Assessment of Energy Loss in Aortic Stenosis and Age-Matched Controls using Bayesian Multipoint Phase-Contrast MRI

Christian Binter[1], Robert Manka[1,2], Simon H. Suendermann[3], Verena Knobloch[1], and Sebastian Kozerke[1,4]
[1]Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland, [2]Dept. of Cardiology, University Hospital Zurich, Zurich, Switzerland, [3]Division of Cardiovascular Surgery, University Hospital Zurich, Zurich, Switzerland, [4]Imaging Sciences and Biomedical Engineering, King's College London, London, United Kingdom

Introduction: The current gold standard for noninvasive assessment of aortic stenosis is Doppler echocardiography. The severity of the disease is judged by values derived from velocity data alone, assuming they are proportional to the loss of energy[1]. Phase-contrast MRI (PC-MRI) offers the possibility to obtain both velocities and Turbulent Kinetic Energy (TKE), a measure of the energy stored in turbulent flow[2]. This energy is eventually dissipated into heat and therefore lost, potentially providing a more exact measure of the additional work load of the heart. Previous smaller studies indicated significant differences in TKE between patients and healthy controls[2,3], however the two groups were not age matched. Aging and related physiological changes such as vessel wall stiffening could influence the TKE baseline in healthy subjects. As part of a larger ongoing study, a potential age dependency of total TKE in the aorta is investigated in this work, as well as the test-retest repeatability of TKE measurements.

$$S(k_v) = S_0 e^{-\frac{\sigma^2 k_v^2}{2}} e^{-ik_v v} \qquad \textbf{eq. 1}$$

$$TKE = \frac{\rho}{2}\sum_{i=1}^{3}\sigma_i^2 \qquad \textbf{eq. 2}$$

Methods: The signal S in PC-MRI can be modeled using **eq. 1**[2]. The mean velocity v is encoded in the phase, and variance σ^2 of the velocity distribution in a voxel leads to signal attenuation dependent on the first moment of the flow encoding gradients (k_v). This variance is a measure of turbulent flow and related to the TKE in that voxel (**eq. 2** – ρ denotes the fluid density, and i indexes measured velocity direction). For analysis, the TKE over all voxels in the ascending aortic arch are integrated (TKE_{total}) and normalized by the stroke volume for inter-subject comparability.

Flow data were acquired using a spoiled 3D phase-contrast gradient echo sequence. To increase the dynamic range of both TKE and velocity measurements, scans with 3 encoding velocities in each direction in addition to a flow compensated reference scan were acquired and combined using a Bayesian approach[3]. Scans were performed on a Philips Ingenia 3T scanner (Philips Healthcare, Best, The Netherlands) with a 28-channel coil. Voxel size was 2.5 mm isotropic, with matrix sizes ranging from 144x144 to 176x176 (16-24 slices) depending on subject anatomy. Twenty-four heart phases were acquired, resulting in a temporal resolution of 31-45 ms. Employing k-t PCA undersampling[4] with a reduction factor of 8 and 15/6 training profiles in phase/slice encoding direction, nominal scan times ranged between 6:45 and 8:20 min. Navigator efficiency was between 30 and 60%. Eighteen healthy subjects, aged 21-80 (56.9±16.9 years) and 3 patients (age: 79-84) with severe aortic stenosis scheduled for valve replacement were measured. Approval of the local Ethics Review Board was obtained and subjects were recruited upon informed consent. Test-retest reproducibility was investigated in 10 subjects by performing two separate scans with a 5 min break in-between, during which the subjects were told to walk around.

Results: The average difference of normalized TKE between test and retest was 0.035±0.023 mJ/ml or 8.9±5.8% of the mean normalized TKE value found in healthy volunteers. **Fig. 1** shows only minor correlation of age and normalized TKE, but a pronounced difference between patients and healthy controls. In **Fig. 2** exemplary TKE maps and flow patterns in a patient and an age-matched healthy volunteer (80 years) are presented. The maps indicate that recirculation alone leads to a moderate increase in TKE while high levels of TKE are primarily caused by jet formation. Mean normalized TKE in the healthy population was 0.46±0.16 mJ/ml, and 3.72±0.66 mJ/ml in the patient group. Peak velocities were 1.35±0.17 m/s and 4.22±0.07 m/s in controls and patients, respectively.

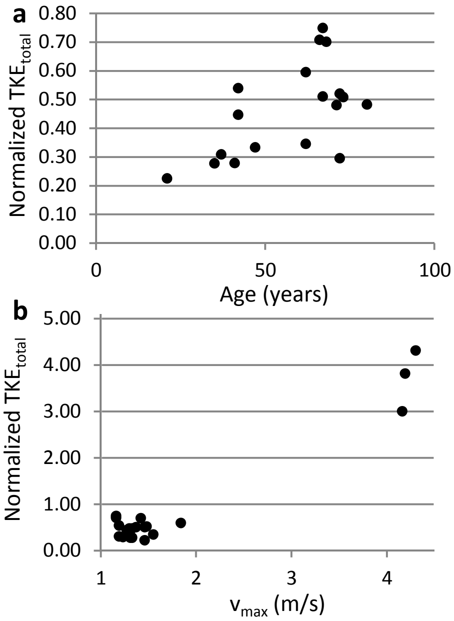

***Fig. 1**: No significant correlation between age and normalized total TKE could be found (a). A pronounced difference in normalized TKE between patients and healthy controls can be seen in (b).*

Discussion and Conclusion: The results suggest that the physiological range of TKE in the ascending aorta show only little variation with age. In conjunction with the high test-retest reproducibility and the significant differences detected between patients and healthy controls the method holds potential for a quantitative assessment of aortic stenosis. The straightforward positioning of the 3D volume in the aortic arch and the insensitivity of Bayesian multi-point PC-MRI to the exact setting of the encoding velocities greatly facilitate clinical application.

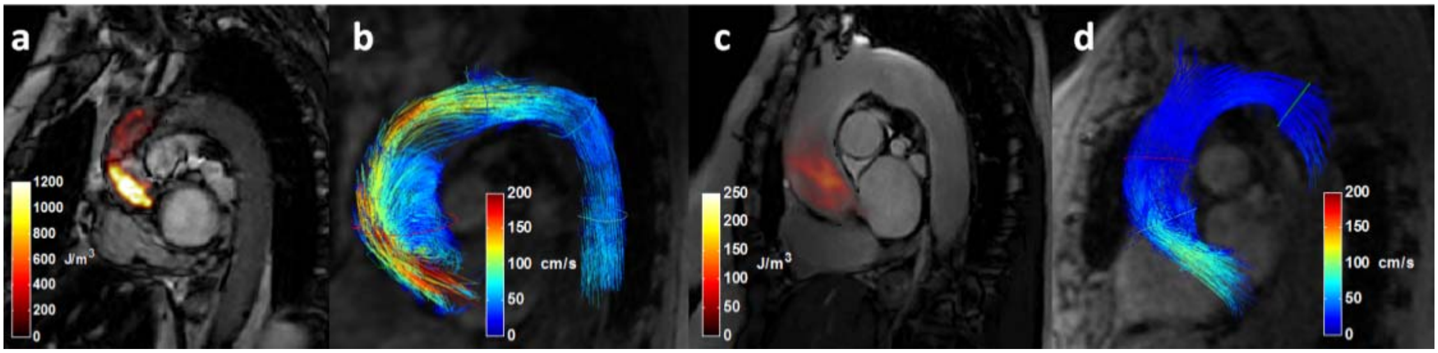

***Fig. 2**: Maps of Turbulent Kinetic Energy and systolic flow patterns in a patient with severe aortic stenosis (a, b) and a healthy, age-matched control (c, d). Recirculation is visible in both cases, although it is clearly more pronounced in the patient. Peak TKE values can be found around the jet in the patient and in the area of recirculation in the healthy control. The level of overall TKE is about 10 time lower in the control (scaling in a and c differs).*

References:

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