Four-Dimensional Magnetic Resonance Velocity Mapping: Velocity Profile of Blood-Flow through the Thoracic Aorta in 10 Healthy Volunteers

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Synopsis: Four Dimensional (4D) Magnetic Resonance velocity mapping is an interesting new technique for evaluation of multidirectional blood flow velocity data, and allows for characterization of complex flow patterns throughout the cardiac cycle. This study utilizes a 4D volumetric dataset to evaluate the velocity distribution of normal blood flow in cross-sectional planes along the thoracic aorta for 10 healthy subjects. Velocity data are then imported into a visualization software package (EnSight, CEI), allowing for interactive navigation of data throughout all time frames. Utilizing 3D visualization tools such as vector fields, streamlines, and transient particle traces, we are able to provide a 4D visual presentation of blood flow throughout the thoracic aorta, as well as specific quantitative data in any phase of the cardiac cycle. The focus of this study is the retrospective quantitative analysis of blood flow velocities in 2D cut planes that are placed at any spatial and temporal location within the 4D data set. This is a clear advantage compared to traditional 2D phase contrast MR imaging technique.

Methods: All procedures were approved by the institutional review board of our institution and informed consent was obtained from all subjects. 4D MR velocity mapping was achieved in 10 human subjects by using a technique described in reference [1]. Time-resolved, 3D anatomic images were acquired simultaneously with three directional velocity fields. Measurements were respiratory compensated and retrospectively gated to the ECG cycle in order to generate a time resolved (CINE) series of 3D data sets. All measurements were performed on a 1.5-T system (Signa CV/i, GE, Milwaukee, WI, G_{max} = 40 mT/m, rise time = 268 µsec). A rf-spoiled gradient echo sequence with velocity encoding along all three spatial directions provides a flexible trade-off between temporal resolution and total acquisition time. Scans were performed with a velocity sensitivity of 200cm/s and the following parameters: FOV= (300×225)mm^2, slab thickness=83.2mm, matrix = (256x144x32), spatial resolution = $(1.17 \times 1.56 \times 2.60)$mm^3), flip angle α = 15 and a bandwidth of BW = +/-62.5 kHz. 4 phase encodes per time frame in combination with three-directional velocity encoding resulted in a temporal resolution (T_{Res}) that was determined by the time needed to collect 16 k-space lines (T_{Res} =16TR). Depending on the obliquity of the imaging slab echo (TE) and repetition (TR) times and thus temporal resolution varied among volunteers (TE = 1.96-2.04ms, TR = 4.79-5.04ms, T_{Res}=76.7-80.7ms). The 4D-flow scan was routinely performed after the MR-Angiogram to achieve maximum signal from the contrast agent remaining in the blood pool. Corrected velocity data were imported into a 3D visualization software package (EnSight, CEI, Inc. Apex, NC). This software program facilitates analysis and visualization of complex 3D and 4D datasets of blood flow by providing a variety of data manipulation tools including 2D velocity vector fields mapped onto selected planes of interest, 3D streamlines and 3D particle traces. Additionally, this software was used to extract planes of three-component velocity data perpendicular to the aorta for further analysis and quantification with a proprietary software program (Aspire2, Stanford University). Data from each of the cross-sectional planes was exported to a custom software program for computation of the component of velocity normal to the plane and to segment the aortic lumen at each time point.

Results: A typical example of 3D visualization using streamlines demonstrates systolic blood flow throughout the entire thoracic aorta (figure A, color coding corresponds to local blood flow velocity magnitude). Qualitative analysis demonstrates high flow velocities (red) in the ascending and descending aorta while the aortic arch demonstrates reduced velocities (green/yellow). For a quantitative analysis multiple cross-sectional planes were placed to transect the thoracic aorta at standardized intervals, allowing for visualization of the velocity profile and quantification of mean velocities and blood flow at pre-defined levels for all cardiac phases (Figure B). Figure C (data from a single volunteer) shows mean velocities and blood flow as a function of slice plane location which are quantified within the aortic lumen for multiple points during the systolic phase of the cardiac cycle. Quantitative data (figure C) confirms the observed velocity changes, with accelerated velocities in the ascending and descending aorta and minimum velocity at the level of the aortic arch (slice plane location 5) for all analyzed systolic phases. Blood flow is highest in the ascending aorta (slice plane locations 1-4) with the expected tapering pattern just distal to the supra-aortic arch vessels (slice plane locations 6-11).

Discussion: 4D volumetric continuous acquisition of data throughout the cardiac cycle is a unique approach in the evaluation of cardiovascular disease. This technique allows for interactive navigation throughout a prescribed 3D data set during any phase of the cardiac cycle. With this approach, we have the ability to arbitrarily place cut-planes throughout the 3D dataset without being hindered by the prospective acquisition of traditional 2D phase contrast MRI. Overall, the quantitative data generated by this study could help to further enhance the clinical utility of cardiac MRI, which is already an essential tool in the diagnosis, monitoring and treatment of cardiac diseases as it provides both anatomical and functional evaluation of the cardiovascular system. Specifically, velocity and flow profiling such as that described in this study could be valuable for the pre-operative work-up and post-surgical care of patients with aortic dissections and aneurysms, and potentially could help risk-stratify patients with these conditions.

References: [1] Markl M, et al. J Magn Reson Imaging. 2003;17:499-506. [2] Walker PG, et al, J Magn Reson Imaging. 1993;3:521-30. [3] Kilner PJ, et al. Circulation. 1993;88:2235-47. [4] Bogren HG, et al J Magn Reson Imaging. 1997;7:784-93. [5] Wigstrom L, et al . Magn Reson Med. 1999;41:793-9.
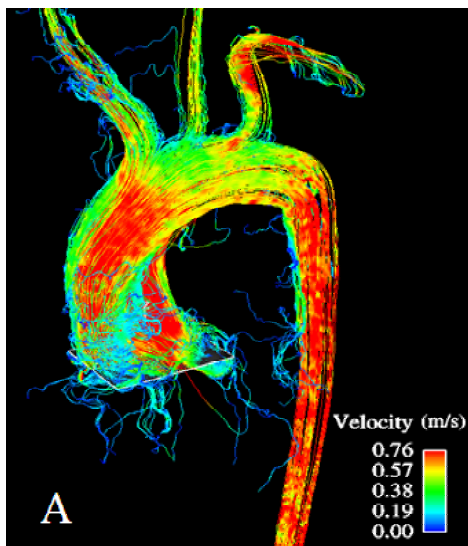
Figure A: Systolic 3D Streamlines are released from a 2D emission plane positioned just distal to the aortic valve during peak systole. The color-encoded streamlines correspond to the integrated instantaneous 3-directional velocity vector field.
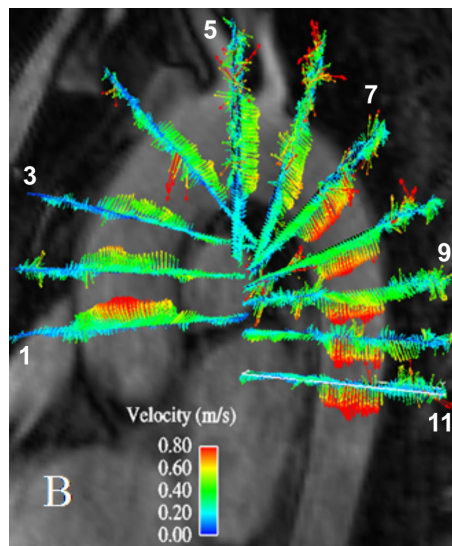
Figure B: 2D cross-sectional planes with vector fields are placed in the 4D data set. Each vector is encoded by color and magnitude representing a 3-directional blood flow velocity at a specific spatial and temporal point within the cardiac cycle.
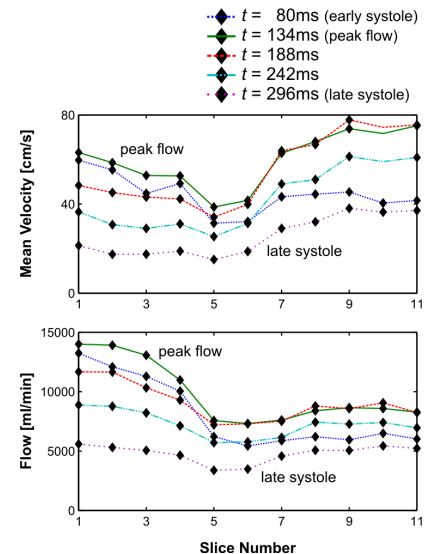
Figure C: Quantitative analysis of mean velocities (top) and flow (bottom) in 11 2D cut planes as depicted in figure B. Individual curves represent the spatial evolution of flow and velocities during five successive systolic cardiac phases along the thoracic aorta.