DANCING ON THE KNIFE-EDGE OF SYMMETRY: ON THE MISUSE OF SYMMETRIC MODELS FOR STUDYING BLOOD FLOW DYNAMICS

David A. Steinman (1,2), Steven C. Kehoe (1,2), Matthew D. Ford (1,2), Hristo N. Nikolov (1), David W. Holdsworth (1,2)

(1) Imaging Research Labs, Robarts Research Institute, London, Ontario, Canada

(2) Department of Medical Biophysics, University of Western Ontario, London, Ontario, Canada

INTRODUCTION

Geometrically symmetric models have traditionally been used for both experimental and computational fluid dynamic (CFD) modeling of blood flow dynamics. In the case of experimental studies, symmetry makes it easier to construct physical models via cost-effective "lost material" techniques, while for CFD studies model symmetry can be readily exploited to reduce the model domain by a factor of two or more. Symmetric models also provide convenient planes from which field plots can be readily extracted and displayed. For these reasons symmetric models are also the tool of choice for validating CFD predictions against experimental measurements.

While convenient for such purposes, however, symmetric models are unnatural in the sense that real blood vessels – not to mention nominally symmetric physical models – are rarely symmetric. The introduction of symmetry into physical or CFD models is nevertheless considered reasonable for simplifying the process of experimentally measuring, simulating, and validating physiological flows. As we demonstrate in this study of a basilar tip aneurysm model, this ostensibly simplifying assumption can, ironically, complicate these processes via the elimination of preferred flow directions and hence the introduction of unstable flow patterns, even under nominally steady, laminar flow conditions.

METHODS

The physical model used for this study was a life-sized, anthropomorphic flow-through model of a basilar tip aneurysm ($D_{basilar}$=3.2 mm), the geometry and construction of which is described by Fahrig et al. [1]. Briefly, the symmetric lumens were numerically milled into matching aluminum molds, into which a low melting-point metal (Cerro Metal Products, Bellefonte PA) was poured. After cooling, these positive lumen cores were mounted in a plastic housing, into which a silicone elastomer (Sylgard 184; Dow Corning, Midland MI) was poured and then cured. The cores were then melted out to produce an optically transparent flow-through model. Two such models were constructed: the first was symmetric about both the coronal and sagittal planes; for the second, symmetry was broken by manually bending the core to tilt the aneurysm bulb out of the coronal plane. This tilted model is shown in Figure 1.

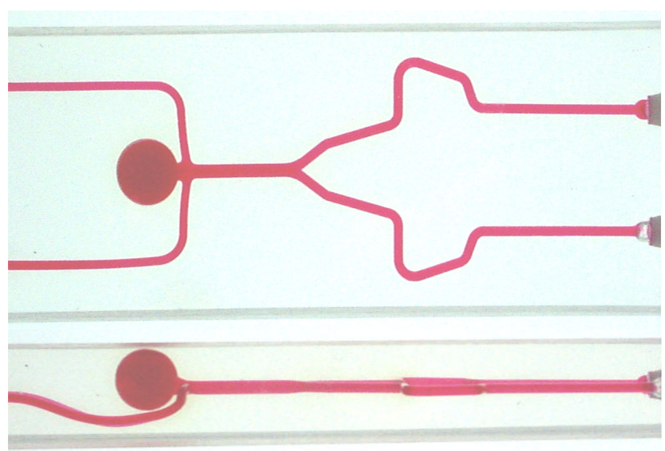

Figure 1: Coronal (top) and sagittal (bottom) views of the tilted basilar tip aneurysm flow-through model.

Flow patterns were visualized using an in-house digital particle imaging (DPI) facility. The DPI system consisted of two 5 mW He-Ne lasers (Melles Griot, Carlsbad CA) lasers producing 1 mm thick fanbeams, which illuminated the center plane of the of the vessel model uniformly from opposite sides. A CCD camera (Panasonic, Secaucus NJ) was used to record the flow of small (~400 µm diameter) reflective particles seeded into a 2:1 volume mixture of water-glycerol blood-mimicking fluid. A series of 640x480 digital images of the mid-coronal or mid-sagittal planes of the vessel model were captured with 16 ms temporal resolution onto an Indy workstation (Silicon Graphics, Mountainview CA). A computer-controlled pump (R.G. Shelley, North York ON) was used to provide steady and physiologically pulsatile flow.

RESULTS

Visualization of steady flow at 5 ml/sec ($Re_{basilar} \approx 600$) in the symmetric aneurysm model demonstrated laminar but unstable flow patterns in the aneurysm bulb, exemplified by the sporadic appearance of vortices on one or the other sides of the nominal plane of symmetry (Figure 2). Doubling the steady flow rate to 10 ml/sec (ie, well above mean flow in the normal basilar artery) introduced more stable, but decidedly asymmetric, flow patterns characterized by a vortex centered roughly in the middle of the bulb (Figure 3). The slight geometrical asymmetry introduced by tilting the aneurysm bulb slightly out of plane was sufficient to re-introduce steady flow at the lower flow rate, albeit of a decidedly asymmetric nature. Although not shown here, these effects of physical model (a)symmetry were also evident under physiologically pulsatile flow conditions.

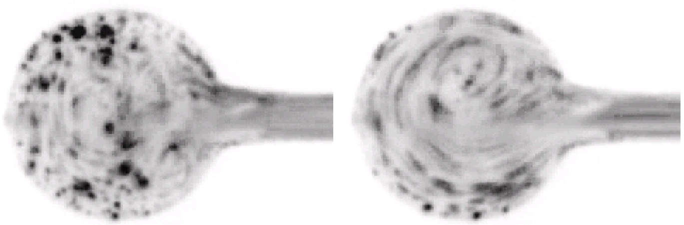

Figure 2: Two frames from a visualization of 5 ml/sec steady flow on the mid-sagittal plane of the symmetric aneurysm model. Note the marked asymmetry of flow on the right compared to that the left, suggesting the presence of chaotic flow or "dancing on the knife edge of symmetry."

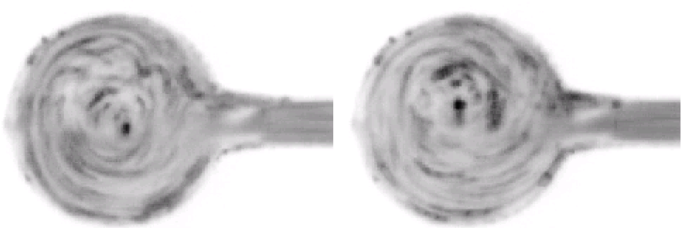

Figure 3: As above, but for steady flow at 10 ml/sec. At this higher flow rate a stable, unidirectional vortex now fills the bulb, indicating the complete breakdown of flow symmetry in this nominally symmetric model.

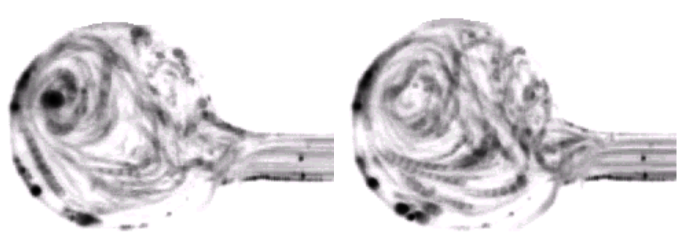

Figure 4: Two frames from a visualization of 5 ml/sec steady flow on the mid-sagittal plane of the tilted aneurysm model. By breaking the physical symmetry of the model, stable flow patterns were introduced at the lower flow rate.

DISCUSSION

Our study demonstrates the practical challenges associated with using geometrically symmetric models to study physiological blood flow dynamics. In particular the symmetric model exhibited the hallmarks of a chaotic system, namely sensitivity to small perturbations in boundary conditions followed by a transition to a more stable but asymmetric flow state.

The inability to maintain stable or symmetric flow patterns in these geometrically symmetric models suggests that they would be difficult "gold standards" for CFD validation studies, since in such cases the CFD models are assumed to be perfectly symmetric. Although it is possible to introduce slight asymmetries into the CFD model, either geometrically or through the flow/velocity boundary conditions, it is often difficult to know exactly how much asymmetry to introduce to mimic and experiment. Moreover, it is difficult to model chaotic flow patterns (such as observed here in the case of the symmetric model at 5 ml/sec) with conventional CFD solvers. Instead, with the advent of high-resolution, non-destructive imaging and rapid prototyping technologies, it is now feasible to construct asymmetric physical and computational models of realistic vessels from the same raw data. A practical downside of this is, however, the loss of those convenient planes of symmetry where velocity measurements are usually made.

Perhaps more importantly, since blood vessels and hence blood flow patterns are known to be asymmetric in vivo, symmetric models may mask important physiological flow dynamics. For example, in their recent study of heart flow dynamics, Kilner et al. [2] proposed that, by minimizing flow separation and recirculation, asymmetry confers a "morphodynamic" advantage that maximizes cardiac output during exercise. Similarly, in studies of aneurysm hemodynamics, model symmetry implies the presence of counter-rotating vortices in the aneurysm bulb, a situation that is unlikely to occur *in vivo* and a flow feature that may overestimate the stagnation of blood and hence thrombotic potential.

CONCLUSIONS

We conclude that physically symmetric models, while convenient and conceptually attractive, can be more challenging to use for validating CFD data and for properly understanding physiological blood flow dynamics.

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