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To cite this article: Nurul Najihah Mohd Nazri *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **788** 012022

IOP Conf. Series: Materials Science and Engineering **788** (2020) 012022 doi:10.1088/1757-899X/788/1/012022

# Effects of blood flow patent and cross-sectional area on hemodynamic into patient-specific cerebral aneurysm via fluid-structure interaction method: A review

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**Abstract.** Fluid-structure interaction (FSI) simulation is carried out to investigate the blood flow analysis in different patient-specific cerebral aneurysms. In this study, we reviewed the studies done on the numerical simulation of blood flow in patient-specific aneurysm by using FSI analysis methods. Based on these studies, the wall shear stress (WSS) plays an important role in the development, growth, and rupture of the cerebral aneurysm. Prediction of the hemodynamic forces near the aneurysmal site helps to understand the formation and rupture of the aneurysms better. Then most of the aneurysms studied are located in the middle cerebral artery (MCA). In the existing considered, many researchers are more familiar with the experimental method in studies of blood flow through cerebral aneurysm compared to the numerical method. Nevertheless, numerical simulation of patient-specific cerebral aneurysms can give a better understanding and clear visualization of WSS distribution and fluid flow pattern in the aneurysm region.

**Keywords.** Blood flow; Modelling Simulation; Cerebral Aneurysm; Fluid-Structure Interaction; patient-specific.

## 1. Introduction

Cerebral aneurysm also is known as a brain aneurysm or intracranial aneurysm is a cerebrovascular disorder that arises due to the weakness in the wall of cerebral artery or vein. This leads to a localized dilation or ballooning of the blood vessel. Cerebral aneurysms can be classified into terminal, lateral or bifurcation aneurysms depending on their relationship with the parent artery. Aneurysms are either acquired later in life or acquired since born due to a genetic condition. Unhealthy lifestyles such as hypertension, smoking, excessive alcoholism, and obesity are highly associated with the development of brain aneurysms. Cerebral aneurysms are generally found in the anterior and posterior regions of the circle of Willis. The rupture of the cerebral aneurysm can cause subarachnoid hemorrhage (SAH) with potentially severe neurologic complications [1]. Many experimental studies have sought to identify the higher and lower WSS distribution, WSS location, pressure, particle residence time and flow impingement that play important roles in the growth and rupture of cerebral aneurysms [2-4]. High WSS is regarded as a major factor in aneurysm development and growth.

In a few years ago, significant progress in computer innovation techniques have made it probable to apply computational fluid dynamics (CFD) for many real applications and has been studied extensively. In additional, the simulation with realistic blood vessel geometry has become a great tool in provides details information on blood flow fields. In numerical simulations of blood flow in patient-specific geometries of an abdominal aortic aneurysm (AAA) quantitatively investigated the stress distribution which hinges on the fluid dynamics conditions and local blood vessel geometry. Generally, the numerical simulations have an expected problem on the specification of the exact boundary conditions, because the incorrect specification of boundary conditions may lead to introduce unphysical numerical solutions.

A numerical simulation is a calculation that is run on a computer following a program that implements a mathematical model for a physical system. Numerical simulations are required to study the system behavior whose mathematical models are too complex to provide analytical solutions, as in most nonlinear systems. The Newton–Raphson method or a different fixed-point iteration can be used to solve FSI problems. These methods solve the non-linear flow equations and the structural equations in the entire fluid and solid domain.

The application of coupled FSI simulation, which combines computational fluid dynamics (CFD) and finite element analysis (FEA), is becoming a popular tool for understanding the interaction between the arterial hemodynamic and the wall deformation and its possible link to intracranial aneurysm rupture [5-16]. By [12–14] and [15-16] used the FSI simulation method to study the magnitude of the aneurysm wall and displacement patterns due to hemodynamic forces for dissimilar patient-specific models and flow conditions. In these studies, have established that FSI simulations have the capability to afford information on the visualize its characteristics and the magnitude of vessel wall motion that current in vivo methods unable to accurately offer [5], [17-19]. Fluid-structure interaction is also the interaction of some deformable structure with an internal fluid flow. The expectation of the fluid dynamics inside the aneurysms through the inclusion of FSI shows significant effect towards WSS. It can be ultimate that, CFD simulations deprived of FSI are not reliable. Furthermore, the mechanical behavior of cerebral aneurysms under fluid dynamics load can only be gained with CFD considering FSI.

We have clearly reviewed the capability of a numerical simulation study of blood flow analysis on real patient-specific cerebral aneurysms using FSI method. Through this study, the effect of WSS, cross-sectional inlet area, and pressure distribution was observed. In the future, the effort to investigate this problem is essential for enhancing the knowledge in the biomedical engineering field.

## 2. Perspective reviews

### *2.1. Development of FSI method on biomedical engineering fields*

Fluid-structure interaction is a crucial contemplation in the designing of many engineering systems, e.g. aircraft, engines, and bridges. Failing to consider the effects of oscillatory interactions can be catastrophic, especially in structures covering materials susceptible to fatigue. The first *Tacoma Narrows Bridge (1940)*, is possibly one of the most notorious cases of large-scale failure. Aircraft wings and turbine blades can break due to FSI oscillations. The FSI with multiphysics problems in all-purpose is often too multifaceted to be solved analytically. Therefore, they have to be analyzed by means of experiments or numerical simulation. Research in the fields of computational fluid dynamics and computational structural dynamics is still ongoing but the maturity of these fields has enabled numerical simulation of FSI.

Nowadays, the FSI method is also developed for biomedical engineering applications. The basic idea of FSI method is to simulate blood flow within specific-patient cerebral aneurysms in order to predict the hemodynamic flow pattern and properties such as velocity, pressure and wall shear stress. Through this, the FSI method has become more appealing to biomedical studies. The respective simulations have been conducted by several researchers, decrypting the biomechanical behavior of the arterial vessel [20-21] using FSI numerical studies on patient-specific cerebral aneurysms [22-23] which are reconstructed from the CT-scan.

IOP Conf. Series: Materials Science and Engineering **788** (2020) 012022 doi:10.1088/1757-899X/788/1/012022

Based on the reviews, the Arbitrary Lagrangian-Eulerian (ALE) method and Navier-Stroke equation were used as the governing equation that is suitable to solve problems with FSI. The density of blood was assumed to be constant with $\rho = 1050$ kg/m$^2$, the dynamic viscosity $\mu = 0.0035$Pa [24] and Poisson's ratio = 0.45 [25]. The Reynold number is normally in the range of $1 \leq Re \leq 400$ for the flow. The optimization methods of the particular methods would further close the gap between numerical simulations and clinical practice encouragement for their dependability, expediency and eventually launching their role in very tough medical decision making.

## 3. Effect of wall shear stress (WSS) on the flow pattern

Hemodynamic values such as wall shear stress (WSS) are significant factors in the growth and rupture of the cerebral aneurysm. However, these factors are strongly ascribed to the flow pattern and thus a flow analysis with poorly modeled boundary conditions may lead to an incorrect hemodynamic model. The incorrect hemodynamic information also may lead to a wrong diagnosis. Therefore, the measurement integrated simulation can provide reliable information on wall shear stress (WSS) distribution, which is an important hemodynamic factor for the diagnosis of vascular disease. By [22] was performed an additional CFD simulation to investigate the WSS with the same boundary conditions. The distribution of WSS magnitudes on the cerebral aneurysms at peak systole are compared in Figure 1. These simulations demonstrated a large change in WSS distribution between case I and III. Both patients shows the WSS were reduced through different cases as indicated by black arrows. Modeling of patients A, more spherical aneurysm showed the reduction of WSS at the aneurysm neck (see Figure 1(a)). However, patient B shows, reduction in WSS occurred nearly the surrounding parent vessel (see Figure 1(b)).

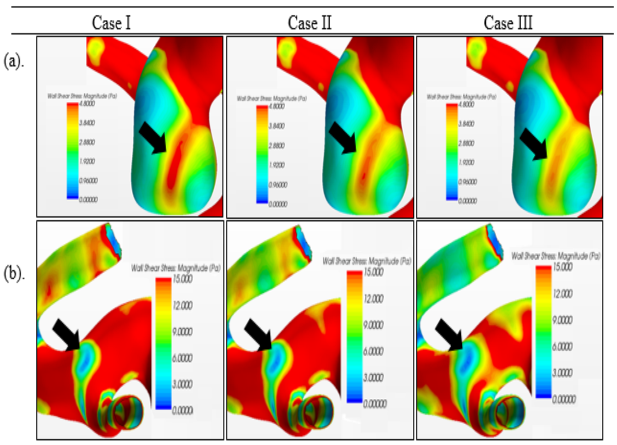


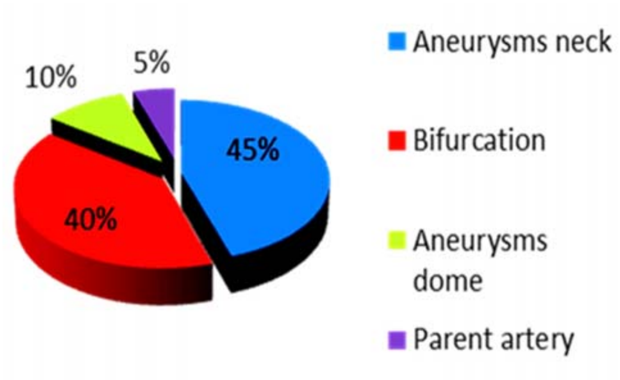

**Figure 1.** Wall shear stress (WSS) distribution on three different cases of CFD analysis setup at the peak systole [22].

In [5-14] studies, the magnitude and distribution of WSS around the middle cerebral artery (MCA) were investigated. As shown in Figure 2(a), about 45% of the maximum location of wall shear stress is located at the neck of the aneurysm [7-10]. This is followed by 40% at the bifurcation, 10% at aneurysms dome and 5% at the parent artery. Figure 2(b) shows that mostly the location of an aneurysm is located at the middle carotid artery (MCA), affecting 11 patients. The lowest one is at ICA and RCA, affecting 2 patients. Aneurysms normally developed at the branching points of arteries with constant blood pressure.

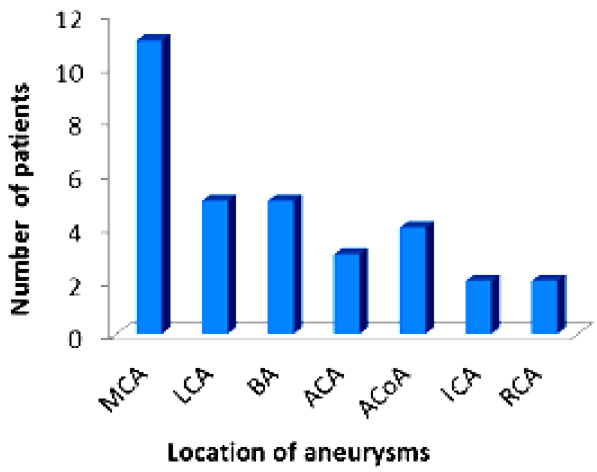
## 4. Effect of cross-sectional area on wall shear stress (WSS)

In the current existing studies [4-24], the lowest cross-sectional area is found at locations with higher wall shear stress distribution. The highest consistency of inlet area is 7.74 $mm^2$ as shown in Figure 3(a). In addition, as shown in Figure 3(b), the maximum range of pressure distribution setting is in between 13 until 14kPa while the minimum range of pressure distribution is in between 8 until 9kPa. Normally, the range of pressure distributions of the patients is between 10 until 16kPa.

The maximum wall shear stress, location of cerebral aneurysms and cross-sectional inlet area of the cerebral arteries are studied. Based on the review, one of the mechanisms associated with aneurysms rupture is the response of aneurysms wall towards WSS and it can be understood only when the biological and mechanical factor is considered. The velocity inlet boundary condition was highly important for correct prediction of fluid dynamic inside cerebral aneurysms. Wall shear stress is one of the main pathogenic factors in the development of saccular cerebral aneurysms. Based on this study, 45% stated that the locations of maximum wall shear stress are located at aneurysms neck. The different size of aneurysm also gave different wall shear stress values



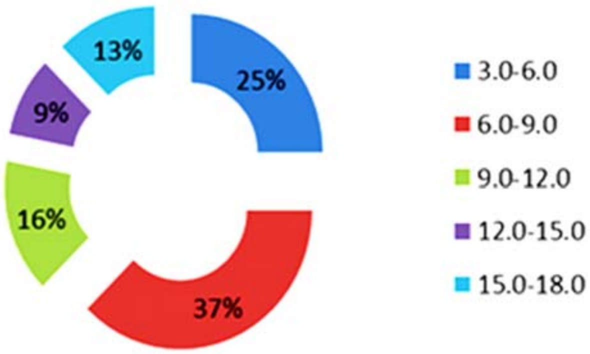

(a)



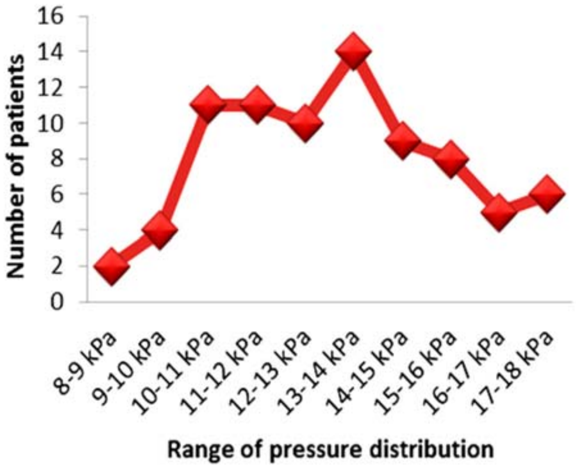

(b)

**Figure 2**(a). The maximum location of wall shear stress (WSS) for patient-specific aneurysms, and (b) The location of aneurysms with the respective number of patients. *Notes: Middle Cerebral Artery (MCA), Left Carotid Artery (LCA), Basilar Artery (BA), Anterior Cerebral Artery (ACA), Anterior Communicating Artery (ACoA), Intracranial Carotid Artery (ICA) and Right Carotid Artery (RCA).*

The most frequent locations are observed in the Middle Cerebral Artery (MCA) [5-14], followed by Left Carotid Artery (LCA), Basilar Artery (BA), Anterior Communicating Artery (ACA), Anterior cerebral artery (ACA) and Right Carotid Artery (RCA). The highest pressure distribution is 13-14kPa. The different pressure distribution depends on the cross-section area and the size of the artery. If different of the area size is obtained, the pressure distribution also will be affected. Normally, the highest consistency of blood flow velocity is between 0.2 until 0.3 m/s.




(a)




(b)

**Figure 3**(a) The range of cross-sectional inlet area of the cerebral arteries, and (b) The range of pressure distribution.

## 5. Conclusions

The most important factor when studying the numerical simulation on patient-specific cerebral aneurysms using FSI is the boundary condition setup. From this factor usually the realistic location of maximum wall shear stress, the blood flow velocity in the inlet area of the cerebral arteries while setting for inlet and outlet boundaries and the pressure distribution can be found. These studies found that the maximum wall shear stress (WSS) normally located at aneurysms neck and most of the location of a cerebral aneurysm is located at the middle cerebral artery (MCA). Hopefully, this study can give a better understanding and visualization of the numerical simulation especially on fluid flow pattern in patient-specific cerebral aneurysms.

**Acknowledgment**
The support of the University Malaysia Pahang under grant RDU180311 and MedEHiT are gratefully acknowledged. The authors of this paper also would like to express their gratitude to Associate Prof. Dr. Shafie Abdullah and Dr. Hartini Mohd Taib from Department of Radiology, Hospital Universiti Sains Malaysia (HUSM) for supporting these research activities.

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