CE-MRA and numerical modeling of the flow in intracranial aneurysms: prediction of regions prone to thrombus formation

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Introduction

Intralumenal thrombus has important clinical sequellae. The presence of intralumenal thrombus in patients with aneurysmal disease can complicate a situation that already has dismal prospects for long-term survival. In intracranial aneurysm, intralumenal thrombus adds a risk of stroke from thrombo-embolism, and a risk of devastating neurological symptoms secondary to mass effect from the distending outer wall, on top of the grave risk posed by rupture. The conditions that result in thrombus layering are only poorly understood. In addition to biochemical factors (such as coagulability), there appears to be an important role that is played by hemodynamic factors that are dependent on lumenal geometry and blood flow rates. MR imaging and MR velocimetry methods can be used to determine the flow conditions on a patient-specific basis either by direct measurement or indirectly, using numerical simulation. Those methods were used to predict the velocity fields in patients who had thrombus-free vessels, and then proceeded to develop extensive intra-aneurysmal thrombus. Predictions of the velocity fields obtained from computations were compared to the regions of thrombus formation observed in vivo.

Methods

CE-MRA has been demonstrated to provide excellent results in determining the lumenal geometries of large blood vessels. In addition, phase mapping MR techniques can be used to measure flow velocities in a blood vessel and to determine the pulsatile variation of these velocities through the cardiac cycle. Despite these advances, determination of important flow features and flow derived parameters, such as wall shear stress or vorticity distribution, require resolution beyond current imaging capabilities. However, the information on lumenal geometries and flow conditions obtained with MRA can be used to construct computational models capable of determining these quantities. In the current study, 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 from which patient-specific lumenal surface geometries were generated. Patients with intracranial aneurysms were recruited to this study using institutionally approved IRB consent. Images obtained at baseline and at follow up studies were co-registered. Regions of pronounced reduction in lumen size were correlated with MRI of soft tissue to determine regions of thrombus formation. Computational Fluid Dynamics (CFD) models were constructed using the geometries and inlet flow conditions measured with MRA at baseline. The flow fields in these models were calculated using a finite-volume CFD solver. Non-Newtonian blood behavior, which can have important effects on the flow in low shear rate regions, was taken into account by using a Herschel-Bulkley viscosity model. Detailed numerical simulations were carried out to model the flow in two giant basilar aneurysms where intra-aneurysmal thrombus had formed.

Results

In the first case, MR angiography demonstrated steady aneurysm growth over five years. In the following year it was noted that a large region of the aneurysmal lumen was filled with thrombus. A computational model was constructed from MRA images taken prior to thrombus deposition. Numerical results predicted the presence of a large region of flow recirculation in the aneurysm bulge, with low velocities and long particle residence time. This slow flow zone can be visualized using a constant velocity surface map (Fig. 1, left panel). An iso-surface with velocity magnitude of 3 cm/s is plotted on top of the vessel outline surface. All regions with velocities equal to or above 3cm/s are shown in light gray and regions with slower velocities are shown as black. Co-registration of the lumenal surfaces obtained with MRA prior to and after the thrombus formation is also shown (Fig. 1, right panel). Comparison of the lumenal changes obtained from MRA data with the velocity iso-surfaces calculated from CFD indicates a strong similarity between the slow flow region predicted in flow simulations and the region that was observed to fill with clot in vivo.

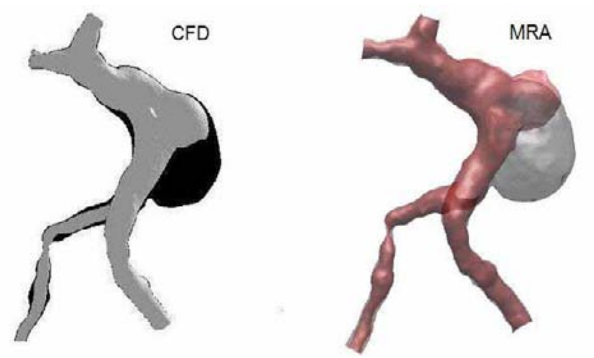
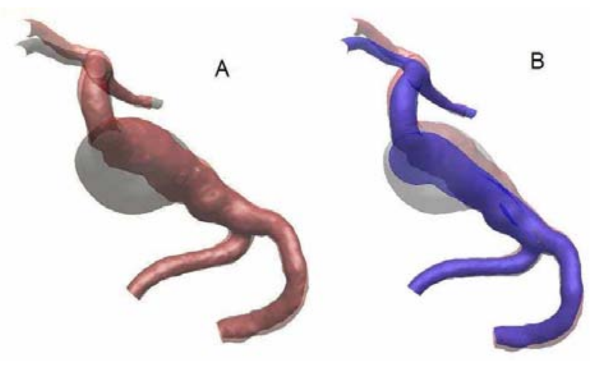


Figure 1 Left: Velocity maps predicted by CFD prior to thrombus formation (regions with velocities >3cm/s are shown as gray, regions with velocities < 3cm/s are shown as black); Right: Co-registration of lumenal surfaces obtained from MRA prior to thrombus deposition (gray) and after thrombus formation (red).

In the second patient, numerical simulations of the flow prior to and following surgical occlusion of a proximal vertebral artery were carried out. Both MR imaging and catheter angiography, performed within 24 hours following this procedure, demonstrated a dramatic reduction in the caliber of the aneurysmal vessel. Balanced FFE images indicated that regions that had previously been patent were filled with intra-lumenal thrombus. The lumenal surfaces obtained prior to, and following surgery, plotted as gray and red respectively, show the region occupied by thrombus (Fig.2A). Patient-specific geometry and flowrates obtained from MR angiography and velocimetry were used to simulate the flow prior to and after surgery. Numerical solutions for steady and pulsatile flows were obtained. Highly three-dimensional flows, with strong secondary flows, were computed in the aneurysm in the pre-surgical and post-surgical conditions. The computational results predicted that vertebral artery occlusion would result in a significant increase in regions where there was slow flow. In particular, in the bulge of the aneurysm, there were large regions where increased particle residence time and velocities lower than 2cm/s were computed. Those slow flow regions were found to fill with thrombus following surgery. The lumenal surfaces determined with CE-MRA were co-registered with constant velocity surfaces predicted by CFD (shown in blue) (Fig.2B).

Figure 2 Aneurysm pre and post occlusion of one vertebral. A: Coregistration of pre-surgical lumenal surface (gray) and post-surgical lumenal surface (red). B: The regions computed by CFD to have velocities > 2cm/s (blue) are superimposed on the lumenal surfaces shown in A.



Conclusions

While the CFD velocity iso-surfaces do not exactly match the observed post-surgical lumen, there is a strong similarity between the regions of thrombus formation and slow flow regions. Predictions of numerical simulation methods are consistent with changes observed in longitudinal MRI studies of aneurysm geometry. Non-Newtonian flow models were found to be valuable for predicting regions of thrombus deposition. MR imaging was demonstrated to provide the boundary conditions needed for determination of important hemodynamic descriptors. This study indicates that computational models may provide hypotheses to test in future studies, and might offer guidance for the interventional treatment of cerebral aneurysms.