Estimation of transvalvular flow jet angle using 4D flow MRI and flow jet shear layer detection

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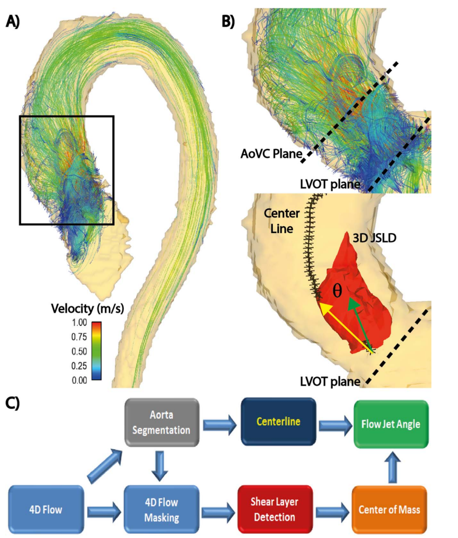

FIGURE 1: Flow jet angle estimation using 4D flow data and jet shear layer detection method. A) Velocity streamlines inside the 3D segmentation of the aorta (segmentation obtained from the 3D PC-MRA). The black box indicates the region magnified in 'B'. B) Dashed lines indicate the level of the left ventricle outflow tract (LVOT) and vena contracta (AoVC). The AoVC plane was used to estimate the 2D flow jet angle. Jet shear layer detection (JSLD) was computed from the full 4D flow dataset. The resulting lateral view of the 3D JSLD structure (red volume) and volume centerline (black) is shown. The centerline vector (yellow arrow) and 3D JSLD center of mass vector (green arrow) determine the jet flow angle. C) Workflow schematic for the computation of the 3D JSLD jet angle.

Purpose: Patients with aortic dilation often exhibit eccentric transvalvular flow jets. The angle of the flow jet from the aorta centerline, or the flow jet angle (FJA), has been reported as a risk factor for aortic dilation in bicuspid aortic valve patients[1]. In recent studies, we introduced a jet shear layer detection (JSLD) method for the automated characterization of the transvalvular flow structure across the aortic valve[2,3]. The objective of this study was to develop and apply a new algorithm for the semiautomatic evaluation of FJA using a 3D JSLD structure based on 4D flow MRI data. Results in 30 patients with aortic dilation and varying degrees of aortic valve stenosis were compared to the manual calculation of flow angle using 2D analysis planes placed at the site of the vena contracta.

Table 1

Subject Characteristics

Table 1

	All	Controls	Ao Dilation	Ao Dilation + Stenosis	p-value
n	30	10	10	10	
Age (years)	56 ± 17	41 ± 16	62 ± 10*	64 ± 14*	<0.05
Female (n)	7	2	4	1	NS
Height (cm)	174 ± 13	178 ± 12	172 ± 15	173 ± 11	NS
Weight (Kg)	83 ± 20	78 ± 12	88 ± 29	83 ± 12	NS
Ejection Fraction (%)	60 ± 6	57 ± 6	64 ± 4*	60 ± 6	<0.05
Stroke Volume (mL)	96 ± 32	85 ± 13	100 ± 47	102 ± 26	NS
Sinus of Valsalva Diameter (mm)	39 ± 6	39 ± 9	42 ± 5	39 ± 4	NS
Mid Ascending Aorta Diameter (mm)	38 ± 9	28 ± 4	47 ± 2*	42 ± 3*	<0.001
Peak Velocity (m/s)	1.8 ± 1	1.1 ± 0.4	1.4 ± 0.5	2.9 ± 0.9*	<0.001

* significant different vs. Group 1

Methods: 30 patients with aortic dilation and tricuspid aortic valves (age=56±17 years, female=7) were identified via retrospective chart review and IRB approval. The mid-ascending aorta (MAA) diameter was used to assess aortic (Ao) dilation and the presence of aortic valve stenosis was assessed with transvalvular peak velocity (PV). Patients were classified into three groups: Controls (MAA<35 mm and PV<1.5 m/s); Ao Dilation (MAA>35 mm and PV<1.5 m/s); Ao Dilation+Stenosis (MAA>35 mm and PV>1.5 m/s). 4D flow MRI was performed at 1.5T and 3T with full volumetric coverage of the thoracic aorta in a sagittal oblique 3D slab (spatial resolution=2.5×2.1×3.2 mm^3; temporal resolution=40-50 ms) using prospective ECG gating and a respiratory navigator placed on the lung-liver interface. Pulse sequence parameters were as follows: 1.5 T scan parameters ranged from TE/TR=2.3–3.4/4.8–6.6 ms, flip angle α=7–15° and the field of view was 340–400×200–300 mm; 3 T scans used TE/TR =2.5/5.1 ms, flip angle α=7–15°, and the field of view was 400×308 mm. 4D flow data were used to compute a 3D PC-MRA which allowed for 3D segmentation of the aorta (Mimics, Materialise, Leuven, Belgium). The segmented aorta was used to calculate: the vessel centerline, a masked velocity field, and the 3D JSLD structure (Matlab, Natick, MA, USA). The 3D JSLD structure was obtained from the peak systolic velocity field, V, by $\nabla(\omega \Lambda V)$ (where ω is the vorticity calculated by a Richardson interpolation scheme) and used to detect the post-valve jet-flow zone, i.e. vena contracta[2, 4]. A centerline segment at the vena contracta was used to obtain a centerline vector and the 3D JSLD structure center of mass vector. Both vectors were then used to estimate FJA (Fig. 1B). A workflow schematic for the 3D JSLD method is shown in Fig. 1C. For reference values, the manual FJA was calculated using 2D planes hand-positioned at the vena contracta (immediately downstream from the aortic valve, Fig. 1B). Both methods were compared by linear regression and Bland-Altman analysis with the 2D FJA as the reference.

Results and Discussion: Patient characteristics are summarized in Table 1. A significant difference between Ao Dilation and Ao Dilation+Stenosis vs. Control was observed for age (p<0.05) and MAA (p<0.001). The ejection fraction was higher in Ao Dilation (p<0.05 vs. Control). Bland-Altman analysis (Fig. 2A) showed that difference between 2D velocity and 3D JSLD FJA increases with MAA diameter and valve stenosis. The FJA derived from 3D JSLD and 2D planar analysis were significantly different between Ao Dilation and Ao Dilation+Stenosis, as compared to Controls (p<0.05, Fig. 2B). Noticeably, the 3D JSLD FJA method detected significant differences between stenotic vs. non-stenotic Ao dilatation (p<0.001) while planar FJA analysis did not. A higher FJA was most likely found in Ao Dilation+Stenosis due to the presence of a larger MAA and a higher degree of valvular obstruction. A significant relationship was found between PV and 3D JSLD FJA (r=0.515, p<0.05), suggesting a relationship of FJA and aortic stenosis severity. The 3D JSLD FJA method detected differences between stenotic and non-stenotic Ao dilation groups, while the 2D method did not. Manual interaction while placing 2D analysis planes may have increased measurement noise. The decreased user interaction required for the 3D JSLD method may reduce measurement noise and enable stratification of flow angle differences between the stenotic and non-stenotic Ao dilation groups. Previous studies suggest that flow jet impingement on the convexity aortic area may led to wall remodeling (i.e. aortic dilation)[5]. Although this is a cross-sectional study and longitudinal outcomes were not examined, it is important to note the positive correlation between aortic dilation and FJA. Furthermore, FJA was observed to be closely related to valve hemodynamics (i.e. PV). This is important given recent findings that FJA is associated with aortic stenosis severity and left ventricle remodeling[6]. Thus, FJA is important to investigate for a relationship to aortic wall remodeling and valve and left ventricle function. These findings highlight a potential application of the JSLD FJA algorithm.

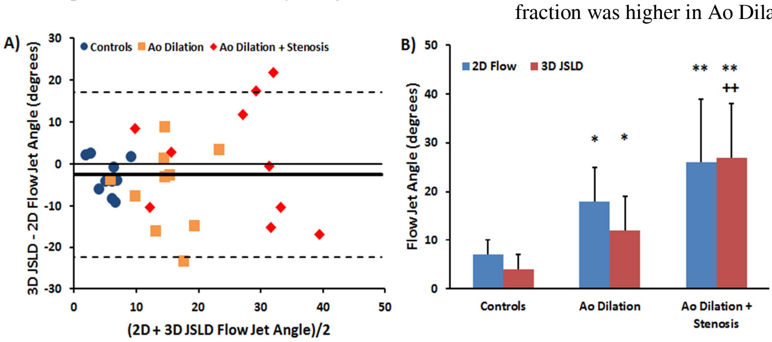

FIGURE 2: A) Bland-Altman plot of comparing the two flow angle measurement methods and B) Flow angle by group and method. JSLD: Jet shear layer detection. *: p<0.05 vs. Controls; **: p<0.001 vs. Controls; ++: p<0.001 vs. Ao Dilation.

Conclusion: The assessment of FJA can be automated using the volumetric 3D JSLD structure and the aorta centerline using data from 4D flow MRI exams. Using this technique, the FJA was found to be significantly higher in patients with severe aortic dilation and aortic valve stenosis. Future longitudinal studies are needed to evaluate the impact of FJA on the progression of aortic dilation.

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