

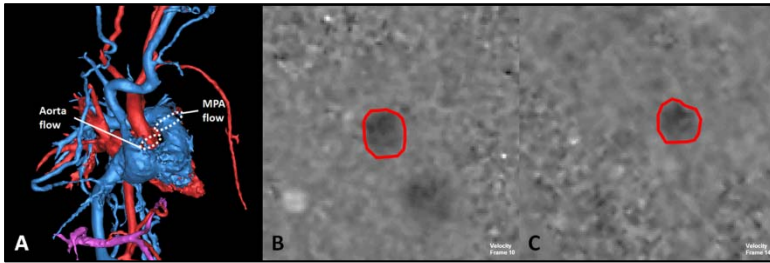
# Flow Quantification with 4D Flow-Sensitive MRI: Validation in Patients with Congenital Heart Disease

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**Purpose:** The aim of this study was to validate blood flow measurements through the ascending aorta (AscA) and main pulmonary artery (MPA) using a 3D radially undersampled, time-resolved, 3D flow-sensitive MRI technique in patients with congenital heart disease (CHD).

**Background:** Cardiac imaging is critical in patients with CHD for delineating cardiovascular anatomy and cardiac function. Imaging has a critical role in therapeutic planning and follow-up after therapy. MRI is particularly useful in assessing cardiovascular anatomy and function in patients with right-sided heart defects and in older patients with abnormalities affecting the distal ascending aorta and aortic arch. The use of cardiac MRI in patients with CHD is currently limited by (1) the very long examination times (up to 90 minutes), (2) challenging double oblique scan plane localizations for standard 2D flow measurements in various locations, and (3) the need for suspension of respiration during image acquisition which often requires the use of general anesthesia in younger, uncooperative patients and breathholds otherwise. Free breathing, 4D PC MR with three-directional flow encoding has the potential to simplify the image acquisition and streamline the analysis of blood flow in patients with CHD.



**Fig. 1** (A) Volume-rendered image from PC VIPR dataset in 6 month-old male with pulmonary vein stenosis. The isotropic spatial resolution allows for retrospective analysis in arbitrary scan planes with no loss of spatial resolution. Time-resolved, 2D slices through the AscA (B) and MPA (C) were generated from this data and analyzed offline.

**Methods:** This prospective study enrolled twelve subjects – 2 F/10M, 20.2±23.6 yrs (range: 3-70yrs) – with variety of different types of CHD according to our IRB-approved and HIPAA-compliant protocol. Studies were performed on clinical 1.5T (n=8) and 3.0T (n=4) scanners (GE Healthcare, Waukesha, WI). LV and RV stroke volumes (SV) were calculated from CINE 2D SSFP images covering the entire heart (acquired spatial resolution = 0.9-1.6mm x 1.5-1.8mm, slice thickness = 5-8mm, TR = 2.6-3.7ms; TE = 0.8-1.4ms) analyzed on a dedicated cardiac workstation (ReportCard 2.0, GE Healthcare, Waukesha, WI). 2D PC MR (VENC = 150-400cm/s; acquired spatial resolution = 0.9-1.4mm x 1.6-2.7mm, slice thickness = 5-8mm, TR = 4.5-7.8ms; TE = 2.3-4.6ms) through the AscA and MPA was used for flow quantification (CV Flow 3.3, MEDIS, Leiden, NL) with subtraction residual phase terms [5]. 3D radially undersampled, time-resolved PC MRI with three-directional velocity encoding, covering the entire chest, was performed using PC VIPR (Vastly undersampled Isotropic Projection Reconstruction) [1-2] with the following scan parameters: VENC = 70-350cm/s; isotropic acquired spatial resolution = 0.8-1.4mm, TR = 6.4-10.6ms; TE = 2.1-3.3ms, scan time = 10.5-16.0min. This approach uses retrospective ECG gating with a temporal filtering scheme [2] similar to view sharing in Cartesian encoding and a free breathing acquisition with adaptive respiratory gating of bellows. Quantification of flow through the AscA and MPA from the PC VIPR datasets was performed offline on custom built MatLab software (The Mathworks, Natwick, MA). 2D datasets were generated from the PC VIPR data (Fig. 1) matching the orientation of the 2D PC acquisitions. AscA and MPA flow with PC VIPR was compared to LVSV and RVSV, respectively, obtained from the 2D SSFP using linear regression and Bland-Altman analysis. AscA and MPA flows quantified using 2D PC and PC VIPR were compared using Bland-Altman analysis.

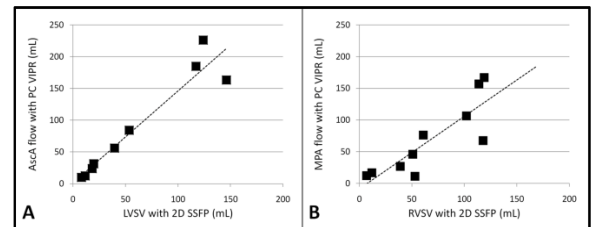
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**Results:** AscA and MPA flow measured with PC VIPR had a strong correlation with LVSV ( $R^2=0.912$ ) and RVSV ( $R^2=0.719$ ) measurements obtained from the 2D SSFP image analysis (Fig. 2). The results of the Bland-Altman analysis are summarized in Table 1. There was a positive slope to the differences between PC VIPR and 2D SSFP, with greater differences observed with larger stroke volumes. In addition, differences in AscA flow measurements were greater than those for MPA flow.

**Summary:** In this study, we have conducted an initial feasibility study of flow quantification through the AscA and MPA in patients with a variety of CHD conditions using 3D radially undersampled, time-resolved PC MRI (PC VIPR) and 2D PC. Flow values obtained with PC VIPR correlated very well with the standards of reference, CINE 2D bSSFP and 2D PC. Interestingly, the differences in flow measurement were greater for the AscA than the MPA and increased with larger stroke volumes. These differences can possibly be attributed to several factors including breathhold vs. free breathing acquisitions, temporal filtering of the PC VIPR data, variations in heart rate through the long PC VIPR acquisition, and differences in the phase correction methods [4,5]. These results provide encouraging evidence that PC VIPR has the potential to quantify blood flow in complex CHD patients, with future work aimed at a better understanding of the sources and solutions to the errors observed in these measurements.

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**References:** [1] KM Johnson, et al. Magn Reson Med 2008; 60:1329-1336. [2] KM Johnson, et al. Conf Proc IEEE Eng Med Biol Soc, 2009; 1:4057-4060. [3] KM Johnson and M Markl. Magn Reson Med 2010; 63:349-355. [4] Chernobelsky J Cardiovasc Magn Reson 2007; 9(4):681-5. [5] P Gatehouse, et al. J Cardiovasc Magn Reson 2010; 12:5.



**Fig. 2** (A) Linear regression of stroke volume through the aorta as measured by 2D SSFP of the LV and PC VIPR, (B) Linear regression of stroke volume through the main pulmonary artery as measured by 2D SSFP of the RV and PC VIPR.

| Bias                    | PC VIPR vs. 2D SSFP |        | PC VIPR vs. 2D PC |        | 2D PC vs. 2D SSFP |       |
|-------------------------|---------------------|--------|-------------------|--------|-------------------|-------|
|                         | AscA                | MPA    | AscA              | MPA    | AscA              | MPA   |
| Mean (ml)               | 28.30               | 1.27   | 27.68             | -0.02  | 2.10              | -1.29 |
| Standard deviation (ml) | 34.45               | 31.43  | 30.34             | 24.84  | 9.02              | 23.84 |
| Slope                   | 0.42                | 0.32   | 0.43              | 0.17   | 0.00              | -0.15 |
| Intercept (ml)          | -2.62               | -20.73 | -3.92             | -11.69 | 1.97              | 8.79  |

**Table 1** Summary of Bland-Altman analysis of differences in measurement of AscA and MPA flow.