Clinical Evaluation of Aortic Coarctation with 4D Flow MR Imaging

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Introduction: Four-dimensional MR velocity mapping (4D Flow) is well suited for evaluation of multidirectional blood flow velocity data from the human aorta. Previous studies have employed the technique to characterize complex flow patterns in the thoracic aorta of healthy subjects and patients with aortic pathology, including ascending aortic aneurysm [1,2]. This study utilizes 4D volumetric datasets to evaluate patients with history of aortic coarctation. Flow analysis based on 2D phase contrast MR is the standard of care for evaluation of collateral flow associated with coarct; the presence of collateral flow indicates a significant coarct that may require intervention [3]. In order for 4D Flow to be a clinically viable tool for evaluation of coarct patients, it must be reasonably fast and generate reliable flow data, as well as offer advantages over the standard MR protocol. We address these first two objectives using parallel imaging in a direct comparison of 4D Flow and 2D PC data in patients. With regard to its advantages, 4D Flow allows for continuous breathing, does not require prospective placement of 2D planes for PC acquisition, and offers a unique method of analyzing flow data that is not available by traditional 2D PC imaging. By utilizing 3D visualization tools such as vector fields, streamlines and particle traces, we are able to provide a 4D visual presentation of secondary flow characteristics unique to coarct, which may be useful for better understanding and possibly predicting post-intervention complications.

Methods: Time-resolved, velocity-encoded PC MRI was employed to assess aortic blood flow in 8 individuals: 4 patients with coarct and 4 healthy subjects. This technique has been previously validated [1]. The 3D anatomic images were acquired simultaneously with three directional velocity fields. Measurements were respiratory compensated and retrospectively gated to the ECG cycle. 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). Scans were performed with an 8-channel cardiac coil and the following imaging parameters: VENC = 160 cm/s, fractional FOV= (300 x 270) mm^2, slab thickness = 78 mm, matrix = (256 x 192 x 30), spatial resolution = (1.17 x 1.41 x 2.60) mm^3, temporal resolution = 74-77 ms. Parallel imaging (GRAPPA) with an acceleration factor of 2 was used, with scan times ranging from 12-16 minutes. 4D Flow was performed after the standard clinical MR evaluation for coarct, which includes 2D PC in the proximal descending aorta ("Prox DsAo") and at the diaphragm, and an MR-Angiogram with gadolinium. Corrected velocity data were imported into 3D visualization software (EnSight, CEI, Inc. Apex, NC). This software program enables the visualization of complex 3D and 4D datasets by providing a variety of data manipulation tools including 2D velocity vector fields mapped onto planes of interest, 3D streamlines and particle traces. Planes of data perpendicular to the aorta were extracted for further analysis and quantification with a proprietary software program (Aspire2, Stanford University).

Results: Direct comparison of blood flow calculated with 4D and 2D PC data at standard levels for analysis in coarct patients showed good correlation and agreement between the two techniques; a comparison of representative data sets is included as Figure C. Strong correlation of blood flow data is demonstrated at the Prox DsAo (r = 0.99, limits of agreement -4.09 to 10.47 ml/beat) and at the diaphragm (r = 0.99, LOA = 0.28 to 5.2 ml/beat). The change in flow from the Prox DsAo to the diaphragm, which is key for evaluation of collateral flow, also shows good correlation; for the numerical change, r = 0.98 and LOA = -4.69 to 5.58 ml/beat, and for the percentage change, r = 0.99 and LOA = -7% to 9%. These results are comparable to previously reported data comparing 2D and 4D flow data without parallel imaging in healthy subjects [5]. With 4D visualization techniques, secondary blood flow features were evaluated in patients and compared to healthy subjects, both those included in our study and those from the literature [2,4]. There appears to be a tendency toward exaggerated, left-handed helical flow in the DsAo in patients status post coarct repair. This is best demonstrated in a patient with an angulated aortic arch and aneurysmal prox DsAo status post patch repair of coarct (Figures A and B).

Discussion: 4D volumetric acquisition of PC MR data throughout the cardiac cycle is an effective way of evaluating blood flow in the thoracic aorta. Our study offers clinical validation of flow data generated by 4D Flow, and employs parallel imaging to reduce scan time in order to make the technique clinically feasible. Direct comparison of 2D and 4D PC blood flow data at the levels used for routine clinical evaluation of collateral flow in coarct patients demonstrates good correlation and agreement between the two techniques. One clear advantage of 4D Flow is that it affords the ability to arbitrarily place cut-planes throughout datasets without being hindered by the prospective acquisition of traditional 2D PC MR. The principal advantage of 4D Flow, however, is its ability to dynamically visualize blood flow in 3D throughout the cardiac cycle. With 3D visualization software, we have employed tools such as vector fields, streamlines and particle traces to characterize complex, secondary blood flow features unique to coarct patients. We have observed a tendency toward exaggerated helical flow in the descending aorta in these patients. While work needs to be done to evaluate whether abnormal secondary flow features visualized by 4D Flow in patients with aortic pathology are of clinical significance, we postulate that detailed characterization of abnormal flow patterns may be useful for better understanding and possibly predicting post-intervention complications in patients status post repair of aortic coarctation. This is one of the first clinical applications of 4D Flow in patients with aortic coarctation.

References: [1] Markl M et al. J Magn Reson Im. 2003;17:499-506. [2] Hope TA et al. J Mag Reson Im, in press (2007). [3] Steffens JC, Higgins CB et al. Circulation 1994;90:937-43. [4] Kilner PJ, et al. Circulation 1993;88:2235-47. 1997;7:784-93. [5] Stalder AF et al. ISMRM abstract 2007.

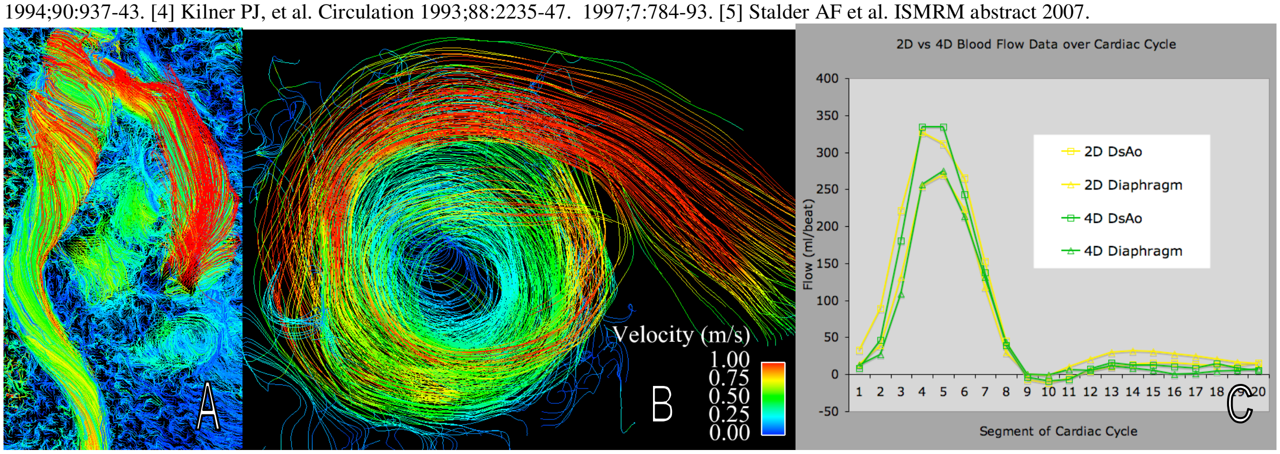

Figure A: Oblique-sagittal 4D data set centered about the aorta with a curved vector field applied during post-processing. Color-encoded streamlines correspond to the 3D velocity magnitude of the local systolic blood flow. Note the angulated aortic arch in this patient status post patch repair of aortic coarctation.
Figure B: Exaggerated helical flow in the aneurysmal proximal descending aorta is better characterized by streamlines released from a plane orthogonal to the aorta at this level, and then visualized along the axis of the aorta.
Figure C: A comparison of flow calculations from 2D and 4D data sets over the cardiac cycle at the proximal descending aorta and at the level of the diaphragm.