New Method for Efficient, Volumetric Quantification of Aortic Hemodynamics

Michael J Rose[1], Kelly Jarvis[2,3], Varun Chowdhary[2], Alex J Barker[2], Bradley D Allen[2], Joshua D Robinson[4,5], Michael Markl[2,3], Cynthia K Rigsby[1,2], and Susanne Schnell[2]

[1]Medical Imaging, Ann & Robert H. Lurie Children's Hospital of Chicago, Chicago, IL, United States, [2]Radiology, Northwestern University, Chicago, IL, United States, [3]Biomedical Engineering, Northwestern University, Chicago, IL, United States, [4]Pediatrics, Northwestern University, Chicago, IL, United States, [5]Pediatric Cardiology, Ann & Robert H. Lurie Children's Hospital of Chicago, Chicago, IL, United States

Introduction: In patients with aortic valve disease elevated systolic peak velocity is an important clinical measure to estimate pressure gradients (via the simplified Bernoulli equation) and thus the severity of valve stenosis [1]. Accurate measurement of peak systolic velocity is crucial as it drives patient management. Currently, standard methods for measuring peak blood flow velocity are Doppler echocardiography (echo) and 2D phase contrast (PC) MRI [2]. Both methods, however, rely on manually positioned 2D analysis planes and are observer dependent and/or may miss the true peak velocity due to inaccurate plane placement. In addition, both techniques rely on 1D velocity encoding, which can result in underestimation of peak velocity in case of complex high velocity flow jets as often seen in patients with abnormal aortic valves. Both features (2D planes, 1D encoding) limit the quality of the results to the accuracy of the plane placement by the user and do not accommodate for complex, helical flows that are signature to some congenital heart diseases, such as bicuspid aortic valve (BAV). In contrast, 4D flow MRI can be employed to assess blood flow with 3D velocity encoding and full volumetric coverage of the aorta and is therefore not limited by 2D plane placement. However, previous strategies to calculate peak velocity from 4D flow data were time consuming, required the manual placement, and did not offer an easy to view image of systolic velocity patterns [3]. In this study, we employ a new and easy to use approach based on systolic velocity maximum intensity projections (MIPs) and aortic region of interest analysis to determine peak velocity based on aortic 4D flow MRI data. The aim was to test the feasibility and effectiveness of this approach to determine peak velocity in the ascending aorta (AAo), aortic arch (arch), and descending aorta (DAo) of pediatric patients with BAV. We hypothesize that the volumetric velocity MIP based analysis of 4D flow data can better accommodate complex blood flow in the aorta of BAV patients and will provide 1) good inter-observer variability coupled with short analysis time and 2) higher systolic peak velocities compared to 2D PC-MRI and echo.

Methods: 41 pediatric patients (age = 14 ± 4 (min: 3 max: 24) years, male:female = 27:14) with diagnosed BAV received 4D flow MRI included in a physician-ordered cardiac MR assessment as part of this IRB-approved study. MRI scans were performed at 1.5 T (Avanto or Aera, Siemens, Germany) with spatial resolution = 2.2-4.1 x 1.6-2.5 x 1.9-4.0 mm^3, temporal resolution 37.6-40.8 ms, TE/TR/FA = 2.3-2.6 ms/4.7-5.1 ms/15° and velocity sensitivity = 150–400 cm/s. 4D flow data were preprocessed to reduce noise and artifacts caused by velocity aliasing and phase offset errors (Maxwell terms, eddy currents). 3D PC-MR angiograms were computed from 4D flow data as described previously [4] and used to obtain a 3D segmentation of the aorta (Mimics, Materialise, Belgium), which was used to mask the 4D flow velocity field. The time-resolved masked aorta velocity field was used to generate a velocity MIP in sagittal, coronal and axial views (Fig. 1). For each voxel, peak systole was defined as the maximum absolute velocity during the first 300 ms of the cardiac cycle. All MIP analysis was performed using an in-house tool (Matlab, MathWorks, USA). Prior to peak velocity quantification, MIPs were eroded by 1 or 2 voxels to omit false positive voxels at the vessel wall. Next, the aortic peak velocity was automatically extracted from the entire velocity MIP (global peak velocity). In addition, three regions of interest (ROIs) were manually drawn to include the AAo, aortic arch, and DAo as illustrated in Fig. 1 and used to determine regional peak velocity for each aortic segment. All ROIs were adjusted to exclude velocity noise potentially present near vessel edges (see Fig. 1C, D). Velocity MIP analysis in all 41 patients was performed by 2 observers in a blinded manner. Inter-observer variability was determined by the Bland-Altman method. In addition, processing time for the in-house tool was recorded for each patient and by each user. Finally, results from velocity MIP analysis in the AAo were compared to peak velocities obtained by echo in a subgroup of 24 patients and by 2D PC-MRI in a subgroup of 18 patients.

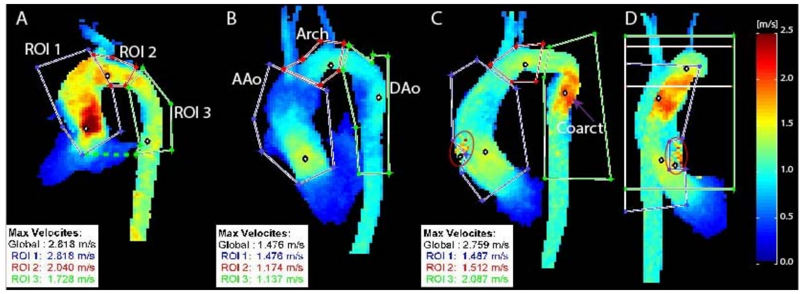

Figure 1: Systolic velocity MIPs and ROI analysis in three BAV patients. ROI 1 is placed in the AAo, starting right below the valve and ending at the brachiocephalic trunk. ROI 2 starts right after ROI 1 and ends distal to the left subclavian artery. ROI 3 starts after ROI 2 and ends at the level of the lowest point of the valve as illustrated by the dotted line in A. A) BAV patient with high velocity close to the aortic root. B) BAV patient with normal velocity in the AAo. C) A BAV patient with aortic coarctation (Coarct) in the proximal DAo. Note the difference in global and ROI 1 peak velocity in C due to noise in the global aortic 3D segmentation. This noise (circled in red) is cropped out by ROI 1 and is absent in ROI 1 max velocity calculations. D) The coronal view of the patient in C.

Results: The average processing time for the velocity MIP analysis was 98 s (user 1: 120 ± 60 s, user 2: 76 ± 30 s). Bland-Altman analysis of inter-observer variability (Figure 2) showed very good agreement (mean difference = 0.01m/s, limits of agreement = 0.42m/s) resulting in an average mean difference of 3.8% between observers. 4D flow derived peak velocities in the AAo were significantly higher compared to 2D PC-MRI (2.28±0.79 vs 1.80±0.83, p=0.016) and similar to echo (2.18±1.01 vs 2.10±1.05, p=0.59) indicating the potential of 4D flow to improve peak velocity quantification using MRI by volumetric coverage and 3D velocity encoding. This was confirmed by Bland-Altman analysis for 4D flow vs echo (Figure 3) and 4D flow vs 2D PC-MRI which showed mean differences of 0.08 m/s and 0.48 m/s, respectively indicating systemic underestimation by 2D PC-MRI.

Conclusions: This new approach for measuring peak aortic velocities with 4D flow data offers three key advantages over echo and 2D PC-MRI: more accurate peak velocity assessment; assesses an entire volume rather than a 2D plane; and the capability to be coupled with additional 4D flow results, such as 3D visualization of hemodynamics. Additionally, it has benefits previously unseen in peak velocity assessment with 4D flow data: short analysis time on the scale of a couple minutes; and velocity patterns that are easily seen in the generated MIPs. For clinicians, these advantages would mean more informed grading of valve stenosis severity while still maintaining a reasonable analysis time. Further automation of the tool could improve user variability.

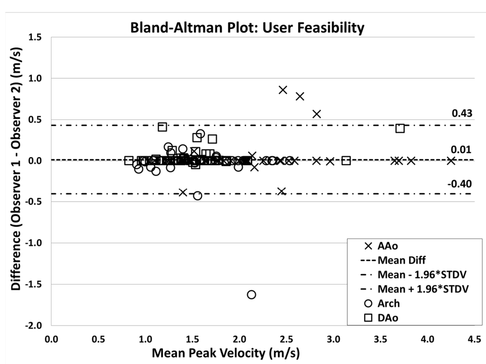

Figure 2: Bland-Altman plot comparing the difference in velocity results between the 2 users.

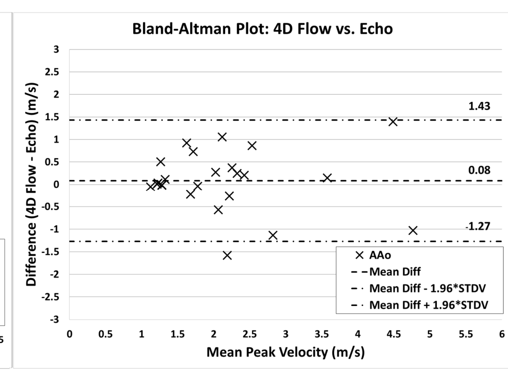

Figure 3: Bland-Altman plot comparing the velocity results of 4D Flow and echo.

References: 1. Otto CM et al. *J Am Coll Cardiol* (2006). **2.** Nordmeyer S et al. *J Magn Reson Imaging* (2013). **3.** Markl M et al. Curr Cardiol Rep (2014) **4.** Markl M. et al. *J Magn Reson Imaging* (2007).

Funding: NIH R01HL115828 and K25HL119608