In vivo MR Velocimetry in Intracranial Aneurysms: Computational Fluid Dynamics Specification and Validation

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Introduction: Although the evolution of intracranial aneurysmal disease is generally known to be related to the hemodynamic forces on the vessel wall, a detailed understanding of the role of different hemodynamic descriptors in this process has not been determined. In order to establish those relationships, it is essential to be able to estimate hemodynamic forces in vivo. Computational Fluid Dynamics (CFD) methods are able to compute the velocity field in patient-specific vascular geometries for pulsatile physiological flow. Those simulations require geometric and hemodynamic boundary values. Although modalities other than MR have been used as a basis for CFD, they use simplifying assumptions on flow boundary conditions. In this study, we investigated whether the calculated velocity fields were sensitive to assumptions on flow in the inlet vessels. In addition, we compared CFD predictions of the in-plane velocity field to the corresponding in vivo MR velocimetry measurements.

Methods: Twenty three patients with fusiform intracranial aneurysms who were not candidates for therapeutic intervention were recruited to this study using approved IRB consent. High resolution (0.6 x 0.6 x 1.2 mm), contrast-enhanced MRA (CE-MRA) images of the cerebral blood vessels were used to obtain contours of the aneurysmal arteries and to generate patient-specific lumenal surface geometries. In addition, MR phase mapping velocimetry methods were used to obtain through-plane flow values in the inlet vessels. The flow fields in these models were calculated using a finite-volume Computational Fluid Dynamics (CFD) solver. For each patient, the total flow through the aneurysm, measured using MR-velocimetry as the sum of the flow through each vertebral, was determined. The sensitivity of CFD results to variations in inlet flow rates was studied for several basilar aneurysm geometries by arbitrarily adjusting the ratio of flow in the right to the left vertebral artery. Several inlet flow scenarios were simulated for each model, including the two limit cases where one of the supplying vertebrals was occluded. The flow fields calculated with CFD in several patient models were also compared to in vivo MR measurements. Pulsatile and steady flow simulations were carried out using patient-specific flowrates, obtained from MR velocimetry data. Two-dimensional slices in the longitudinal plane of the aneurysm were studied. The distribution of the calculated velocity magnitude was compared to MR in-plane velocity images made in vivo.

Results: Numerical simulations indicated that in the great majority of cases, altering the inlet flow ratio resulted in major changes of the flow fields predicted in the aneurysm. Only in cases where there was a long section of normal vessel distal to the vertebral junction and proximal to the aneurysm, was the intra-aneurysmal flow relatively unaffected by the vertebral flow ratio. The flow streamlines calculated in one of the patient-specific geometries are shown in Fig. 1. The three cases shown correspond to the following scenarios: all the flow is provided by the left vertebral with the right vertebral occluded (case A); the flow divides equally (case B); and the final case is the reverse of the first case (case C). In case A, the jet propagates along the unaffected wall of the lesion and impinges at the distal end of the collateral aneurysm wall. A large recirculating flow region with slow, retrograde flow is observed in the bulge. In case C, the jet crosses the vessel and impinges at the proximal end of the aneurysm bulge. Both entering jets, although not as strong as those noted in the other cases, can be observed in case B. This deflection of the high velocity jet formed in the aneurysm belly and changes of the recirculating flow regions result in different shear stresses induced by the flow on the aneurysm wall, which may have important implications for aneurysm growth.

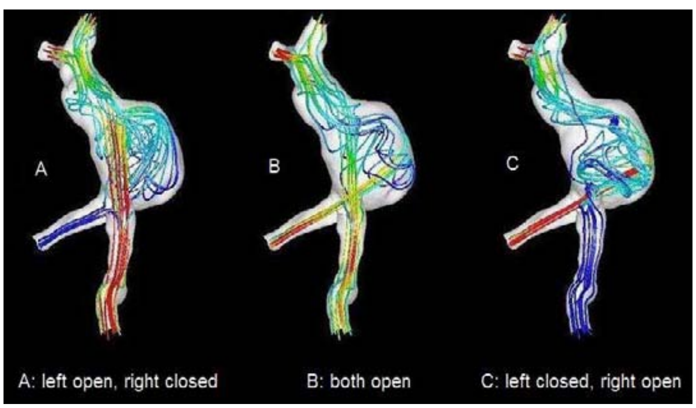

Figure 1 Flow streamlines for different inlet flowrate ratio between the vertebral arteries: Case A: Right – closed, Left – open; B: Right – 50%, Left – 50%; C: Right – open, Left – closed.

Comparison of the computational and MRI results for two different patients is shown in Fig. 2. The patient shown in the top row has a severe stenosis of the right vertebral artery, so most of the flow entered through the left vertebral. The flow fields obtained in vivo look strikingly similar to the CFD results. A high velocity jet streams up the right lateral wall of the basilar artery and impinges on the opposite wall of the aneurysm. Retrograde flow along the bulging aneurysm wall and a large slow flow region in the bottom of the bulge is observed in both images. Good agreement between the numerical and in vivo data is also observed for the other patient, shown in the bottom row of Fig.2. A high velocity jet propagates along the basilar artery wall while a large slow, retrograde flow region is formed in the bulge of the aneurysm.
Velocity fields obtained with CFD and in-vivo MR imaging for the other patients who were studied were also found to in good qualitative agreement.

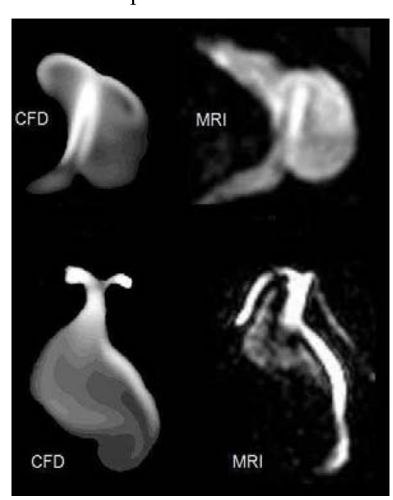

Figure 2 Velocity field obtained with CFD (left panel) and in-vivo MR imaging (right panel) for two giant basilar aneurysms.

Conclusion: The results of the study demonstrate that realistic, patient-specific inlet flow conditions are required in order to obtain accurate and relevant computational models of the flow in aneurysmal vessels, and that MR-based methods are suitable for this task. This capability can provide an insight into the progression of disease and hence aid in the evaluation of therapeutic options that are available for a given patient.