Sunrise Session CV-4D-flow: Ready for Primetime?

4D-flow: How we Process It?

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Background: 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.

4D Flow MRI: In 4D flow MRI, velocity is encoded along all three spatial dimensions throughout the cardiac cycle, thus providing a time-resolved 3D velocity field[7-9]. 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’, see figure 1A). 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 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.

Preprocessing and Corrections: There are multiple sources of phase offset errors in PC and 4D flow MRI that can degrade image quality and impair measurements by introducing inaccuracies in flow quantification. The most commonly encountered inaccuracies include phase offset errors due to eddy currents[10], Maxwell terms[11], and gradient field nonlinearity[12]. It is thus important to apply appropriate correction strategies to compensate for these potential sources of error before further processing of the data for 3D visualization or flow quantification. While correction for Maxwell terms and gradient field non-linearity are typically performed during image reconstruction (without the need for user interaction), eddy current correction cannot easily be automated and has to be integrated into the data analysis workflow.
The most commonly employed strategy for eddy current correction is based on the methodology presented by Walker et al. in 1993[10]. The approach is based on thresh-holding to identify regions with static tissue. These regions are then used to estimate eddy current induced linearly varying phase offset errors which are subsequently subtracted from the entire image. An alternative strategy requires the scanning of a large spherical (static) phantom directly after the 4D flow

scan with identical imaging parameters followed by the subtraction of the resulting phase difference images from the in-vivo 4D flow data. However, the long scan time and logistics needed to perform the additional 4D flow phantom scan make this option less desirable and image based correction is most often used. Unfortunately, no unified strategies, algorithms or software across different MR system vendors and 4D flow MRI applications exist. Nevertheless, studies have shown that 4D flow MRI can be reliably used for 3D visualization and flow quantification if appropriate correction strategies such as proposed by Walker et al[10] are employed.

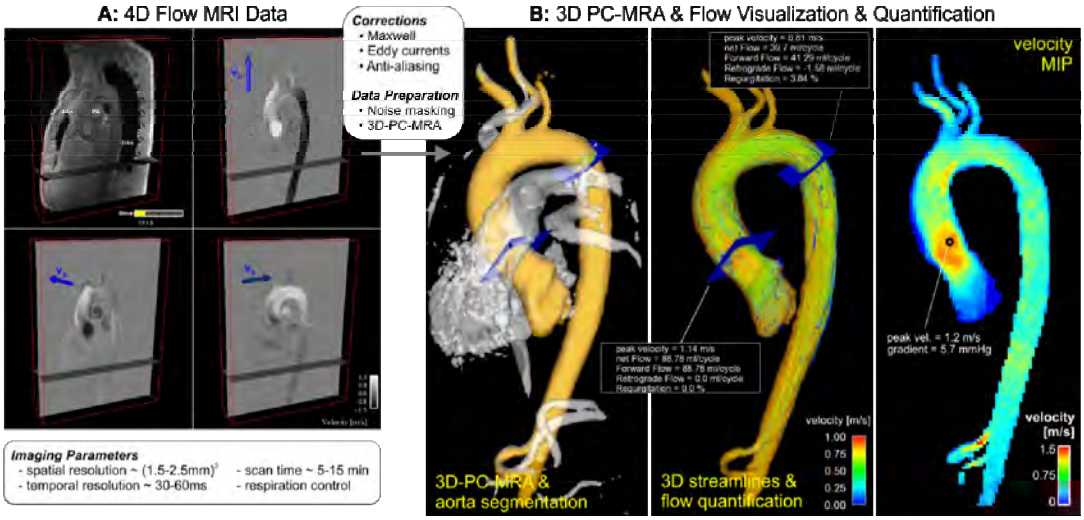

Figure 1: Acquisition of 4D flow MRI data (A) and visualization and quantification of 3D hemodynamics (B) in the aorta of a healthy subject. The 4D flow data comprises information along all 3 spatial dimension, 3 velocity directions and time in the cardiac cycle. A 3D phase contrast angiogram (B, iso-surface rendering of the aorta) can be calculated from 4D flow MRI data to aid visualization and placement of analysis planes for retrospective flow quantification. Calculation of a systolic maximum intensity projection (MIP, right) provides a quick and easily analyzable overview over systolic velocity distribution and location of peak systolic velocity and Bernoulli pressure gradient.

3D Phase Contrast MR Angiography (3D PC-MRA): A 3D anatomic representation of the underlying cardiovascular geometry can provide the anatomic orientation needed for 3D flow visualization and retrospective flow quantification. The 4D flow data itself can be used to approximate the vascular geometry by generating a 3D PC-MRA dataset without the need for an additional MRA acquisition. Based on PC-MRA applications in the early days of MRI[13], several strategies for the 4D flow based calculation of 3D PC-MRA data have been presented. In general, all techniques are based on identifying regions with high blood flow velocities in the phase difference images and suppression of background signal by signal intensities in the anatomical magnitude images.[13, 14]. Although being a 'side product' of 4D flow MRI limited by spatial resolution, a 3D PC-MRA outline or transparent surface rendering of the vascular structures of interest (as shown in figure 1B) is greatly helpful for volumetric analysis and visualization.

3D Blood Flow Visualization: For the qualitative evaluation of 4D flow MRI data, various options are available for 3D blood flow visualization[15-22]. Most approaches use 2D analysis planes which are positioned in the vessel of interest. These analysis planes are used to emit 3D streamlines or time-resolved 3D pathlines for flow pattern visualization. 3D streamlines

represent traces along the instantaneous 3D blood flow velocity vector field for an individual cardiac time-frame. For example, figure 1B illustrates the use of peak systolic 3D streamlines and systolic velocity maximum intensity projection (MIP) to visualize the spatial distribution of aortic blood flow velocities. Color-coding by velocity magnitude facilitates the visual identification of regions with high systolic flow velocities.
For visualization of the temporal evolution of 3D blood flow over one or more heartbeats, time-resolved pathlines are the visualization method of choice. Color-coding of these traces allows for the visualization of velocity changes or to trace the flow pattern to its origin. Time-resolved pathlines are best viewed and displayed dynamically (movie mode) to fully appreciate the dynamic information and changes in blood flow over the cardiac cycle.

Retrospective Flow Quantification: Comprehensive visualization of blood flow in a 3D volume of interest enables a better understanding of the underlying pathologies, e.g. after a complex heart or aorta reconstruction surgery. The ability to perform additional quantitative analysis based on 4D flow MRI data has the potential to greatly impact diagnosis and patient management. In contrast to traditional 2D CINE PC-MRI, 4D flow MRI enables the retrospective quantification of hemodynamic parameters at any location within the 3D data volume at an offline workstation following acquisition[23-25]. For the quantification of standard flow parameters, 2D analysis planes can be flexibly positioned in any artery or vein. The 3D PC-MRA data can be used to define the outline of the vessel lumen and subsequently calculate peak and mean velocities, total flow, net flow, or retrograde flow. An example for the use of 4D flow MRI and retrospective quantification of flow parameters in the ascending and descending aorta is shown in figure 1B.
A number of studies comparing 2D CINE PC-MRI and 4D flow MRI have shown excellent agreement for flow quantification[26, 27]. Furthermore, good scan-rescan reproducibility and low inter- and intra-observer variability of 4D flow MRI based flow quantification has been demonstrated for intracranial, cervical, thoracic and abdominal applications[26-29]. It should be noted that a number of groups have presented strategies to assess more advanced hemodynamic parameters such as wall shear stress, pressure difference, pulse wave velocity, turbulent kinetic energy and others [23, 30-38].

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