Modelisation of a cerebral aneurysm

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Abstract: This project presents a fluid-structure interaction (FSI) study of the aneurysm mechanics. The 2D model is composed of three domains (blood, artery and aneurysm) and used to investigate the effect of different physical parameters on the aneurysm deformation: the aneurysm wall thickness, the pressure at the outlets, the blood velocity at the inlet and some characteristics of the artery and aneurysm wall. The study showed that the wall thickness of the aneurysm and the pressure at the outlets have effects on the aneurysm mechanics, while the two last parameters did not seem to act on the aneurysm deformation.

Keywords: modelisation, COMSOL, fluid-structure interaction, cerebral aneurysm, biomechanics.

1. Introduction

An aneurysm is a deformation of the arterial wall. It is due to a weakness of the wall structure that cannot resist to the blood flow anymore. It results in the formation of a balloon shape extension, which can break at some point. This is called an aneurysm rupture and usually leads to the death of the patient. A cerebral aneurysm is an aneurysm that occurs in the arteries of the brain. It can be due to a congenital defect or to a head trauma. About five percent of the population develops a cerebral aneurysm during lifetime [1]. The chances of surviving after a cerebral aneurysm rupture are very small and they depend on several factors as the person's age, its neurological conditions or the duration between the first symptoms and the emergency treatment administration. Fortunately, most cerebral aneurysms are small and about 50 to 80 percent of all aneurysms do not rupture during a person's lifetime.

Nowadays, there are three options for treating intracranial aneurysms [2]:

- Observation
- Craniotomy with clip ligation (clipping): permanent clips
- Endovascular occlusion with the use of detachable coils (coiling): detachable clips

The first option (i.e. observation) includes routine periodic follow-up with imaging techniques and various visits to the physician in order to review the investigations done.

The second option is the clipping of aneurysms: it requires a craniotomy, an opening in the skull, performed by a neurosurgeon while the patient is under general anesthesia. Permanent clips are placed across the neck of the aneurysm, excluding it from the circulation.

The last approach is the endovascular coiling which is performed by a neurosurgeon. The patient is usually under general anesthesia during the placement of detachable coils. The use of angiographic techniques allows to place a microcatheter into the aneurysm and then, detachable coils of different sizes and shapes are deployed in order to decrease the amount of blood or even to stop its flow inside the aneurysm. Detachable coils have been increasingly used as a less physiologically stressful alternative in some patients, who already have severe brain injury.

Currently, it is difficult to detect the aneurysm before it breaks, because there is usually no visible symptom. Once it has been detected, numerical methods can be used to estimate the risk of rupture. Numerical studies have already been done using software as ANSYS, ABAQUS or COMSOL. They test the shear stress, the pressure distribution and the velocity of blood inside the aneurysm to predict the risk of breaking. Starting from an article on the stent technology in cerebral aneurysm [3], we decided to analyze the effects of different parameters from the model (without stent) on the aneurysm deformation. The parameters tested are the aneurysm wall thickness, the blood velocity at the inlet, the pressure at the outlets and some characteristics of the artery and aneurysm wall. Comparing the results with the initial study, we wanted to determine what was the impact of each of these parameters on the aneurysm deformation.

2. Methods

We built our model according to the parameters given in the article. As the article's authors did not use the same version of COMSOL (COMSOL Multiphysics 3.5 versus 4.2), we had to adapt some of the parameters values and physics.

2.1. System

Cerebral aneurysms occur mostly at the junction of the anterior cerebral artery (ACA) with the anterior communicating artery (ACoA). For the purpose of our project, we used a 2D model, but in the second part of our project, we built a 3D model to verify our results. The system is made of two tubes representing the ACA, having an intersection with a smaller tube (ACoA) and a half-disc (aneurysm). The blood flows through the artery from bottom to top, thus, there are one inlet (ACA) and two outlets (ACA and ACoA).

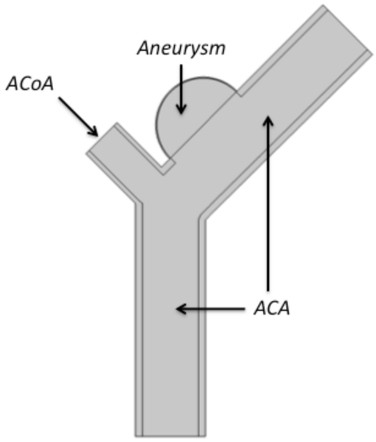

Figure 1. Model 2D geometry

The values for the geometry are summarized in the following table.

Parameters		Values
Diameter	*ACA*	2.4 mm
	ACoA	1.5 mm
	Aneurysm	4 mm
Wall thickness	*ACA*	0.3 mm
	ACoA	0.19 mm
	Aneurysm	50 μm
Length	*ACA*	10 mm
	ACoA	3 mm
Angles	*intern*	90°
	extern	135°

Table 1. Summarize of the geometry parameters

The model is made of three different subdomains, which are blood, artery and aneurysm.

2.2. Physical laws

As the arterial wall and the aneurysm wall have different properties, we defined them as two different subdomains.

The artery was modeled as a Hyperelastic Neo-Hookean material, with a density ρ of 960 kg/m^3. Neo-Hookean materials are described according to the strain-energy function:

$$W_s = \frac{1}{2}\mu(I_1 - 3) - \mu \ln(J_{el}) + \frac{1}{2}\lambda[\ln(J_{el})]^2$$

With μ, the shear modulus, given as 6204106 N/m^2 and I_1, the first principal invariant of the right Cauchy-Green strain tensor. The initial bulk modulus λ is calculated as 20μ - $2\mu/3$ N/m^2. The aneurysm was considered as a Hyperelastic Mooney-Rivlin material, with a density ρ of 960 kg/ m^3. This material is described with the following strain-energy function:

$$W_s = c_1(I_1 - 3) + c_2(I_2 - 3) + \frac{1}{2}\kappa(J_{el} - 1)^2$$

with c_1 and c_2, the material parameters defined as $c_1 = 15$ N/cm^2 and $c_2 = 4$ N/cm^2, and I_1 and I_2, the two principal invariants. We set an initial bulk modulus κ of 6 MPa. By using more parameters for the aneurysm subdomain than for the artery subdomain, the precision of the aneurysm wall reaction is increased compared to the one of the arterial wall. Indeed, the Neo-Hookean equation is a specific case of the Mooney-Rivlin equation (for $c_2 = 0$). By using a simplified equation to model the artery wall reaction, we reduced the computation time.

The blood was assumed to be an incompressible flow. The Navier-Stokes equations were used to describe its behavior through the artery and the aneurysm:

$$\rho(u_{fluid} \cdot \nabla)u_{fluid} = -\nabla p + \mu\nabla^2 u_{fluid}$$

$$\mathrm{p}\nabla \cdot u_{fluid} = 0$$

with a density ρ of 1060 kg/m^3 and a viscosity μ of 0.005 Ns/m^2.

To model interactions between blood, artery and aneurysm walls, we used the fluid-structure interaction physics (FSI). This physic can perform bidirectional fluid-structure interactions: the fluid viscous and pressure forces influence on the artery and aneurysm elastic structure, while the wall forces act back on the fluid. In other words, it couples dynamics of fluid mechanics and structure mechanics.

Initial conditions were necessary at the inlet and at the two outlets. An average velocity of 36 cm/s was set at the inlet and the outlet pressure is defined as 7333 Pa. A prescribed displacement of 0 was set on x and y directions for the three openings.

2.3. Numerical model

The model was implemented in COMSOL Multiphysics 4.2a (v4.2.1.166). The solver was set stationary and fully coupled. We used different mesh sizes for our geometry in order to optimize the computation time and the precision of the results. The fluid mesh was calibrated for fluid dynamics and predefined as coarse (element size between 0.824 mm and 0.369 mm). Indeed, we did not need precise fluid modeling for the purpose of this study. Triangular elements were used.

The boundaries between the fluid and the solid parts (internal walls of the geometry) were calibrated for fluid dynamics and predefined extra fine (element size between 0.16 mm and 0.0184 mm). Quadrilateral elements were used. We set two boundary layers with a stretching factor of 1.2 and a thickness adjustment factor of 6. This allowed to model more precisely the interactions between the artery / aneurysm walls and the blood. The reminding of the geometry (walls of the artery and aneurysm) was meshed with a normal, calibrated general physics mesh. The elements were defined as quadrilateral.

3. Results

The velocity and pressure profiles with the parameters from the article (i.e. an aneurysm wall thickness of 50 μm and a pressure at the outlets of 7333 Pa) can be seen on Figure 2. On this figure, the velocity magnitude can be seen on the left description in m/s and the von Mises stress on the right in N/m^2.

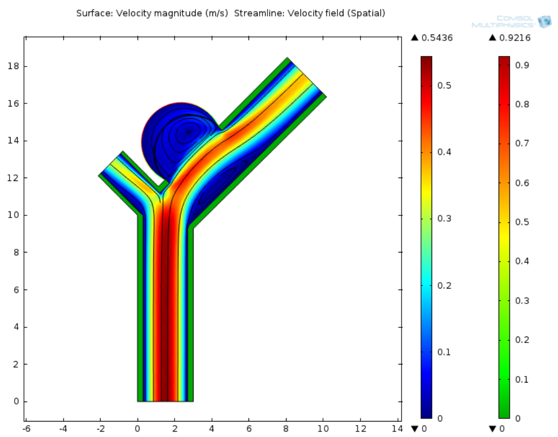

Figure 2. Velocity profile for the 2D geometry simulation

After having tested different values for the four mentioned parameters (i.e. aneurysm wall thickness, inlet velocity, outlets pressure and wall characteristics), we observed that only two of them showed significant results: the blood pressure at the two outlets and the aneurysm wall thickness.

4. Discussion

As observed in the results, only two of the tested parameters seem to have a significant influence on the aneurysm mechanics (i.e. the aneurysm maximum displacement).

The aneurysm maximum displacement due to the change in these parameters can be seen on Table 2. Thus, when the pressure at the outlets increases, the maximum displacement also increases and when the aneurysm wall thickness increases, the maximum displacement decreases, which is logical. Indeed, this shows that the aneurysm wall thickness directly influences on its mechanics.

Pressure change		Thickness change	
Pressure	**max displ.**	**thickness**	**max displ.**
5000 Pa	0.55 mm	0.03 mm	2.74 mm
7333 Pa	0.93 mm	0.05 mm	0.93 mm
9000 Pa	1.30 mm	0.1 mm	0.39 mm
10000 Pa	1.59 mm	0.3 mm	0.14 mm

Table 2. Maximum displacement corresponding to the pressure and thickness of the aneurysm wall

4.1. Verification

First, we used a simpler geometry to show that the physic, the conditions and the initial values were coherent with what we expected. This geometry was a simple tube on which we applied the fluid-structure interaction conditions used for the 2D simulation. We obtained a velocity profile as expected: a parabolic profile with a high blood flow at the center of the artery, which decreases while going to the walls. At the walls, the velocity is very small, almost zero, which respect the no-slip condition.

Then, we used a 3D model of the geometry, but with a simpler physic (i.e. laminar flow module) instead of the complete physic (i.e. fluid-structure interaction). This 3D model allowed us to verify that the fluid parameters produced a flow respecting the fluid dynamics rules. It also allowed us to compare the blood flow and the pressure inside the aneurysm to the ones obtained with the 2D model.

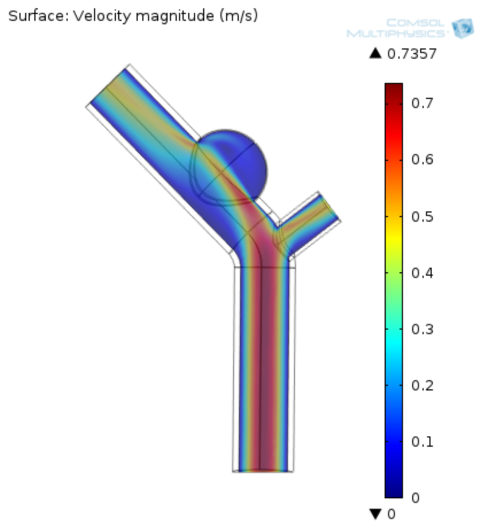

Figure 3. 3D simulation with the laminar flow physic (simpler physic in 3D)

The results seemed realistic: the flow is more important after the inlet and decreases after the intersection of ACA and ACoA. Compared with the 2D blood flow (Figure 2), we can observe that the flow shapes are mostly similar in both geometries. There is a significant change at the aneurysm entry between the 2D and 3D model. We think it is due to the fact that in 2D, we used a half-disc for the aneurysm, while in 3D, the aneurysm was modeled with a sphere and this difference may have an impact on the flow development. This hypothesis was verified in the following subsection.

To compare the pressure obtained with the 2D and the 3D geometry, we recorded its value at the edge of the aneurysm for different initial outlets pressures. The following table shows our results.

Outlets pressure	Pressure at edge of aneurysm 3D	Pressure at edge of aneurysm 2D
5000 Pa	5083.76 Pa	5017.42 Pa
7333 Pa	7416.76 Pa	7350.59 Pa
9000 Pa	9083.76 Pa	9017.67 Pa

Table 3. Comparison between the 2D and 3D model for the pressure at the edge of the aneurysm

Table 3 shows that there are some changes of pressure between the 2D and 3D model. As the differences seem to be proportional and small (about 66 Pa for the three cases), we can consider the 2D model results close to the ones obtained with the 3D model.

The verification steps showed that our 2D FSI model gives relevant results that are consistent with the fluid dynamics laws. Moreover, the results for the blood flow and the pressure inside the aneurysm are closed to the ones obtained with a 3D laminar flow model.

4.2. Validation

First, we compared our 2D results with the article simulation results (Figure 4). We expected some differences as they performed a fluid-solid interaction study with a 3D structure. Nevertheless, the velocity profile is quite similar and the major difference occurs at the aneurysm entry. As we mentioned in the previous part, this is probably due to the fact that in 3D, a sphere models the aneurysm, while in 2D a half circle was used and then joined to the artery.

Then, we compared our 3D laminar flow simulation results to the results obtained in the article with the 3D fluid-structure interaction model. Comparing Figure 3 and 4, we can conclude that the results are similar and the same perturbation of the aneurysm can be observed on both figures, which confirms the hypothesis that modeling the aneurysm with a sphere induces perturbations in the flow shape.

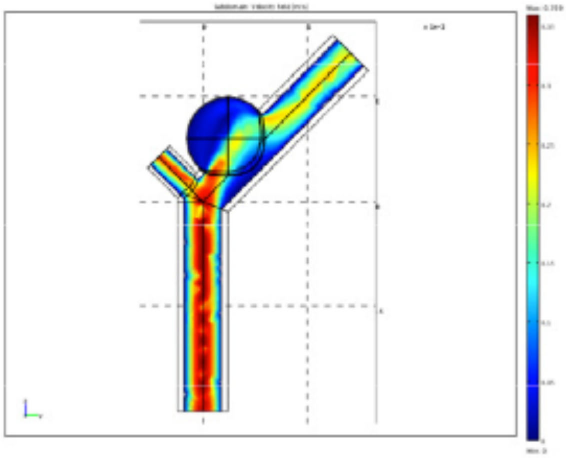

Figure 4. Velocity magnitude [m/s] in a 3D geometry (from the article)

4.3. Limitations

Even if the 2D model seems to have a similar blood flow than the one obtained in the article with the 3D model, we cannot consider it as representative of a real blood flow simulation. For more realistic results, a 3D model with the fluid-structure interaction physics is required.

The second limitation is about the parameters we chose for the thickness of the walls, the inlet velocity and the outlets pressure. We assumed them to be constant while, in a living body, we know there are some fluctuations.

The last limitation is to forget about the external environment side effects. Indeed, the tissues may have impact on the aneurysm, due to the tissues reaction on the aneurysm displacement. However, it is very difficult to integrate such parameters in a numerical study.

4.4. Improvements

As we only succeeded to do a 2D geometry with the complete physic (i.e. fluid-structure interaction) and a 3D geometry with the simple physic (i.e. laminar flow), it would be a great improvement to have 3D geometry simulation with the fluid-structure interaction module in order to have more realistic results. We tried to do it, but we faced many problems such as the time of convergence and the mesh setting. Indeed, the model seems to be too complicated to run without simplification of the mesh, but this would reduce the validity of the simulation.

Moreover, it would be interesting to test the influence of other parameters on the aneurysm deformation. For example, we could combine the change of thickness with the change of pressure or vary the distance between the intersection of the ACA/ACoA branches and the aneurysm.

As mentioned before, taking into account the effect of the tissues reaction on the aneurysm mechanics would allow us to have more realistic results. Nevertheless, as the model is already too complex to be run completely, the external effects can probably not be modeled easily.

5. Conclusion

The influence of four different parameters on the aneurysm deformation was evaluated during this study and two of them seem to have a significant influence: the aneurysm wall thickness and the blood pressure at the two outlets. However, this study is not exhaustive and we cannot exclude the fact that other non-test parameters may have an important impact on the aneurysm mechanic. Moreover, a 3D geometry would probably lead to a more realistic simulation of the problem. For a future study, it would be interesting to improve our model and test it with more parameters.

As mentioned in the introduction, the numerical studies cannot be used as long as the aneurysm has not been detected in a patient brain. Nevertheless, as cerebral aneurysms are very current in the population, there is an important interest in being able to determine if it may break in a close future or not depending on some of its characteristics. As we have seen through this project, numerical methods have an important role to play in this research.

Acknowledgements

This project was conducted through the course ‘Numerical Methods in Biomechanics’ given by Dr. Alexandre Terrier, at EPFL (Ecole Polytechnique Fédérale de Lausanne), Lausanne, Switzerland. The authors are grateful to Dr. Alexandre Terrier and Adeliya Latypova for their help and advices during this project.

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