CE-MRA and MR velocimetry in the determination of hemodynamic forces in longitudinal studies of intracranial aneurysm growth

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Introduction: The evolution of intracranial aneurysmal disease is known to be related to the hemodynamic forces on the vessel wall, however a detailed understanding of the role of different hemodynamic descriptors in this process has not been determined. In order to establish this relationship it is essential to estimate hemodynamic relevant descriptors on a patient-specific basis, monitor changes in aneurysm morphology over time for those patients, and correlate observed changes in morphology to flow effects. CE-MRA provides an excellent tool for non-invasively defining the 3D lumenal geometry, and MR velocimetry provides the flow values needed as input in numerical simulations that can be used to predict hemodynamic forces. This study was performed on patients with aneurysms that were unsuitable for treatment, and who were followed over time.

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 0.63 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 generate patient-specific lumenal surface geometries. Lumenal surfaces obtained from MRA studies at annual intervals were co-registered, and volume changes were calculated. In order to ensure that volume differences were due to actual physiological changes rather than to differences in threshold settings, vessels that were undiseased and that are assumed to remain unchanged over time were used as reference for the volume change calculations. Computational models were constructed for patients with substantial aneurysm growth. MR phase mapping velocimetry methods were used to obtain through-plane flow values in the inlet vessels. In addition, 3D steady state MRI was performed to define the outer wall of the aneurysm. The flow fields in these models were calculated using a finite-volume computational fluid dynamics (CFD) solver. Wall shear distributions obtained from numerical simulations were compared with aneurysm growth patterns.

Results: The correlations between the WSS distribution and aneurysm changes indicated increased growth in regions of low WSS. The influence of low WSS on lumenal growth was impacted by the presence of intralumenal thrombus. In an example of a patient with no lumenal thrombus, Figure 1, most of the flow is supplied by one of the proximal vertebral arteries, the other being almost occluded by stenosis. The entering jet propagates along the unaffected aneurysm wall and a large region filled with slow, recirculating flow is formed in the aneurysm bulge. This slow flow region leads to very low wall shear values at the aneurysm surface. The area of the aneurysm wall where WSS is lower than a threshold value (0.25Pa) is shown in red, and the area with the WSS above this threshold is blue (Fig. 1 left panel). Aneurysmal growth was observed over time and is demonstrated in co-registered images as shown on the right panel of Figure 1. The growth started slowly and then proceeded with increasing rate up to 40% volume increase per year. The location of aneurysm growth correlates with the region of low wall shear that is predicted by CFD.

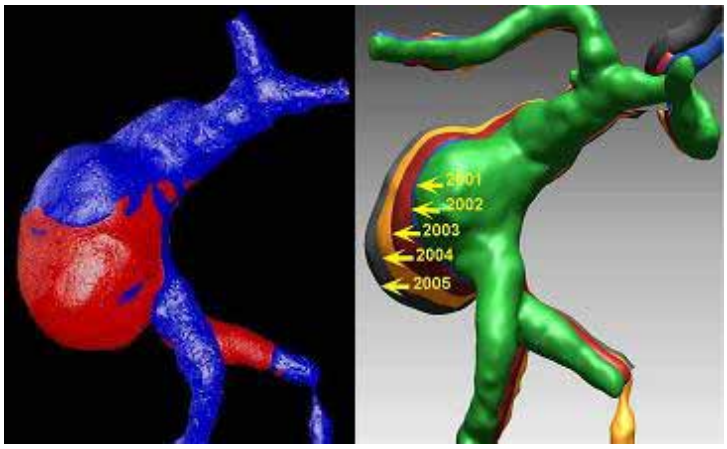

Fig 1 Left: Aneurysm lumenal surface with WSS>0.25Pa (blue) and WSS<0.25Pa (red). Right: Aneurysm growth observed over time.

In the case of a patient where a large fraction of the aneurysm is filled with intra-lumenal thrombus, co-registration of the lumenal surfaces demonstrated steady aneurysm growth with approximately 12% volume increase each year. This geometry is presented on the right panel of Figure 2, where the outer wall is shown in blue, the lumenal surface observed at baseline is yellow and the lumenal surface one year later is red. The CFD simulation results showed a high velocity jet propagating along the left lateral basilar wall which was unaffected by aneurysmal disease, and pronounced retrograde flow on the contralateral wall. This retrograde flow forms a strong secondary flow vortex in the aneurysm bulge, leading to very low WSS over almost the entire aneurysm surface (Fig.2 left panel). While the area with WSS below the threshold value is very large, most of it is adjacent to the thrombus, and no lumenal growth was noted in those regions. The growth is observed only at the superior aspect of the aneurysm, where the WSS is below the threshold and no thrombus is present between the slow flow region and the arterial wall.

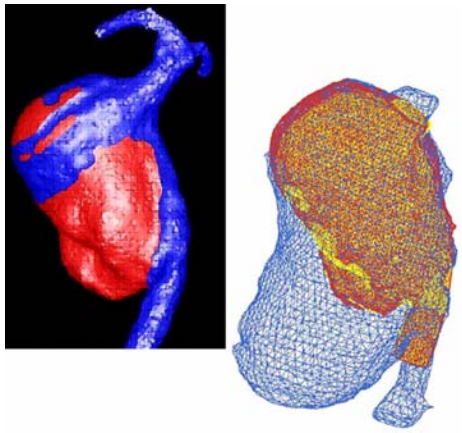

Fig. 2 Left: Aneurysm lumenal surface with WSS>0.25Pa (blue) and WSS<0.25Pa (red). Right: Baseline lumenal surface (yellow), lumenal surface one year later (red), and surface of thrombus (from steady state MRI).

Conclusions: These results indicate that the lumen of aneurysms is likely to grow in regions where the endothelial layer lining the vessel wall is exposed to abnormally low wall shear stress. They also demonstrate the feasibility of using geometric (CE-MRA), and functional (MR-velocimetry) MRI measures to construct relevant hemodynamic models. While hemodynamics is only one of the factors in the complex biophysical processes associated with aneurysmal disease, establishing the influence of different flow descriptors on aneurysm progression would provide an insight into the biophysical mechanisms underlying aneurysm progression, and could allow MR-based CFD simulations to be used in planning surgical interventions.