Universität zu Köln

Center for Data and Simulation Science

Technical Report Series
Center for Data and Simulation Science

Daniel Giese, Alexander Heinlein, Axel Klawonn, Jascha Knepper, and Kristina Peters

Comparison of MRI measurements and CFD simulations of hemodynamics in intracranial aneurysms using a 3D printed model - Influence of noisy MRI measurements

Technical Report ID: CDS-2019-11
Available at http://kups.ub.uni-koeln.de/id/eprint/9671
Submitted on May 29, 2019

Comparison of MRI measurements and CFD simulations of hemodynamics in intracranial aneurysms using a 3D printed model - Influence of noisy MRI measurements

Daniel Giese[1], **Alexander Heinlein**[2,3], **Axel Klawonn**[2,3], **Jascha Knepper**[2], and **Kristina Peters**[1]

[1] University of Cologne, Faculty of Medicine and University Hospital Cologne, Institute for Diagnostic and Interventional Radiology, Cologne, Germany
[2] University of Cologne, Department of Mathematics and Computer Science, Cologne, Germany
[3] University of Cologne, Center for Data and Simulation Science, Cologne, Germany, URL: *cds.uni-koeln.de*

MRI (Magnetic Resonance Imaging) measurements and CFD (Computational Fluid Dynamics) simulations for blood flow in intracranial aneurysms are compared for a benchmark problem. In particular, it is shown that noise and other artifacts in the MRI measurements have an influence on certain properties of the flow field, e.g., on the boundary flow and mass conservation.

Copyright line will be provided by the publisher

1 Introduction

MRI (Magnetic Resonance Imaging) measurements are frequently used in the diagnosis of the cardiovascular system, e.g., intracranial aneurysms. However, they are typically subject to noise and artifacts that disturb the measured flow field. In particular, the precision of the MRI measurements is quite poor for velocities in vicinity of the walls. This is due to a worse signal- to-noise ratio (compared to high velocities) and the so called partial volume effect. The velocities in vicinity of the walls are important for the computation of the wall shear stresses, which are particularly important for the diagnosis of intracranial aneurysms because they are a measure for the likelihood of rupture of aneurysms. Moreover, mass conservation of the MRI flow field is typically impaired. We investigate these disadvantages of MRI-measured flow fields based on the benchmark introduced in [2], i.e., we compare the MRI measurements to CFD simulations.

2 Benchmark Problem

We use the geometry depicted in fig. 1 to compare the numerically simulated flow field with MRI measurements. Long sections of in- and outflow minimize the influence of boundary data on the flow near the aneurysm; see [2] for further details.

For the convenience of the reader we now quote verbatim the description of the MRI measurements as in [2]:

MRI measurements: The printed model was connected to a pump and introduced into a 3 Tesla MRI system (Ingenia, Philips, Best, The Netherlands). The pump (Acandis, Pforzheim, Germany) was placed outside the magnet room, connected via tubing to the model and generated a continuous flow (rate: $1.76\,\mathrm{ml}^3/\mathrm{s}$) through the phantom. Water and a contrast agent (Dotarem, Guerbet, Villepinte, France) with a concentration of $1.7\,\mathrm{mmol/l}$ were used. A three-dimensional gradient-echo sequence with three-directional phase-contrast flow encoding acquisition sequence [1] was used to measure velocities in the model with an isotropic resolution of $0.3\,\mathrm{mm}$, reconstructed to $0.15\,\mathrm{mm}$. The velocity encoding value (VENC) was set to $30\,\mathrm{cm/s}$. To correct for background phases, the measurement was repeated with the pump turned off and the phase subtracted from the first measurement.

Mathematical model: Given a domain Ω and the kinematic viscosity ν we model a fluid using the time dependent incompressible Navier-Stokes equations for a Newtonian fluid. Specifically, we seek to approximately solve

$$\begin{aligned} \frac{\partial u}{\partial t} - \nu\Delta u + (u\cdot\nabla)u + \nabla p = 0, &\quad \text{in } \Omega,\\ \operatorname{div}(u) = 0, &\quad \text{in } \Omega, \end{aligned}$$

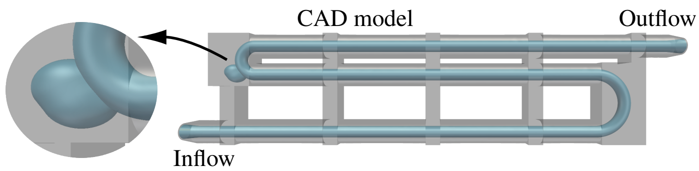


Fig. 1: CAD geometry. Vessel diameter: $4\,\mathrm{mm}$. Approximate aneurysm dimension: $7{\times}5{\times}4\,\mathrm{mm}$ (volume: $90\,\mathrm{mm}^3$); cf. [2].

with a parabolic inflow profile at the inlet, a no-slip condition at the vessel wall and a do-nothing Neumann condition at the outlet. We use a convective-explicit formulation to linearize the Navier-Stokes equations.

Copyright line will be provided by the publisher

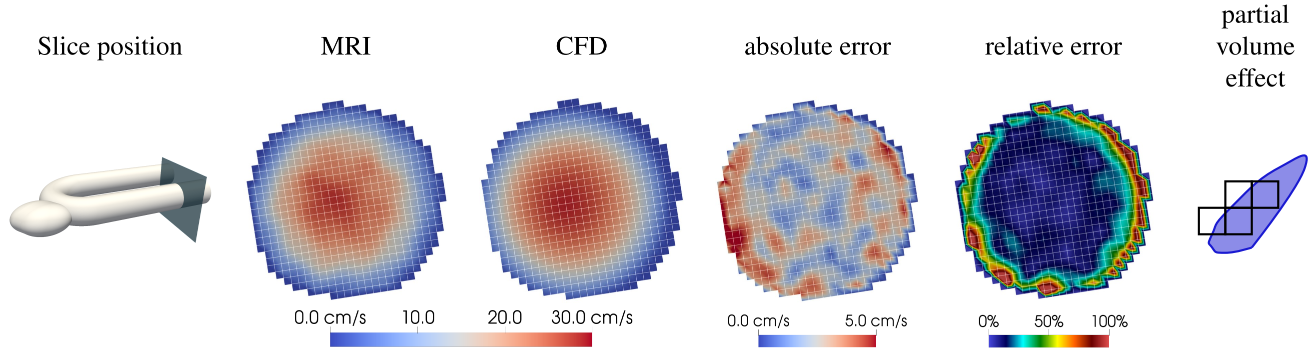


Fig. 2: Relative error large near boundary due to noise and partial volume effect. The slice position is marked in the top-left image.

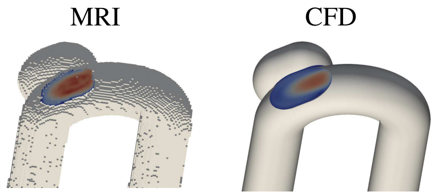
3 Numerical Simulation

Based on a CAD geometry a volume mesh was generated yielding 9.2 mio. degrees of freedom. The numerical simulation is carried out based on version 3.8.8 of LifeV [3]. The time discretization is done with a BDF-1 scheme and the space discretization with stabilized $\mathcal{P}_1$-$\mathcal{P}_1$ elements. Specifically, for the inf-sup and convection stabilization the PSPG (Pressure Stabilized Petrov-Galerkin) and SUPG (Streamline-Upwind Petrov-Galerkin) approaches [4] are used. For some more details, see [2].

The presented numerical results are based on steady state solutions and were computed using a kinematic viscosity of $\nu = 1.0\,\mathrm{mm}^2/\mathrm{s}$. Furthermore a parabolic inflow profile (flow rate: $1.76\,\mathrm{cm}^3/\mathrm{s}$) was prescribed, which results in a peak velocity of a fully developed flow in a straight tube (vessel diameter: $4\,\mathrm{mm}$) of $28.0\,\mathrm{cm/s}$.

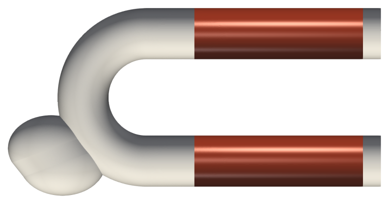
In fig. 2, we highlight one key advantage of CFD simulations over MRI measurements. At the position of the depicted slice (left image), the flow profile is almost parabolic. The visual comparison shows a good agreement between the MRI measurement and the CFD simulation (center left images) as is verified by the absolute error. However, the relative error grows towards the boundary. This is to be expected: On the one hand, MRI voxels near the boundary are partially outside of the geometry (*partial volumen effect*, right image), which creates a smearing effect. On the other hand, MRI measurements outside of the geometry are pure noise, which can introduce artifacts near the boundary. For these reasons and the comparatively lower resolution of MRI images, accurate computations of wall shear stresses can be difficult [1].

In fig. 3, the CFD simulation computes an almost zero flow rate at the interface of the aneurysm and the vessel; in theory this should be identical to zero. The MRI measurement, due to noise, shows a much larger value. In fig. 4, the mean velocities in two sections are given. For the CFD simulation these values are almost identical, whereas the MRI measures significantly different values.



	MRI	CFD
area [cm^2]	0.140	0.162
flow rate [cm^3/s]	0.251	0.008

Fig. 3: CFD: Accurate flow rate at aneurysm-vessel interface (exact solution: zero). MRI: Large (relative) error in flow rate.



	mean vel. [cm/s]	
	top part	bottom part
MRI	12.82	13.47
CFD	13.93	13.96

Fig. 4: Similar mean velocities in CFD simulation w.r.t. to the bottom and top section. Comparatively large deviations in MRI measurement.

ACKNOWLEDGEMENT: The computations were carried out on the Cologne HPC cluster CHEOPS. ParaView (*paraview.org*) was used for the visualization.

References

[1] J. Szajer, K. Ho-Shon, A comparison of 4D flow MRI-derived wall shear stress with computational fluid dynamics methods for intracranial aneurysms and carotid bifurcations - A review, Magn Reson Imaging, 48, 62-69 (2018).

[2] D. Giese, A. Heinlein, A. Klawonn, J. Knepper, K. Peters, Comparison of MRI measurements and CFD simulations of hemodynamics in intracranial aneurysms using a 3D printed model - A benchmark problem, Technical Report CDS-TR 2019-9, preprint at http://kups.ub.uni-koeln.de/id/eprint/9670, Center for Data and Simulation Science, University of Cologne, 2019.

[3] L. Formaggia, M. Fernandez, A. Gauthier, J. F. Gerbeau, C. Prud'homme, and A. Veneziani, The LifeV Project. Web. *lifev.org*.

[4] T. E. Tezduyar, Stabilized Finite Element Formulations for Incompressible Flow Computations, ADV APPL MECH, 28, 1-44 (1991).

Copyright line will be provided by the publisher