A New Approach for Time-Resolved Phase Contrast MRA

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Introduction: MR angiography (MRA) is widely applied in the clinical routine to analyze vascular malformations. While most applications are based on contrast enhanced MRA, Phase Contrast (PC)-MRA has proven to be a useful alternative [1,2]. However, most approaches provide only the time-averaged 3D lumen and thus static 3D vessel segmentation, which does not account for temporal changes such as the substantial motion of the thoracic aorta during the cardiac cycle. It was the purpose of the study to extract time-resolved 3D PC-MR angiography from ECG gated PC-MRI data with 3-directional velocity encoding using fully automated feature based fuzzy clustering for dynamic aortic lumen segmentation. This approach was applied and evaluated in 11 healthy subjects and 12 patients with different cardiovascular pathologies.

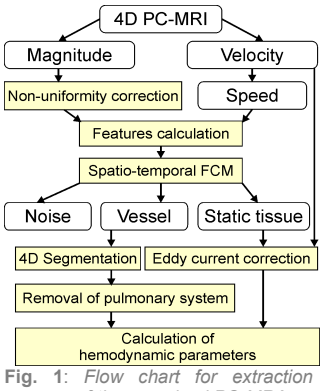

Fig. 1: *Flow chart for extraction process of time-resolved PC-MRA*

Methods - Data Analysis: Fuzzy clustering algorithms (here fuzzy c-means, FCM) classify the image by grouping similar data points in the feature space into clusters [3]. For the calculation of aortic PC-MRA, the aim was to group voxels of the time-resolved 3D PC volume into 3 clusters labeled as noise, static tissue and flow/vessel lumen for each time frame. To yield more homogeneous regions and to remove outliers, we modified the FCM algorithm by incorporating spatio-temporal information into the membership assignment function and thus allowing the spatio-temporal neighborhood (1 voxel in each +/- direction) of a voxel to influence its labeling. To correct for signal variations related to the multi-element coil used for data acquisition, a non-uniformity correction was performed on the magnitude data using a technique described in [4]. To account for possible velocity aliasing all calculations were performed using velocity vector magnitude (speed). For each voxel, four features were chosen for FCM: 1) sum of squares PC-MRA [2], 2) pseudo complex difference PC-MRA [5], 3) non-uniformity corrected magnitude and 4) mean value of the haar wavelet coefficients (for 2 scaling values) of the velocity-time course in a temporal neighborhood of 5 voxels. A spatio-temporal FCM algorithm was applied until the maximal change in values representing cluster membership was less than 0.2%. Subsequently, each voxel was assigned to a specific cluster for which the membership was maximal. Furthermore to improve the segmentation of diastolic time frames, voxels in the peak systolic time frames were labeled according to their distance from the vessel boundaries; core voxels (with distance > 3 voxels) were copied to all diastolic time frames. Additionally, a 3D holes closing algorithm was applied for each time frame. To enable the calculation of hemodynamic parameters (flow, mean velocities, etc.) in the aorta only, automatic removal of the pulmonary system was performed based on vector field homogeneity [6] and a subsequently applied flood fill algorithm. Voxels classified by FCM algorithm as static tissue were used for eddy current correction of the velocity data [7]. The data processing workflow is illustrated in fig. 1.

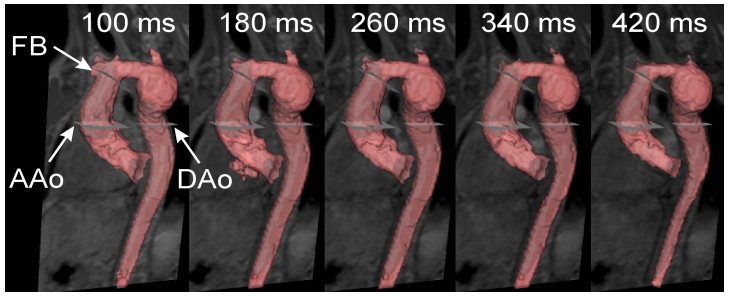

Fig.2 *Time-resolved 3D PCMRA in a patient with aneurysm in DAo, displayed at 5 time frames; white arrows indicate the position of the analysis planes*

Methods - MR Imaging: 11 young healthy subjects (mean age 24.6 years, 4 females) and 12 patients with different cardiovascular pathologies (mean age 29.7 years, 5 females; 8 patients with coarctation, 2 with aortic aneurysm, 1 with bicuspid aortic valve and 1 with aortic insufficiency) were included in our study after approval by the local ethic committee and written informed consent. All patients received contrast agent. Data were acquired on 1.5T and 3T systems (Avanto and TRIO, Siemens, Germany) using an ECG gated and respiration controlled rf-spoiled gradient echo phase contrast sequence with three-directional velocity encoding (spatial / temporal resolutions 1.9-2.9x1.6-1.7x2-3.5 mm^3 / 39.2 – 48.8 ms, venc = 150-230 cm/s).

Methods - Validation: For validation of the geometric accuracy of the derived time-resolved aortic geometry, 3 planes were placed at anatomical landmarks: 1) in the ascending aorta at the level of the lower edge of the pulmonary artery (AAo), 2) proximal to the first branch of the supra-aortic vessels (FB), 3) and at in the descending aorta at the same height as plane 1 (DAo) as shown in figure 2. As reference standard, the aortic lumen contours in all 3 planes were segmented manually for each time frame in the cardiac cycle. Area, mean velocity and flow were calculated for manual (reference standard), time-resolved and time-averaged (static) PC-MRA. Bland-Altman analysis was performed (Tab.1) and flow and area time-curves were plotted for each position (Fig.3, illustration for AAo position only).

Results: The time-resolved 3D PC-MR angiography in Figure 2 shows good vessel depiction in peak systolic time frames (180-340 ms). During early systole (100ms) and in diastole (402ms), the vessel boundaries especially in the distal descending aorta are not completely depicted. Similar results were obtained for all other volunteers and patients. Different pathologies had no influence on the segmentation quality. However, in 10 of 12 patients the automatic removal of the pulmonary system was incomplete; in healthy subjects, the removal was incomplete for 3 of 11 data sets. Bland-Altman analysis (Tab.1) revealed that time-resolved PC-MRA in most cases underestimated hemodynamic parameters compared to manual segmentation approach; but in some cases (AAo position in patients), time-resolved PC-MRA overestimated values probably due to incomplete removal of pulmonary system and thus incorporating values from other vessels into the calculations. Time-resolved flow curves (Fig. 3) derived with automatic segmentation were underestimated in most cases compared to reference standard (healthy/patients: 7.5 ± 5.1% / -0.5 ± 3.8% difference in AAo, 8.3 ± 5.6% / 3.5 ± 2.4% difference in FB, 9.5 ± 4.3% / 4.3 ± 4.0% difference in DAo). Time-resolved area were underestimated in healthy subjects (7.8 ± 5.2% difference in AAo, 10.0 ± 4.0% in FB and 14.3 ± 2.5% in DAo). In patients, areas in AAo (-5.5 ± 4.5 % difference) and in FB (-0.7 ± 2.2%) were overestimated and underestimated in DAo (6.9 ± 3.3%) compared to manual segmentation.

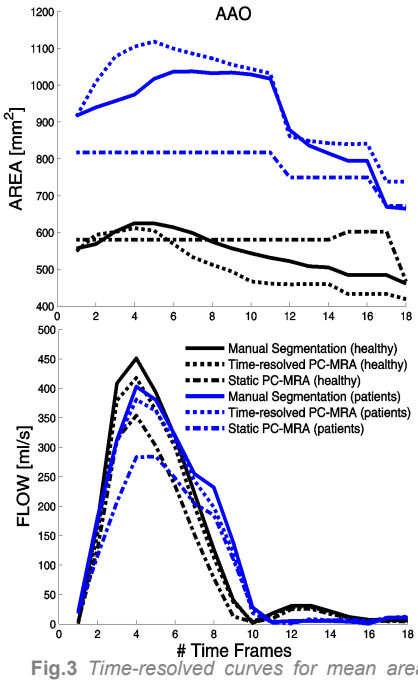

Fig.3 *Time-resolved curves for mean area (upper plot) and mean flow (lower plot); averaged over healthy subjects (black) and patients (blue). Solid lines represent manual segmentation; dotted lines – time-resolved and dashed lines – averaged PC-MRA*

Discussion and Outlook: Preliminary results indicate the potential of FCM for time-resolved 3D vessel segmentation. Limitations of the current implementation are related to low velocity in early systole and in diastole, which resulted in incomplete depiction of vessel boundaries during these time frames. Thus, time-resolved PC-MRA tends to underestimate the derived hemodynamic parameters. But in comparison to the rigid segmentation, flow could be determined more accurately (s.Fig 3) Advantages of the presented approach are that time-resolved segmentation follows the general motion of the aorta during the cardiac cycle. As a result, the incorporation of the noisy values from outside the vessel is reduced compared to a rigid segmentation.

		Area[mm^2]	Mean Vel.[m/s]	Flow [ml/s]
		Mean Difference ± 1.96 Standard Deviation (minimum – maximum)		
AAo	Healthy	25.8 ± 119.8 (337.0 - 819.4)	0.003 ± 0.015 (0.1 - 1.1)	7.6 ± 30.7 (-20.9 - 575.4)
	Patients	-50.4 ± 252.2 (377.2 - 2374.5)	-0.002 ± 0.030 (0.0 - 1.2)	5.9 ± 59.7 (-184.7 - 760.2)
FB	Healthy	31.8 ± 150.4 (321.9 - 752.1)	0.001 ± 0.047 (0.0 - 1.0)	4.6 ± 54.1 (-41.2 - 561.4)
	Patients	-1.4 ± 179.1 (294.3 - 1171.9)	0.004 ± 0.050 (0.0 - 1.1)	8.0 ± 53.9 (-194.6 - 658.9)
DAo	Healthy	43.6 ± 102.7 (184.1 - 497.9)	0.005 ± 0.016 (0.1 - 1.0)	5.8 ± 20.9 (-37.1 – 356.2)
	Patients	30.1 ± 109.4 (127.3 - 615.4)	0.004 ± 0.019 (0.1 - 1.2)	4.9 ± 19.1 (-95.7 – 432.7)

Tab. 1: *Results from Bland-Altman-Analysis for area, mean velocity and flow at 3 defined positions for healthy subjects and patients. Values are given as bias ± limits of agreement; in brackets minimum-maximum range is given*

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