Studying the hemodynamics in cerebral arteries using image-based computational fluid dynamics and 4D phase-contrast magnetic resonance

J. R. Cebral[1], C. M. Putman[2], M. Alley[3], R. Bammer[3], and F. Calamante[4,5]

[1]Computational and Data Sciences, George Mason University, Fairfax, VA, United States, [2]Interventional Neuroradiology, Inova Fairfax Hospital, Falls Church, VA, United States, [3]Department of Radiology, Stanford University, Stanford, CA, United States, [4]Brain Research Institte, Florey Neurosciences Institutes (Austin), Melbourne, Victoria, Australia, [5]Department of Medicine, University of Melbourne, Melbourne, Victoria, Australia

Introduction

Knowledge of the in vivo hemodynamics in cerebral arteries is important to better understand the underlying mechanisms of initiation and progression of cerebrovascular diseases. The hemodynamics in cerebral arteries and aneurysms has been studied using image-based computational fluid dynamics (CFD) modeling as well as 4D phase-contrast magnetic resonance (PC-MR) imaging [1-4]. Each of these approaches has a number of strengths and limitations. This study compares the blood flow patterns in cerebral arteries of normal subjects determined by 4D PC-MR and image-based CFD techniques in order to assess their consistency and to highlight their differences. The goal was not to validate (or disprove) any of the two methodologies but rather to identify regions where disagreements are to be expected and to provide guidance when interpreting the data produced by each technique.

Methods

Time-resolved 4D PC-MR images of the major cerebral arteries at the level of the Circle of Willis were acquired on three young normal subjects. These images were obtained on a GE 3T scanner (FOV=180x180 mm, matrix=300x180x30, TR/TE=5.46 ms/2.12 ms, α=15°, NEX=1, and Venc =100 cm/s along each axis) using an eight-channel head array coil and peripheral gating by a finger-pulse oxymeter. The data were zero-filled to a reconstruction matrix of 512x512x60 resulting in an interpolated spatial resolution of (0.35x0.35x0.8) mm^3. The three velocity components were reconstructed at 20 time points evenly spaced over the R-R interval.

Subject-specific computational models of the major cerebral arteries were constructed from the magnitude images of the 4D PC-MR data using a seeded region growing algorithm followed by an iso-surface deformable model [5]. The vascular models were meshed with an advancing front method using a spatial resolution of 0.1 mm. Time dependent flow rates in the inflow vessels were measured by integrating the through-plane PC-MR velocity component over the artery lumen on a slice perpendicular to its axis. The vessel lumens were manually segmented on the corresponding magnitude images. Blood flow was modeled by the 3D unsteady Navier-Stokes equations, which were numerically solved using an implicit finite element method [6] and imposing the physiologic pulsatile flow rates measured from the PC-MR data. Visualizations of the CFD and PC-MR flow fields were created after interpolating the PC-MR data to the CFD finite element grid points.

Results

Blood flow patterns obtained from CFD models and the PC-MR measurements were compared for a total of three normal subjects. The results for one of the subjects are presented in Fig.1. A volume rendering of the PC-MR magnitude image and the corresponding vascular model are shown in panels a and b, respectively. Flow streamlines originating in the internal carotid arteries (ICA) and basilar artery (BA) at peak systole for the PC-MR and CFD data are shown in panels c and d, respectively. Blood flow velocity magnitudes on selected cutting planes through the ICAs and the BA are shown in panels e and f for both the PC-MR and CFD data. These visualizations show that qualitatively, the major flow structures, swirling flows, flow directions in communicating arteries, etc. observed in the PC-MR images and the CFD simulations coincide. However, there are a number of differences: a) the velocity magnitudes tend to be higher in the CFD models, b) secondary flows (rotational or non-axial velocity components) are weaker in the PC-MR images, making the flow pattern more parallel or laminar, c) flow recirculation regions observed in the CFD models near vessel bifurcations are not well captured by the PC-MR images, d) the flow fields derived from the PC-MR images are not divergence-free and some streamlines stop erroneously inside the vascular domain. The cutting planes show the non-trivial skewed velocity profiles produced by the curving, branching and tapering arteries with non-uniform distributions of velocity magnitudes along the vessels. These visualizations show that qualitatively the complex PC-MR and CFD velocity profiles are remarkably similar. As noted before, the CFD models tend to exhibit larger velocity magnitudes than the corresponding PC-MR images, however the shape of the velocity profiles, regions of low and high flow speed, location of maximum velocities, etc. are in good agreement.

Discussion

Phase-contrast magnetic resonance imaging and image-based computational fluid dynamics techniques yield qualitatively consistent representations of the in vivo hemodynamics in the major cerebral arteries. However, each technique has limitations that introduce differences between the corresponding blood flow velocity fields. Namely, MR suffers from limited spatial and temporal limitation and artifacts related to signal loss in regions of disturbed or complex flows, and spatial and temporal averaging. On the other hand, image-based CFD is limited primarily by the accuracy of the geometry of the vascular model which is the main cause of the observed differences in the blood flow speed. It is important to understand these differences in order to better interpret the results obtained with these complementary techniques, and to be aware of the regions along the arteries where each technique is expected to over-simplify the flow patterns or yield under or over-estimations of the blood velocity magnitude.

References

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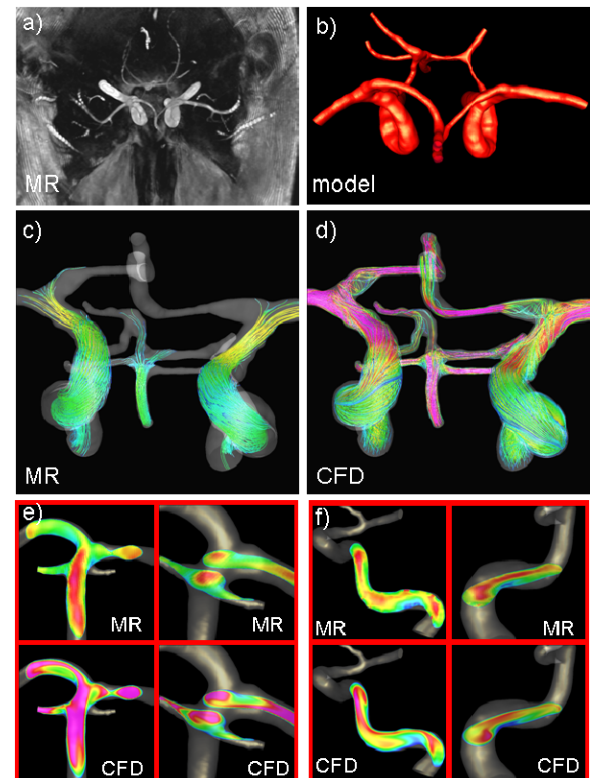6. Cebral JR, et al. IEEE TMI 24(1) : 457-467, 2005.

Fig.1: *CFD & PC-MR velocity fields in cerebral arteries.*