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

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Introduction

Attempts to monitor the progression of aneurysmal disease of the intracranial vessels have been hampered by an inability to non-invasively determine the flow lumen and intraluminal thrombus. Recent advances in MR imaging provide the ability to determine the lumenal surface from CE-MRA, and to determine the location of thrombus using either 3D balanced steady state imaging or 3D spin-echo imaging. In addition, MR velocimetry permits the determination of inlet flow conditions. Together, the structural and functional imaging measurements can be used to provide the boundary conditions for numerical computations of the velocity fields in the vasculature. This approach was used to compute the hemodynamic forces acting on patients with untreatable aneurysms at baseline, and those forces were then correlated with observed changes in the surface morphology observed at follow-up studies.

Methods

We analyzed the data from 13 patients with intracranial aneurysms who were not candidates for therapeutic intervention and who 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. 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 subjects were calculated using a finite-volume computational fluid dynamics (CFD) solver. A number of hemodynamic descriptors were evaluated for these patients including wall shear stress (WSS), the spatial gradient of wall shear stress, and the temporal variation of wall shear stress. Lumenal changes were evaluated using two different metrics; total volume change and local surface displacement normal to the vessel. We report here on the correlation of the surface displacement with low wall shear stress. In order to relate changes in lumen morphology to the local wall shear stress, each aneurysm surface was divided into a number of patches (Fig. 1).

Results

In cases where there was substantial intraluminal thrombus, there was no apparent relationship between evolution of the outer wall morphology and wall shear stress on the lumenal (thrombus) surface. In regions where the endothelial surface was directly exposed to low shear stress, and the endothelium was in direct contact with the vessel wall (i.e., not superposed on thrombus) local displacement normal to the surface indicated increased growth in regions of low WSS. Statistical analysis confirmed a correlation between the low wall shear and aneurysm growth. Figure 2 shows a basilar aneurysm with areas with WSS lower than a threshold value (0.25Pa) in red, and areas with the WSS above that threshold in blue (Fig. 2 right panel). Aneurysmal growth was observed over time and is demonstrated in co-registered images as shown on the left panel of Figure 2.

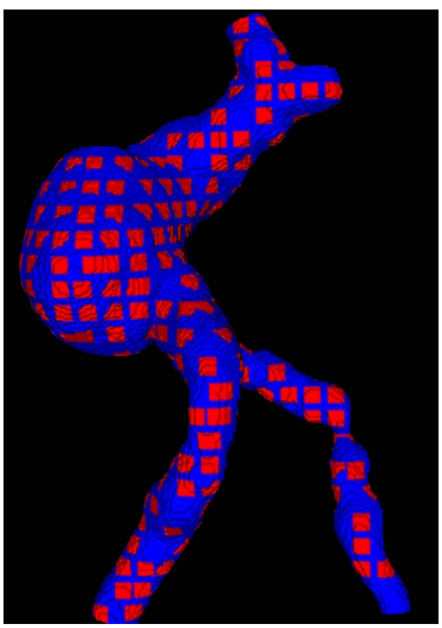

Fig 1 Aneurysm lumenal surface showing analysis patches where normal surface displacement was calculated and correlated to local wall shear stress.

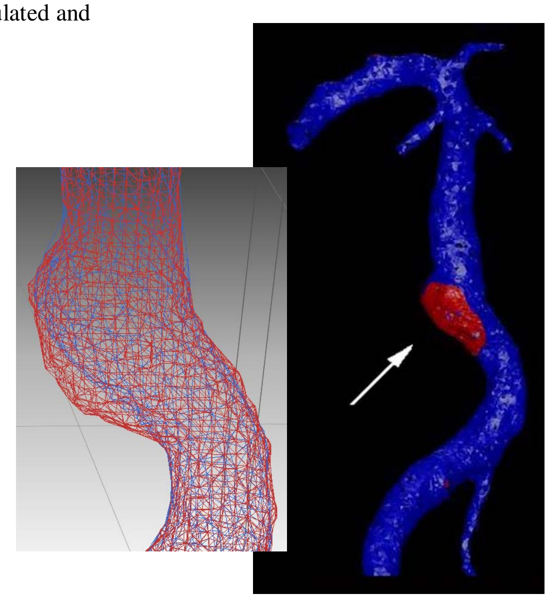

Fig 2 Displacement of lumenal surface from baseline (blue mesh) to one-year follow-up (red mesh) is shown on left. A binary map of WSS is shown on the right with regions of WSS > 0.25 Pa shown in blue, and regions less than that value shown in red, demonstrating close agreement between the region of observed growth and the region of low wall shear stress (arrow).

Conclusions

These results indicate that hemodynamic forces likely play an important role in aneurysm progression. MR methods provide a powerful means to determine both structurally and physiologically important descriptors of the disease process. Non-invasive monitoring provides the ability to monitor disease progression in a way that has not previously been possible.