Identifying regions of abnormal wall shear stress in patients with bicuspid aortic valves

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Introduction: Patients with congenital bicuspid aortic valves (BAV) are prone to progressive aortic dilatation and/or dissection. In this context, prophylactic surgical replacement of the dilated aorta is recommended for BAV patients based on simple size criteria (maximal diameter). Given a recent survey demonstrating that cardiac surgeons do not follow the guidelines determining surgical resection strategies[1], we believe that alternative imaging parameters may assist for better prognostic and surgical therapy guidance. Wall shear stress (WSS) is a promising imaging risk stratification parameter given its association with vascular wall remodeling[2]. In addition, recent developments in 4D flow MRI techniques permit regional volumetric assessment of WSS capable of indicating regions possibly at risk for maladaptive tissue remodeling. Therefore, in this study we demonstrate the use of a novel methodology to compare 3D WSS patterns in individual BAV patients with 3D WSS patterns averaged over a population of multiple healthy volunteers.

Methods: Prospectively ECG gated 4D flow MRI of the thoracic aorta using a free-breathing navigator was performed in 10 healthy controls (6 males, 4 females) and 11 BAV patients (10 males, 1 female) undergoing ascending aorta (AAo) replacement surgery (table 1) on 1.5 and 3T scanners (Espree, Avanto, Skyra, Aera, Siemens, Erlangen, Germany). 7 patients had fusion of the right and left coronary cusps (RL), whereas 4 patients had fusion of the right and noncoronary cusps (RN). Spatial resolution was 1.7-3.6x1.7-2.7x2.2-3.0 mm^3; temporal resolution was 36-43ms (13-23 timeframes); TE/TR/FA was 2.2-2.8ms/4.5-5.3ms/7-15° and the VENC was 150cm/s for healthy controls and 150-400cm/s for BAV patients. The 4D flow MRI data were corrected for Maxwell terms, eddy currents and velocity aliasing. The thoracic aorta was segmented from PC-MRA images averaged over the cardiac cycle[3] in MIMICS (Materialise, Leuven, Belgium). WSS was calculated as previously described[4] and averaged over 5 systolic phases. A cohort-averaged control WSS map was created by registering the segmentations of the aorta and the geometry that showed the smallest deviation with the average control aorta shape was chosen. The WSS vectors of each control were interpolated onto this geometry and averaged over all controls, which resulted in the control mean and standard deviation (SD) WSS map. To determine the presence of abnormal WSS, the BAV patients were registered and WSS was interpolated to the control geometry. For each individual patient, abnormal WSS was defined as values that were higher or lower than the mean control WSS at the same map location, by 1.96 standard deviations (i.e. mean±1.96*SD, Fig. 1). In addition, a P-value map was created by comparing WSS values on each point on the control geometry between the control and BAV cohort using a Wilcoxon rank sum test. Results were summarized for 6 aorta sections in terms of percent of the region higher (+) or lower (-) than 1.96 times the controls for the BAV subjects (Fig. 1 & Table 2, regions 1&2: inner/outer ascending aorta AAo, 3&4: inner/outer aortic arch, 5&6: inner/outer descending aorta DAo).

Table 1. Subject Demographics

Properties	BAV	Controls	P-value
Age (y)	49±18	50±14	0.92
SOV (cm)	4.5±0.8	3.0±0.5	<0.001
MAA (cm)	4.4±0.7	2.9±0.5	<0.001

SOV = Sinus of Valsalva diameter
MAA = Mid-Ascending Aorta diameter

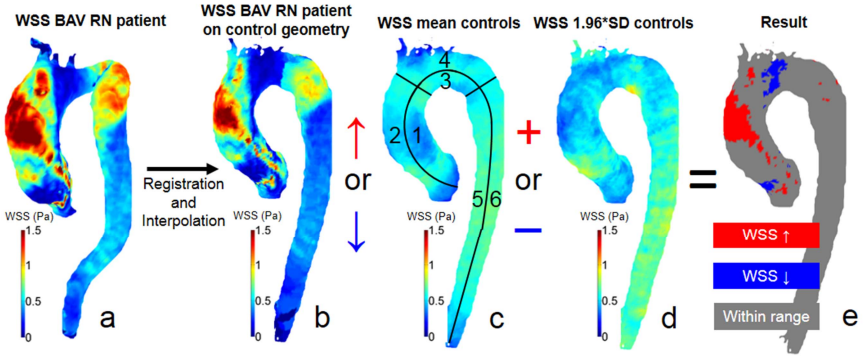

*Fig. 1. (a) Individual WSS of a BAV RN patient. (b) WSS of the BAV RN patient registered and interpolated to the control geometry. (c) The mean WSS map of the controls. (d) 1.96*SD WSS map of the controls. (e) Regions of the BAV patient with abnormal WSS.*

Results: Individualized WSS heat maps and a P-value map were successfully created for all subjects. The methodology detected abnormal regional WSS in the BAV patients, mainly prevalent in regions 2 and 4: on the outer curvature of the AAo (table 2 and Fig. 2). Significant negative correlations were found between the Sinus of Valsalva diameter and the percentage region of high WSS in the inner (R^2=0.78, p<0.001) and outer curvature (R^2=0.46, p<0.05) of the AAo. Furthermore, a significant correlation was found between the mid-ascending aorta diameter and the percentage region of elevated WSS on the outer curvature of the AAo (R^2=0.4, p<0.05).

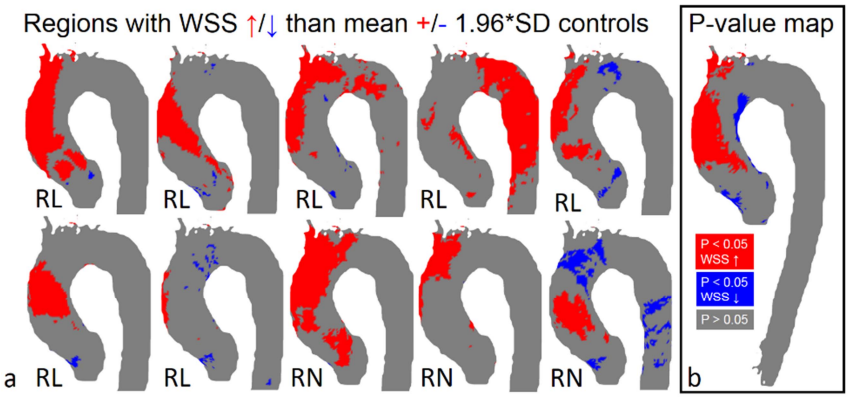

Fig. 2. (a) Regions of abnormal WSS for the remaining 10 patients. Red and blue respectively represent regions of higher and lower WSS than the controls. (b) P-value map for the 11 BAV patients compared to the 10 controls. Red and blue respectively represent significantly higher and lower WSS than the controls. Gray represents no significant differences in WSS.

Table 2. Percent of the regions with higher (+) or lower (-) WSS

Region	Mean Area (%)	P-value area (%)
1 + / -	8±5 / 2±1	6 / 13
2 + / -	21±13 / 2±2	28 / 11
3 + / -	9±15 / 2±2	0 / 5
4 + / -	16±18 / 1±3	21 / 0
5 + / -	3±8 / 0±2	0 / 0
6 + / -	2±7 / 0±1	0 / 0

Discussion/Conclusion: The proposed method enables the identification and localization of abnormal WSS in individual BAV patients. Elevated WSS in BAV patients was found most frequently on the outer curvature of the AAo and the arch. This result corroborates previous studies using WSS averaged over a number of patients at manually placed planes [4]. The advantage of this technique is that it provides a method to identify abnormal regions of relative WSS in the entire aorta for a single subject, and over the entire surface of the aorta (as opposed to 2D cut planes). This may aid in developing individualized resection strategies and may ultimately aid in the identification of regions at risk for aortopathy.

References: [1] Verma et al. J Thorac Cardiovasc Surg (2013) [2] Lehoux et al. J Biomech (2003) [3] Bock et al. ISMRM (2007) [4] van Ooij et al. JMRI (2013) [4] Barker et al. Circ Cardiovasc Imaging (2012)

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