Quantitative Physiology

4D Flow Imaging of Vascular and CSF Dynamics

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The intrinsic motion sensitivity of magnetic resonance imaging (MRI), which is exploited in phase contrast (PC) MRI, can be used directly acquire and quantify blood flow without the need for Gd contrast material. 4D flow MRI provides a non-invasive method for the qualitative and quantitative characterization of blood flow in heart and great vessels in 3D [1-6]. Currently, ECG synchronized 4D flow MRI (also termed 'flow sensitive 4D MRI', 'time-resolved 3D velocity mapping', or '4D velocity mapping') can be employed to detect and visualize global and local blood flow characteristics in entire targeted vascular regions. As a result, 4D flow MRI permits the assessment of three-directional blood flow with full volumetric coverage of cardiac chambers or cardio- or neurovascular regions of interest such as the thoracic aorta or the large cerebral arterial and venous system.

In 4D flow MRI, velocity is encoded along all three spatial dimensions throughout the cardiac cycle, thus providing a time-resolved 3D velocity field. Data acquisition is synchronized with the cardiac cycle and data collection is distributed over multiple cardiac cycles using so called ‘'k-space segmentation’ techniques (only a fraction of the entire 4D flow data is measured during each cardiac cycle, the data is successively collected over multiple RR-intervals). After completion of the 4D flow acquisition, four time-resolved (CINE) 3D datasets are generated ('magnitude' data depicting anatomy and three flow datasets representing velocities ‘Vx, Vy, and Vz’). For typical cardiovascular applications, scan times between 5 and 15 minutes can be achieved depending on heart rate, spatio-temporal resolution and anatomic coverage. For thoracic and abdominal applications, respiration control is thus needed to minimize breathing artifacts. The 4D flow raw data (see figure 1A) can include up to 5000-10000 individual images. As a result, efficient pre-and post-processing strategies are needed to translate the acquired information on cardiovascular anatomy and blood flow into clinically useful information.

For the 3D visualization of cardiovascular hemodynamics and flow patterns, the most commonly used techniques are 3D streamlines and time-resolved 3D pathlines[7-9]. 3D streamlines are instantaneous traces which run parallel to the direction of the measured blood flow velocity field, and are independently computed for each time frame in the cardiac cycle to represent the instantaneous velocity field iso-contours. Figure 1 illustrates the use of 3D streamlines to depict systolic 3D flow patterns in the thoracic aorta. Time-resolved 3D pathlines utilize the full 4D (3D and time) information and represent the path a massless particle would trace over time, and are highly dependent on the predefined seed, or ‘release’ point. Pathlines can be used to visualize the spatio-temporal dynamics of pulsatile 3D blood flow patterns and can be thought of as the path a massless red blood cell would trace in the vasculature under investigation. Both streamlines and pathlines are often color coded to display the local absolute blood flow velocity (see figure 1). The anatomic and velocity information of the 4D flow data can additionally be used to derive a 3D phase contrast angiogram (3D PC-MRA), which can be combined with 3D

blood flow visualization to guide anatomic orientation and analysis plane placement for flow quantification (see figure 1).

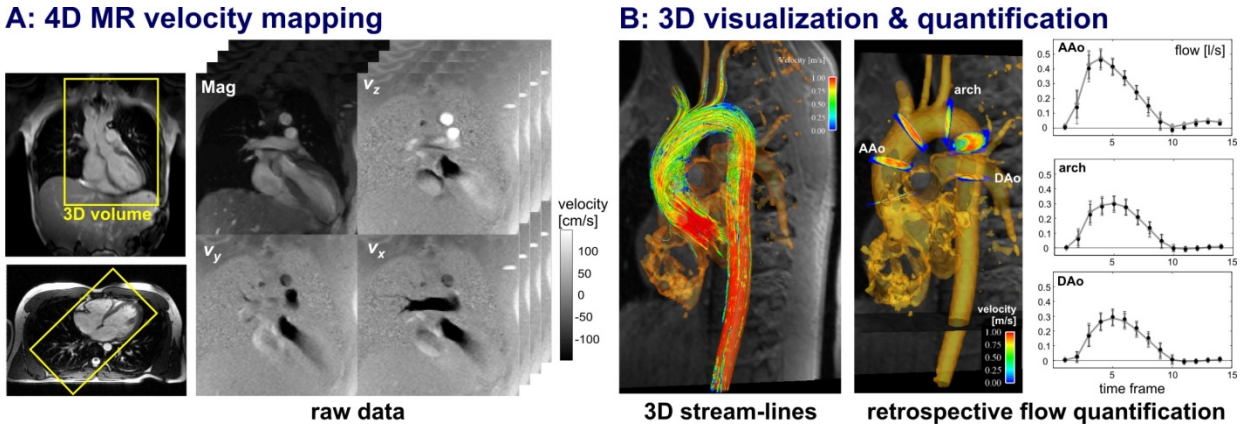

Figure 1: Acquisition of 4D flow MRI data (A) and visualization and quantification of 3D hemodynamics (B) in the aorta. The 4D flow raw data comprises information along all 3 spatial dimension, 3 velocity directions and time in the cardiac cycle. A 3D phase contrast angiogram (B, iso-surface rendering of the aorta) can be calculated from 4D flow MRI data to aid visualization and placement of analysis planes for retrospective flow quantification.

A benefit compared to traditional 2D PC-MR imaging is related to the possibility to flexibly quantify and visualize cardiovascular blood flow as illustrated in figure 1B. A growing number of patient studies have demonstrated the potential of 4D flow MRI for improved characterization of cardiovascular disease.

Previously reported results include the application of 4D flow MRI for the analysis of 3D blood flow in the heart[10-16], atria[17,18] and heart valves[19-22], the thoracic[22-31] and abdominal aorta[32], the main pulmonary vessels[33-36], carotid arteries[37-40], large intracranial arteries and veins[41-45], the arterial and portal venous systems of the liver[35,46-49], peripheral arteries[50], and renal arteries[51-53] as well as cerebrospinal fluid (CSF) flow[54,55].

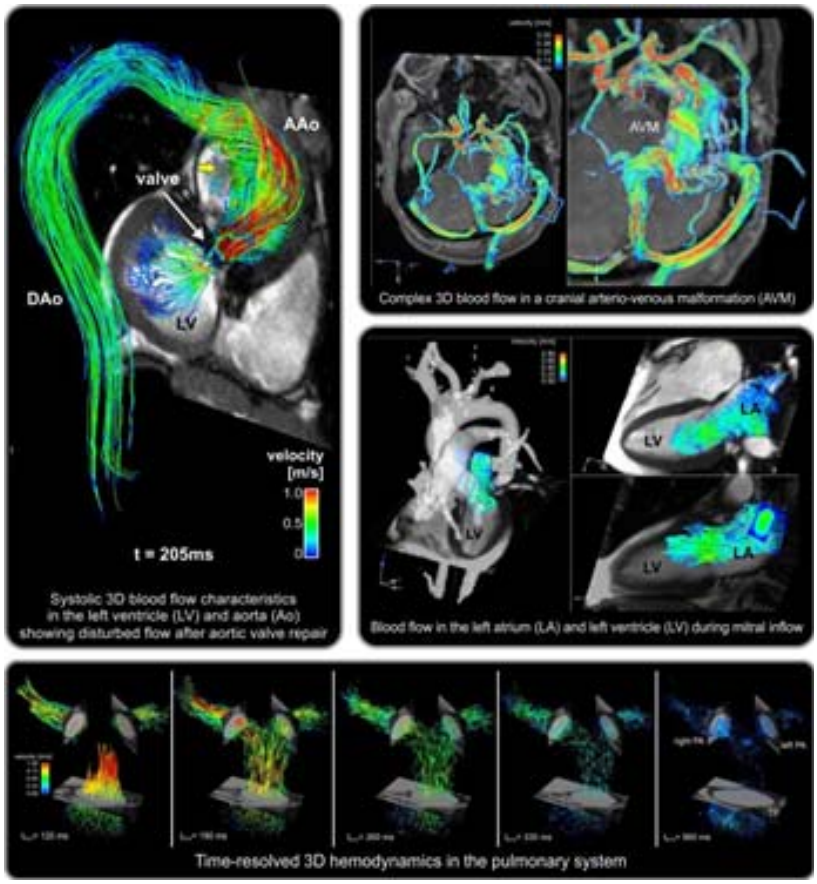

Figure 2: Examples for 3D blood flow visualization in different application areas of 4D flow MRI.

A key limitation is related to the long acquisition times which may be problematic for some patients or in case of irregular heart rate or breathing patterns. In this context, new spatio-temporal imaging acceleration techniques (compressed sensing, k-t BLAST, k-t GRAPPA, etc.)[56-58] are promising since redundancies in two spatial encoding and the temporal dimensions can be utilized to speed up data acquisition. New methods based on the combination of phase contrast MRI and fast sampling strategies, e.g. echo-planar imaging and radial imaging with 3D PC-VIPR[52,59], have been reported and are promising for further reduction in total scan time and/or increased spatial or temporal resolution.

The presentation will provide an introduction into methodological aspects related to the quantification of vascular hemodynamic and CSF flow based on 4D flow MRI and illustrate its potential for the assessment and understanding of altered hemodynamics in the presence of cardio- and neurovascular disease.

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