Platform for Comprehensive Hemodynamic Analysis of 4D PC MRI Data

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Introduction: Recently, several novel approaches for rapid MR imaging have allowed for the acquisition of volumetric, phase contrast images of cine velocity fields for the examination of vascular anatomy and function in clinically acceptable scan times. Among those acquisitions is phase contrast vastly undersampled projection reconstruction (PC VIPR) [1], a truly 3D radially undersampled acquisition, that provides both anatomical and velocity information with high spatial resolution and volumetric coverage. These data can be processed to not only generate angiograms and allow for velocity and flow measurements, but also to derive additional hemodynamic parameters of significance such as trans-stenotic pressure gradients and wall shear stress. Such parameters are thought to play an important role in the progression of cardiovascular disease and these new PC MR acquisitions can become powerful tools for their assessment. While the comprehensive information can be very valuable, the large data volume with high spatial and temporal information requires new approaches for efficient post-processing, visualization, and extraction of the clinically relevant parameters. PC VIPR scans can generate upwards of 30,000 images per exam with typical data sets including five image sets: magnitude, complex difference, and velocities in x, y, and z with 320 slices and 20 time frames per data set. While pressure measurements derived from PC VIPR had been validated against catheter measurements in phantoms and in animal models [4], flow measurements have not been validated previously because of the lack of multiplanar reformatting tools for cine velocity fields. The purpose of our work was the development and validation of a software platform that streamlines hemodynamic analysis, including flow measurements with automatic alignment with respect to vessel orientation.

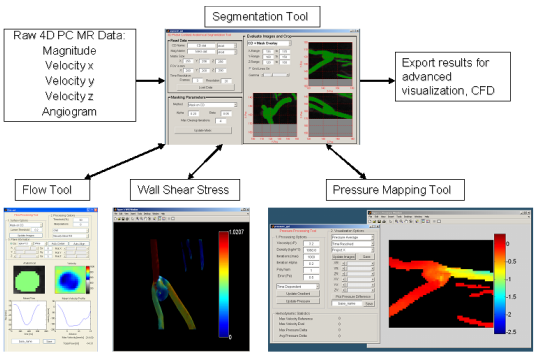

Figure 1: Flow chart for software platform. The 4D PC MRI data are first segmented and can then be loaded into processing tools for the calculation of flow, wall shear stress or pressure maps.

Methods: Data were acquired with a dual-echo PC VIPR trajectory with cardiac and respiratory gating on 1.5T and 3T clinical systems (GE Healthcare) [2]. Typical scan parameters were: (1.0-1.25 mm)^3 isotropic spatial resolution in approximately 5 (10) min scan time without (with) respiratory gating, imaging volume: 32x32x16 cm^3, VENC of 50-100 cm/s (application specific). The post-processing platform was developed using Matlab (MathWorks) in order to process and visualize results, enable quantitative measurements, and derive additional hemodynamic parameters. Figure 1 shows the workflow of our approach. First, the reconstructed PC VIPR data are loaded into a segmentation tool in order to reduce the size of the data set for more efficient processing. The knowledge of vessel boundaries is also essential for the calculations of flow, wall shear stress, and pressure gradients, which are all available processing tools. Next, the data can be loaded into the analysis plug-ins to (1) measure and visualize flow, (2) derive pressure maps [3], or (3) calculate wall shear stress [4] from the velocity fields with volumetric coverage. For improved flow measurements from the 3D data, the analysis plane can be automatically aligned perpendicular to the vessel path and averaged over multiple adjacent planes from the 3D volume. Flow measurements are derived by integration of the velocity vectors over time and vessel area, which can be defined either automatically or by manual selection of a ROI in the magnitude or complex difference images. Derived cine and time average velocity and flow measurements can be exported as data files. While the tools allow for simple visualizations of volumetric, time-resolved voxel data such as velocity vector fields and/or maps of pressure gradients and wall shear stress, these data can also be exported for advanced visualization with software tools such as Ensight (CEI, Apex, NC) or additional analysis or comparisons with computational fluid dynamics (CFD) calculations.

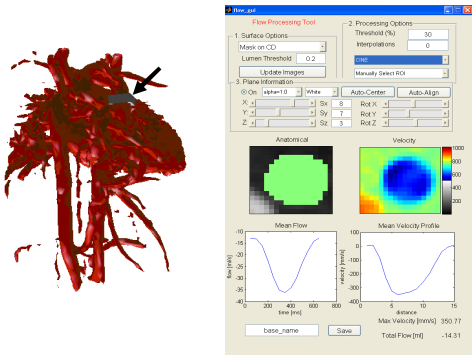

Figure 2: *Flow analysis for a patient with* congenital heart disease. *The grey arrow points to the ROI box that is automatically centered and aligned with the segmented vessels shown as a volume rendered display (a). 2D cine representations of the vessel under investigation are calculated and analyzed for through plane velocities and flow rates based on ROIs (b).*

To validate the results for velocity and flow measurements, a phantom experiment with tubes and an MR compatible flow pump (CompuFlow 1000 MR, Shelley Medical Imaging Technologies, London, ON, CA) was conducted with PC VIPR acquisitions. For these measurements, a flow phantom consisting of a tube with 5/16" (7.94 mm) diameter surrounded by doped water was connected to the pump and filled with a blood-mimicking fluid (BMF-MR, Shelley Medical Imaging Technologies). The flow rates as measured with the software were compared to the flow pump settings (accuracy of the flow pump is rated as +-1%) for two VENC settings (60 cm/s and 120 cm/s) with flow rates varying between 1.5 ml/s and 24 ml/s (mean velocities of 3cm/s and 48.5 cm/s).

Results: Figure 2b summarizes the results of the phantom study in a Bland-Altman analysis. . Measurements acquired with a VENC of 120 cm/s were on average, 0.4% less than the pump flow rate, and measurements acquired a VENC of 60 cm/s were 3.5% less than the pump flow rate. Figure 3 shows a snapshot of the flow and velocity analysis tool for data from an 18 months old boy with pulmonary venolobar (Scimitar) syndrome. Among other parameters, the through-plane flow of the analyzed vessel segment is displayed as a function of time in the cardiac cycle and as net flow in addition to a velocity profile across the vessel diameter. The vessel area as detected by an automatic algorithm is displayed as a green overlay.

Discussion and Conclusions: A new software platform was implemented for the comprehensive analysis of hemodynamic information obtainable from high resolution PC MR datasets. Flow measurements obtained from PC VIPR were validated using automated multiplanar reformatting capabilities, demonstrating good accuracy. This platform will be helpful for streamlined analysis in various vascular territories to possibly identify clinically significant hemodynamic parameters for tasks such as early diagnosis, treatment monitoring, and understanding of disease development. Future work will include collaboration with computational fluid dynamic (CFD) experts to derive WSS which can not be obtained experimentally.

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References: [1] TL Gu *et al*, *AJNR* 26(4), 743-9, 2005 [2] KM Johnson *et al*, *PROC ISMRM*, 733, 2008. [3] D Lum *et al*, *Radiology* 245(3), 751-60, 2007. [4] R Moftakhar *et al*, *AJNR* 28(9), 1710-4, 2007.

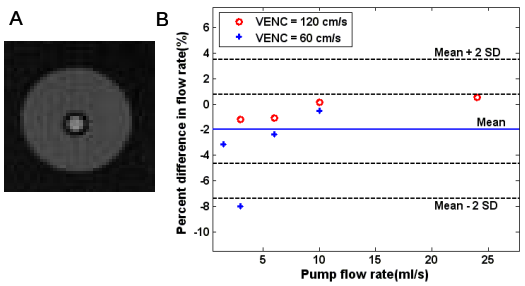

Figure 3: A: *Axial image of the flow phantom used for validation* ***B:*** *Bland-Altman analysis of constant flow scans acquired with PCVIPR over a range of flow rates with 2 VENCs*