Advanced respiratory navigator strategies for 4D flow MRI

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Purpose: 4D flow MRI is a powerful technique to non-invasively measure, visualize and quantify 3D blood flow in the heart and large vessels. However, scan times are on the order of 5-15 minutes and respiratory motion during this time period can severely degrade image quality. 4D flow MRI is thus often performed in combination with a respiratory motion navigator placed on the diaphragm[1] to gate data acquisition. A 'navigator acceptance window' must be defined relative to the end-expiratory position, and data is accepted when the breathing position falls within the predefined window (fig. 1). To improve navigator performance, the acquired data can be phase-encoded according to respiratory position (adaptive phase encoding)[2]. Due to inter-individual differences in respiration patterns, however, the fixed navigator acceptance window results in variable scan efficiency, scan time and image quality[3]. The aim of this study was to test a novel navigator gating strategy based on dynamic adjustment of the lower threshold of the navigator acceptance window to maintain a fixed, user selected, scan efficiency in combination with a navigator training phase. The feasibility of this approach for providing more stable 4D flow MRI scan times for different respiration patterns while maintaining image quality was evaluated in n=10 normal volunteers.

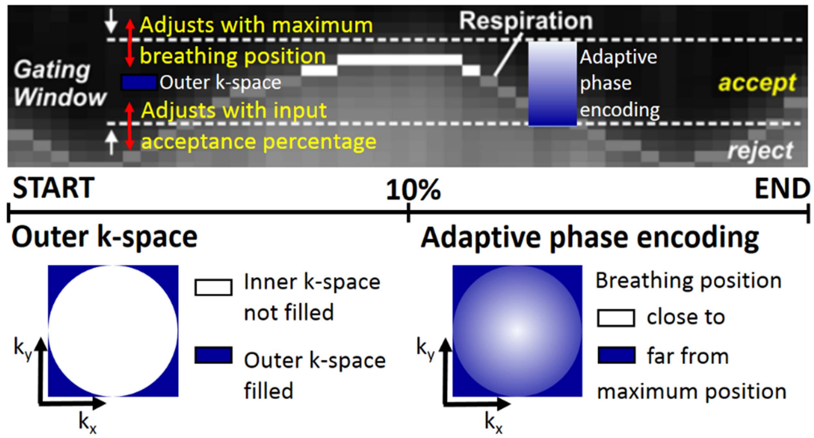

Fig 1. Schematic display of the new navigator sequence

Methods: The new navigator strategy (Fig. 1) combined the following features: 1) Real time-adjustment of the navigator acceptance window - when the number of accepted k-lines exceeds/goes below the user selected scan efficiency, the lower acceptance threshold is increased/decreased in real time, reducing/increasing the width of the acceptance window, 2) Adaptive phase encoding - the acquired data were phase-encoded in k_y-k_z-space according to respiration[3]. Data acquired during end-expiration with the least motion were assigned to the center of k-space, 3) Training phase - The first 10% of phase encodes were assigned to the outer edge of k-space to allow initial adjustment of the acceptance window. ECG and navigator gated 4D flow MRI of the thoracic aorta was performed in 10 volunteers (age: 47±16 y/o, range: 23-71y/o, 8M, 2F) on a 1.5T MAGNETOM Aera and a 3T MAGNETOM Skyra system (Siemens Healtcare, Erlangen, Germany, spatial resolution = 3.19-3.66x2.13-2.44x2.4-2.6mm^3; temporal resolution = 38.4-39.2ms, TE/TR/FA = 2.4-2.5ms/4.8-4.9ms/7°; Venc = 150cm/s). Four 4D flow MRI scans were acquired: 1) conventional navigator[2], 2) acceptance window set to 60%, 3) 80% and 4) 100%. All 4D flow MRI data were corrected for Maxwell terms, eddy currents and velocity aliasing. For all four scans, time-averaged 3D PC-MRA data[4] and systolic 3D streamlines (Ensight, CEI Inc, Apex, NC) emitted from a plane in the mid-ascending aorta (MAA) were calculated. Both 3D PC MRA and streamline data were scored by an experienced radiologist between 0 (poor quality) and 3 (best quality). In addition, net flow and systolic maximum velocity were quantified at the MAA. 3D segmentation of the aorta (Mimics, Materialize) was performed to compare all peak systolic velocities inside the aortic lumen between new (fixed efficiency) and conventional (fixed acceptance window) navigator settings. The Kruskal-Wallis test was used to test for significant differences across scans; P<0.05 was considered significant.

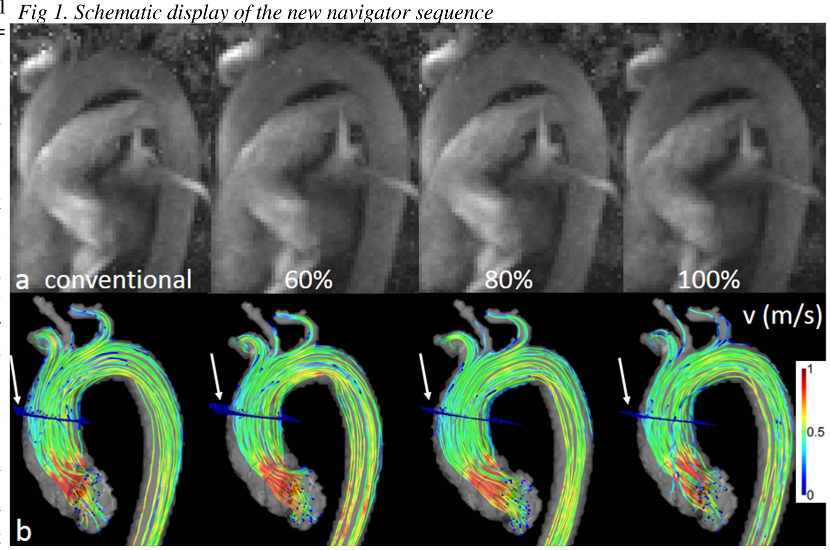

Fig 2. (a) Typical PC-MRA maximum intensity projections and (b) peak systolic velocity streamlines released from the plane indicated by the white arrow.

Results: The average 4D flow scan efficiency with conventional navigator settings was 74±13%. Total 4D flow scan times were 11±2min, 13±2min, 10±2min and 8±2min for the conventional navigator and fixed 60%, 80% and 100% acceptance, respectively. No significant differences between scans were found for 3D PC-MRA or 3D flow visualization (streamlines) quality. Table 1 shows similar net flow and systolic maximum velocities in the MAA for all scans. Bland-Altman and correlation analysis comparing all velocities in the entire aorta between the conventional navigator scans and the three fixed efficiency settings show excellent agreement with a strong correlation (Pearson ρ = 0.8-0.9), low mean differences and limits of agreements (table 1). Overall, the 80% fixed navigator efficiency showed best performance.

Table 1. Planar analysis: Net flow and maximum velocity. Volumetric analysis: Mean difference, Limits of Agreement (LOA) and Pearson ρ for the fixed navigator settings compared to the conventional navigator.

Navigator acceptance	Planar analysis		Volumetric analysis - Bland Altman		
	Net Flow (ml/cycle)	Maximum velocity (m/s)	Pearson ρ	Mean diff. (m/s)	LOA (m/s)
Conventional	84±18	0.98±0.14	-	-	-
60%	76±18	1.02±0.18	0.84±0.10	0.00±0.06	0.27±0.06
80%	77±17	0.97±0.19	0.89±0.05	-0.01±0.05	0.23±0.05
100%	74±18	1.00±0.26	0.83±0.10	0.03±0.07	0.28±0.06
P-value	0.38	0.94	0.17	0.11	0.06

Discussion/Conclusion: The findings of our study demonstrated the feasibility of the navigator gating strategy for 4D flow MRI with fixed scan efficiency and thus more predictable total scan time while maintaining quality of 3D PC-MRA, 3D flow visualization, and flow quantification. Scan time uncertainties due to breathing as in conventional navigator gating are avoided except for the remaining variability due to heart rate.

References: [1]Stuber et al. Radiology (1999) [2]Markl et al. JMRI (2007) [3]Markl et al. JCMR (2011) [4]Bock et al. ISMRM (2007)

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