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Hemodynamic models of cerebral aneurysms for assessment of effect of vessel geometry on risk of rupture

Alberto Avolio, Azadeh Farnoush, Michael Morgan, Yi Qian

Abstract—**Surgical decisions on treatment of cerebral aneurysms are based predominantly on aneurysm size. This study has assessed the influence of parent vessel geometry on intra-aneurysmal flow patterns and mass flow rate using computational fluid dynamics and finite element modeling of straight and curved vessels feeding saccular aneurysms of varying size and aspect ratio. Simulation results have shown that aneurysms of similar shape and size but with curved parent vessels can have more than 2 fold increase in flow rate, with markedly different flow velocity patterns and development of secondary flows. These are significant hemodynamic factors that can contribute to increased risk of aneurysm rupture, in addition to aneurysm size. The dependency of parent vessel geometry is a function of aneurysm aspect ratio and shows minimal dependency at an aspect ratio of 1.68. These findings could be used for improved quantification of risk of rupture of cerebral aneurysms detected from clinical imaging modalities and to aid surgical decision making.**

I. INTRODUCTION

Cerebral aneurysms and associated complications affect 2-5% of the population [1]. Information on this came essentially from studies investigating aneurysms following rupture with consequential morbidity and mortality [1-3]. However, with increase in application of clinical imagining (eg CT and MRI angiography) and developments in neuroradiology, there is increased detection of unruptured aneurysms [2],[3]. This suggests that a greater proportion of the population may be affected than what is currently known [4]. In addition, detection of asymptomatic unruptured aneurysms presents a significant surgical dilemma, where the risk of aneurysm rupture, if not treated, has to be weighed against the risk of brain surgery. Current treatment options include surgical clipping and insertion of endovascular coils and stents, all of which have complication rates of 5-15% [5].

Based on largely empirical observations, the International Study of Unruptured Intracranial Aneurysms (ISUIA [6]) recommended that size be considered a predominant factor for surgical decisions [7]. Aneurysms of diameter > 5 mm are generally offered treatment [8]. However, there is considerable controversy [8] as the majority of aneurysms rupture at a smaller size than that identified by ISUIA [9]. Other studies also suggest that size is of less importance [10,11]. Furthermore, there is no direct evidence that links size to risk of rupture. Size may be correlated with other characteristics, such as vessel geometry and aneurysm irregularity [12]. However, with the accumulation of quantitative information regarding aneurysm morphology, there is increasing evidence that size *per se* is not a strong predictor of aneurysm rupture [13,14].

Because of the fluid dynamic forces acting on aneurysms, hemodynamic factors such as wall shear, intra-aneurysmal pressure and instability of flow patterns are significant determinants of aneurysm rupture [15], [16]. These factors are highly dependent on both the shape of the aneurysm itself and the geometry and dimensions of the parent vessels [17].

The aim of this study was to determine the effect of the geometry and dimensions of parent vessels on intra-aneurysmal mass flow rate and velocity pattern in uniform saccular aneurysms of varying sizes, quantified in terms of aspect ratio.

II. METHODS

A. Vascular Model

The model structure for the saccular aneurysm and feeding arteries is shown in Fig. 1. Aneurysm depth was in the range 6-10 mm; parent artery vessel diameter, 4-6 mm; fundus,10 mm. A finite volume model (FVM) was constructed for the vascular structures comprising straight and curved parent vessels. Vessels lengths were selected to achieve fully developed flow. Aneurysm size and shape was described by the aspect ratio (Fig 1).

B. Numerical Simulation

Computational fluid dynamic (CFD) analysis was conducted using commercial software (ANSYS CFX 11). Simulations were performed with steady laminar flow (nominal value 0.3 L/min). Models contained a minimum of $4x10^5$ cells for convergence of calculations. All calculations were performed with vessels and aneurysm assumed to be thin walled rigid structures. Blood was considered a Newtonian fluid with density of 1100 kg/m^3 and dynamic viscosity of 0.0035 Pa.s

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A.Avolio is with the Australia School of Advanced Medicine, Macquarie University, Sydney, Australia (email: alberto.avolio@mq.edu.au)
A. Farnoush is with the Australia School of Advanced Medicine, Macquarie University (email: azadeh.farnoush@students.mq.edu.au)
M. Morgan is with the Australia School of Advanced Medicine, Macquarie University, Sydney, Australia (email: Michael.morgan@mq.edu.au)
Y. Qian is with the Australia School of Advanced Medicine, Macquarie University, Sydney, Australia (email:yi.qian@mq.edu.au)

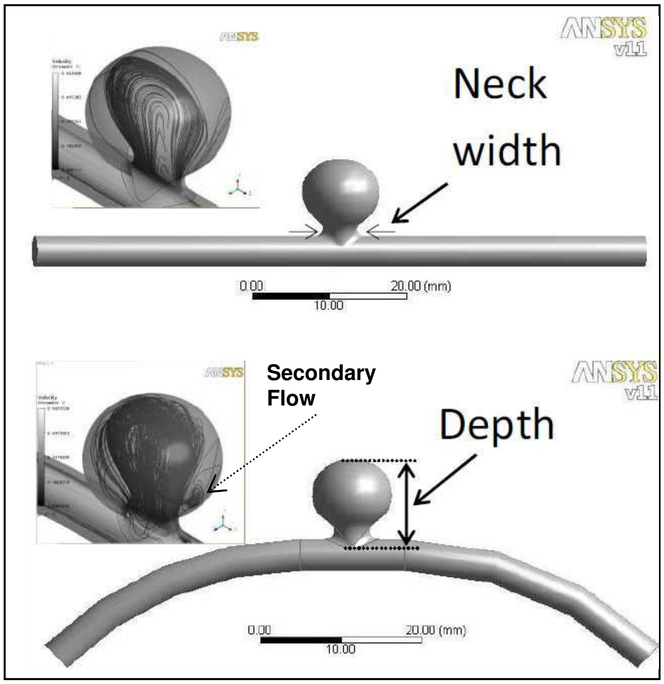

Figure 1. Configurations used for models of saccular aneurysms being fed by straight (upper) and curved (lower) parent vessels. Aneurysm aspect ratio is defined as the ratio of depth to neck width. Fundus distance (central width) was constant (10mm) for all values of aspect ratios. Upper and lower left panels shows the respective intra-aneurysmal flow patterns for straight and curved parent vessels for aneurysms of similar shape and size. Higher velocities and secondary flows are seen in the aneurysms fed by curved parent vessels. Models shown are for 4 mm diameter parent vessel and 10 mm aneurysm depth.

III. Results

Simulation results showed that for all aspect ratios, relative intra-aneurysmal flow was greater for curved parent vessels and increased for both geometries with decreasing diameter of parent vessels (Table). In addition, aneurysms with curved parent vessels showed markedly different flow velocities with development of secondary flows (Fig 1)

Table

Diameter (mm)	Depth (mm)	Aspect Ratio	Qs (%) Straight	Qc (%) Curved	Ratio (Qc/Qs)
6	10	1.90	0.71	1.10	1.55
	8	1.68	0.49	0.82	1.66
	6	1.32	0.35	0.59	1.67
5	10	1.90	1.02	1.97	1.93
	8	1.68	0.79	1.35	1.72
	6	1.32	0.60	1.15	1.90
4	10	1.90	2.22	4.61	2.08
	8	1.68	1.47	2.62	1.79
	6	1.32	0.88	2.03	2.30

Diameter refers to the parent vessels. Qs and Qc are the intra-aneurysmal flow rate as percentage of total flow for straight and curved parent vessels respectively. Depth refers to the longest dimension as in Fig 1.

The ratio Qc/Qs showed a dependency on parent vessel diameter for aspect ratios of 1.23 and 1.90, but less so for the aspect ratio of 1.68 (Table, Fig. 2) where it varied between 1.66 and 1.79 for parent vessel diameters of 6 and 4 mm respectively.

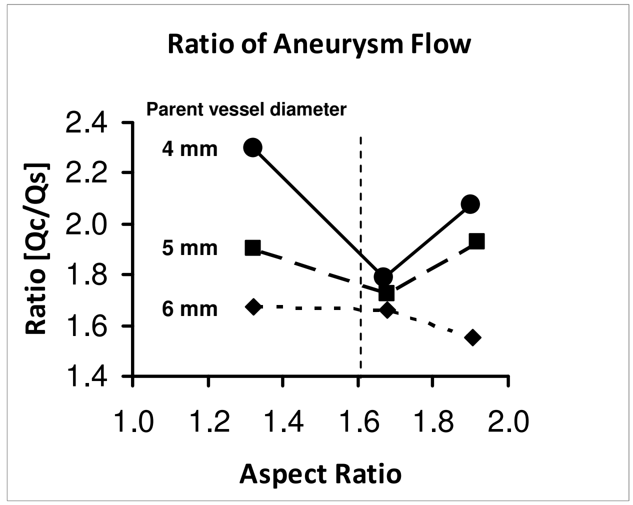

Figure 2. Ratio of relative intra-aneurysmal flow for curved (Qc) and straight (Qs) parent vessels as a function of aneurysm aspect ratio for parent vessel diameter of 4 mm (circles), 5 mm (squares) and 6 mm (diamonds). Ratio Qc/Qs shows a greater dependency on aspect ratio for smaller parent vessel diameter, but markedly reduced dependency for aspect ratio of 1.68. This value is close to the critical values of 1.6 proposed by Ujiie et al [18] above which over 80% of saccular aneurysms ruptured.

IV. Discusison

This study examined the effect of parent vessel size and geometry on intra-aneurysmal mass flow rate and velocity pattern with change in aneurysm aspect ratio using numerical simulation and finite element modeling techniques. Findings suggested that the dependency of aneurysmal flow on parent vessel geometry is not uniform with both vessel size and aneurysm aspect ratio. This was consistent with other modeling studies which showed the importance of including the upstream portion of the parent vessel of cerebral aneurysms for accurate representation of intra-aneurysmal hemodynamics [17]. Our results show that there is a greater dependency on aspect ratio for smaller vessels (4 mm diameter) than larger vessels (6 mm). Dependency on vessel diameter reduces to a minimum for an aspect ratio of 1.68.

In a study of 129 patients with ruptured aneurysms and 72 patients with 78 unruptured aneurysms, Ujiie *et al* [18] found that 90% of unruptured aneurysm had an aspect ratio less than 1.6, while 80% of ruptured aneurysms showed an aspect ratio greater than 1.6. In the study by Weir et al [19] the aspect ratio was obtained in 774 aneurysms of 532 patients with ruptured and unruptured aneurysms. They found that an aspect ratio greater or smaller than 1.6 had a rupture rate of 69% and 19%, respectively, whereas an aneurysm size greater than 10 mm had a 60% rupture rate in comparison with an aneurysm size equal to or less than 10mm with a

51% ruptured rate. They concluded that 56% of unruptured aneurysms had an aspect ratio equal to or less than 1.6 while 88% of ruptured aneurysms had an aspect ratio greater than 1.6.

These studies indicate that the size of a saccular aneurysm (conventionally measured as depth, Fig 1) is not a strong indicator of risk of aneurysm rupture and that aspect ratio may be a stronger predictor. However, we have shown that hemodynamic factors related to risk of rupture, such as intra-aneurysmal mass flow rate and disturbed flow, also depend on aspect ratio and on parent vessel size and geometry. The critical value of aspect ratio of 1.6 determined from clinical audits [18] is close to the value we have obtained of 1.68 for minimum dependency on both parent vessel size and aspect ratio (Fig 2). The corollary of this finding is that a saccular aneurysm with aspect ratio away from this value (e.g. 1.32) that is fed with smaller (4mm) curved parent vessel has a 2.3 fold the mass flow rate than a similar one fed with a straight parent vessel (Table) and so could be susceptible to rupture. Hence, the inclusion of parent vessel geometry to studies quantifying risk of rupture based on aneurysm features (eg aspect ratio) would improve the assessment and provide a better means to inform surgical decision making.

Limitations. The simulations reported in this study were conducted in vessels assumed to be rigid and thin walled. Although this does not represent the viscoelastic arterial properties and finite wall thickness, other studies have found a marked increased in stiffness of cerebral aneurysms compared to systemic vessels [20]. This partly justifies the rigid wall assumption, although in future simulations we will compare differences found with models based on fluid-structure interaction [21]. The further limitation of the Newtonian blood viscosity has also been found to have minimal effect in arteries of the caliber used in these simulations [22].

V. Conclusion

Current surgical decisions are largely based on aneurysm, size. However, CFD analysis in finite element models of cerebral aneurysms has shown that the diameter and shape of the parent vessels have a significant impact on aneurysm flow pattern and mass flow rate. These factors should be taken into consideration in decisions related to aneurysm treatment options.

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