Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2016,28(3):462-472
DOI: 10.1016/S1001-6058(16)60650-9
www.sciencedirect.com/
science/journal/10016058

A joint computational-experimental study of intracranial aneurysms: Importance of the aspect ratio*

Simon Sui-Man LAI[1], Abraham Yik-Sau TANG[2], Anderson Chun-On TSANG[3], Gilberto Ka-Kit LEUNG[3], Alfred Cheuk-Hang YU[4], Kwok Wing CHOW[2]
1. Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong, China,
E-mail: simonlai@hotmail.com.hk
2. Department of Mechanical Engineering, University of Hong Kong, Hong Kong, China
3. Department of Surgery, Li Ka Shing Faculty of Medicine, University of Hong Kong, Hong Kong, China
4. Department of Electrical and Computer Engineering, University of Waterloo, Ontario, Canada

(Received September 20, 2015, Revised April 1, 2016)

Abstract: Rupture of a cerebral aneurysm (abnormal swelling of blood vessel in the brain) will cause subarachnoid hemorrhage, and will result in an alarming rate of mortality and morbidity. A joint computational-experimental study is conducted to assess the importance of the aspect ratio in the dynamics of blood flow. The aspect ratio is defined here to be the ratio of the height of the aneurysm to the linear dimension of the neck. Idealized models of such aneurysms located near a bifurcation point were investigated. Numerical simulations for hemodynamic properties like shear stress and flow rate were performed. The computational results were verified experimentally with specially fabricated phantoms, blood mimicking fluid and Doppler ultrasound imaging. Excellent agreements were obtained. Two features are highlighted, providing information in the intensely debated link between rupture risk and geometric factors. On increasing the aspect ratios, firstly, a jet impinging on the distal part of the neck can be observed, and secondly, a region of positive shear stress gradient can be found there. Furthermore, computational analyses for four patient-specific models were conducted to correlate with the results of idealized models and to provide further clinical insight.

Key words: intracranial aneurysms, aspect ratio, Doppler ultrasound

Introduction

The applications of computational and experimental techniques of fluid mechanics to study the human cardiovascular system have received intensive attention recently[1]. Arterial aneurysms are abnormal dilatations of blood vessels. Mechanisms for their generation and development are still not fully understood[2], but vascular biology and hemodynamics are believed to play crucial roles. Besides large blood vessels like the abdominal aorta and the thoracic aorta, such aneurysms also occur frequently in smaller vessels, e.g. intracranial (or cerebral) aneurysms in the circulation system in the brain[3].

* **Biography:** Simon Sui-Man LAI (1985-), Male, Master, Research Associate
Corresponding author: Abraham Yik-Sau TANG, E-mail: aystang@hku.hk

With increasingly sophisticated imaging techniques, more such cerebral aneurysms are detected before catastrophic events occur. These abnormal swellings may occur in as much as a few percent of the total population[4]. The main risk of cerebral aneurysms is the phenomenon of rupture, which leads to subarachnoid hemorrhage. The rate of mortality is alarming, and any necessary subsequent medical procedure for surviving patients poses a heavy financial burden for the society. The traditional treatment for unruptured aneurysms is open surgery, but recently endovascular methods have proven to be effective and less traumatic[5]. However, the risk of rupture needs to be balanced against the risk of treatment.

Scientifically, the hemodynamics and properties of the vortices and impingement zone associated with these aneurysms have been investigated[6]. Among all these geometric and dynamic factors, e.g., size and location of the aneurysms, pressure, flow rate and shear stress, we focus on the aspect ratio. The aspect ratio (AR) is commonly defined to be the ratio of the aneurysm depth to the dimension of the neck, and has been demonstrated clinically to be a statistically significant quantity in terms of assessing the risk of rupture[7-9]. Indeed for irregular shaped aneurysms, a volume to ostium area ratio has also been proposed[10]. The main idea behind these proposals is that slower flow in high AR sacs might lead to various processes in vascular biology, which will weaken the aneurysm wall[11]. This conjecture is difficult to prove explicitly with the present state of scientific knowledge. Hence, in clinical experiments, elastase induced aneurysms in rabbit had been investigated[11].

The main goal of this work is to conduct a joint computational-experimental study on intracranial aneurysms. Such swellings usually occur along the sidewall of a parent vessel (fusiform aneurysms) or near a bifurcation point (saccular aneurysms).

Computational investigations on bifurcation aneurysms have captured the attention of researchers. The effect of aneurysm geometry, the roles of low shear stress and high pressure in aneurysm rupture have been assessed. As the AR of the aneurysm increased, a reduction in the wall shear stress and an intensified wall pressure were observed, which could lead to a higher risk of rupture[12]. After the deployment of a high porosity stent, numerical simulations of an idealized model of a basilar tip aneurysm exhibited substantial reductions in the velocity field, pressure and shear stress[13]. Furthermore, computations under a non-Newtonian fluid assumption were performed on cerebral aneurysm models with the presence of daughter saccules[14]. Complex flow patterns were observed inside the aneurysms, which might imply a greater chance of rupture. These studies demonstrate the merit of computational fluid dynamics (CFD) in analyzing the highly complex flow patterns inside the aneurysmal sac.

On the other hand, phantom studies and enhanced imaging techniques to improve the understanding of the dynamics of intracranial aneurysms had also been carried out. Particle image velocimetry measurements of spherical aneurysm models were compared with computer simulations. Small variations in the geometric shape might produce significant changes in the hemodynamic parameters like vorticity and shear stress[[15]. High frame rate angiography and computer fluid dynamics simulations had been assessed jointly, and these two approaches produced very good agreements[16].

The idea here is to employ still another measurement technique, namely, ultrasound imaging, to study models of cerebral aneurysms. Important merits of ultrasound technology include (1) the noninvasive nature, (2) affordability, and (3) no known harmful side effects. Indeed abdominal aortic aneurysms induced in mice had been measured by ultrasound with the additional advantages of rapid imaging speed, reproducibility, and high resolution[17]. In contrast, the usage of ultrasound imaging to blood flow issues in the brain has not been extensive. One direction is to assess if vasospasm in the middle cerebral artery will reduce the flow in the corresponding extracranial internal carotid artery[18]. Indeed this potential of contrast-enhanced ultrasound imaging to visualize the flow dynamics in cerebral aneurysms during neurosurgical procedure is valuable[19], and would be examined in this work with the issue of varying the aspect ratio.

The plan of the paper can now be described. The CFD formulation, the fabrication of the phantom and experimental setup will be explained. The matching between CFD and experiments will then be discussed. Finally, conclusions will be drawn.

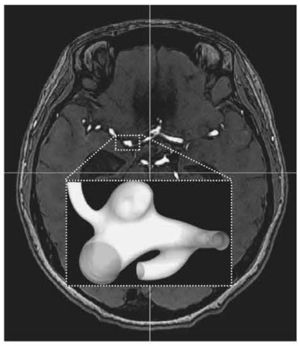

Fig.1(a) Aneurysm morphology of a real patient

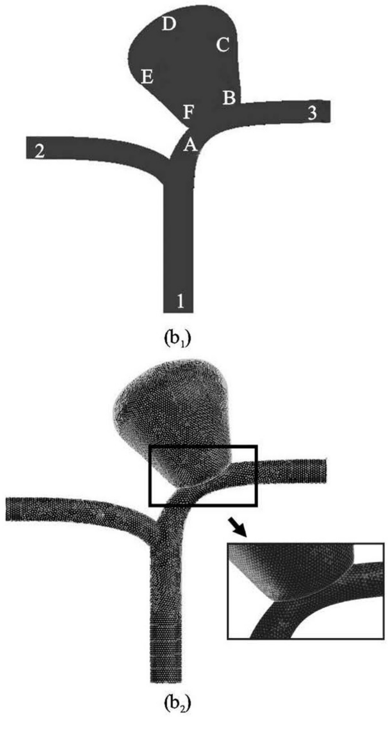

Fig.1(b) Schematic diagram of the generalized model utilized in this study, with the location of different points near and inside the aneurysm (b_1) Computational mesh of the numerical model for AR = 2.0 (b_2)