4D Flow MR Imaging

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Magnetic Resonance Imaging (MRI) techniques provide non-invasive methods for the highly accurate anatomic depiction of the heart and vessels. The intrinsic motion sensitivity of MRI can be used to image vessels as in phase contrast (PC) MR-angiography or to quantify blood flow and motion of tissue[1,2]. Such techniques offer the unique possibility to acquire spatially registered functional information simultaneously with the morphological data within a single experiment[3]. To synchronize flow or motion sensitive measurements with periodic tissue motion or pulsatile flow, data acquisition is typically gated to the cardiac cycle and time resolved (CINE) anatomical images are collected to depict the dynamics of tissue motion and blood flow during the cardiac cycle[4]. Visualization and quantification of blood flow and tissue motion using PC MRI has been widely used in a number of applications. Characterization of the dynamic components of blood flow and cardiovascular function provide insight into normal and pathological physiology[5,6].

Traditionally, MRI imaging of flow is accomplished using methods that resolve two spatial dimensions (2D) in individual slices. Alternatively, 3D spatial encoding offers the possibility of isotropic high spatial resolution and thus the ability to measure and visualize the temporal evolution of complex flow and motion patterns in a 3D-volume. In this context, ECG synchronized flow sensitive 3D MRI using 3-directional velocity encoding (also termed 'flow sensitive 4D MRI' or 'time-resolved 3D velocity mapping') can be employed to detect and visualize global and local blood flow characteristics in targeted vascular regions (aorta, cranial arteries, carotid arteries, etc.)[7] Due to the acquisition of at least four data sets for three-directional velocity encoding, phase contrast MRI inherits a trade-off between spatial/temporal resolution and total scan time. For thoracic and abdominal applications respiration control (e.g. navigator gating for 3D methods) can therefore be necessary to avoid breathing artifacts[8].

Several effects can introduce imperfection in the resulting flow sensitive 4D MRI data, which cause errors in velocity measurements. Major sources of inaccuracy in velocity encoded images include eddy current effects, Maxwell terms, gradient field distortions, and velocity aliasing[9,10]. Any further data analysis is therefore typically preceded by pre-processing strategies including eddy current and Maxwell correction, noise filtering, application of anti aliasing algorithms, etc.[11,12].

For the subsequent analysis and visualization of complex, three-directional blood flow within a 3D volume, various visualization tools including 2D vector-fields, 3D streamlines and time-resolved 3D particle traces have been proposed[13]. Several groups have reported advances in the application of flow sensitive 4D MRI including the analysis of blood flow through artificial valves[14], ventricular and atrial flow patterns[15,16], blood flow characteristics in the thoracic aorta[17,18,19,20], peripheral vessels[21], carotid arteries[22], large intracranial arteries[23,24], as well as flow in the pulmonary and venous systems[25,26].

Moreover, since flow sensitive 4D MRI data reflects the true underlying time-resolved blood flow velocity vector field, it is possible to quantify the directly measured (e.g. flow rates) or derived parameters such as pressure difference maps[27], wall sheer stress[28], pulse wave velocity[29], and others. Findings in recently reported studies combining the complete spatio-temporal coverage of flow-sensitive 4D MRI and advanced quantification strategies are promising and may help to define new clinical markers for the improved characterization of cardiovascular disease. Examples include relative pressure mapping within the heart and

aorta[30] or renal arteries[31], wall shear stress analysis in the thoracic aorta[32], or assessment of onset and dynamics of regional turbulence in the aorta[33] .
A representative data acquisition and data analysis strategy for the 3D visualization of blood flow characteristics as well as regional quantitative evaluation of flow and wall parameters is illustrated in the figure below.

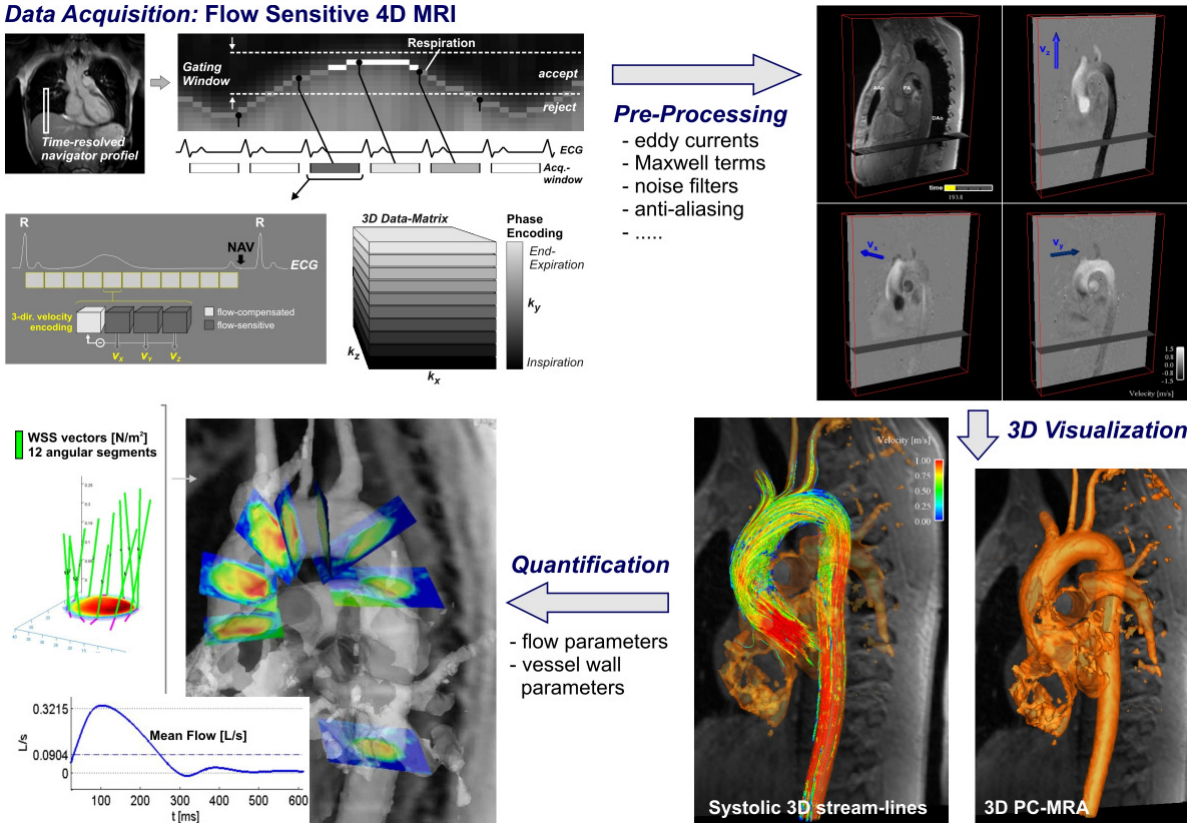

Figure: Data acquisition and processing chain for flow sensitive 4D MRI in the aorta using adaptive navigator gating and prospective ECG gating. The late diastolic navigator signal (NAV) of the lung–liver interface is used to gate the acquisition and define the k-space location of the phase encoding step used in the next cardiac cycle. For each time frame three-directional blood flow velocities (v_x, v_y, and v_z) are collected in an interleaved manner. Pre-processing of the resulting data (anatomical 3D CINE images and three-directional velocity data) is performed to correct for measurement inaccuracies and reduce noise. Subsequent 3D blood flow visualization permits the depiction of time-resolved 3D vascular hemodynamics within the entire thoracic aorta (here: systolic 3D stream lines inside time-averaged 3D-PC-MRA iso-surface which can be derived from the flow-sensitive 4D data and used as anatomical orientation). Quantitative analysis of blood flow and vessel wall parameters such as segmental wall shear stress can be performed in user selected 2D planes at any location along the vascular tree.

A disadvantage of phase contrast MRI is related to the need for multiple acquisitions for encoding a single velocity direction, resulting in long scan times. New methods based on the combination of phase contrast MRI and fast sampling strategies, e.g. radial imaging with 3D PC-VIPR, have been reported and are promising for further reduction in total scan time and/or increased spatial or temporal resolution[34]. In addition, the total acquisition time or temporal and spatial resolution associated with a specific MR technique may be further improved by using new spatio-temporal imaging acceleration[3536] and/or partial k-space update methods (view sharing)[37].
In summary, a number of recent studies indicate the potential of flow sensitive 4D-MRI for the detailed visualization of complex flow patterns associated with healthy and pathologic hemodynamics. The nature of such datasets (3 spatial dimensions, 3 blood flow velocity directions and time) points towards the potential of flow-sensitive 4D MRI to provide detailed quantitative flow and vessel wall parameters with complete vascular coverage.

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