Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Flow instability detected in ruptured versus unruptured cerebral aneurysms at the internal carotid artery

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ARTICLE INFO

Article history:
Accepted 6 March 2018
Available online xxxx

Keywords:
Cerebral aneurysm
Flow instability
Wall shear stress
Computational fluid dynamics
Internal carotid artery

ABSTRACT

Flow instability has emerged as a new hemodynamic metric hypothesized to have potential value in assessing the rupture risk of cerebral aneurysms. However, diverse findings have been reported in the literature. In the present study, high-resolution hemodynamic simulations were performed retrospectively on 35 aneurysms (10 ruptured & 25 unruptured) located at the internal carotid artery (ICA). Simulated hemodynamic parameters were statistically compared between the ruptured and unruptured aneurysms, with emphasis on examining the correlation of flow instability with the status of aneurysm rupture. Pronounced flow instability was detected in 20% (2 out of 10) of the ruptured aneurysms, whereas in 44% (11 out of 25) of the unruptured aneurysms. Statistically, the flow instability metric (quantified by the temporally and spatially averaged fluctuating kinetic energy over the aneurysm sac) did not differ significantly between the ruptured and unruptured aneurysms. In contrast, low wall shear stress area (LSA) and pressure loss coefficient (PLC) exhibited significant correlations with the status of aneurysm rupture. In conclusion, the present study suggests that the presence of flow instability may not correlate closely with the status of aneurysm rupture, at least for ICA aneurysms. On the other hand, the retrospective nature of the study and the small sample size may have to some extent compromised the reliability of the conclusion, and therefore large-scale prospective studies would be needed to further address the issue.

1. Introduction

Cerebral aneurysms are anatomically featured by a focal pathological dilatation of cerebral vessels, affecting approximately 3–5% of the adult population (Etminan and Rinkel, 2016). An incidental finding of asymptomatic aneurysms often poses a great challenge to clinical decision making due to the lack of definite criteria for assessing the rupture risk of cerebral aneurysms (Greving et al., 2014; Juvela et al., 2013). Some untreated aneurysms may maintain a stable state for years, whereas others may keep growing and suddenly rupture to cause subarachnoid hemorrhage that is usually associated with high mortality or severe morbidity (Connolly et al., 2012). On the other hand, treatments of unruptured aneurysms sometimes carry a risk of inducing complications that may exceed the inherent risk of aneurysm rupture (Wiebers et al., 2003). In this context, how to assess the rupture risk of cerebral aneurysms has long been an issue of wide concern.

It has been suggested that hemodynamic factors play important roles in the initiation, growth and rupture of cerebral aneurysms (Dolan et al., 2013; Sadasivan et al., 2013). Computational fluid dynamics (CFD) studies have identified some specific hemodynamic characteristics related to the status of aneurysm rupture, such as high area proportion of low wall shear stress (WSS) (Jou et al., 2008; Lu et al., 2011; Xiang et al., 2011a,b), low minimum WSS (Lauric et al., 2014; Zhang et al., 2016), high maximum WSS (Cebral et al., 2011) and low pressure loss coefficient (Takao et al., 2012). In addition, high-frequency oscillatory or turbulent WSS has been found by cell biological studies to play potential roles in the regulation of endothelial function (Davies et al., 1986; Himburg et al., 2007).

Inspired by the findings of cell biological studies, an increasing number of hemodynamic studies have turned to investigating flow instability in cerebral aneurysms, attempting to explore new biomechanical mechanisms underlying aneurysm rupture (Baek

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https://doi.org/10.1016/j.jbiomech.2018.03.014
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Please cite this article in press as: Xu, L., et al. Flow instability detected in ruptured versus unruptured cerebral aneurysms at the internal carotid artery. J. Biomech. (2018), https://doi.org/10.1016/j.jbiomech.2018.03.014

et al., 2010; Ford and Piomelli, 2012; Valen-Sendstad et al., 2011, 2013; Varble et al., 2016; Xu et al., 2016). The occurrence of flow instability during the deceleration phase of a cardiac cycle was reported by a CFD study on aneurysms at the internal carotid artery (ICA) (Baek et al., 2010), and the phenomenon was later confirmed by another CFD study on basilar artery aneurysms (Ford and Piomelli, 2012). In addition to flow instability occuring within a cardiac cycle (herein termed as intra-cycle flow instability), inter-cycle flow instability (i.e., the intensity of flow instability varies from one cardiac cycle to another) has been detected in a middle cerebral artery (MCA) aneurysm (Valen-Sendstad et al., 2011). Subsequent CFD studies revealed the prevalence of inter-cycle flow instablity in ruptured MCA aneuysms (Valen-Sendstad et al., 2013; Xu et al., 2016), implying that there might be a potential link between flow instability and the status of aneurysm rupture. However, a more recent study on MCA aneurysms did not find an evident correlation between flow instability and the status of aneurysm rupture (Varble et al., 2016).

The conflicting findings in the field of flow instability remain poorly explained and may be related to the location of aneurysm and setup of computational model that differed significantly among existing studies. To reduce uncertainties in flow instability detection arising from aneurysm location and boundary condition setting, the present study focused on aneurysms at the same location, i.e., the ICA, where the flow fields have been found insensitive to hemodynamic conditions distal to the aneurysms (Baek et al., 2010; Evju et al., 2013), as opposed to aneurysms at large bifurcations (Liang et al., 2016). A total of 35 ICA aneurysms with known rupture status were studied retrospectively with high-resolution hemodynamic simulations. The results were statistically analyzed to investigate the correlations of flow instability and other hemodynamic parameters with the status of aneurysm rupture.

2. Methods

2.1. Geometric model

The data of 35 ICA aneurysms (including 10 ruptured and 25 unruptured) were acquired from the Aneurisk database (Aneurisk-Team, 2012). All these aneurysms were of sidewall type according to the definition of sidewall aneurysm (Baharoglu et al., 2012). The geometric models of the aneurysms and adjacent arteries have already been reconstructed from medical images using the Vascular Modeling Toolkit (Antiga et al., 2008) with the data being freely accessible to researchers. In this study, these models were processed to simplify hemodynamic simulations by cutting off the remote arterial segments while retaining the entire ICA and major cerebral arteries to guarantee a reasonable simulation of flows entering and leaving the aneurysms (Castro et al., 2006; Valen-Sendstad et al., 2014). Furthermore, the outlets of each model were extended (using straight tubes) in the normal

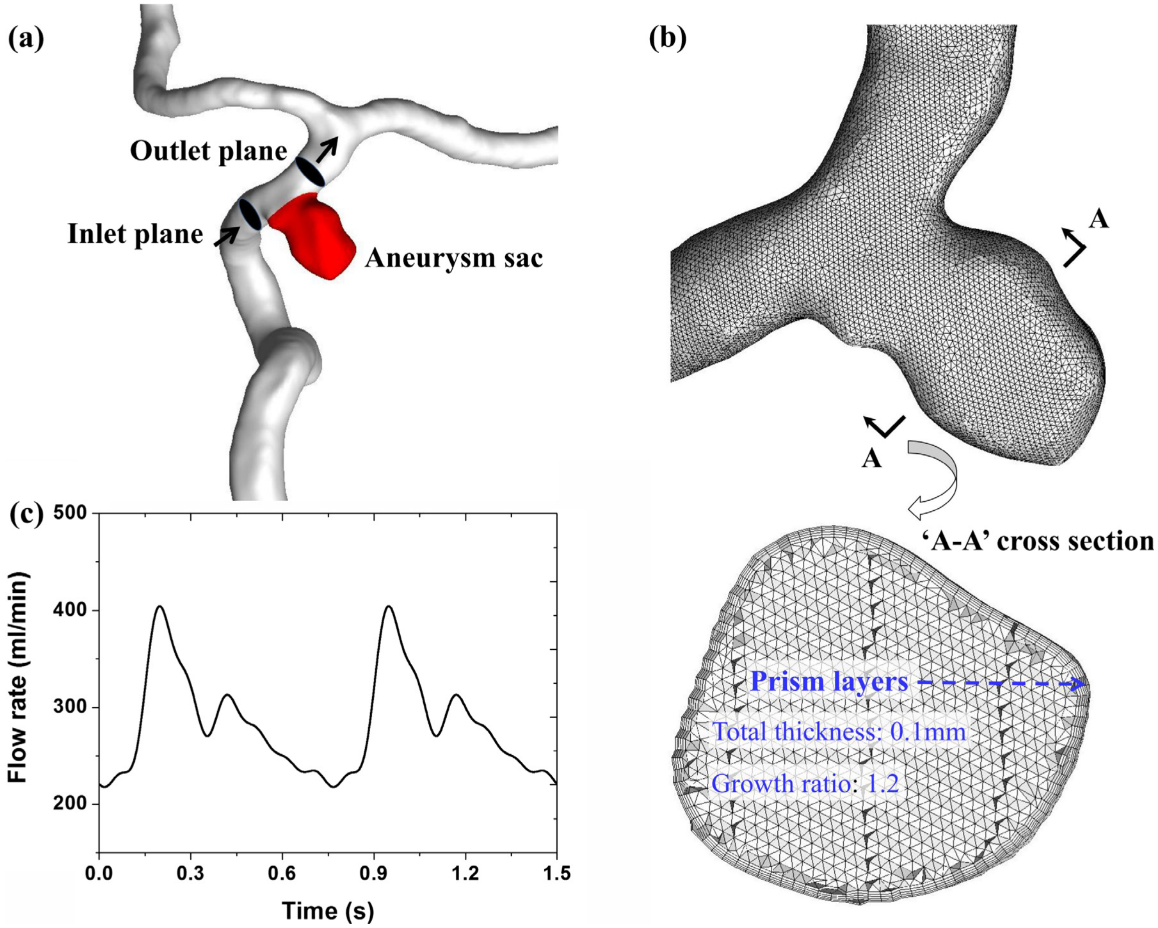

Fig. 1. Setup of CFD model: (a) identification of the aneurysm sac (denoted by red) and definition of inlet and outlet planes used to calculate trans-aneurysmal pressure/energy loss; (b) outside view of the mesh model and sectional view of internal tetrahedral elements and prism elements mapped along the aneurysm wall; and (c) flow waveform imposed at the model inlet. It is noted that the magnitude of the flow waveform is determined by the inlet area of each model given that a uniform mean inflow velocity (=0.31 m/s) is adopted for all models. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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