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# Hemodynamic characterization of geometric cerebral aneurysm templates

Priya Nair [a,*], Brian W. Chong [a,b], Aprinda Indahlastari [a], James Lindsay [a], David DeJeu [a], Varsha Parthasarathy [a], Justin Ryan [a], Haithem Babiker [c], Christopher Workman [a], L. Fernando Gonzalez [d], David Frakes [a,e]

[a] *School of Biological and Health Systems Engineering, Arizona State University, Tempe, AZ, United States*
[b] *Mayo Clinic Hospital, Phoenix, AZ, United States*
[c] *Endovantage, Scottsdale, AZ, United States*
[d] *Department of Neurosurgery, Duke University School of Medicine, Durham, NC, United States*
[e] *School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, AZ, United States*

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## ABSTRACT

Hemodynamics are currently considered to a lesser degree than geometry in clinical practices for evaluating cerebral aneurysm (CA) risk and planning CA treatment. This study establishes fundamental relationships between three clinically recognized CA geometric factors and four clinically relevant hemodynamic responses. The goal of the study is to develop a more combined geometric/hemodynamic basis for informing clinical decisions. Flows within eight idealized template geometries were simulated using computational fluid dynamics and measured using particle image velocimetry under both steady and pulsatile flow conditions. The geometric factor main effects were then analyzed to quantify contributions made by the geometric factors (aneurysmal dome size (DS), dome-to-neck ratio (DNR), and parent-vessel contact angle (PV-CA)) to effects on the hemodynamic responses (aneurysmal and neck-plane root-mean-square velocity magnitude ($V_{rms}$), aneurysmal wall shear stress (WSS), and cross-neck flow (CNF)). Two anatomical aneurysm models were also examined to investigate how well the idealized findings would translate to more realistic CA geometries. DNR made the greatest contributions to effects on hemodynamics including a 75.05% contribution to aneurysmal $V_{rms}$ and greater than 35% contributions to all responses. DS made the next greatest contributions, including a 43.94% contribution to CNF and greater than 20% contributions to all responses. PV-CA and several factor interactions also made contributions of greater than 10%. The anatomical aneurysm models and the most similar idealized templates demonstrated consistent hemodynamic response patterns. This study demonstrates how individual geometric factors, and combinations thereof, influence CA hemodynamics. Bridging the gap between geometry and flow in this quantitative yet practical way may have potential to improve CA evaluation and treatment criteria. Agreement among results from idealized and anatomical models further supports the potential for a template-based approach to play a useful role in clinical practice.

## 1. Introduction

Aneurysmal geometry is an important factor that is considered in clinical practice during cerebral aneurysm (CA) risk evaluation and treatment planning. Extensive studies focusing on the natural history of aneurysms have identified dome size (DS) as an important predictor of growth and rupture risk. For example, CAs with DS greater than 10 mm in diameter have been found more prone to rupture (Ishibashi et al., 2009; Wermer et al, 2007; Brisman et al., 2006; Wiebers, 2003). However, Forget Jr et al. (2001) reported that most ruptured aneurysms coming into the clinic had DS less than 10 mm. This finding indicates that aneurysm size should not be considered as a lone predictor in evaluating CA risk. While many larger aneurysms are treated

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*Abbreviations and conventions:* CA, cerebral aneurysm; DS, dome size; DNR, dome-to-neck ratio; PV-CA, parent-vessel contact-angle; WSS, wall shear stress; $V_{rms}$, root-mean-square velocity magnitude; CNF, cross-neck flow; CFD, computational fluid dynamics; PIV, particle image velocimetry; IBTA, idealized basilar tip aneurysm; ABTA, anatomical basilar tip aneurysm; SS, sum of squares

[*] Correspondence to: School of Biological and Health Systems Engineering, Arizona State University, 501 E Tyler Mall, BLDG ECG RM # 334, Tempe, AZ 85287, United States. Tel.: +1 480 205 6530; fax: +1 480 727 7624.
*E-mail address:* priyanair@asu.edu (P. Nair).

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almost immediately, management of small CAs is still a gray area because the tradeoff between associated treatment and rupture risks is often unclear (especially when evaluated based on size alone) (Sonobe et al., 2010).

Aneurysmal dome-to-neck ratio (DNR) is another important geometric factor considered during treatment planning. DNR is defined as the ratio of maximum width of the aneurysmal dome to the diameter of the neck. Aneurysms with lower DNR, or wide-neck aneurysms, often present difficult treatment challenges, such as potential for coil herniation into the parent-vessel (Brinjikji et al., 2009; Weir et al., 2003). As a result, the lesions are commonly treated with assistive techniques (e.g., stent-assisted coiling or balloon remodeling). DNR also ties in with rupture risk; aneurysms with large DNR have been found more prone to rupture (Weir et al., 2003).

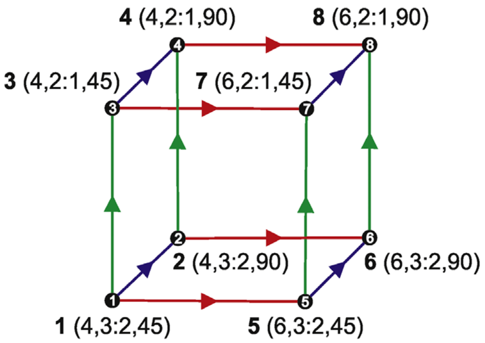

**Fig. 1.** Cube representing a two-level full-factorial experimental design based on three geometric factors: aneurysmal dome size, dome-to-neck ratio, and parent-vessel contact-angle. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

In addition to DS and DNR, a number of other geometric factors such as parent-vessel contact-angle (PV-CA) have also been linked to aneurysmal outcomes (Hoi et al., 2004). However, there is considerable evidence to support that hemodynamics such as aneurysmal and neck-plane root-mean-square velocity magnitude ($V_{rms}$), aneurysmal wall shear stress (WSS), and cross-neck flow (CNF) may play equally or even more important roles (Babiker et al., 2012; Cebral et al., 2011; Mut et al., 2011; Xiang et al., 2011; Baharoglu et al., 2010; Sforza et al., 2009; Lasheras, 2007; Cebral et al., 2005; Hoi et al., 2004, Jou et al., 2003). Not surprisingly, it is also well known that geometric factors are key determinants of CA hemodynamics (Sforza et al., 2009). Nevertheless, unlike geometric factors, hemodynamics are still considered to a limited degree in current clinical practices for evaluating CAs. A primary reason for this lack of consideration is that hemodynamic data are often unavailable or impractical to acquire in clinical practice.

In this paper, we quantify the effects of geometric variations on aneurysmal hemodynamics in order to attribute specific hemodynamic features to geometric underliers that are routinely quantified in clinical practice. Our objective is to bridge the gap between aneurysmal anatomy and physiology by creating a link between the geometric and hemodynamic blueprints of CAs. Clinically, geometry has already been established as a primary driver of aneurysmal hemodynamics and is currently considered along with hemodynamics to stratify risk (Xiang et al., 2011; Cebral et al., 2005). However, this paper breaks new ground by quantifying the contributions that different geometric factors make to effects on hemodynamic responses. Toward this end, we employ a design of experiments based on parallel computational and bench top data. The statistical relationships between geometry and flow that emerge have potential to play a valuable role in current clinical practices for evaluating CAs and planning their treatments.

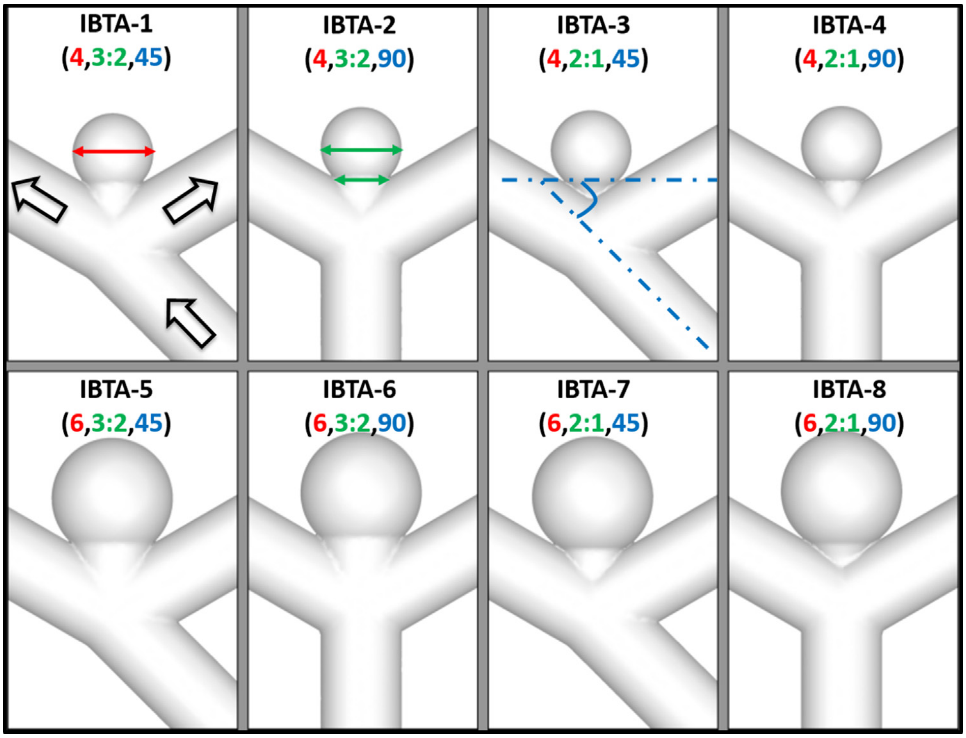

**Fig. 2.** Computational idealized basilar tip aneurysm models corresponding to the corners of the cube in Fig. 1. The numbers in red, green, and blue represent the dome size (in mm), dome-to-neck ratio, and parent-vessel contact-angle (in degrees), respectively. The black arrows in IBTA-1 indicate the directions of inflow and outflows. (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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