Flow investigation inside a cerebral giant aneurysm

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Abstract Cerebral aneurysms are dangerous dilatations of the intracranial vasculature. As these aneurysms are located in the Circle of Willis, which is the essential vessel structure supplying the brain with blood, a rupture leads to drastic consequences for the patient. Physicians are faced with the decision to leave the aneurysm untouched or to intervene. This decision is strongly related to the assessment of rupture risk. It is assumed that hemodynamic factors, i.e. forces resulting from the blood flow itself, play an important role. Thus, a full understanding of correlations between blood flow characteristics and rupture risk is the long-term, ambitious objective of our research. A second aspect that has to be considered is the method of treatment. Several options (clip, coil, flow diverter stenting) are available. A patient-specific analysis and optimization of interventional devices would be ultimately very advantageous. Fluid dynamical simulations provide the most promising tool to reach such ambitious objectives, but require validation.

In this contribution, image-based flow investigations of a steady flow through the silicone phantom model of an anatomically realistic giant aneurysm are presented and used as validation source for computational fluid dynamics (CFD). Therefore, the vessel geometry was segmented and reconstructed from angiography data delivering a geometry suitable for simulations as well as for casting a silicone block with included hollow vessels for optical measurements. A stereoscopic particle image velocimetry (PIV) arrangement featuring an index-matched artificial blood liquid is used to obtain averaged velocity vectors in ten parallel planes through the aneurysm sac. From this data streamlines and isocontours of velocity are presented, which show the three-dimensional rolling motion inside the sac. Several PIV planes are compared to their simulation counterparts and show excellent agreement proving the ability of CFD and its assumptions to reliably capture the essential flow features in such cases. As an outlook, the stereo-PIV setup has been slightly modified to enable 3D Particle Tracking Velocimetry (PTV) at low seeding concentrations.

1. Introduction

Cerebral aneurysms are abnormal bulges of the intracranial vasculature emanating from a weakening of the arterial wall structure. According to Bonneville et al. (2006), statistically, every 20th person of the western population is affected. These aneurysms are often located in the Circle of Willis, which is the essential vessel structure supplying the brain with blood. Thus, a rupture followed by a serious bleeding into the surrounding subarachnoid space comes with severe consequences for the affected person. The mortality rate is reported to be about 60% (Yu et al. (1999)).

After detection of such an aneurysm by medical imaging techniques experts have to decide whether to leave the aneurysm untouched or to intervene. As an intervention is still related to a significant risk for the patient (according to Sadhasivan et al. (2002), the mortality is reported to be almost 18% 30 days after treatment) this decision has to be made under consideration of all possible influencing factors. Of course, assessment of the risk of rupture is one of the most prominent ones. It is assumed that hemodynamic factors, i.e. forces resulting from the blood flow itself, play an important role. Thus, a full understanding of correlations between blood flow characteristics and rupture risk is one major objective of our research in this field.

If a positive decision for medical treatment is retained, a second important aspect has to be considered: which intervention method will lead to the best prognosis for the patient? Typical techniques are surgical clipping of the aneurysm neck, endovascular placement of coils inside the aneurysm or deployment of flow diverter stents. Of course, a meaningful judgement is impossible without the expertise of medical experts. However, as it is intended to fluid-dynamically inactivate the flow within the aneurysm by some type of occlusion, it is possible to derive optimal intervention techniques. This applies in particular to the patient-specific optimization of flow diverter geometry, size and position in order to achieve maximum reduction in flow activity inside the aneurysm. For this purpose, Computational Fluid Dynamics (CFD) is promising.
However, several assumptions have to be made in CFD which require a thorough validation. Medical in vivo imaging techniques still suffer from relatively low resolution, preventing accurate comparisons. Therefore, in vitro experiments featuring high resolution imaging techniques like Particle Image Velocimetry (PIV) in model aneurysm are usually employed to validate CFD simulations (see Ford et al. (2008)). This contribution deals with stereoscopic PIV experiments in a silicone phantom model of an intracranial giant aneurysm, delivering three-component velocity information in ten light sheet planes through the aneurysm sac. Three-dimensional streamlines are constructed from the data, which allow for a comprehensive insight of the complex flow structure within the sac. Additionally, the flow patterns of three different flow rates are compared to CFD results and show excellent agreement, proving successful validation of the simulation approach by the experimental data.

2. Experimental methods

The experiments were carried out using the silicone phantom model of a realistic brain aneurysm (see Fig. 1) with a diameter of roughly 20 mm. Therefor, 3D rotational angiography data from the patient was segmented, manually corrected and smoothed to reduce artefacts resulting from surrounding vessels to produce a computational geometry of the vasculature. The manufacturing of the silicone model required several steps performed by ac.biomed (Aachen, Germany). The geometry was cut and modified slightly as a basis for the silicone block (slots were added to hold typical tube connectors, see again Fig. 1). The vasculature was built by a rapid prototyping technique and fixed inside an acryl glass box. Casting of a two-component silicone liquid (Wacker RT 601, Burghausen, Germany) and careful removal of the rapid prototyping material after silicone hardening were the final step to create the silicone block featuring the hollow vessel structure (see Fig. 2). The total dimensions of the block were 67 mm x 56 mm x 31 mm. 

As transparent substitute fluid for blood, a mixture of distilled water, glycerin, sodium chloride and xanthan gum was used as described in Roloff et al. (2013). This artificial blood liquid (ABL) featured fluid dynamical properties in the range of human blood, i.e. a density of $\rho = 1130 \text{ kg/m}^3$ and shear-thinning behavior with a dynamic viscosity at infinite shear of $\mu = 4.95 \text{ mPa.s}$. Also, the liquid is composed such as to match the refractive index of the silicone block ($n = 1.41$) at room temperature to reduce optical deflections at the curved interfaces of the model (see Fig. 2). For the PIV measurements, small resin microspheres (diameter $d = 10.46 \pm 0.18 \text{ pm}$, density $\rho = 1510 \text{ kg/m}^3$) were as seeding. For best signal-to-noise ratio these particles were doped with Rhodamine B (peak emission at 584 nm) and the camera lenses were equipped with 540 nm optical high pass filters to solely record the particles’ fluorescence light and to suppress unwanted laser light reflections.
The general measurement setup is depicted in Fig. 3. As a strong velocity component normal to the predefined observation surface of the block was expected, a stereoscopic PIV setup was chosen. Hence, it was possible to minimize the inherent perspective error of the standard PIV method and to obtain all three components of the velocity vector for the observed planes. Consequently, two PIV cameras (ImagerIntense, LaVision, Göttingen, Germany), equipped with Scheimpflug adapters and Macro lenses (Zeiss MacroPlanar T 2/50) were installed in oblique viewing direction (-30°/+30° with respect to the outer wall of the silicone block defining the x-y-plane). The block was placed inside a PMMA basin (see right hand side of Fig. 3) utilizing the back window as bedstop for the block. This basin featured oblique windows allowing for a wall-normal viewing direction for both cameras and was filled with the ABL during measurement and calibration. It was constructed to hold a microstage traverse on top, equipped with a two-plane calibration target for calibration purposes.

A double-pulse Nd:YAG-PIV Laser (Spectra Physics) provided illumination of the fluorescent particles through the bottom of the basin and after forming the laser beam into a light sheet (0.5mm thickness). The light sheet planes were aligned parallel to the backside of the basin. Shifting of the planes in z-direction was obtained by traversing of basin and cameras.

![Fig. 2: Silicone block perfused with water (left) and ABL (right).](image)

![Fig. 3: Measurement setup involving gauge pressure and differential pressure sensors (1 and 2), ultrasonic flow meter (3), precision valve (4), PIV laser (5), PIV cameras in oblique viewing arrangement (6), acryl glass basin including silicone model (7) as well as liquid tanks (8 and 9) (left); photograph of the illuminated basin with silicone model (right).](image)

The liquid circuit consisted of a peristaltic pump (Watson Marlow 520Du, UK) hoisting the liquid from the bottom tank to the upper tank. This upper tank was constantly flooded to ensure a constant head pressure, delivering steady flow conditions at the inlet of the aneurysm. Both tanks were continuously stirred by magnetic mixers to avoid sedimentation of the tracer particles. The flow rate through the aneurysm had to be regulated manually by a precision valve and monitoring of the data from an ultrasonic flow meter (Sonoflow IL.52/3, Sonotec, Halle, Germany) that was calibrated for the artificial blood liquid. The standard tube connectors for linking the aneurysm block to the liquid circuit were modified with pressure drillings in order
to measure the gauge pressure at the inlet (Kobold SEN-3277 B146, Hofheim, Germany) as well as the pressure loss from inlet to outlet (BD Sensors DMD 331, Thierstein, Germany). The measured data can be found in Table 1.

3. PIV Results

A total of 10 planes almost entirely covering the aneurysm sac were measured (see Fig. 4). Microtraversing of basin and cameras allowed to precisely position the light sheet planes with interplane distances in z-direction, i.e. in plane normal direction, by 2 mm. Only the outermost planes were shifted by 1 mm. Prior to placement of the aneurysm block itself, for each z-position the 3D calibration target was placed inside the basin so that the light sheet was grazing the front plane of the target and camera images for calibration could be recorded.

![Fig. 4: Positioning of the PIV light sheet planes through the aneurysm model.](image)

Three different steady flow rates ranging from 200 ml/min to 400 ml/min were used for the measurements. Averaged values for flow rate, gauge pressure at inlet of the block and pressure loss through the aneurysm block are given in Table 1.

**Table 1: Perfusion details for the flow experiments**

<table>
<thead>
<tr>
<th>Label</th>
<th>“200”</th>
<th>“300”</th>
<th>“400”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate in ml/min</td>
<td>200.1 ± 1.1</td>
<td>299.5 ± 0.7</td>
<td>400.1 ± 0.6</td>
</tr>
<tr>
<td>Gauge pressure in mmHg</td>
<td>106.1 ± 0.2</td>
<td>95.4 ± 0.1</td>
<td>83.3 ± 0.1</td>
</tr>
<tr>
<td>Pressure loss in Pa</td>
<td>333.8 ± 4.4</td>
<td>667.6 ± 3.7</td>
<td>1142.7 ± 4.2</td>
</tr>
</tbody>
</table>

For recording and processing of the PIV measurements the software DaVis 8.16 (LaVision, Göttingen, Germany) was used. Three image pairs per second were recorded for five minutes at each flow rate and for each plane. Processing steps involved calibration, particle self-calibration, masking of the aneurysm by a time-series maximum image, subtraction of a time sliding minimum image and a multi-pass stereo cross-correlation with final interrogation window size of 16 x 16 px and 50% overlap, resulting in a velocity vector every 200 μm. Visualization of the data was carried out via Ensight (CEI, Apex, NC, USA).

![Fig. 5: Velocity vectors resulting from stereo PIV measurements for 200 ml/min (left), 300 ml/min (center) and 400 ml/min (right) flow rate (mind the different colorbar scales).](image)
From the averaged velocity vectors in Fig. 5 the global flow structure inside the aneurysm can be visualized. The high velocity stream from the inlet forms a jet spreading widely in the bottom region of the aneurysm wall. As the outlet is situated opposite to the inlet on the bottom side, a significant part of the flow directly exits the aneurysm here (short-cut flow). The other part streams upwards along the aneurysm wall forming a large vortex structure that fills the entire aneurysm sac, inducing a large-scale rotating motion. This can be better observed in Fig. 6, where streamlines are plotted which have been integrated from the interpolated three-dimensional three-component (3D3C) dataset of all 10 PIV planes.

![Fig. 6: Post-processed streamlines inside the aneurysm sac for 200 ml/min (left), 300 ml/min (center) and 400 ml/min (right) flow rate (mind the different colorbar scales).](image)

Apparently, most of the flow then leaves the aneurysm around the axis of rotation of this vortex. With increasing flow rate the velocities inside the aneurysm increase as expected (note the different scales of the colorbars). Fig. 7 depicts isocontours of the velocity magnitude (0.25 m/s), from which it can be seen that at 400 ml/min flow rate the high velocity zone penetrates widely into the sac, following the large-scale vortex. At both lower flow rates only the bottom inflow jet features such high velocities.

![Fig. 7: Isocontours of velocity magnitude for 200 ml/min (left), 300 ml/min (center) and 400 ml/min (right) flow rate.](image)

### 4. CFD simulations and comparison to measurements

An important aim of the experimental investigation was to validate the results of numerical simulations and to strengthen the trust of physicians into hemodynamic simulations. Therefore, the surface of the phantom model was detected with high resolution (50 μm) using a micro-CT scanner (Nanotom S 180, GE-Phoenix, Wunstorf, Germany). It is important to mention that this represents a crucial step for valid comparisons, since the original surface model and the manufactured silicone model considerably differed. After the three-dimensional reconstruction, a fine surface re-meshing was applied and the volume was spatially discretized using a suitable combination of tetrahedral and prismatic elements. The mesh was generated using ANSYS ICEM CFD 14.0 (Ansys Inc., Canonsburg, PA, USA) and contained approximately 6.1 million elements with an average cell size of 0.1 mm.

The measured flow rates were used as inlet boundary conditions and a relative zero pressure was defined at the outlet. The walls were assumed to be rigid and no-slip boundary conditions have been applied. The artificial blood liquid was treated as an incompressible, laminar fluid. The shear-dependency of the viscosity...
was modeled using the Carreau-Yasuda model, whereas all model parameters have been measured in our rheology lab in advance.

The three steady hemodynamic simulations were carried out with STAR-CCM+ 9.02 (cd-adapco, Melville, New York, USA) and the numerical solution was considered as converged after the residuals decreased below a value of $10^{-5}$. The subsequent comparison of the measured and simulated velocity fields was performed using the post-processing software EnSight (CEI, Apex, NC, USA). Fig. 8 illustrates the in-plane velocity magnitudes for three different locations using the same colorbar. Overall, an excellent agreement between both independent methods is visible and the main flow patterns are captured in a nearly identical manner. Regions of high velocity gradients, which are particularly important for the analysis, are found at very similar locations. Slight differences can be recognized close to the center of the aneurysm where nearly no motion is present. The numerical solution overestimates the size of this area. However, the comparison reveals that CFD can be safely and accurately used in order to investigate the blood flow behavior within intracranial aneurysms.

**Fig. 8:** Velocity magnitude comparison for three planes at 200 ml/min inflow rate: hemodynamic simulation (left) vs. optical measurement (right)

### 5. Conclusions and Outlook

In this work stereoscopic PIV measurements of the steady flow inside the model of a cerebral giant aneurysm have been presented. The data of ten parallel light sheet planes delivering full three-component velocity vectors has been used to compute streamlines and isocontours of velocity from which a
comprehensive insight into the vortical flow structure inside the aneurysm sac can be derived. CFD simulations of the steady flow show very good agreement with the in-vitro measurements, proving the ability of CFD to reliably predict hemodynamic features.

In further steps the aneurysm model will be equipped with different flow diverter stents. Then, it will be investigated experimentally how such a device alters the hemodynamic conditions in the model. An interesting option for image-based characterization is 3D Particle Tracking Velocimetry (3D PTV) because it allows 3D3C measurements at low seeding concentrations. Particularly after stent deployment, when flow activity inside the aneurysm sac will hopefully be heavily reduced, sedimentation of tracer particles will be unavoidable. Thus, a low number of tracer particles may be beneficial. A first test using the stereo camera setup was carried out by forming the laser beam into a volume illumination. A very low seeding number density (roughly 90 particles per camera image) allowed 3D reconstruction of the particle positions using epipolar triangulation. Tracking with a nearest neighbor approach and utilizing the Hungarian Algorithm delivered 3D scattered velocity vectors shown as color-coded spheres in Fig. 9 (summed up over the sequence of 500 images).

Fig. 9: 3D particle positions inside the aneurysm sac coded by velocity magnitude as evaluated by the PTV experiment.

More detailed PTV experiments, reducing assignment ambiguities are ongoing and will be used to check again whether CFD can also reliably characterize the hemodynamics after stent deployment. Of course, computational modeling of the flow diverter geometry requires more modeling effort for the CFD and thus these results need to be even more carefully crosschecked with experimental methods.

6. Acknowledgements

The authors are grateful to Prof. Skalej and to his team from the institute of neuroradiology, Magdeburg for providing the angiography data. Many thanks go to Dr. Rannabauer, IWF, Magdeburg for \( \mu \)-CT-scanning of the phantom model and particularly to Dr. Geisler, DLR, Göttingen for valuable discussions regarding the stereo PIV setup. Financial support by the STIMULATE project of the BMBF is also kindly acknowledged.

6. References

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