Whole Heart Flow Sensitive 4D MRI

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Introduction: MR studies using velocity encoding in 2D planes of acquisition and subsequently the more comprehensive 3D and 3-directionally encoded techniques (flow sensitive 4D MRI) have provided information on multidirectional in-vivo blood flows [1-3]. However, the comprehensive assessment of flow through the whole heart and the adjacent great vessels has been lacking. Therefore, previous investigation of altered cross-compartmental hemodynamics in the presence of cardiovascular disease relied on the interpretation of regional flow patterns in separately acquired images rather than inclusive, whole heart flow visualization. It was the aim of this study to optimize flow sensitive 4D MRI to acquire and visualize a comprehensive overview of principal blood movements through both sides of the human heart and great vessels. Within a single acquisition, anatomy and spatially register multi-directional flow were measured in both left (LV) and right (RV) ventricular systems including atria, the central venous supply, the ventricular outflow tract, the pulmonary trunk, and the thoracic aorta. The evolution and distribution of flow was evaluated in 10 healthy volunteers and 2 patients with complex flow alterations due to congenital heart disease.

Methods: All measurements were performed on a 3T system (TRIO, Siemens, Germany) using ECG and adaptive navigator gating. Methodological advances compared to previous studies [4] included velocity encoding (*venc* = 150cm/s) gradient optimization resulting in shortened echo (*TE*=2.4ms) and repetition time (*TR*=4.8ms) and improved temporal resolution (38.4ms). Additionally, parallel imaging was added (GRAPPA, *R*=2) to shorten total scan time. Whole heart flow sensitive 4D MRI (spatial resolution = 2.5 x 2.5 x 2.8mm³, scan time ~ 25-35min) was performed in 10 healthy volunteers and 2 patients with congenital heart disease. Both patients underwent surgical repair (extracardiac total cavopulmonary connection, TCPC) directly connecting the blood flow from the venae cavae to the pulmonary arteries bypassing the right ventricular system.
Data analysis included the calculation of a 3D phase contrast (PC) MR angiography form the 4D MR data which was combined with co-registered 3D flow visualization (EnSight, CEI, USA). The description of the paths by which the blood flow is directed though the heart was achieved by 3D streamline calculation based on forward- and backward tracking of the measured multidirectional blood flow velocities (3D flow connectivity mapping, figure 1) or time-resolved 3D particle traces (figure 3) [3, 5]. Emitter planes were placed in the left and right pulmonary veins, the left ventricle, the ascending aorta, the inferior and superior vena cava, and the main pulmonary artery. Traces along the measured velocities were color coded according to their anatomic origin. Additional flow quantification was performed using home built software. (Matlab, USA).

Results: Whole heart 3D flow connectivity mapping (figure 1) illustrated the complex intra-cardiac flow pathways. At user-defined points in time, blood supply to the atria, chambers, or outflow tracts could be differentiated with respect to its origin. Intra-atrial vorticity was apparent on both sides, particularly during atrial filling (figure 1A). Despite its complexity, time-resolved 3D particle traces revealed a remarkable temporal synchrony of flow changes through the left and right heart. Ventricular filling was characterized by coinstantaneous flow directed towards the apex of both ventricles. While RV inflow demonstrated a complex umbrella-like flow pattern, the LV inflow remained conically shaped with clearly separated inflow channels (figure 1B). During late diastole, slow flow vortices developed in both ventricles supporting the mixture of blood prior to the ejection phase. Next, the recirculating blood flow was redirected towards the outflow tracts into a more organized straight flow channel into the aorta and pulmonary trunk, respectively. Similar flow pathways were seen in all normal subjects. Quantification of local flow patterns (figure 2) illustrated the advantage of the comprehensive acquisition method, allowing for post-hoc analysis of flows in freely selected regions.
Results from a patient after TCPC are shown in figure 3. Time-integrated 3D particle traces depict flow pathways originating in the inferior (IVC, yellow) and superior (SVC, blue) venae cavae into the pulmonary system (PA) and illustrate the direct connection of the IVC and SVC to the PA. The observed filling patterns of the left and right pulmonary arteries are inconsistent with earlier reports [6] and suggest that blood flow in single ventricle patients after TCPC might be more complex than previously anticipated.

Discussion: The study demonstrated that whole heart hemodynamic analysis is feasible. Combined with analysis tools that allow for a quantitative and versatile qualitative analysis it may serve as a potent analysis tool in future clinical applications such as complex flows in congenital heart disease. These finding illustrate the potential to analyze the principal direction changes of flow through the heart and large vessels and to identify altered distributions of flow associated with pathology or surgical intervention.

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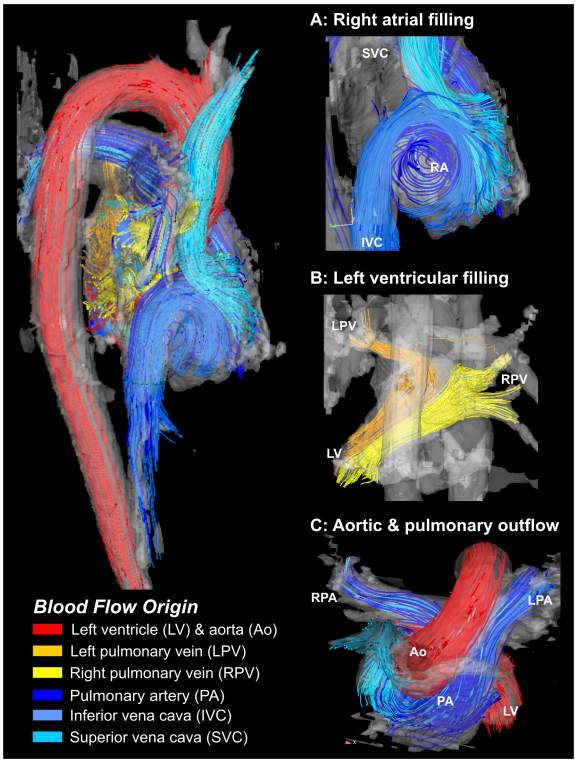

Fig. 1: 3D stream-line connectivity mapping and color coding based on the blood flow origin. **Left:** 3D stream-lines during ventricular systole within the entire heart, atria, and surrounding venous and arterial system. **Right:** Flow channels illustrating vortical filling of the right atrium (**A**), pulmonary venous flow and left ventricular filling as viewed from behind (**B**), outflow into the aorta and left and right pulmonary arteries (**C**).

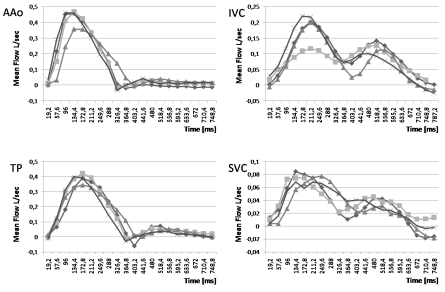

Fig. 2: Quantification of time-resolved blood flow in 4 volunteers. The graphs represent typical pulsatile flow waveforms in the asc. aorta (AAo), the pulmonary artery (PA), the superior (SVC), and inferior vena cava (IVC).

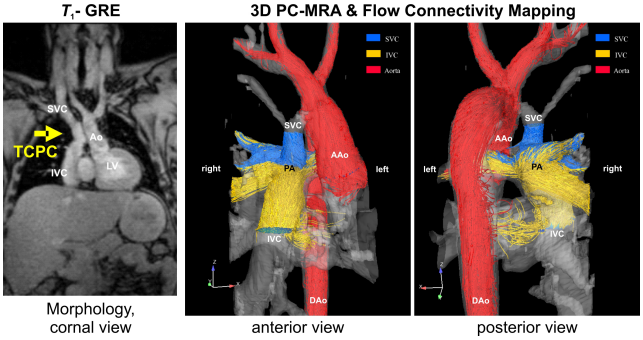

Fig. 3: Whole heart flow in a patient with congenital heart disease (single ventricle and TCPC). PC-MRA in conjunction with 3D flow connectivity mapping clearly shows blood flow from the venae cavae (blue & yellow) directly routed into the left and right pulmonary arteries.