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Experimental and Numerical Dye Washout Flow Visualization

Flow analysis in the realistic model of pathologic artery enlargement (aneurysm)

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Abstract : Flow visualization in realistic models is very important for the study of pathological vessel enlargements (aneurysms). Furthermore, flow visualization may help in treatment decisions. However, the most interesting parameter, the wall shear stress, is difficult to measure in vivo. This parameter can be provided by computational fluid dynamics. However, the numerical methods don't visualize the results as does of the dye washout method – a method often used in flow studies. This experimental method simulates the cine angiograms acquired during contrast agent injection used in medicine. In this paper we present the dye washout visualization of CFD results and compare these results with the conventional dye washout experiments in the same aneurysm model under steady flow conditions.

Keywords : Visualization, Dye Washout, CFD.

1. Introduction

Dye washout is a broadly used method in experimental flow visualization. This method is commonly used for flow studies in models pathologic vessel enlargements (aneurysms) (Gobin et al., 1994). The method allows a qualitative assessment of intraaneurysmal flow. There are two main reasons to use this method. First, the method simulates the cine angiograms used in clinical medicine. The angiograms are acquired non-invasively using X-rays during the injection of contrast agent into blood vessels. Second, the method allows flow visualization in aneurysm after experimental simulation of coil embolization. Endovascular coil embolization is a therapeutic option. The method is based on filling of the aneurysm with ultrafine platinum-coated spiral wire (coils) via a catheter. However, only about 30% of the aneurysmal volume may be filled with coils. The effect depends on the resulting flow disturbance. This post-coiling flow is very difficult to measure using quantitative methods such as LDA or PIV because coils prevent optical acquisition.

One important hemodynamic parameter implicated in the aneurysm growth and rupture is wall shear stress. The wall shear stress distribution is very difficult to measure by any experimental method. However, this can be done by computational fluid dynamics (CFD). With the recent development of the 3D medical imaging it is now possible to reliably simulate blood flow in anatomically realistic vessel geometries. In order to correlate numerical and experimental investigations in realistic models a visualization method of the numerical results is needed, which simulates the experimental dye washout.

This paper presents the results of flow visualization using quantitative dye washout in a realistic aneurysm model before and after filling with coils. The results of the numerical simulation of the same geometry represent the distribution of the wall shear stress and the initial results of the numerical simulation, which simulate and visualize the numerical dye washout.

2. Methods and Materials

2.1 Reconstruction of the aneurysm geometry

For surgical planning, a computerized tomography (CT) angiography was performed. CT resulted in slices of 2 mm thickness with 1 mm distance in a 512x512 pixel matrix with a 16-bit gray scale. These raw data were used for three-dimensional reconstruction of a bifurcation aneurysm. By means of the image processing program AMIRA (TGS Inc., San Diego, USA) a geometrical reconstruction of the aneurysm was performed. In order to extract the aneurysm, threshold and semi-automatical image segmentation was performed for each slice. Then, all slices with the aneurysm contour were stacked up to construct a 3D isosurface of the aneurysm. After applying smoothing algorithms, a solid geometric model was constructed and a stereolithographic (STL) data file was created (see Fig. 1).

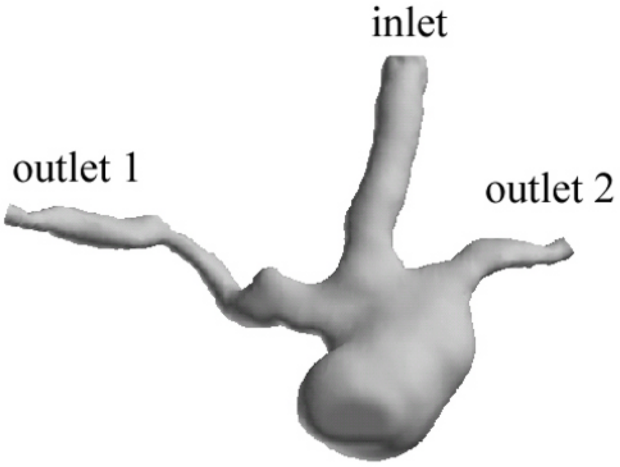

Fig. 1. Surface geometry of the reconstructed aneurysm.

For numerical study the STL file was transformed into an unstructured three-dimensional mesh of about 200,000 tetrahedral cells as a result of an average space resolution of 0.3 mm. The mesh was generated using the geometry and grid pre-processor GAMBIT (Fluent Inc., Lebanon, USA).

For experimental study a threefold upscaled aneurysm model was fabricated using rapid prototyping technique in order to produce a rubber mold. The mold was filled with hot wax resulting in a cast, which was used to fabricate a transparent silicone model (see Fig. 2).

Fig. 2. Transparent silicone model of the aneurysm with and without coils.

2.2 Quantitative dye washout

Steady aneurysmal flow with Reynolds number Re=300 and flow ratio 50:50 was visualized by the dye washout method. Before washout the aneurysm volume was filled completely with a solution of the dye Blue E 132/Indigotine (Schumann and Son, Germany) diluted in water (0.3 g/l). The washout process was recorded by a CCD camera (Canon MV30, Japan) during illumination of the model from the backside. The acquired images were digitized and processed using the Scion Image program (Scion Corp., USA). The grayscale value was averaged over region of interest (ROI) representing the aneurysmal volume for each image. The values were normalized using images of the aneurysm filled with the dye and pure water. The resulting curve describes the washout process. Different experiments were performed. First, the flow in the native aneurysm was studied. Then, we studied the flow in the aneurysm filled with coils. Three different degrees of coils filling (5, 10 and 15 % volume packing) were used.

2.3 Numerical study

Computation of the steady blood flow in the reconstructed aneurysm was performed with flow solver FLUENT6 (Fluent Inc., Lebanon, USA). FLUENT is commercial software, which was in-house well validated for complex laminar flows including recirculations. The simulations were based on three-dimensional Navier-Stokes equations for incompressible Newtonian fluid flow. Simulations were done with the second order upwind discretization scheme for the convective terms of the Navier-Stokes equations. The pressure-velocity correction method SIMPLEC was used to improve the convergence of solution in cases of complicated flow patterns including recirculations. A no-slip boundary condition was set at rigid walls. Reynolds number Re=300 and flow ratio 50:50 were simulated. A constant dynamic viscosity of 0.0035 Pas was set. The inflow was defined as a plug velocity profile. The choice of the inlet velocity profile is not significant since the fully developed velocity profile develops in the duct after the length **L**, which is 1.12 times the inlet diameter **d** ($\mathbf{L}=\mathbf{d}\text{x}0.065\text{x}\mathbf{Re}^{0.5}$; Sigloch, 1991). At the outflow branches constant pressures were set up, defining the flow ratio.

2.4 Numerical dye washout visualization method

In order to simulate numerically the dye washout method an unsteady simulation of the steady flow with an implicit time discretization scheme of the first order was performed. During unsteady simulation the pressure-velocity correction method PISO was used. Species transport model implemented by FLUENT was applied. At time point zero the whole aneurysm volume was initiated with so-called colored water (colored water fraction 1), whereas pure water was defined at the inlet (colored water fraction 0). The mass diffusivity of colored water was defined by an estimation of the Indigotine diffusion coefficient $D=1.27\text{x}10^{-8}$ m^2/s. Results of this simulations are distributions of the colored water fraction for different time steps. These data were used as input data for the flow visualization. A method of projected tetraeders of Shirley and Tuchman (Shirley et al, 1990) was applied. A transfer function, which defines the calculated values of color and transparency, was adopted for Lambert-Beer's law. This law describes the light intensity as a function of material concentration and path. It is valid for Indigotine that was experimentally proofed. Arguments of the transfer function are the calculated color fraction and tetraeders thickness in the projection direction.

The novelty of the proposed method is that it represents a visualization of numerical simulations, which may be compared with experimental data. The conventional contour and vector plots such as slipstream visualization technique using particle tracking, which was proposed for flow visualization in the aneurysms (Steinman et al., 2003), can not represent the results obtained during dye washout experiments.

3. Results

3.1 Dye washout before and after coils filling

Figure 3 shows some images of the washout process in the native aneurysm. The time step between each two images is 30 s. The period of 30 s. during experiment is equal to 1 s. of real time if calculated by means of the Strouhal number Sh.

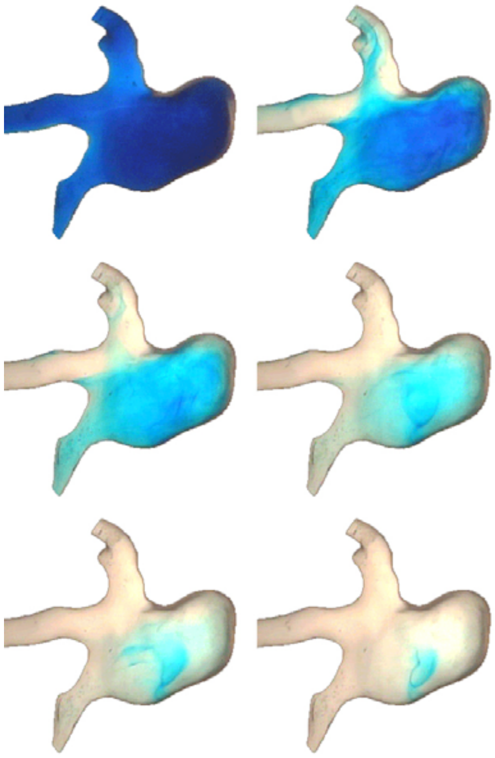

Fig. 3. Images of the dye washout in the native model of the reconstructed aneurysm.

Flow visualization revealed the following properties of the investigated aneurysm flow: The main stream of the inlet branch (left branch – Fig. 3) meets upper aneurysm wall in the neck region forming a stagnation point flow. The flow divides into two streams. One flows directly in the upper branch outlet 1 (see Fig. 3) resulting in a fast washout of this branch. The other flows mainly in the aneurysm sack forming at least 3 vortex formations and leaving the aneurysm mainly through the lower branch outlet 2. One strong vortex is located near the lower sidewall of the aneurysm resulting in a long-standing dye concentration at this region.

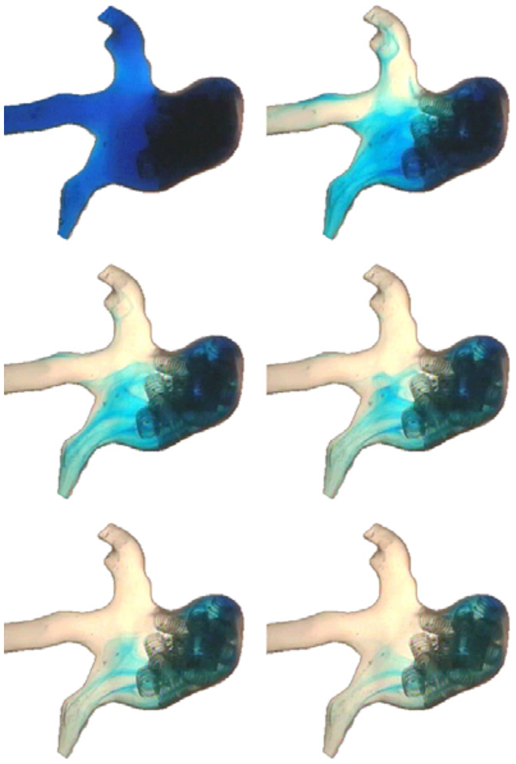

Fig. 4. Images of the dye washout in the aneurysm model filled with coils (15 % packing).

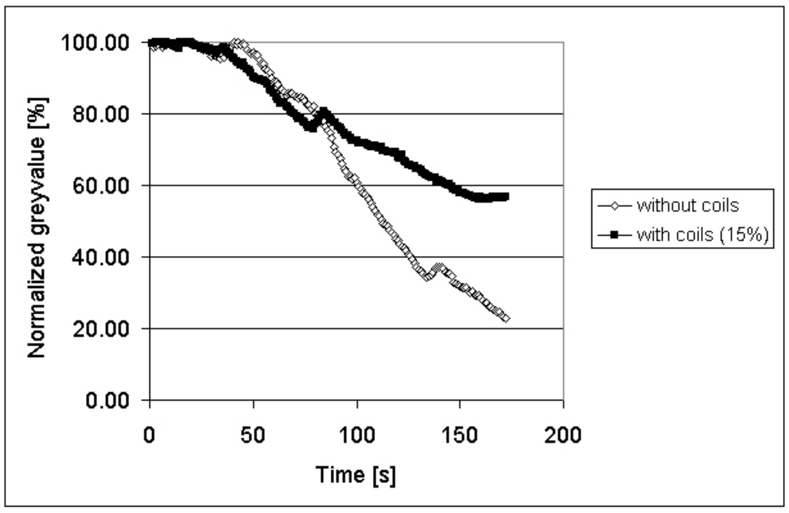

Fig. 5. Quantified washout process of the aneurysmal flow with and without coils.

In a next set of experiments, flow visualization in the aneurysm with coils was performed. The results revealed a significant change of the washout process for coils packing up 10%. Figure 4 shows some images of the washout process in the aneurysm filled with coils (15 % packing). The time step between each two images is again 30 s. The flow visualization revealed following features of the flow disturbed by coils: The upper branch is washout faster. Dye in the dome region of the aneurysm stays for a longer time. This results in the dye visible in the lower branch also in the last image of the Fig. 4. Figure 5 shows a quantification of the dye washout process. The resulting curve of the averaged greyvalue vs. time shows significant low washout for flow in the coiled aneurysm if compared with a native aneurysmal flow.

3.2 Results of the numerical study

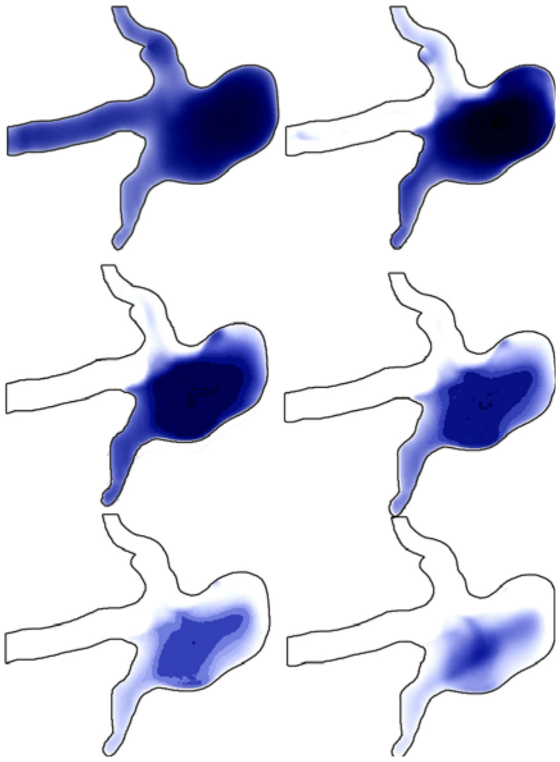

Fig. 6. Visualization of numerical results without coils.

The results of the flow simulation in the aneurysm revealed the same flow features that we noted after dye washout visualization. Figure 6 shows the results of the new visualization method, which simulates the dye washout process. Comparison of Figs. 3 and 6 shows the same flow features reflected in the same regions of the fast and slow washout. However, the main result of the numerical flow simulation may be to consider the distribution of the wall shear stress (see Fig. 7). Low wall shear stress leads to the wall remodeling (change of the thickness and material wall structure) and hence define the regions of possible rupture.

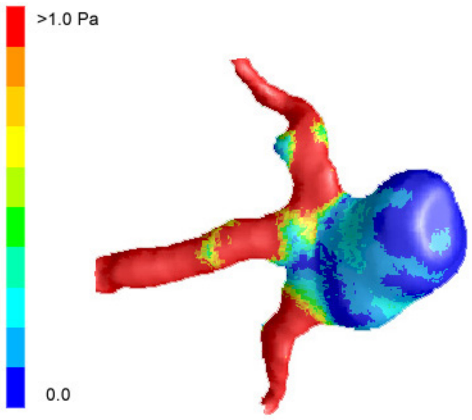

Fig. 7. Distribution of the wall shear stress in the aneurysm.
Note that red color marks all values of the wall shear stress higher than 1 Pa.

4. Conclusion

A combined method of experimental and numerical study was proposed in order to study the flow in the realistic models of the aneurysms. The combined method may be used to study the flow alteration due to therapeutic treatment of aneurysms by introduction of coils in the aneurysm volume. In order to validate the results of numerical study a visualization method simulating the dye washout experiment is proposed. Furthermore, the proposed method of the numerical data representation allows qualitative and quantitative image based analysis of hemodynamic in complex geometries and makes it comparable with cine angiograms.

The novelty of the proposed method is that it represents a visualization of numerical simulations, which may be compared with experimental data. The conventional contour and vector plots such as slipstream visualization technique using particle tracking, which was proposed for flow visualization in the aneurysms (Steinman et al, 2003), can not represent the results obtained during dye washout experiments. The future work will be concentrated on the investigation of correlation between quantified dye washout and areas of low wall shear stress

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