Time-Resolved 3D Velocity Mapping in the Thoracic Aorta: Three-Directional Blood Flow Patterns in Healthy Volunteers and Patients

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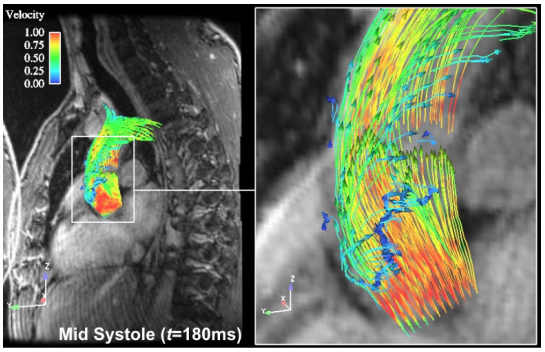
Synopsis: An analysis of thoracic aortic blood flow in normal subjects and patients with aortic pathology is presented. 3D phase contrast MRI (3D CINE PC) was employed to obtain a volumetric time resolved three-component velocity acquisition of the entire thoracic aorta. Blood flow visualization tools were applied in a study with 10 normal volunteers and demonstrated right-handed helical out flow, late systolic retrograde flow, and accelerated passage through the aortic valve plane. The effects of common pathologies in the thoracic aorta on spatial and temporal blood flow patterns were illustrated in clinical cases including ascending aortic aneurysms, aortic regurgitation, and aortic dissection.

Methods: All experiments were performed on a 1.5T MR system (Signa CV/i, GE, WI, USA) using a rf-spoiled gradient echo pulse sequence. All procedures were approved by the institutional review board of our institution and informed consent was obtained from all subjects. Measurements were respiratory compensated and retrospectively gated to the ECG cycle to generate a CINE series of 3D data sets. Data were acquired using a bandwidth of *BW*=+/-64kHz, a flip angle of $\alpha = 15°$ and 3-directional velocity encoding in combination with four views per segment such that the temporal resolution was defined by the time needed to collect 16 k-space lines (T_{Res}=16TR) [1]. All volunteer scans were performed with identical velocity sensitivity (*venc*=200cm/s), volume coverage (FOV=(300x225)mm^2, slab thickness=83.2mm) and spatial resolution ((1.17x1.56x2.60)mm^3). Since the strength of the imaging gradients can vary with obliquity, echo (*TE*) and repetition (*TR*) times and thus temporal resolution were slightly different among volunteers (*TE* = 1.96-2.04ms, *TR* = 4.79-5.04ms, T_{Res} =76.7-80.7ms). While the number of ECG cycles to acquire an entire 3D CINE PC data set is fixed, the total scan time depends on the heart rate and ranged from 14.8min to 22.6min. Similar data acquisition parameters were used in patient examinations. Post processing of the acquired data included fully automated noise filtering and eddy current correction [2]. Blood flow visualization was performed using a software package (EnSight, CEI, NC, USA) that provided a variety of data manipulation tools including 2D velocity vector fields mapped onto selected planes of interest, 3D streamlines and 3D particle traces. Streamlines and particle traces originated from a set of emitters, which were defined as equidistant grid points in a 2D plane that could be positioned at any spatial location within the imaging volume. While streamlines represent the velocity vector field in a single time frame, particle traces use all available functional information and incorporate the temporal evolution of the velocities over the entire cardiac cycle.

Results: Previously reported blood flow patterns in the thoracic aorta including right-handed helical out flow, late systolic retrograde flow, and accelerated passage through the aortic valve plane were visualized in all volunteers [3-5]. 2D velocity vector fields were successfully used to visualize temporal and spatial variation of the velocities in planes transecting the aortic out flow tract. Streamlines originating from a single set of emitters located at the aortic valve were used to visualize systolic blood flow in the entire thoracic aorta in nine of the 10 healthy volunteers. In the tenth volunteer, a second set of streamline seed points had to be placed at the distal arch to trace velocities through the descending thoracic aorta. For 3D particle traces, a set of emitters at the level of the aortic valve was used to continuously release particles which trace the temporal evolution of blood flow over the entire cardiac cycle. Features that were identified in all healthy volunteers using particle traces include a right-handed helix through the ascending aorta, and a late systolic retrograde flow channel along posterior left aortic wall (figure 1).
In patients with aortic disease, blood flow patterns such as complex circular flow in aneurysms, high flow in the true lumen of a dissected aorta and regurgitant flow jets in aortic insufficiency could successfully be demonstrated using 3D streamlines, 2D velocity vector fields, and 3D particle traces. As an example, figure 2 shows results for a 58 year old patient with a thoracic ascending aortic aneurysm. Systolic streamlines exhibit reverse and vortex type flow features within the aneurysm (white arrow) but otherwise normal flow in the aortic arch and descending aorta. Similar features are also visible in systolic velocity vector fields, reformatted onto a plane transecting the aortic root and ascending aorta (figure 2, top). The z-velocity component was used for color-coding to allow for a better visual separation of forward and backward flow and to enhance the visualization of vortical flow. Comparison of both visualization tools illustrates that streamlines have the advantage of using the full 3D spatial information, while velocity fields are restricted to selected 2D cut-planes.

Discussion: Time-resolved 3D velocity mapping was successfully applied in a study of ten healthy volunteers and four patients with documented aortic pathologies and has proven to be a reliable tool for analysis and visualization of normal characteristic as well as pathological flow features within the entire thoracic aorta. The effects of thoracic aortic disease on spatial and temporal blood flow patterns were illustrated in cases of ascending aortic aneurysms, regurgitation, and dissection. Given the vast amount of information contained within a data set, it is crucial to select a limited number of representative images that encapsulate key anatomic and blood flow related features to make the technique useful for clinical interpretation, while at the same time exploiting the rich nature of the time-resolved 3D data sets.

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.



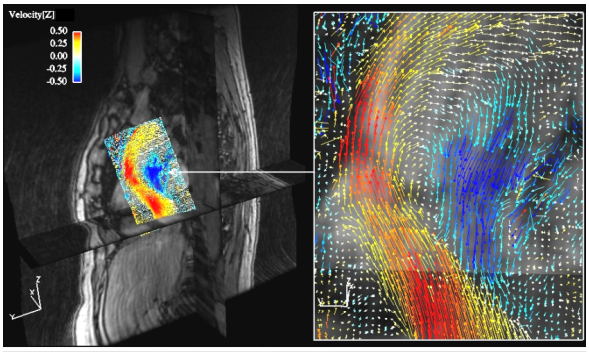


Figure 1 (left): 3D particle-traces (color coded according to velocity magnitude in m/s) in ascending aorta and arch for a healthy volunteer during peak flow (top) and late systole (bottom). Slow retrograde flow along the inner wall of the ascending aorta can be appreciated during late systole (arrows) while elsewhere antegrade flow continues.

Figure 2 (right): Patient with an ascending aortic aneurysm. **Top:** Systolic velocity vector fields color coded according to their z-velocity component (in m/s). **Bottom:** 3D streamlines in the entire thoracic aorta. The color-coding corresponds to the magnitude of the local systolic blood flow velocity. Magnified regions demonstrate reverse and vortical flow fields within the ascending aortic aneurysm.