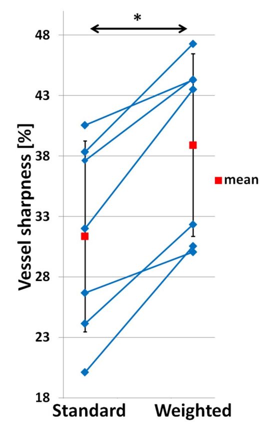

***Figure 3:** Individual vessel sharpness measurements for conventional SN ('Standard') and the respiratory SI-displacement-dependent weighting of central k-space positions approach ('Weighed').*

Results. Acquisition and reconstruction were successful for all datasets. On average, the percentage of k-space readouts that fully contributed to the final image was 40.3±13.7% of the total amount of data. Vessel sharpness increased in each case with the weighted approach with respect to the conventional SN reconstruction (Fig 3). Conventional self-navigation reconstruction resulted in an average vessel sharpness of 31.4±7.88%, while respiratory displacement-dependent weighting led to 38.9±7.55% ($p < 0.001$) (Fig 4). Average CNR measured on the standard reconstructions was 18.6±5.76, while that obtained with the weighted reconstruction increased to 20.4±3.26 (Fig 4), which was not found to be statistically significant (p=NS).

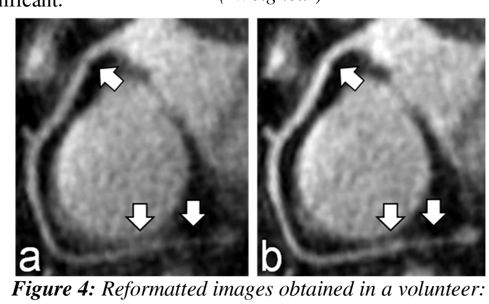

***Figure 4:** Reformatted images obtained in a volunteer: a) Conventional SN. b) Respiratory SI-displacement-dependent weighting of central k-space. Consistent with the numerical findings, an improved vessel delineation and contrast is observed in b).*

Discussion & Conclusion. We have tested the hypothesis positive that respiratory SI-displacement-dependent weighting of central k-space positions improves image quality when compared to more conventional SN approaches. This improvement may be attributed to a reduced contribution of the signal that is obtained from respiratory outlier positions. This suggests that image quality in SN coronary MRA can be improved without the need for sophisticated motion correction schemes or oversampling that leads to scan prolongation. Such reconstruction methods can retrospectively be applied while there is no need for modified data acquisition schemes.

References. **1**.Ehman, Radiology, 1989, **2**.Stehning, MRM, 2005, **3**.Piccini,MRM, 2012, **4**.Manke, MRM, 2003, **5**.Piccini, MRM, 2011, **6**.Song, MRM, 2000, **7**.McConnell,MRM, 1997, **8**.Etienne, MRM, 2002.