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NUMERICAL SIMULATION OF CEREBRAL ANEURYSM FLOW: PREDICTION OF THROMBUS-PRONE REGIONS

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ABSTRACT

Introduction. Computational modeling of the flow in cerebral aneurysms can elucidate the role of hemodynamic factors in aneurysm progression.[1] The deposition of intralumenal thrombus in intracranial aneurysms adds a risk of thrombo-embolism over and above the risk posed by mass-effect and rupture. In this study, patient-specific computational models were constructed from MR Imaging data for three patients that had thrombus-free cerebral 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. Pulsatile flow simulations were carried out in patient-specific models of three cerebral aneurysms where intra-aneurysmal thrombus had formed. In two cases, patients who had thrombus-free aneurysms were monitored with MRI because of poor treatment options 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) lumenal geometries were obtained from high-resolution 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. The governing Navier-Stokes equations were solved with a finite-volume package, Fluent. Non-Newtonian blood behavior, which can have important effects on the flow in low shear rate regions, was taken into account by use of a Herschel-Bulkley viscosity model.[2] 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 CFD in baseline geometries show large regions of recirculating flows with low velocities and shear stresses. To compare numerical results to the 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 (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, showing the regions with velocities above certain threshold 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 level of agreement between CFD-predicted iso-surfaces and follow-up lumenal geometries improved when non-Newtonian effects were taken into account.

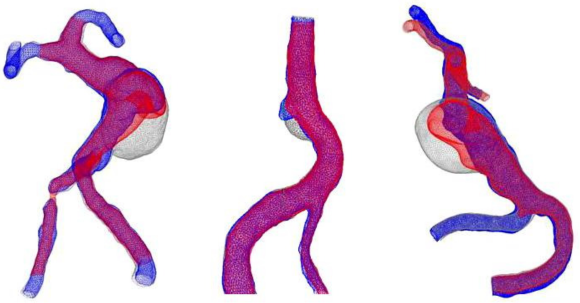

Fig. 1 Co-registration of lumenal surfaces obtained from MRA prior to thrombosis (gray) and after thrombus formation (blue) with velocity iso-surface predicted by CFD (red).

The maximum 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 remain almost unchanged over the cardiac cycle and are significantly smaller than these values in the patent regions.

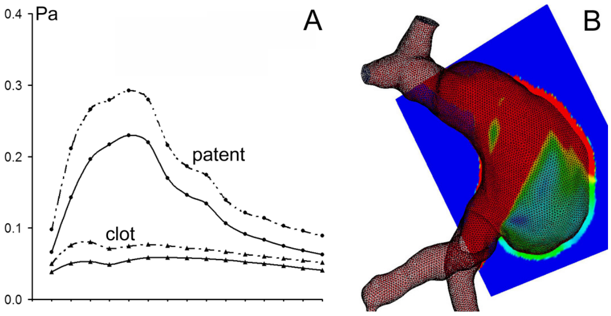

Fig. 2 A: Pulsatile changes of space-averaged maximum shear calculated in the base-line geometry for patent and thrombosed regions. Solid lines – Newtonian flow; dashed lines – non-Newtonian flow. B: Low shear observed in regions later observed to be occupied by thrombus.

Conclusions. Numerical simulations of the flow in three patient-specific cerebral aneurysm models demonstrate a strong similarity between the regions of thrombus formation and regions shown by CFD 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 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. 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.

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