4D phase contrast MRI in intracranial aneurysms: A comparison with patient-specific computational fluid dynamics with temporal and spatial inflow velocity boundary conditions as measured with 2D phase contrast MRI

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Introduction: It is believed that hemodynamic factors such as inflow jet size, impingement zone and wall shear stress, contribute significantly to aneurysm formation, growth and rupture. Studies attempting to predict these risk factors are mostly based on computational fluid dynamics (CFD) simulations. A disadvantage of CFD is that many assumptions are used. Therefore, time-resolved 3D phase contrast MRI (4D PC-MRI) for the assessment of these hemodynamic features may be preferred. However, up to now this technique has suffered from insufficient resolution. In this study high resolution 4D PC-MRI measurements in intracranial aneurysms are presented and these are compared with patient-specific CFD simulations in which a spatial and temporal velocity profile in three directions as measured with through-plane PC-MRI (2D PC-MRI) is prescribed as inflow boundary conditions.

Materials & methods: Retrospective gated 2D and 4D PC-MRI measurements were performed on a 3T MR system (Philips Healthcare, Best, Netherlands) in an 8-channel head coil in 4 patients. The study was approved by the local ethics committee and informed consent was given by the subjects. The slice for 2D PC-MRI was placed perpendicularly to the artery proximal to the aneurysm. Scan parameters 2D PC-MRI: Voxel size: 0.62x0.62x3 mm; FOV: 200x200 mm; TE/TR: 5.7/8.5 ms; FA: 10°; Cardiac phases: ± 36. Scan parameters 4D PC-MRI: Voxel size: 0.8x0.8x0.8 mm; FOV: 200x200x20 mm; TE/TR: 3.0/5.8 ms; FA: 15°; Cardiac phases: 10. Both scans used a Venc of 100x100x100 cm/s and a SENSE factor of 3. The lumen in both scans was semi-automatically segmented for all cardiac phases and in every slice of the fast field echo images using a level set evolution algorithm [1]. An additional Time-Of-Flight (TOF) sequence was performed to assess the anatomy of the aneurysm. The geometric vascular models used by CFD were automatically created from 3D Rotational Angiography datasets. The 2D PC-MRI slice was registered onto the TOF geometry of the aneurysm. This TOF geometry with the 2D PC-MRI velocity information was subsequently registered onto the CFD mesh. As a last step, the 2D PC-MRI velocity information was interpolated to the faces of the CFD inflow boundary. Murray's law [2] was used for outflow boundary conditions. CFD was performed using FLUENT (Ansys, Canonsburg, PA, USA), with density 1060 kg/m^3 and viscosity 0.004 Pa.s. To minimize transient effects, the third of three simulated cardiac cycles was used for comparison with 4D PC-MRI. Sizes of the meshes are given in table 1. Simulation time was ±5 days. For a voxel-wise comparison between the 4D PC-MRI and the CFD results, the CFD velocity information was registered and interpolated to the 4D PC-MRI data.

Table 1: Size, location and mesh size of the aneurysms

	Location	Size (mm, l x w x h)	# tetrahedral cells in mesh
Ane 1	Left Middle Cerebral Artery	13.1 x 7.6 x 8.1	2.029.112
Ane 2	Basilar Artery	8.7 x 6.3 x 7.4	1.422.476
Ane 3	Right Middle Cerebral Artery	14.7 x 8.1 x 9.6	1.657.049
Ane 4	Right Middle Cerebral Artery	7.21x 5.4 x 6.3	975.627

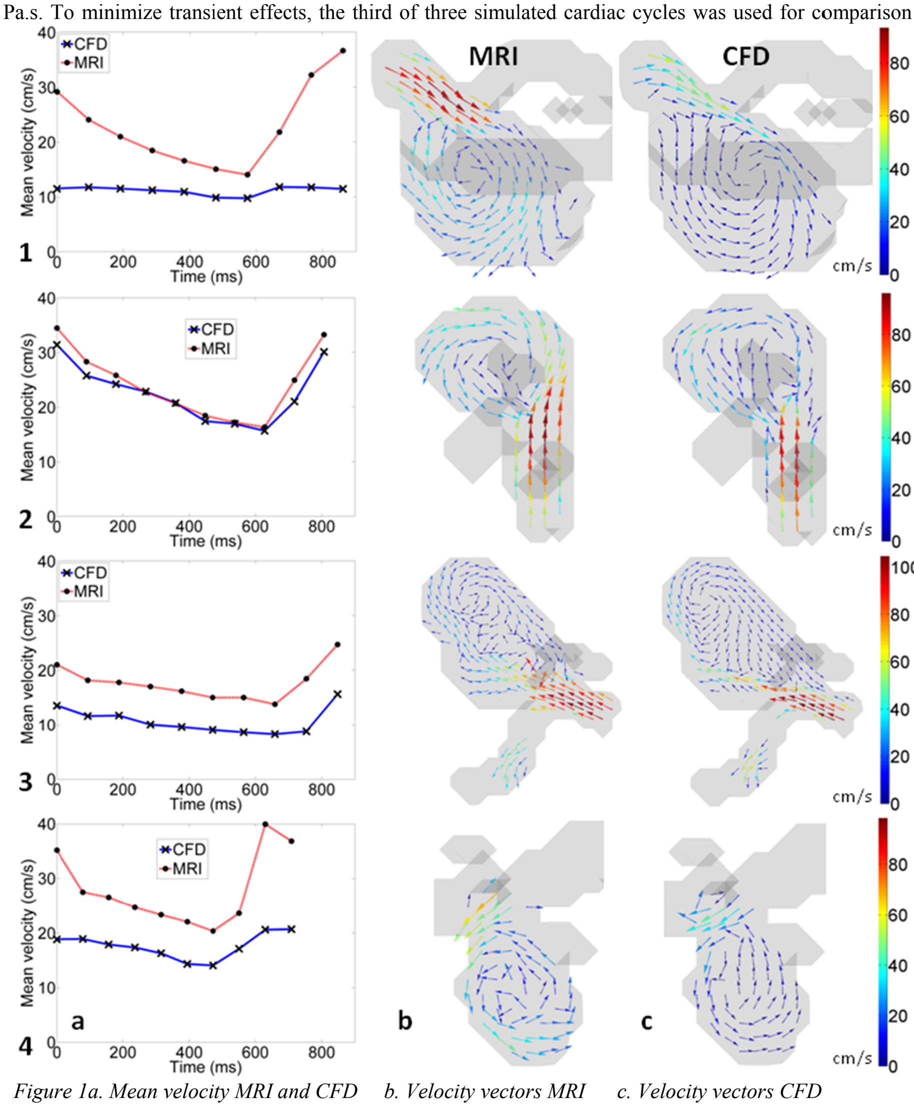

Figure 1a. Mean velocity MRI and CFD b. Velocity vectors MRI c. Velocity vectors CFD

Results: In figure 1a the mean velocity in the aneurysms is displayed. The velocity vectors in a characteristic slice for the 4D PC-MRI measurement and CFD simulation are displayed in column b and c respectively. In table 2 the mean and standard deviation of the paired difference between the 4D PC-MRI and CFD velocity magnitude are given as well as the median of the angles between the velocity vectors in 4D PC-MRI and CFD. The mean velocity in aneurysm 2 corresponded well, whereas for aneurysm 1, 3 and 4 the mean velocity in the CFD simulation was lower than in the 4D PC-MRI measurement. This is also shown in table 2. The standard deviations of the paired difference were similar for all aneurysms. Qualitative similarities between the velocity vectors for the 4D PC-MRI measurement and CFD simulation can be appreciated for all aneurysms, see figure 1b and c. High and low velocities were observed in similar regions as well as the main vortices. This is reflected by the similar median of the angles between 4D PC-MRI and CFD for all aneurysms, shown in table 2.

Table 2: Mean, standard deviation of the paired difference and median angle between 4D PC-MRI and CFD

	Ane 1	Ane 2	Ane 3	Ane 4
Mean (cm/s)	11.6	1.6	7.0	10.5
SDp (cm/s)	12.7	12.8	10.0	13.2
Median angle (°)	22.8	23.6	36.3	22.4

Discussion/Conclusion: Lower mean velocities in CFD may be attributed to noise in the 4D PC-MRI measurements and possible discrepancies in viscosity between CFD and 4D PC-MRI. Although the inflow velocity assumption in CFD is minimized by using the 2D PC-MRI measurement, other assumptions as the use of Murray's law and a static geometry remain unsolved. The flow patterns simulated with CFD may therefore deviate from measured flow patterns in 4D PC-MRI. In CFD, however, the resolution is much higher, and non-interpolated results show more flow details. Thus, for hemodynamic assessment, CFD and 4D PC-MRI may complement each other.

References: [1] Li et al. Proc IEEE CVPR'05, San Diego, USA 2005;1:430-436 [2] Murray. Proc Natl Aca Sci USA;12(3):207-14 (1926)