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Aneurysm

# Patient-specific hemodynamic analysis of small internal carotid artery-ophthalmic artery aneurysms

Aichi Chien, PhD[a,*], Satoshi Tateshima, MD[a], James Sayre, PhD[b], Marcelo Castro, PhD[c], Juan Cebral, PhD[c], Fernando Viñuela, MD[a]

[a]*Division of Interventional Neuroradiology, David Geffen School of Medicine, University of California, Los Angeles, CA 90095, USA*
[b]*Department of Biostatistics, School of Public Health, University of California, Los Angeles, CA 90095, USA*
[c]*Department of Computational Sciences, George Mason University, Fairfax, VA 22030, USA*

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**Abstract**

**Background:** Prophylactic treatment of unruptured small brain aneurysms is still controversial due to the low risk of rupture. Distinguishing which small aneurysms are at risk for rupture has become important for treatment. Previous studies have indicated a variety of hemodynamic properties that may influence aneurysm rupture. This study uses hemodynamic principles to evaluate these in the context of ruptured and unruptured small aneurysms in a single location.

**Methods:** Eight small internal carotid artery-ophthalmic artery (ICA-Oph) aneurysms (<10 mm) were selected from the University of California, Los Angeles, database. We analyzed rupture-related hemodynamic characteristics including flow patterns, wall shear stress (WSS), and flow impingement using previously developed patient-specific computational fluid dynamics software.

**Results:** Most ruptured aneurysms had complicated flow patterns in the aneurysm domes, but all of the unruptured cases showed a simple vortex. A reduction in flow velocity between the parent artery and the aneurysm sac was found in all the cases. Inside the aneurysms, the highest flow velocities were found either at the apex or neck. We also observed a trend of higher and more inhomogeneous WSS distribution within ruptured aneurysms (10.66 ± 5.99 Pa) in comparison with the unruptured ones (6.31 ± 6.47 Pa) ($P < .01$).

**Conclusion:** A comparison of hemodynamic properties between ruptured and unruptured small ICA-Oph aneurysms found that some hemodynamic properties vary between small aneurysms although they are similar in size and share the same anatomical location. In particular, WSS may be a useful hemodynamic factor for studying small aneurysm rupture.

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*Keywords:* Cerebral aneurysm; Hemodynamics; Flow analysis; Wall shear stress

## 1. Introduction

In general, prophylactic treatment of unruptured brain aneurysms remains controversial [9,11,14,25-27]. International studies have shown that the risk of aneurysm rupture increases as the aneurysm size increases, supporting treatment of larger aneurysms [27]. On the other hand, many small aneurysms are observed conservatively due to the lower risk of rupture compared with the risk of morbidity and mortality related to treatments. Recent advancements in medical imaging technology have helped the early detection of unruptured brain aneurysms, and more small aneurysms are found before rupture [2,14]. Among conservatively observed small brain aneurysms, some grow over time with a corresponding increase in the risk of rupture; however, reports have also shown that certain small aneurysms rupture without evidence of any growth [8,13,25]. Although they are

*Abbreviations:* CFD, computational fluid dynamics; ICA-Oph, internal carotid artery-ophthalmic artery; SD, standard deviation; WSS, wall shear stress.

* Corresponding author. Tel.: +1 310 794 7921; fax: +1 310 206 5958
*E-mail address:* aichi@ucla.edu (A. Chien).

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similar in diameter, it appears that a subpopulation of small brain aneurysms possess a different rupture risk than others. Identification of small brain aneurysms at high risk for rupture is crucial for evaluating the risks of inaction and treatment [9,15].

Intraaneurysmal hemodynamics has been intensively studied to understand the etiology and natural history of brain aneurysms. In the last decade, a variety of intraaneurysmal hemodynamic research has been published that shows the importance of intraaneurysmal flow characteristics [3,4,6,12,19,20,22,24]. Using patient-specific angiographic data for flow simulation, recent flow analysis studies have suggested that certain hemodynamic parameters, such as flow pattern, flow impingement, and wall shear stress can be used to evaluate the risk of aneurysm rupture [5,19,20,24].

The objective of this research is to use patient-specific hemodynamic simulation to study small aneurysm rupture. Because hemodynamic results are sensitive to aneurysm anatomical location [1,16], to minimize its influence, we compared flow characteristics between ruptured and unruptured small aneurysms at the same anatomical location.

## 2. Methods

### 2.1. Case selection

To include as many cases as possible from a single location, we studied the internal carotid artery-ophthalmic artery (ICA-Oph) aneurysm, the most common aneurysm location in our database [17]. A total of 276 patients with ICA-Oph aneurysms who underwent endovascular treatment in the Division of Interventional Neuroradiology, University of California, Los Angeles, Medical Center, from 1996 to 2008 (May) were screened. Patients having angiographic images acquired with sufficient 3-dimensional geometrical detail were selected. A total of 32 in our database satisfied these criteria, and 12 aneurysms met the criteria for small aneurysms, with the greatest diameter less than 10 mm. Because vasospasm may greatly affect the intraaneurysmal hemodynamics, 4 aneurysms with angiographic evidence of vasospasm in the parent artery were excluded [10,21]. Ultimately, 4 ruptured and 4 unruptured small ICA-Oph aneurysms were included in this study.

### 2.2. Image collection

Aneurysmal 3-dimensional rotational angiography was obtained using a Philips Integris unit (Philips Medical Systems, Best, The Netherlands) before the embolization procedure and then transferred to the Philips Integris workstation for 3-dimensional voxel generation. Because it is difficult to collect images of ruptured aneurysms before the event of rupture, images of ruptured aneurysms were acquired within 24 hours of rupture. Using those images to model ruptured aneurysms, we assumed limited arterial and hemodynamic changes in the 24 hours after rupture.

### 2.3. Computational fluid dynamics simulation

Image-based computational fluid dynamics (CFD) software developed by researchers at George Mason University (Fairfax, VA) was used for the hemodynamic simulation [5,28]. For each aneurysm, the 3-dimensional voxel data obtained from rotational angiography was first transferred to a Dell 490 workstation, and the computational model was constructed semiautomatically through segmentation, surface generation, and 3-dimensional grid generation. Normal pulsatile flow conditions measured from a healthy subject using magnetic resonance phase contrast measurement were imposed on the model [5]. The unsteady incompressible Navier-Stokes equations were implemented and solved under the Newtonian fluid assumption. Blood was assumed to have uniform viscosity of 0.004 Pa·s. Because information about the aneurysm wall elastic properties is not yet obtainable, the rigid and no-slip boundary condition was assumed for the aneurysm wall in the current simulation [5,19].

Although studies have suggested the importance of incorporating the entire circle of Willis into hemodynamic analysis, this type of simulation has been unable to model small vessels such as ophthalmic arteries [1,5]. To realistically analyze the hemodynamic properties in ICA-Oph aneurysms, models focusing on the internal carotid artery segment incorporating ophthalmic arteries were used. This approach assumed that the flow in the ophthalmic artery has more influence on a ICA-Oph aneurysm than the flow in circle of Willis because this part of the ICA is not within the circle of Willis [1,5].

### 2.4. Results analysis

The hemodynamic results at the peak of the pulsatile flow time point were carefully examined. The qualitative flow characteristics, such as flow patterns, locations of flow impingement, and impingement size, were evaluated by both AC and ST for each aneurysm. Flow pattern was categorized depending on whether the flow in the aneurysm formed a single vortex or multiple associated vortices. The *flow impingement location* was defined as the position where the inflow jet contacted the aneurysmal wall. It was classified as neck, body, or apex. The impingement size was considered large if the area of impingement was more than half the reference region. For example, if the impingement location was at the neck of the aneurysm, then the impingement size was considered large if the impingement area was larger than half of the neck. Otherwise, the impingement size was recorded as small. Detailed examples of different hemodynamic characteristics can be found in Cebral et al [4].

Values of flow velocity and wall shear stress (WSS) were also compared between ruptured and unruptured cases. To study hemodynamic value changes due to the formation of the aneurysm, hemodynamic results from parent arteries and aneurysm sacs were compared [19]. We obtained hemodynamic results from 6 different locations as indicated