Pressure Difference Measurements in Stenotic Flow Phantom: Comparison of 4D Flow MRI, Computational Fluid Dynamics, and Pressure Wire Measurements

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Target Audience: Those interested in MR flow imaging and potential derivative biomarkers

Purpose: Transstenotic pressure gradients obtained from catheter measurements are clinically used to assess hemodynamic significance and guide treatment choices. Pressure gradients can be estimated noninvasively from Doppler ultrasound (US) or 2D phase contrast (PC) MRI using a simplified Bernoulli equation. However, they are highly subjective to location and orientation and in the case of 2D PC, errors arising from acceleration and turbulence [1]. 4D PC MRI with dynamic, three-directional velocity encoding has potential to derive the spatial and temporal distribution of pressure differences and additionally account for viscosity effects. This approach has been used *in vivo* and compared to other pressure measures with success [2-4]. However, many factors impact the accuracy of pressure measures including pressure recovery, imaging parameters, and algorithm choice. *The purpose of this study* is to compare 4D phase contrast (4D PC) MRI pressure measurements in a stenosis phantom with pressure catheter measurements as well as with computation fluid dynamics (CFD).

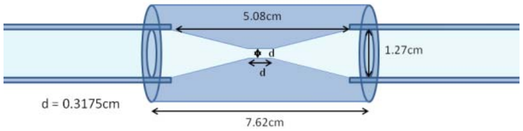

Figure 1: Stenosis phantom geometry with dimensions colored by material. The stenosis is connected to a programmable flow pump.

Flow (ml/s)	Pressure Probe	CFD		PC VIPR			
				Venc150	Venc300	Venc150	Venc300
		Navier-Stokes	Bernoulli	Navier-Stokes		Bernoulli	
7.5	7.46	5.54	5.59	6.48	6.54	5.08	5.39
15	20.50	19.60	19.91	20.08	18.32	18.54	15.19
22.5	26.49	41.70	42.41		38.94		45.75

Table 1: Pressure differences measured with the different techniques in the stenosis phantom. Maximum velocities calculated with CFD and measured with MRI were used with the simplified Bernoulli equation to calculate pressure differences for comparison.

Methods: ***Stenosis Model***: A phantom, approximating a pediatric aortic coarctation was precision machined from polycarbonite to match geometry shown in Figure 1. The phantom was encapsulated in water bath and connected to a programmable flow pump (CompuFlow 1000 MR, Shelley Medical Imaging Technologies, London, ON, CA) using blood mimicking fluid (ρ=1.02 g/cm^3, μ=4.1 *cP*). Pressure and imaging measurements were made at three constant flow rates: 7.5 ml/s, 15 ml/s, and 22.5 ml/s. ***Pressure Probe:*** A fiber optic, microeletromechanical pressure probe (opSens, Quebec, Quebec, CA)[5] was used to measure pressure at 17 points 10 mm apart along the long axis of the phantom. ***MRI:*** Volumetric, time-resolved PC MRI data with 3-directional velocity encoding were acquired on a 3T MRI system (MR750, GE Healthcare, Waukesha, WI) with a 3D radial sequence, PC VIPR [6] with V_{enc}s of 150 and 300 cm/s: 0.5mm^3 isotropic spatial resolution, TE_{150}=3.2ms/TE_{300}=3.1ms, BW=83.33 kHz, TR 6.2ms, 10,000 projections, scan time ~ 10 min). PC VIPR pressure gradients were calculated from 4D PC MRI data using the Navier-Stokes [6] and Bernoulli equations. ***CFD:*** A stationary 2D axisymmetric CFD model of the stenosis was generated in COMSOL (Comsol, Inc. Burlington, MA) using a laminar inflow and outflow boundary conditions of 7.5 ml/s, 15 ml/s, and 22.5 ml/s. Pressure differences were also calculated from CFD derived maximum velocities using the simplified Bernoulli equation.

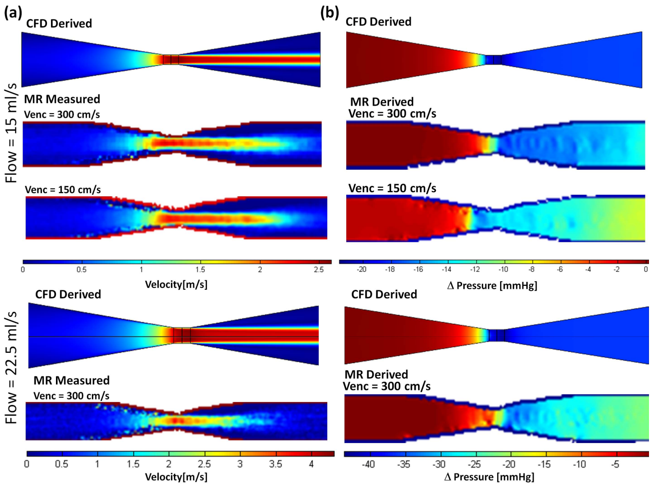

Figure 2: Results from CFD and PC VIPR at Venc = 150 cm/s and Venc = 30 cm/s at a flow rates = 15 and 22.5 ml/s: (a) velocity fields and (b) calculated pressure maps. A single central slice of volumetric 4D PC MRI and CFD data is displayed.

Results and Discussion: Figure 2 shows velocity and pressure maps from CFD calculations and 4D PC MRI. Peak velocities are similar in each case; however, the velocity jet is more persistent in CFD data. Peak pressure drops from CFD, probe and 4D PC were relatively similar (Table 1), however 3D PC shows pressure recovery post-stenosis which is not seen in CFD or probe data. Pressure difference calculated with the pressure probe at a flow rate of 22.5 was lower than expected, likely due to significant probe motion from unsteady flow including contact with the phantom wall. Disagreement in the velocity and pressure fields likely arises from turbulence distal to the stenosis which leads to errors in both 4D PC and CFD measures. The MR data is offset spatially from CFD data due to acceleration effects. Bernoulli pressure differences varied from Navier-Stokes as much as 18%.

Conclusions: Pressure gradients calculated from 4D PC MRI data in a stenosis phantom were comparable to those obtained from pressure probes and computational fluid dynamics. Bernoulli pressure differences measurements showed some variation from Navier-Stokes measurements. The Bernoulli method does not produce a pressure map, is dependent on the location of the maximum velocity measurements and could vary in accuracy based on the geometry of the stenosis. Additional work will be done to further investigate potential errors in pressure measurements due to pulsatile flow, spatial resolution, and turbulence.

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REFERENCES: [1] Oshinski JN *et al. J AM Coll Cardiol* 1996; 28:1818-26 26 [2] Lum DP *et al. Radiology* 2007; 245:751-6 [3] Bley *et al. Radiology* 2011; 216:266-73 [4] Bock J et al., MRM 2011; 66:1079-88 [5] Kao TW, Taylor HF. Opt Lett 1996;21:615-617 [6] Johnson KM *et al. MRM* 2008;60:1329-36 [6] Tyska *et al. JMRI* 200;12:321-9