Assessment of intracranial aneurysm thrombosis with patient-specific computational models based on MRI data

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Introduction

The deposition of intralumenal thrombus in intracranial aneurysms adds a risk of thrombo-embolism on top of the risk posed by mass-effect and rupture. In addition to biochemical factors, an important role in the thrombus deposition process may be 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. In this study, patient-specific computational models were constructed from MRA data for three basilar aneurysm patients that had thrombus-free aneurysms and then proceeded to develop intra-lumenal thrombus. Predictions of the velocity and shear stress fields obtained from the 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 and balanced steady state MRI is effective in delineating the outer wall. In addition, phase mapping MR techniques can be used to measure flow velocities and to determine the pulsatile variation of these velocities through the cardiac cycle. Computational models based on lumenal geometries and inlet flow obtained from MR can determine important flow parameters, such as vorticity or shear stress distribution, that require resolution beyond current imaging capabilities. In the current study, detailed numerical simulations were carried out to model the flow in three basilar aneurysms where intra-aneurysmal thrombus had formed. In two of these cases, the patients were monitored with MRI because of poor treatment options. These patients had thrombus-free aneurysms and then proceeded to develop intra-lumenal thrombus. In the third case the thrombus formed following surgical occlusion of one vertebral artery. The baseline (thrombus-free) and follow-up (following thrombus deposition) geometries of the lumenal boundaries were obtained from high-resolution (0.6 x 0.63 x 1.2 mm) CE-MRA images of the cerebral blood vessels. Flow inlet conditions required for CFD modeling were measured in the proximal feeding arteries using in vivo MR velocimetry. In all cases, the flow was modeled in the baseline geometries and CFD results were correlated with the regions of thrombus deposition observed in vivo. 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. In order to obtain a quantitative comparison between the CFD and MRA data, space-averaged velocities and maximum shear stresses were calculated in the regions that were observed to clot and in the regions that were shown to be patent at the follow-up study, and the changes of these parameters during the cardiac cycle were analyzed for Newtonian and non-Newtonian results.

Results

The flow fields predicted by computational models constructed from baseline geometries show large regions of recirculating flows with low velocities and shear stresses. To compare numerical results to the lumenal changes observed in vivo, the surfaces obtained with MRA prior to and after thrombus deposition, were co-registered with CFD-predicted velocity iso-surfaces obtained for all patients (Fig. 1). The difference between the baseline, thrombus-free geometries (shown in gray), and the follow-up geometries after thrombus formation (shown in blue) correspond to the regions occupied by the thrombus. The slow flow zones predicted by CFD are visualized by plotting velocity iso-surfaces on top of the vessel outline surfaces, thus showing all the regions with velocities equal to or above this value in red and leaving the regions with slower velocities empty. There is good agreement between the predicted low velocity zones and regions observed to clot by the follow-up MR study. In two of the cases, the agreement between CFD-predicted velocity iso-surfaces and follow-up lumenal geometries improved when non-Newtonian effects were taken into account.

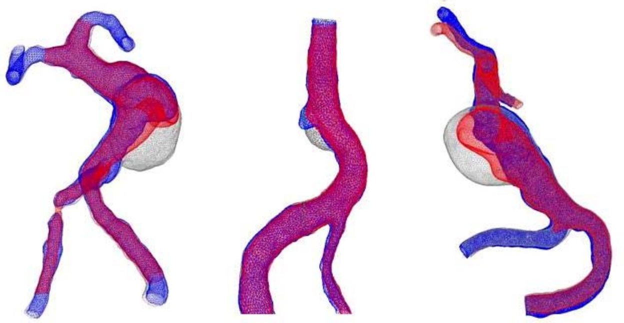
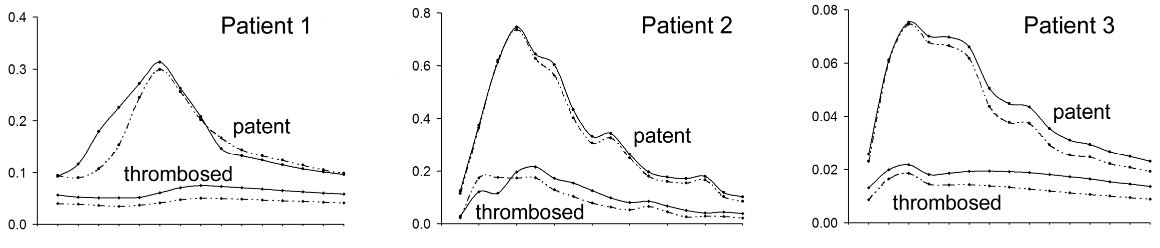


Figure 1 Co-registration of lumenal surfaces obtained from MRA prior to thrombosis (gray) and after thrombus formation (blue) with velocity iso-surface predicted by non-Newtonian flow simulations (red).

The pulsatile changes of the averaged velocities and shear stresses predicted with CFD in the baseline geometry regions that were observed to clot and those that remained patent are shown in Fig. 2. The maximum shear at each point was calculated as one half of the difference between the maximum and minimum eigenvalues of the shear stress tensor. The maximum shear and velocity values calculated in the regions that were later observed to clot are significantly smaller than these values in the patent regions. Both shear stresses and velocities computed in the regions observed to clot remain almost unchanged over the cardiac cycle. The non-Newtonian flow effects resulted in smaller velocity and shear values predicted in both patent and clotted-off regions.

Figure 2 Space-averaged maximum shear calculated for the base-line geometry for regions remaining patent and those occupied by thrombus in the follow up geometry. Solid and dashed lines correspond to Newtonian and non-Newtonian results, respectively.



Conclusions

Numerical simulations of the flow in three patient-specific intracranial aneurysm models demonstrate a strong similarity between the regions of thrombus formation and regions shown by computational modeling to be occupied by slowly flowing blood. A correlation was also found between the calculated low shear stress regions and the regions that were later observed to clot. 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 thrombus deposition regions in aneurysms with massive flow recirculation zones. MR imaging was demonstrated to provide the boundary conditions needed for determination of important hemodynamic descriptors. The study demonstrates that numerical modeling of the aneurysmal flow can provide valuable information for the evaluation of aneurysm treatment options on a patient-specific basis.