Computational Fluid Dynamics Modeling of Intracranial Aneurysms:

Qualitative Comparison with Cerebral Angiography[1]

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Rationale and Objective. The purpose of this study is to determine whether computational fluid dynamics modeling can correctly predict the location of the major intra-aneurysmal flow structures that can be identified by conventional angiography.

Materials and Methods. Patient-specific models of three cerebral aneurysms were constructed from three-dimensional rotational angiography images and computational fluid dynamic simulations performed. Using these velocity fields, contrast transport was simulated and visualizations constructed to provide a "virtual" angiogram. These models were then compared to images from high frame rate conventional angiography to compare flow structures.

Results. Computational fluid dynamics simulations showed three distinct flow types ranging from simple to complex. Virtual angiographic images showed good agreement with images from conventional angiography for all three aneurysms with analogous size and orientation of the inflow jet, regions of impaction, and flow type. Large intra-aneurysmal vortices and regions of outflow also corresponded between the images.

Conclusions. Patient-specific image-based computational models of cerebral aneurysms can realistically reproduce the major intra-aneurysmal flow structures observed with conventional angiography. The agreement between computational models and angiographic structures is less for slower zones of recirculation later in the cardiac cycle.

Key Words. Cerebral aneurysms; rotational angiography; computational fluid dynamics; cerebral angiography.

Cerebral aneurysms are widely believed to form and grow on the basis of hemodynamic interactions with the wall biology. Researchers have used a variety of tools to study these complex biological phenomena including animal, in vitro models, and computational models (1–8). The goal of these experiments has been to approximate the in vivo environment so that theories can be developed and further tested in more realistic systems. Ultimately, a link between the research and the clinical outcomes (i.e., aneurysmal growth and rupture) is necessary to reach an understanding of the relative importance of the forces or mechanisms that are discovered. Previously used methods fall short of this goal because they cannot reproduce the in vivo state of a particular patient. Until recently, computational studies have been only performed on idealized aneurysm geometries or approximations of a specific patient geometry. As computational techniques have improved, more refined models have been constructed, leading to a transition from idealized geometries to "realistic" models based on typical patient anatomies. Most recently, studies have tried to replicate the exact anatomy of specific patients to connect specific hemodynamic factors to

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clinical events, allowing statistical analysis in a patient population (9, 10). Despite these more sophisticated methods, one question still remains: Are these models accurately reproducing what is occurring in a specific patient?

Without accurate in vivo measurements for comparison, a complete validation of computational methods is not possible. But, there is growing evidence that computational methods are reliably reproducing the in vivo intravascular environment. Comparisons with a variety of simplified experimental biological systems have shown good correlation with computational models (11–16). In addition to this direct validation, sensitivity analysis has been performed to obtain an understanding of the influence of a variable within a physiologic range are on the results of a specific model (17, 18). These analyses have been done to test a variety of assumptions used in modeling including flow rates, flow asymmetries, inflow boundary conditions, Newtonian properties of fluids, reconstruction/grid generation techniques, and small branch segmentation (17, 19). Even without knowing the exact value of the input variable, this analysis can measure the influence of changes (or errors) in the variable would have on the results of a simulation. Previous work has shown that inaccuracies in geometry have the largest potential for adversely influencing intra-aneurysmal hemodynamics (17). Other variables appear to have only minor effects on the models and are considered higher order variables.

Although there currently are no proved methods for doing noninvasive in vivo measurements of flow, pressure, or wall shear stress in cerebral aneurysms, there are some techniques that can give some qualitative flow information. Conventional cerebral angiography has long been used for defining the anatomy and flow patterns of the intracranial vessels. Using high frame rates and/or judicious use of masking techniques, intra-arterial DSA can image inflow jets and some zones of recirculation in many aneurysms (20, 21). MR angiography can provide similar information with appropriate postprocessing of the time of flight data acquisitions (8). These methods are not sufficient to give accurate quantitative measures of intra-aneurysmal hemodynamics but do give a direct representation of the intra-aneurysmal flow structure and therefore make possible a qualitative comparison. For this study, we use images from conventional angiograms in selected aneurysms to determine the major intra-aneurysmal flow structures and conventional 3D rotational angiography to define the patient-specific 3D geometries. Our purpose is to determine whether our computational fluid dynamic (CFD) method can correctly predict and explain the observed flow structures as a means of providing evidence to support the validity of the CFD method.

Table 1
Cases selected for study

Patient	Location	Size (mm)	Rupture	Flow type
1	LICA	25	Yes	IV
2	LICA	11	No	III
3	RMCA	5	Yes	I

METHODS

Patients and Images

Three patients with cerebral aneurysms were selected from our database in order to study whether CFD could predict the major intra-aneurysmal flow structures found on conventional angiography. The aneurysms that were selected had different flow types and had high frame rate conventional angiography images with definable major flow structures. These angiographic images were obtained using a short injection (10 ml/sec for total volume of 3 ml) and biplane angiography at 7.5 frames/sec using DSA. Characteristics of these aneurysms are summarized in Table 1. Patient-specific geometries were obtained by rotational acquisition during conventional cerebral angiography using a Philips Integris system. (Philips Medical Systems, Best, The Netherlands). The images used for the 3D reconstruction were obtained during a 180-degree rotation and imaging at 15 frames/sec for a total of 8 seconds. The corresponding 120 projection images were reconstructed into a 3D dataset of $256 \times 256 \times 256$ voxels covering a field of view of 54.02 mm on a dedicated Phillips workstation. The voxel data was exported into a PC for mathematical vascular modeling using a recently developed methodology (17, 22, 23).

Vascular Models

Vascular models were constructed from the 3D rotational angiography (3DRA) images using geometric deformable models (24). High-quality volumetric finite element grids composed of tetrahedral elements were then generated using an advancing front technique to fill the space inside these geometrical models (25–27). The mesh minimum resolution was approximately 0.16 mm. The meshes contained roughly 2.2 million (M), 2.5 M, and 2.2 M elements for patients 1 through 3, respectively. In all these