Flow residence time predicts the location of intra-aneurysmal thrombus: Numerical modeling based on MRA and MRV data

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Introduction

Intracranial aneurysms may grow in size over time and, in some cases, may develop intra-aneurysmal thrombus. This can present an increased risk of thrombo-embolism. In addition to biochemical factors, an important role in the thrombus deposition process may be played by local hemodynamic factors that are dependent on luminal geometry and blood flow rates. Modern state of the art MR angiography 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. The actual role of hemodynamics in aneurysmal disease progression can be determined by correlating flow descriptors obtained from computational fluid dynamic (CFD) modeling with aneurysmal changes observed with medical imaging in longitudinal studies. In the current work we have used a new post-processing technique, referred to as “virtual ink” which is similar to advection of a contrast agent, to investigate the effect of increased flow residence time (RT) on thrombus deposition in cerebral aneurysms. Unlike the standard approach for RT computations, where particles are tracked and the time spent by a particle in the domain is calculated, the proposed virtual ink technique is an Eulerian approach, providing RT estimation at any location in the computational model. MR angiography and velocimetry data were used to construct patient-specific numerical models of the flow in three basilar aneurysms with known regions of thrombus deposition. The flow RT maps computed with CFD in the base-line geometries were compared with intra-aneurysmal regions that were observed to clot at the follow-up MRI studies.

Methods

MRI data acquired in longitudinal studies of three patients, who had thrombus-free aneurysms which then proceeded to develop intra-luminal thrombus were used in the study. The baseline (thrombus-free) and follow-up (following thrombus deposition) luminal geometries were obtained from high-resolution (0.6 x 0.63 x 1.2 mm) CE-MRA images of the cerebral vessels. Flow inlet conditions required for CFD modeling were measured in the proximal feeding arteries using in vivo phase-contrast MR velocimetry (PC-MRV). In all cases, the flow was modeled in the baseline geometries and computational 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 observed in larger aneurysms, was taken into account by using a Herschel-Bulkley viscosity model. The flow RT was estimated by simulating the advection of a passive scalar, or “virtual ink”, in the pulsatile flow fields. For all models, the virtual ink was injected at the inlets and carried by the flow through the aneurysmal geometries. The diffusion coefficient was set to zero to ensure pure advection. The value of the scalar at the inlet was set equal to 1, thus regions where the scalar value is close to 1 are filled with ink, while regions where its value is zero are considered ink-free. The flow regions with the ink value above a certain threshold can be readily shown using a color map, which provides a useful flow visualization tool. An injection of virtual ink was simulated for a number of cardiac cycles and then followed by ink-free flow simulation that was continued until the ink was completely washed-out of the geometries. The RT map can be obtained by calculating the difference between the times of the virtual ink arrival and departure at a given point. The RT value at each site is updated at every time step: if the virtual ink value remains higher than the threshold, the RT is increased by the time step interval. A logistic regression with a clustering by patient method was performed to test the statistical significance of the association between RT and thrombus location.

Results

The propagation of the virtual ink through the vascular geometries provides important information on the flow fields and can serve as an excellent method for flow visualization. In all three cases, the ink quickly propagates through the proximal vessels and is carried through the aneurysms by high-velocity jets. The ink is observed in the distal parts of the aneurysms and at the outlets prior to filling the recirculation flow regions in the aneurysmal bulges. It takes a full cardiac cycle to fill most of the lesions and several cardiac cycles to reach the near wall regions where the flow velocities are particularly slow. In the wash-out phase of the simulation, the ink-free blood, again, flows quickly through the healthy part of the vascular geometries, while remaining significantly longer in the aneurismal bulges. The images showing the wash-out of the virtual ink by the ink-free flow are presented in Fig. 1 for one subject.

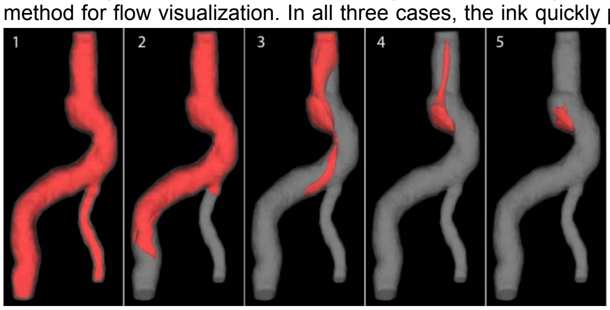

Figure 1 Tracer wash-out in basilar aneurysm model. The regions filled with virtual ink are shown in red. The ink is entrapped in the recirculating flow observed in the aneurysmal bulge.

The total time required for the ink to wash-out from the aneurysmal geometries was equal to 40 seconds for Patient 1; 14.7 seconds for Patient 2; and more than 30 seconds for Patient 3. These results demonstrate that the recirculating flow in these regions is essentially separated from the flow in the rest of the geometry. The flow separation regions, where the ink is trapped for a number of cardiac cycles after the rest of the geometry is ink-free, are located in the same position where clot was observed to form in the follow-up studies. For the patient described above the region of increased RT predicted by the virtual ink technique is compared to the region of thrombus deposition in Fig. 2. The correlation analysis conducted for all patients demonstrated a significant relationship between the near-wall regions with CFD-predicted increased RT and the regions of thrombus deposition observed with MRI in vivo. Increased RT in the near-wall regions is likely to facilitate platelet aggregation and attachment of forming blood clots to the vessel wall. The virtual ink technique may also be useful for simulations of contrast agent distribution in patient-specific vascular geometries, which would have additional applications to the optimization of CE-MRA.

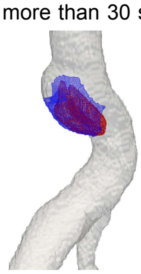

Figure 2 Intra-aneurysmal region with increased RT (red) and region of thrombus deposition observed at follow-up MR study (blue).

Conclusions

The results show that intra-aneurysmal regions with increased flow residence time are prone to thrombus deposition. The “virtual ink” technique, based on advection of a passive scalar, provides flow visualization as well as an easy estimation of flow residence time. The study demonstrates that correlation of hemodynamic factors obtained from computations with MRI data acquired in longitudinal studies can provide important additional information on aneurysm progression on a patient-specific basis.

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