

#### 4D Flow MRI in aortic valve disease demonstrates altered distribution of aortic blood flow helicity

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**Introduction:** 3D blood flow characteristic within the aorta play an important part in the health of individuals. An important flow pattern is helical flow, a corkscrew-like motion along the principal direction of flow which is considered to be a normal feature in healthy subjects [1]. However, due to aortic valve disease or aortic pathology, helical flow can increase which may be associated with disease progression. Previous literature presented only qualitative evaluation of helical flow [2]. Recently, a quantitative method, using a global helical flow index based on particle traces, was introduced [3,4]. A different approach based on helicity quantification in 2D cross-sections distributed along the aorta for 12 healthy subjects revealed a consistent direction of rotation over the entire aorta with high clockwise helicity in the aortic arch [5]. The aim of his study was 1) to evaluate the test-retest reliability of helicity quantification in healthy subjects and 2) to compare helical flow of healthy individuals to patients with aortic valve disease involving strong helix flow formation.

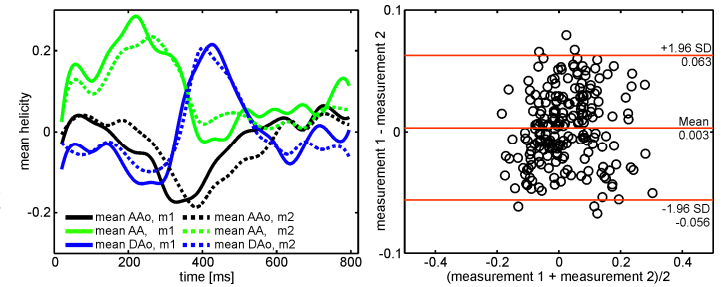
**Methods:** 12 healthy subjects (age: 25±3, 4f/8m), repeated analysis in 10 of the 12 healthy subjects (age: 26±4, 3f/7m) after 1 year for test-retest reliability, 16 bicuspid aortic valve (BAV) patients with left-right coronary leaflet fusion (age: 48±16, 4f/12m), 3 aortic valve stenosis (AS) patients (age: 63±10, 1f/2m) and 1 patient with aortic insufficiency (AI) (age: 61, 1m) were examined on 1.5/3T system (MAGNETOM Avanto/ MAGNETOM Trio Tim, Siemens, Germany). ECG synchronized prospectively gated and respiration controlled navigator gated 4D flow-sensitive MRI was performed. Scan parameters were as follows:  $venc=150-250\text{cm/s}$ , flip angle= $7^\circ/15^\circ$ , temporal resolution= $37.6-40.8\text{ms}$ , spatial resolution= $2.0\times2.0\times2.2\text{mm}^3$ . PC-MRA was used for anatomic orientation in 3D (EnSight, CEI, USA) to position equally spaced (distance= $10\text{mm}$ ) analysis planes (19-30 2D cross-sections) covering the ascending aorta (AAo), the aortic arch (AA), and the proximal descending aorta (DAo). For each analysis plane, the aortic lumen over all time-frames was manually segmented (Matlab, The Mathworks, USA). For each pixel in the segmented lumen,

normalized helicity =  $\frac{\vec{v} \cdot \vec{\omega}}{|\vec{v}| |\vec{\omega}|}$ , where  $\vec{v}$  is the velocity vector and  $\vec{\omega}$  the vorticity vector was calculated, resulting in values between -1 (counter clockwise rotation) and +1 (clockwise rotation) [6]. Normalized helicity provides information of direction and intensity of helical flow.

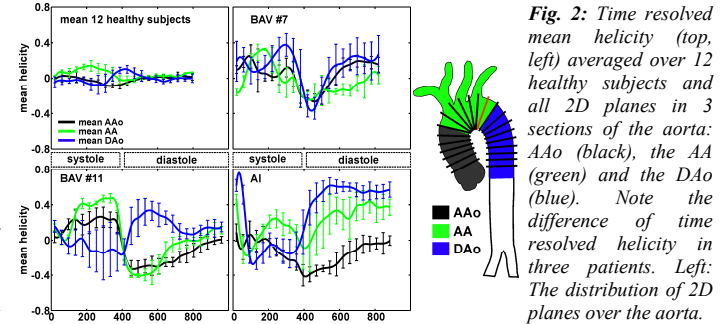
**Results:** Figure 1 shows the test-retest reliability of the repeated analysis of helical flow. On the *left* a comparison of time resolved mean helicity averaged over all healthy subjects and over all planes in the AAo (black), the AA (green) and the DAo (blue) for each measurement. On the *right* a Bland-Altman analysis for both measurements of temporal and spatial mean helicity for each plane. The bias (0.003) and the limits of agreement ( $\pm 0.06$ ) indicate a good correlation between both measurements. A comparison of the averaged mean helicity of all healthy subjects with 3 selected patients is shown in figure 2. Healthy subjects show increased mean helicity (-0.2 to 0.2) during systole and early diastole. Patients reveal much higher mean helicity (-0.4 to 0.4) over the entire cardiac cycle. Note the different direction of rotation compared to the healthy subjects. Figure 3 (*left*) illustrates color coded and interpolated mean helicity over the aorta of each healthy subjects and the repeated measurements. All healthy subjects show similar distribution of helicity with maximum helicity in the AAo and the beginning of the DAo. For patients (*right*) the distribution of mean helicity over the aorta reveals strong variations of mean helicity in direction of rotation and an increase of mean helicity compared to the healthy subjects. These findings are supported by a comparison of absolute peak mean helicity during systole and diastole between all 12 healthy subjects, 9 BAV patients and a patient with AI in figure 4. BAV patients demonstrated a significant (t-test:  $p<0.001$ ) increase in peak mean helicity during systole and diastole.

**Discussion:** In this study mean and absolute peak mean helicity in 2D planes, equally distributed along the aorta, for 12 healthy subjects and 20 patients were analyzed. Results show a good repeatability of time resolved mean helicity for healthy subjects. Remaining differences might be due to shifted and tilted slice positioning for the two different acquisitions. Quantification of helicity in patients with aortic valve disease revealed an expected significant increase of mean and peak mean helicity. There was a considerably more heterogeneous distribution of mean helicity in the aorta over all patients. This study provides the possibility to quantitatively correlate severity and progression of aortic disease in terms of 3D flow characteristics. The evaluation of normalized helicity has the potential to serve as a biomarker to understand the development of aortopathies.

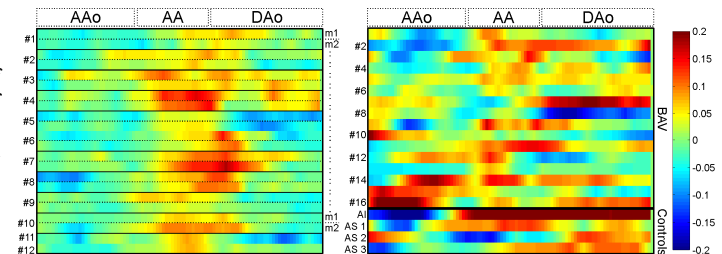
**References:** [1] Kilner et al., Circulation 1993, 88(5 Pt 1), pp. 2235-2247; [3] Morbiducci et al., Annals of Biomed. Eng., 2009, 37(3), pp. 516-531; [5] Lorenz et al., Proc. ISMRM, 2011, #3412;



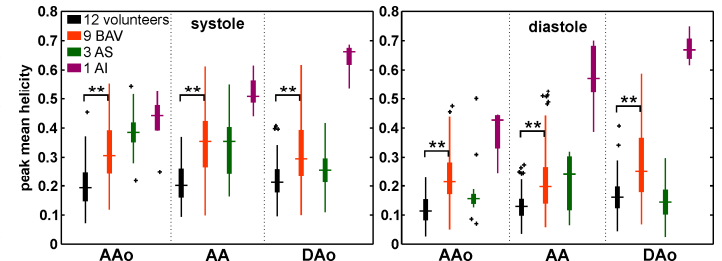
**Fig. 1:** Test-retest performance of time resolved mean helicity (left) for 10 out of 12 healthy subjects. Left: Mean helicity was averaged over all 2D planes in the AAo (black), the AA (green) and the DAo (blue) and averaged over all healthy subjects for measurement 1 (solid line) and measurements 2 (dashed line). Time between measurements was approx. one year. The same number of planes was placed along the aorta at approx. the same position. Right: Bland-Altman analysis for both measurements.



**Fig. 2:** Time resolved mean helicity (top, left) averaged over 12 healthy subjects and all 2D planes in 3 sections of the aorta: AAo (black), the AA (green) and the DAo (blue). Note the difference of time resolved helicity in three patients. Left: The distribution of 2D planes over the aorta.



**Fig. 3:** Color coded and interpolated mean helicity over all planes of the entire aorta for 12 healthy subjects and the repeated measurements (m1 & m2) for the first 10 healthy subjects (left). Results for 20 patients are also shown (right). Clockwise rotation is indicated by red color, counter-clockwise rotation by blue color. Note the discrepancy of the color pattern compared to healthy subjects.



**Fig. 4:** Comparison of absolute peak mean helicity shows a significant increase for the BAV patients and the AI patient during systole and diastole. The AS patients show an increase of peak mean helicity only during systole. \*\*  $p<0.001$ .

[2] Frydrychowicz et al., J. Comput. Assist. Tomogr., 2007, 31(1), pp. 9-15; [4] Morbiducci et al., Biomech Model Mechanobiol, 2011, 10, pp. 339-355; [6] Moffatt et al., J. Fluid Mech, 1969, 35, pp. 117-129