XVII Konferencja Naukowo-Techniczna

TKI2024

TECHNIKI KOMPUTEROWE W INŻYNIERII

15–18 października 2024

Blood flow simulations in a cerebral aneurysm secured by a flow diverter stent

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ABSTRACT: Intracranial aneurysms (IAs) can rupture when not treated properly which leads to haemorrhagic stroke, permanent brain damage and, consequently, permanent disability, coma or even death. Once the physicians decide to treat the aneurysm with the chosen endovascular procedure (stent-assisted coiling, flow diverter or intrasaccular stenting), they have to select a particular implantable device, e.g. model/type of the stent. Such a choice is based mainly on the experience of the physicians. The main objective of this research was to show a potential use of computational fluid dynamics (CFD) tools in supporting the medical personnel by offering objective and quantitative data regarding the hemodynamic changes in the aneurysm region caused by implanting different models of the Flow Diverter stent (Derivo device with the following nominal diameters: 4.5, 5.0, 5.5, and 6.0 mm). The results obtained during this preliminary study shown a direct relationship between the stent porosity and hemodynamic environment inside the aneurysm sac. The less porous the stent, the more it promotes the possible aneurysm thrombosis. This could be concluded by observing larger regions of stagnant blood with higher viscosity. Despite limiting the inflow/outflow within the aneurysm sac, investigated flow diverter stent did not inhibit inflow to the ophthalmic artery.

KEYWORDS: CFD, intracranial Flow Diverter, blood flow simulations

1. Introduction and research objective

In the Europe, cardiovascular diseases (CDs) constitute in 23% of the mortality rate for females and 27% for males [1]. Aneurysms are ones of CDs that usually look like a bulging on the arterial walls. They are formed when the stress exerted on the weakened arterial walls is too high. Untreated aneurysm can rupture leading to a haemorrhagic stroke, permanent brain damage and, consequently, permanent disability, coma or even death.

The most dangerous aneurysms are located at the aorta and in the region of the brain. One can find varied information regarding the prevalence of the intracranial aneurysms (IAs) within the human population: 5.0-8.0% [2], 1.5-8.0% [3], 0.4-3.6% (cadaveric studies) and 3.7-6.0% (angiographic examinations) [4].

Early detection of the aneurysm presence and a choice of the most suitable method of its treatment are of an utmost importance in clinical practice. When it comes to a treatment of cerebral aneurysms, currently there are two possibilities, i.e. surgical procedures and endovascular methods. Among the latter group, one can distinguish the following types: *coiling* together with its modifications (*stent-assisted coiling*, *balloon-assisted coiling*), *Flow Diverter* stents and *Intrasaccular Flow Disruptors*.

Flow Diverters (FDs) are made of elastic, circular wires and they are significantly less porous than the standard stents. Due to high mesh density, FDs reduce an inflow to the aneurysm sac, and thus they may lead to a formation of an environment suitable for intrasaccular thrombosis (regions of low velocity and elevated viscosity). Currently, Flow Diverters are offered by numerous companies with varied shapes and dimensions. Some of the most commonly used FDs include: Derivo, Pipeline Embolization Device PED, p64 and Surpass devices.

The choice of the FD to be implanted for the given patient is made by a physician based on her/his experience. However, this can be additionally supported by computational fluid dynamics (CFD) which has been already proposed, but the stents were usually either explicitly present or replaced with a simplified porous layer [5, 6, 7]. The main objective of this research was to show that CFD with Immersed Solid Method can support the selection of the most optimal FD stent for the given patient. For that purpose, we conducted in-silico studies of blood flows in patient-specific model of the cerebral vasculature, before and after the virtual implantation of the selected FDs. We have chosen Derivo stents with the following nominal diameters: 4.5, 5.0, 5.5, and 6.0 mm.

2. Methods: numerical domain

Patient-specific geometry of intracranial arteries was reconstructed based on biomedical imaging acquired during angiographic Computed Tomography examination. This stage was completed with the use of custom-developed software called Anatomical Model Reconstructor, AMR. Then, inside the ANSYS SpaceClaim module, previously prepared geometry was transformed into a surface model compatible with SolidWorks software.

The Derivo stent geometries, fitted to the patient-specific model, were based on the manufacturer's data, and they were prepared with the use of custom-developed algorithm and SolidWorks software. The final topology of the stent mimicked its real behaviour – depending on the curvature and cross section of the parent artery, the stent elongated leading to a creation of pores of varied areas. The larger the nominal diameter of the stent, the larger the elongation and, consequently, the larger the pores.

The stationary numerical simulations of the blood flow around the stent were achieved by utilizing the Immersed Solid Method. For that purpose, the authors had to include a significant local condensation of the elements in vicinity of the stent wires. The most optimal meshes were selected after mesh independence tests. Blood was modelled as an incompressible shear-thinning fluid (viscosity represented by a modified power law), while general flow was assumed to be isothermal and adiabatic one with turbulence model set as k-ω SST. The inlet boundary condition (including Prandtl velocity profile) corresponded to a physiological inflow through specific brain-supplying arteries, while for the outlet cross sections pressure was set at 11.5 kPa. Each simulation was treated as completed once the convergence criteria reached the value of 10^{-6}.

3. CFD results analysis

A qualitative comparison of blood velocity proved that the stent presence influences blood flow directioning – greater volume of blood is directed towards the free flow regime (see fig. 1). Despite limiting the blood flow through the stent wires, blood supply to the ophthalmic artery (its inlet cross section was covered by the stent) was not affected negatively – we even noticed a slight increase in the blood volume delivered to this vessel.

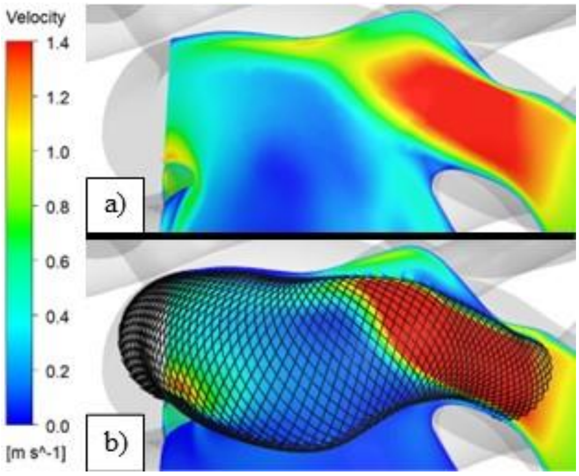

Fig. 1. Blood velocity near the aneurysm: a) geometry without the stent, b) geometry with 4.5 mm Derivo stent

We decided to analyse relative volume of stagnant blood (RVSB) and relative volume of viscous blood (RVVB) since these two parameters might indicate whether the environment is suitable for intrasaccular blood clotting. The former parameter corresponds to regions where blood velocity is lower than 0.01 m/s, whereas the latter one is defined as areas in which blood is characterized by viscosity larger than 0.0069 Pa·s – see tab. 1.

Table 1. RVSB and RVVB for all the analysed case studies

	no stent (ref.)	Ø 4.5	Ø 5.0	Ø 5.5	Ø 6.0
RVSB	0.00%	2.29%	1.02%	0.48%	0.37%
RVVB	0.37%	20.11%	13.41%	6.35%	4.81%

As can be seen, with an increase of the nominal stent diameter, there is a decrease in the volume of stagnant and highly viscous blood. It means that the less porous the stent, the better the conditions suitable for intrasaccular blood clotting. Similarly, a decrease of nominal stent diameter results in a decrease in pressure and wall shear stress (WSS) at the aneurysm wall – see fig.2.

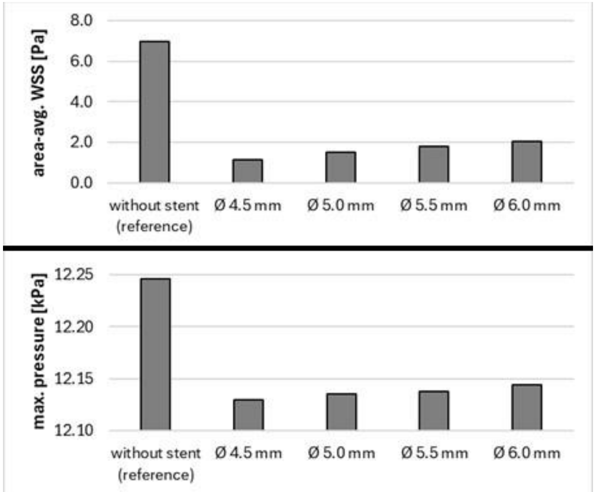

Fig. 2. Comparison of stress magnitudes exerted on the aneurysm wall for all case studies

4. Conclusions

The following conclusions could be drawn:

1) Immersed Solid Method is sufficient to analyse an influence of the stent presence on blood flow hemodynamics.
2) Stent porosity directly affects the flow hemodynamics – it limits the blood flow through its structure.
3) The larger the nominal stent diameter, the larger the pores and the lower the blood flow inhibition.
4) The less porous the stent, the more possible the creation of an environment suitable for intrasaccular thrombosis (higher RVSB and RVVB parameters).
5) The less porous the stent, the larger the reduction of pressure and WSS. As a result, the chances of aneurysm rupture could be lowered.

This research was carried out during the project LIDER14/0034/2023, financed by NCBR (Poland).

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