Comparison of Velocity Vector Fields and Turbulent Kinetic Energy Measured by MRI and Particle Tracking Velocimetry in a Realistic Aortic Phantom

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Introduction

The assessment of velocity vector fields using three-dimensional Phase Contrast (PC) MRI is increasingly used to study the cardiovascular circulatory system [1]. As the encoding velocity v_{enc} is typically adjusted according to the peak velocity of the pulsatile flow, the assessment of low velocities results in reduced velocity-to-noise ratio (VNR) as the encoding range of ±pi is not optimally used. A multi k_v-point acquisition method has been proposed to improve VNR, which, however, leads to prolonged scan times. With the use of spatiotemporal acceleration techniques, scan times can be shortened and the acquisition of additional k_v points becomes feasible. Additionally, Turbulent Kinetic Energy (TKE) may be computed to map dissipative losses [2-3].

In the present work we aim to compare velocity and TKE values obtained with multi k_v-point PC MRI relative to Particle Tracking Velocimetry (PTV), which serves as the reference standard for mapping fluctuating velocities in-vitro.

Methods

An elastic cast of an aortic arch equipped with a mechanical aortic valve (St. Jude Medical Inc., St. Paul, MN, USA) was set up in a pulsatile flow conduit [4]. In a second experiment, one leaflet of the valve was fixed in order to simulate a stenotic valve. For the MRI data acquisition, the setup was measured using a velocity encoded, cardiac triggered 3D gradient echo sequence on a 3T Philips Achieva System (Philips Healthcare, Best, The Netherlands). Within a scan time of 33 min, 5 velocity encodes according to v_{enc}= [200, 100, 50, 28, 20] cm/s in each spatial direction plus a non-encoded reference segment were acquired with 5x k-t undersampling and 11x6 training profiles with a temporal resolution of 46 ms. Images were reconstructed using k-t PCA [5]. Velocities v and intra-voxel standard deviation σ were computed using Bayesian parameter estimation [6-7] corresponding to following signal model: $S(k_v) = S_0 \cdot e^{-\frac{\sigma^2 k_v^2}{2}} \cdot e^{-ivk_v}$ [2]. In the PTV experiment, moving particles were tracked over 30 cardiac cycles. Mean and fluctuating velocities were derived from the average and standard deviation of repeated PTV measurements.

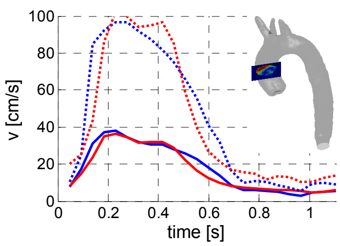

Fig. 1: Maximal and mean velocity profiles of pulsatile flow measured with MRI (blue) and PTV(red) in the stenosed experiment.

Results

Fig. 1 shows the waveform of the pulsatile fluid flow for the stenosed experiment measured with MRI and PTV in the cross section shown. The velocity vector fields in Fig. 2 show high agreement for high and low velocities. The vortex on the right side is well captured with both techniques. Linear regression resulted in $v_{MRI} = 0.93v_{PTV} + 3.2$ cm/s with correlation coefficient $r^2 = 0.73$ for the bileaflet experiment and $v_{MRI} = 0.91v_{PTV} + 2.6$ cm/s with $r^2 = 0.72$ for the stenosed experiment. In Fig. 3 velocity and TKE profiles are demonstrated for a systolic time point. The profiles in Fig. 3b) represent the two velocity peaks induced by the bileaflet valve. TKE values in Fig. 3b) are very low due to low velocities. For the stenosed experiment, the jet of elevated velocities up to 100cm/s is surrounded by increased TKE values >50 J/m^3.

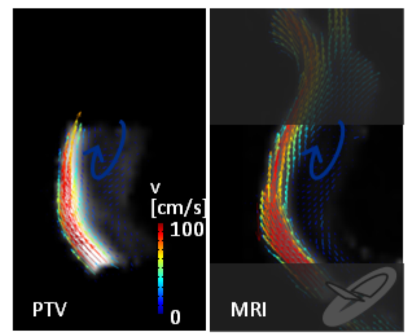

Fig. 2: Velocity vector field in the ascending aorta at t = 0.32s for the stenosed experiment.

Discussion

The comparison of velocity and TKE values acquired with 6-k_v- point PC-MRI and PTV shows very high agreement for the acquired range. This proof-of-concept experiment will be extended with the consideration of fewer k_v-points to shorten the scan time. In future experiments, higher velocities will be applied to cover the whole range of healthy and pathologically relevant values.

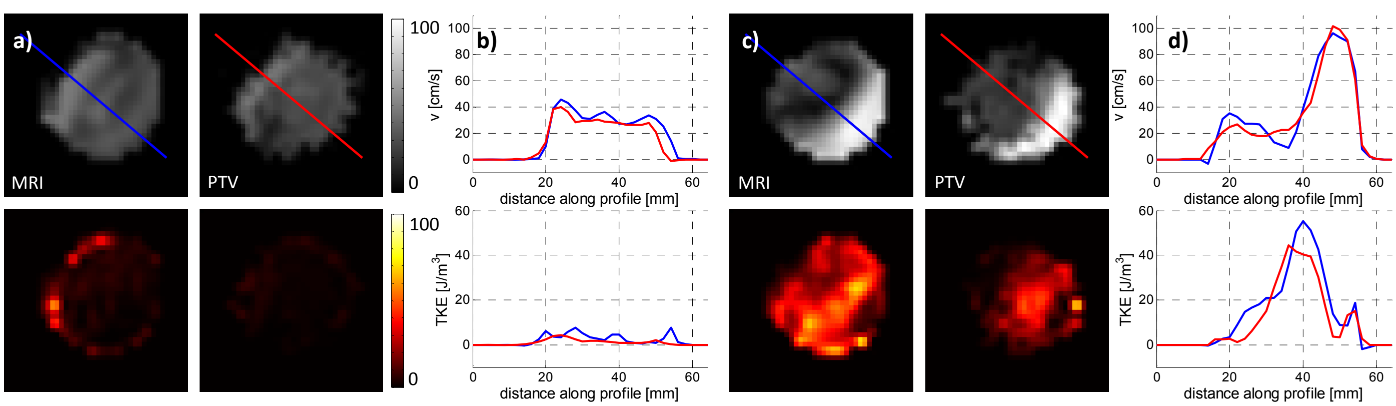

Fig. 3: Velocity (top row) and TKE (bottom row) profiles for the slice shown in Fig. 1 at t =0.23s for the bileaflet (a) and the stenosed valve (c). The profiles in b) and d) show a cross section as indicated in the velocity images. The same profiles are shown for TKE.

References

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Acknowledgement
SNF K-32K1_120531/1