Cardiovascular MRI: Vascular Flow & Angiography

Research Promises: Faster Methods, 4D

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The intrinsic motion sensitivity of MRI, which is exploited in phase contrast (PC) MRI, can be used directly acquire and quantify blood flow[1,2]. PC-MRI can be employed to encode blood flow velocities along all dimensions and offers the possibility to acquire spatially registered information on three-directional blood flow simultaneously with the morphological data within a single examination.
In clinical routine, PC-MRI is typically accomplished using methods that resolve two spatial dimensions (2D) in individual slices and encode just the component of time-resolved velocity directed perpendicularly to the 2D plane. This approach allows measurements of forward, regurgitant and shunt flows in congenital and acquired heart disease.

A number of more advanced and promising flow MR imaging techniques have been reported, which allow a more comprehensive emulation of blood flow characteristics, e.g.

- Real time phase contrast MRI for the evaluation of flow changes on short time scales[3,4]
- Fourier or Bayesian multi-point velocity encoding to encode flow velocities as a separate dimension and assess sub-voxel velocity distributions[5-7]
- 4D flow MRI for the comprehensive analysis of complex time-resolved 3D blood flow characteristics[8-10]
- Direct encoding of the acceleration component of blood flow[11,12]

In this presentation the focus is set on the comprehensive evaluation of cardiovascular hemodynamics using 4D flow MRI, the use of advanced acceleration techniques for accelerated flow imaging, and the assessment of beat-to-beat changes in blood flow using real-time phase contrast MRI.

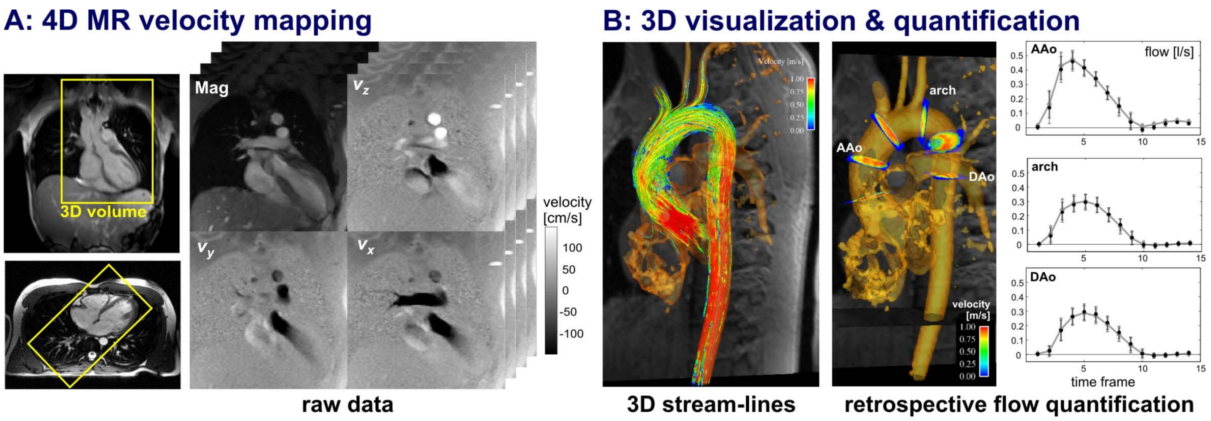

Figure 1: Acquisition of 4D flow MRI data (A) and visualization and quantification of 3D hemodynamics (B) in the aorta. The 4D flow raw data comprises information along all 3 spatial dimension, 3 velocity directions and time in the cardiac cycle. A 3D phase contrast angiogram (B, iso-surface rendering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

4D flow MRI provides a non-invasive method for the qualitative and quantitative characterization of blood flow in heart and great vessels in 3D [8,13-17]. 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. 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 1.Several groups have reported advances in the application of 4D flow MRI including the analysis of blood flow through artificial valves, ventricular and atrial flow patterns, blood flow characteristics in the heart, thoracic aorta, peripheral vessels, carotid arteries, large intracranial arteries, as well as flow in the hepatic, pulmonary and venous systems[18-40].

Visualization of cardiovascular blood flow using 4D flow MRI has improved the understanding of normal and pathologically altered cardiovascular hemodynamics. A number of studies have shown that relatively small and unsuspicious alterations in cardiac and vascular anatomy such as a mild ascending aortic aneurysms or moderate valve disease triggered surprisingly extensive alterations of local blood flow patterns. Such results indicate a potentially important role for the comprehensive analysis of hemodynamic changes based on 4D flow MRI rather than relying on simple anatomical parameters (vessel diameters, stenosis grade, etc.). However, the predictive and diagnostic value of the analyzed flow patterns and quantitative parameters are still limited. The presently available data does not (yet) allow prognostic statements and larger trials including follow-up MR examinations before and after therapy or during the progression of disease are needed to evaluate the clinical value 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-PCA, k-t BLAST, k-t GRAPPA, etc.)[41-43] 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[20,44], have been reported and are promising for further reduction in total scan time and/or increased spatial or temporal resolution.

While 4D flow provides reliable and reproducible information of persistent cardiovascular flow patterns, quantification of arrhythmic or respiration induced changes in flow may be additional important metric characterizing cardiovascular diseases such as atrial fibrillation or complex congenital heart disease. A number of groups have utilized optimized protocols for the real-time assessment of 2D blood flow. To achieve sufficiently high frame rates needed for real-time flow acquisitions, several strategies have been proposed. In a recently reported method, the 2D flow imaging pulse sequence combines an echo planar imaging (EPI) readout module and with parallel acceleration in the temporal direction (T-PAT) and a novel reconstruction algorithm, shared velocity encoding (SVE)[45,46]. SVE is used to further improve temporal resolution based on the concept to share sets of full k-space data between adjacent frames and doubles the effective frame rate.

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