MR determination of flow fields in patient-specific models of intracranial aneurysms using 7D PC-MRI

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Introduction

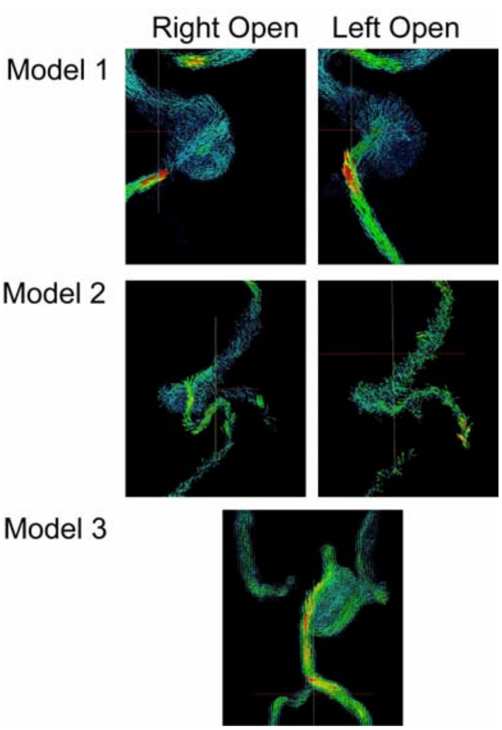
Determination of the hemodynamic forces in intracranial aneurysms is of great importance in providing the surgeon with guidance as to the optimal intervention for treating aneurysmal disease, and to obtain insight into the mechanisms that cause certain aneurysms to grow rapidly while others remain quiescent. One approach to the determination of these forces is to use computational fluid dynamics (CFD) methods. It is also possible to directly measure velocity fields using PC-MRI methods[1]. Implementation of PC-MRI methods with high spatial and temporal resolution of the 3-vectors of flow velocity throughout the vasculature of interest and through the cardiac cycle were investigated using patient-specific geometries and flow conditions. These results can be used to validate CFD methods and to directly estimate flow fields for different simulations of vertebral takedown. These studies investigated parameter adjustment in measurement of flow fields in geometrically exact models of aneurysmal disease.

Methods

Thirteen patients with intracranial aneurysms were enrolled using IRB consent. Patients with fusiform vertebro-basilar aneurysms were imaged with CE-MRA and PC-MRI to determine lumenal geometry and flow waveforms in the inlet and outlet vessels, respectively. The 3D CE-MRA data was surface rendered for CFD and for 3D modeling. Three geometries were selected for the manufacture of flow models. Intra-aneurysmal flow is dominated by geometry and these three cases were selected to provide a diversity in flow conditions. The lumenal surface was reproduced by stereolithography, and further casting was performed to provide hollow flow models which were exact replicas of patient aneurysms. These models were connected to a flow loop which provided physiological flow conditions equal to the flow measured in vivo for these subjects. A time-resolved 3D PC-MRI sequence with imaging parameters of TR=54 ms, TE=9.3 ms, flip angle =15°, VENC=30-50 cm/s, matrix 256x224, slice thickness=4 mm, in-plane resolution 0.7 mm X 0.7 mm, and an imaging time of 35 min, was implemented with velocity encoding along each of the three encoding axes, and cine imaging was performed to determine the velocity vectors through the cardiac cycle. In addition, these results were compared to results obtained using sequential 2D PC-MRI to collect the same data over the volume of interest.

Results

The PC-MRI studies clearly demonstrated both qualitative and quantitative features of the flow in these complex geometries. In two of the cases, occlusion of one or other of the inlet branches drastically altered the dominant flow streams. In the other case, where there was a long segment of normal vessel distal to the junction of the vertebral branches and proximal to the aneurysm, flow within the aneurysm was relatively unaffected by vertebral branch occlusion (Fig. 1). All cases were in excellent agreement with predictions from CFD. Regions of flow recirculation were clearly demonstrated and areas of low wall shear stress could be qualitatively identified although quantitative estimates of wall shear stress were unreliable since there was low sensitivity to slow flow given the presence of a large dynamic range of velocities and the requirement to avoid aliasing of the high velocity regions. Imaging with 3D spatial encoding permitted smaller voxel sizes and provided improvements in SNR compared to 2D spatial encoding.



Conclusion

This study demonstrates that PC-MRI measurements provide consistent validation of patient-specific CFD. Further, it demonstrates that exact phantom replicas can be used to predict patient-specific hemodynamic factors after different interventional treatments and to validate CFD predictions of the outcome of different surgical interventions. The use of realistic flow models provides an opportunity to optimize competing strategies for improving the efficiency of acquiring PC-MRI studies. They also provide a standard of truth which can be used in the evaluation of strategies (such as undersampling k-space) which have the potential to introduce errors that might go undetected when used in vivo.

Figure 1: The flow fields within the aneurysm models resulting from keeping only one flow inlet open.

References

1. Wigstrom L.,*et al.* Temporally resolved 3D-Phase-contrast imaging. *Magn Reson Med.* 1996;36:800-3