4D Blood Flow in the Left Heart

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Introduction: Due to the complex 3-dimensional (3D) nature of the beating left heart and flow direction through the chambers, normal physiological as well as pathologically altered blood flow conditions are difficult to assess in-vivo. MR studies using comprehensive 3-dimensional (3D) and 3-directionally encoded techniques, (flow-sensitive 4D MRI) have given information on multidirectional blood flows and offer the possibility to measure and visualize the temporal evolution of complex flow patterns within a 3D-volume encompassing vascular segments or even the entire beating human heart [1-2]. In this study, the technique was employed to systematically identify and evaluate the existence and extent of typical flow patterns in the left heart. A second aim was to evaluate how increased age affects left atrial and left ventricular flow characteristics.

Methods: All examinations were conducted on a 3T MR system (TRIO, Siemens, Germany) using prospective ECG-gating and adaptive diaphragm navigator gating. Whole heart flow-sensitive 4D MRI was performed in 10 normal volunteers divided in two age groups <30 years (n=5, 25.2 ± 2.49 years) and > 50 years (n=5, 59.8 ± 5.76 years).Data acquisition consisted of a previously described k-space segmented rf-spoiled gradient echo sequence with interleaved 3-directional velocity encoding (spatial resolution = 2.5 x 2.5 x 2.8mm³, temporal resolution = 38.4ms, scan time ~ 15-25min).
To translate the comprehensive nature of the data (3 spatial dimension, 3 velocity direction and time) into images that can be visually assessed and analyzed, 3D visualization was employed (EnSight v. 8.2, CEI, Apex, NC, USA). The description of the flow dynamics though left heart was achieved by traces of massless virtual particles (3D particle traces) demonstrating the time-resolved intra-cardiac blood flow. Particle traces originated from interactively positioned emitter planes placed in the left and right pulmonary veins. From each of the emitter planes traces along the measured velocities were calculated and color coded according to their anatomic origin to identify the blood flow paths with respect to their vascular origin. To improve anatomic orientation, data from separately performed 2D CINE SSFP scans in standard 2-chamber and 4-chamber orientation were combined with the 4D flow data via image fusion (not shown). Semi-quantitative flow patterns analysis included the identification and grading of the following systolic and diastolic flow patterns in consensus reading:

- Left atrium: Systolic and diastolic vortex formation for flow originating in each of the 4 pulmonary veins
- Left ventricle (2-chamber and 4-chamber view): laminar early diastolic in-flow into ventricle, visibility of secondary in-flow by atrial contract, diastolic vortex formation at base, mid, apex; end-diastolic flow reversal prior to ejection; laminar and helical systolic out-flow in aorta.

Results: Systolic and diastolic left atrial vortex formation was more pronounced for blood originating from the left pulmonary veins compared to right side in both age-groups. However, vortex formation was enhanced during diastole in younger individuals, whereas in systole stronger vortex formation was demonstrated in all but one pulmonary vein in the older individuals (see figure 3 and 4). LV in- and outflow was laminar in all examined subjects independent of age. Highest number and extent of vortices were found in the midventricular and basal parts of the LV in all individuals. In contrast, only few and typically small apical vortices were seen (figure 4). Interestingly, secondary in-flow due to diastolic atrial contraction was visible in the majority of older volunteers (average grading 1.2 ± 1.3) but was not seen in the young subjects. Helical right- handed formation of the LV outflow was increased in older volunteers.

Discussion: Probably due to the more cranial location of the left pulmonary veins, we found pronounced vortex formation in the blood flow derived from the left side, which was mainly in clockwise direction as viewed from the back. It has been described in first studies that LV vortices were reduced in patients with LV dysfunction [3]. To date, however, it is unknown how helical blood flow in the atrium is altered by valve insufficiency or atrial arrhythmia. Vortices in the LV are necessary to redirect the blood flow toward the aortic valve and the knowledge of their extent is essential to judge the effect of aneurysm formation after myocardial infarction. In literature vortices next to the anterior mitral leaflet and smaller vortices near the posterior mitral leaflet have been described [4]. Notably, we found further vortical flow patterns in midventricular parts of the LV (see figure 1). Atrial contraction with consecutive second filling of the LV was only seen in some of the older individuals. This may be due to an increase of atrial contribution to LV filling in this age group. The fact that this feature was not seen in younger individuals might be caused by the prospective ECG gating of our sequences, which means that only data representing about 80-90% of the heart cycle were acquired after triggering from the R wave. The knowledge of the blood flow in the healthy heart is essential for further patient studies in cardiac disease.

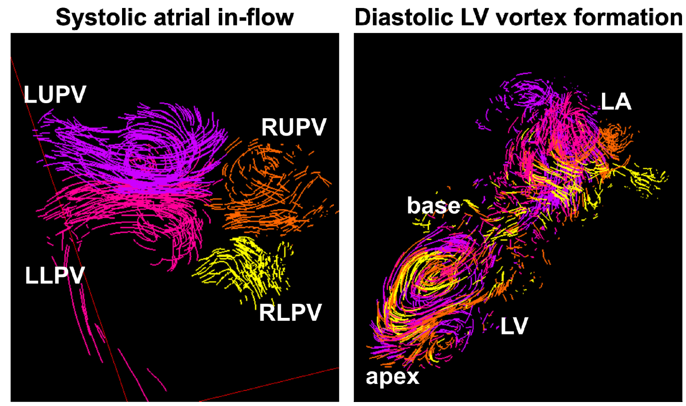


Fig. 1: *Systolic left atrial filling flow pattern (left), diastolic LV vortex formation (right). The different colors represent the blood flow origin: purple: left upper (LUPV) pink: left lower (LLPV) pulmonary vein, orange: right upper (RUPV), yellow: right lower (RLPV) pulmonary vein.*

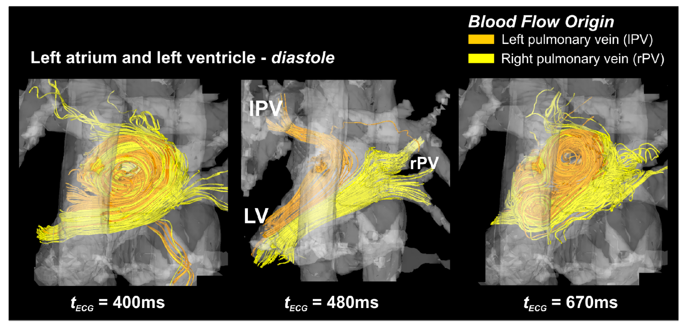


Fig. 2: *Diastolic left atrial and ventricular inflow characteristics with substantial vortex formation in the left atrium and laminar ventricular filling with clearly separated left and right flow channels.*

Fig. 3: *Cumulative results of flow pattern grading during systole. All flow patterns were graded according to: 0: not existent, 1: mild, 2: moderate, 3: pronounced; vortex orientation: clockwise or anti-clockwise.*

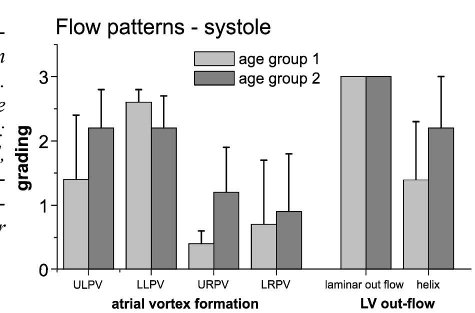
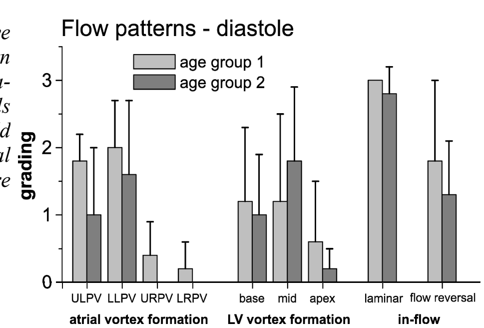


Fig. 4: *Cumulative results of flow pattern grading during diastole. Most individuals demonstrated a mild to moderate apical flow reversal before aortic valve opening.*



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