In-plane PC-MRI as a tool for verification of non-Newtonian CFD models of the flow in cerebral aneurysms

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Introduction

Current state of the art MR angiography and phase-contrast velocimetry methods provide lumenal geometries and flow boundary conditions required for patient-specific computational fluid dynamics (CFD) modeling of the flow in cerebral aneurysms. CFD models constructed from in vivo imaging data can provide valuable information on the hemodynamic forces that is difficult to obtain from medical imaging alone. The flow conditions in giant aneurysms, where strong jets and large recirculation and stagnation regions are observed, may cause blood to exhibit non-Newtonian behavior. In order to take these blood properties into account, it is crucial to select an appropriate viscosity model. In the current study, in-plane PC-MRI imaging is used to evaluate non-Newtonian model parameters by comparing flow fields predicted with CFD to in vivo imaging results.

Methods

High resolution CE-MRA images of the cerebral vessels were used to obtain patient-specific lumenal geometries for two giant basilar artery aneurysms. Phase-contrast MR velocimetry (PC-MRV) provided flowrate measurements in the arteries proximal to the aneurysm through the cardiac cycle. In addition to the through-plane velocimetry, an in-plane PC-MRI scan was acquired in the longitudinal plane of the aneurysm, prescribing the plane to include the vertebral arteries at the aneurysm inlet and the distal basilar artery. CFD simulations were carried out using patient-specific geometries and inlet conditions obtained from MRA and MRV data. Non-Newtonian behavior was modeled using the Carreau viscosity model, accounting for shear-thinning blood properties. Two different sets of the Carreau model parameters, one used by Johnston et al.[1] (referred below as "the 1st model") and the other used by Lee and Steinman[2] (referred below as "the 2nd model") were used to calculate the non-Newtonian viscosity. A simulation with a constant, Newtonian viscosity was carried out as well. The flow fields predicted with CFD for different viscosity models were visually compared to the in-plane MRV images obtained in vivo.

Results

The velocity field predicted by Newtonian flow simulation shows a high velocity jet crossing the entire lesion and impinging on its opposite wall (Fig. 1A). There is retrograde flow along the bulging aneurysm wall. The non-Newtonian flow fields show a quickly dissipating jet and much less pronounced retrograde flow. The damping effect of the non-Newtonian viscosity is particularly apparent for calculations with the 2nd Carreau model (Fig. 1B). It is important to determine which model provides a better match to the actual, in vivo flow, as these different flow patterns result in different wall shear distributions, which in turn has important implications for the aneurysm progression.

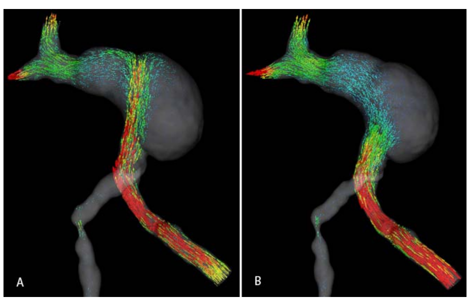

Figure 1 Velocity vectors predicted by CFD. A: Newtonian flow; B: Carreau non-Newtonian viscosity model. Non-Newtonian viscosity causes dissipation of the high-velocity jet.

Comparison of the flow fields predicted by CFD with in vivo PC-MRI data is shown in Fig. 2. Since PC-MRV technique provides velocities averaged over a 5mm-thick slice, the CFD results were re-sampled to obtain velocity fields for 50 two-dimensional planes equally spaced to form a 5-mm-thick volume through the numerical data. The orientation of these planes was matched to the plane used in the PC-MRI acquisition. There is a strong similarity between the in vivo data (Fig. 2A) and the flow field predicted in Newtonian flow simulation (Fig. 2B). The Newtonian model predicts a well-defined high-speed jet and a clearly visible retrograde flow along the back wall of the lesion. The smaller jet formed by the flow entering through the collateral vertebral is also visible. The simulations carried out with the 1st Carreau model (Fig. 2C) predict a more diffuse flow pattern, with the jet dissipating in the middle of the aneurysmal volume. There is some retrograde flow in the aneurysmal bulge, as well as the smaller jet entering through the other vertebral artery; however, these flow features are difficult to discern from the image. The damping caused by the non-Newtonian viscosity calculated with the 2nd Carreau model causes the jet to dissipate almost at the aneurysm entrance (Fig. 2D). The flow in the aneurysmal bulge is almost stagnant, with the exception of a small vortex formed at the proximal end of the lesion. These flow patterns are noticeably different from the in vivo data and we can conclude that the parameters used in the 2nd Carreau model cause excessive damping and do not provide a realistic velocity distribution. The 1st Carreau model predictions, while being closer to the in vivo flow field, are also inferior to the Newtonian viscosity model results.

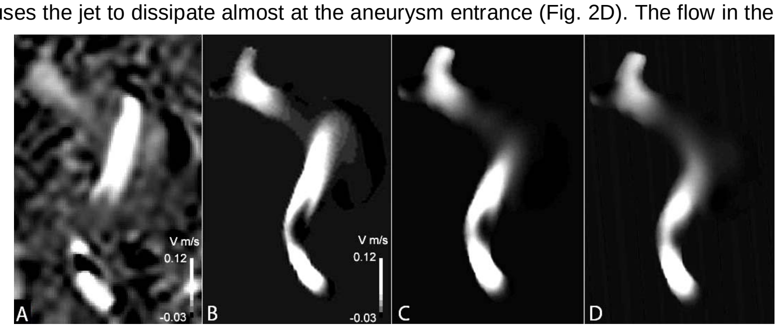

Figure 2 Comparison of CFD-predicted velocity fields and in vivo phase-contrast MRI in-plane velocimetry. A: PC-MRI in-plane phase image (velocity); B: CFD results for Newtonian viscosity; C: CFD results for the 1st Carreau model; D: CFD results for the 2nd Carreau model.

Conclusions

The flow fields predicted by CFD using the Carreau viscosity model with two different set of parameters were compared to Newtonian CFD predictions, as well as to the in-plane PC-MRI data obtained in vivo. The Newtonian flow field shows better agreement with the in vivo flow than does the non-Newtonian results obtained in both cases. Thus, while CFD provides high resolution data (such as local wall shear values) that cannot be accurately obtained from imaging only, PC-MRI is important for verification of the numerical predictions and evaluation of the modeling assumptions.

References:

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2. Lee SW, Steinman DA. On the Relative Importance of Rheology for Image-Based CFD Models of the Carotid Bifurcation. Journal of Biomechanical Engineering 2007;129(2):273-278.