Validation of 4D velocity mapping using 5-point PC-VIPR for blood flow quantification in the thoracic aorta and main pulmonary artery.

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Introduction: Radially undersampled time-resolved 3D velocity mapping with PC-VIPR has been shown to be an efficient tool for high-resolution hemodynamic analysis with large volume coverage [1]. It allows for simultaneous vessel depiction, visualization of hemodynamics, calculation of blood flow derivatives, as well as basic flow quantification. A recently introduced 5-point velocity encoding strategy for 4D velocity mapping further increases the velocity sensitivity spectrum and signal to noise ratio at little scan time penalty [2]. Therefore, 5-point PC-VIPR seems ideally suited for clinical purposes, where large volume coverage with three directional velocity encoding allows to assess the vasculature of an entire region within a single exam. Our aim was to validate 5-point PC VIPR for measurement of aortic and main pulmonary artery flow in comparison to cardiac MR volumetry (CMR) and standard 2D phase contrast imaging (2D PC-MRI).

Methods: 14 healthy volunteers (determined by case history and contrast-enhanced MR angiography [CE-MRA]) aged 39.2±16.8 (range 22-73) years with a BMI 26.1±3.3 (range 20.6-31.4) were included after IRB-approval and written informed consent.

MR Imaging was performed on a clinical 3T scanner (GE Discovery MR 750, Waukesha, WI) with a 32-channel phase array body coil, using the upper 20 coil elements (NeoCoil, Pewaukee, WI). 5-point PC-VIPR was prescribed as a volume centered over the thoracic vasculature including the aortic arch and the base of the heart with typical imaging parameters: FOV=320x320, acquired spatial resolution: isotropic 1.3mm, venc=150cm/s, TR/TE=6.3-6.7/2.2ms, flip angle=14-22. PC VIPR data was automatically corrected for eddy currents and Maxwell terms. An adaptive respiratory gating scheme with bellows (55% acceptance window) was used, resulting in a total scan time of ~ 11 min. Retrospective cardiac gating and a time-resolved reconstruction with temporal filtering was used. Data was reconstructed to 20 time frames.

Prospectively ECG-triggered 2D PC-MRI was acquired with a product sequence to serve as a reference standard for flow measurements. Imaging parameters were adapted to each individual's breathhold capabilities (<22s, minimum of 15 cardiac phases). Images were acquired in the ascending aorta above the ostia of the coronary arteries (AAO) and the main pulmonary artery distal to the pulmonary valve (MPA).

For standard clinical CINE cardiac imaging (CMR) in short axis sections, a bSSFP sequence with 8mm slice thickness was used.

A clinical contrast-enhanced MR angiography was performed using 0.12mmol/kg BW gadofosveset trisodium (Ablavar, Lantheus, Billerica, MA) at an injection rate of 0.6mL/s via a anticubital i.v.-line for proper alignment of the 2D PC slices, and constant elevation of signal-to-noise throughout the exam [3].

Evaluation of CINE volumetry was achieved on a workstation for cardiac analysis (ReportCard 2.0), and 2D PC MRI data were analyzed with CV Flow 3.3 (MEDIS, Leiden, NL), both installed on an Advanced Workstation (GE Healthcare, Waukesha, WI). To correct for background phase shifts that can corrupt 2D flow measurements, phantom acquisitions were acquired according to the method of Chernobelsky et al. [4]. Analysis of PC-VIPR data was performed by extracting manually placed cutplanes in AAO and MPA (Fig. 1) using a software package capable of displaying cine velocity fields (EnSight, CEI Inc., Apex, NC) which were exported into a previously described MatLab-based tool for hemodynamic analysis [5]. Data was compared with paired t-tests. $p<0.05$ was accepted to indicate statistical significance. Bland-Altman analysis was applied for all comparisons to show the bias between methods, and correlation analysis was performed to reveal association between results.

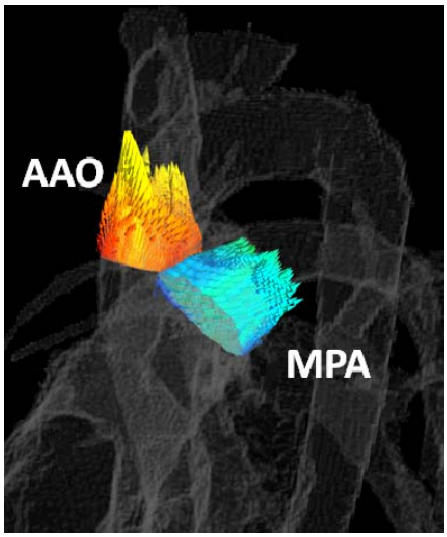

Fig. 1 – Color coded vector plot visualization on the aortic (AAO) and main pulmonary artery (MPA) cutplane in a healthy volunteer. Using EnSight (v9.1, CEI, Apex, NC) analysis planes for 5-point PC-VIPR were then exported to MatLab

	CMR	4D PC	2D PC
AO	101.1mL*	89.6mL	103.0mL*
bias	1.4mL		
+2SD	21.2mL		
-2SD	-18.5mL		
bias		8.4mL	
+2SD		40.1mL	
-2SD		-23.3mL	
MPA	98.5mL*	92.5mL	104.3mL*
bias	-5.9mL		
+2SD	23.1mL		
-2SD	-35.0mL		
bias		-11.7mL	
+2SD		39.5mL	
-2SD		-63.0mL	

Fig. 2 – Comparison of 4D PC-VIPR measurements, CMR, and 2D PC MRI acquisitions for both aorta (AO) and pulmonary artery (MPA). Overall results agree well and differerences show no statistical significance (*). Bland-Altman analysis reveals a slight but clinically acceptable overestimation of values by PC VIPR for the AO and underestimation regarding the MPA.

Results and Discussion: Figure 1 displays the double oblique placement of cutplanes in the ascending aorta and main pulmonary artery. The planes are superimposed on the background of color-coded 3D streamlines emitted from various locations throughout the cardiac chambers and vessels (not part of the analysis) to underscore the feasibility of simultaneous hemodynamic visualization. Figure 2 demonstrates the overall good agreement of measurements from all methods (* indicating $p>0.05$). The Bland Altman analysis shows a small bias between measurements for each vessel with larger variability in the assessment of the MPA. Note that despite the overall underestimation of aortic flow by 5-point PC-VIPR, the measurement bias showed a trend towards overestimation. Being more dependent on some outliers (error analysis is ongoing), linear correlation showed moderate to good correlation for AAO ($r=0.50$) and inferior correlation for the MPA ($r=0.44$). Also, a wider scatter of cardiac output data will help to improve limitations with respect to the correlation. This will be achieved by including patient collectives with altered AAO and MPA flows such as in ischemic and congenital heart disease.

Summary: PC-VIPR with 5-point velocity encoding permits the derivation of quantitative blood flow values in the thoracic aorta and pulmonary artery within clinically acceptable limits. PC VIPR can therefore be used as a diagnostic approach combining quantitative analysis with simultaneous registration of morphology and hemodynamic studies.

References: [1] Gu AJNR 2007, [2] Johnson MRM 2010; [3] Bock MRM 2010; [4] Chernobelsky JCMR 2007; [5] Stalder MRM 2008. **Acknowledgements:** We acknowledge support from the departmental R&D committee, Bracco Diagnostics, NIH (R01 DK083380, R01 DK088925, RC1 EB010384, and R01HL072260), the Coulter Foundation, and GE Healthcare.