REALISTIC CEREBRAL CIRCULATION MODELS FROM MEDICAL IMAGE DATA

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INTRODUCTION

Detailed knowledge of the cerebral hemodynamic conditions is important in a variety of clinical applications [1, 2, 3]. Among these we mention: analysis of blood flow alterations during arterial occlusions, correlation of low flow areas with occurrence of embolic phenomena, analysis of blood flow in cerebral aneurysms to evaluate possible treatments, analysis of blood flow alterations produced by angioplasty and stenting procedures, etc. Realistic patient-specific modeling of the cerebral circulation is a challenging problem due to its geometric complexity, the redundancy of the arterial system, the presence of collateral vessels, and auto-regulation mechanisms. In this paper we present a methodology to construct realistic finite element models of the cerebral circulation using magnetic resonance image data.

METHODS

Arterial Model

Anatomically realistic models of the cerebral arterial system are constructed from magnetic resonance angiography (MRA) images (figure 1a). A tubular deformable model is used to reconstruct each arterial segment independently [4]. After merging these segments [5], a finite element grid is generated using an advancing front technique [6] (figure 1b). This scheme uses adaptive background grids to specify the element size distribution, i.e. higher mesh resolution is automatically increased in regions of high surface curvature.

Blood Flow Model

Blood flow is mathematically modeled by the unsteady incompressible Navier-Stokes equations. For simplicity, a preliminary calculation was performed assuming rigid vessel walls and Newtonian behavior of blood. A fully implicit finite element formulation on dynamic unstructured grids is used to solve these equations [6].

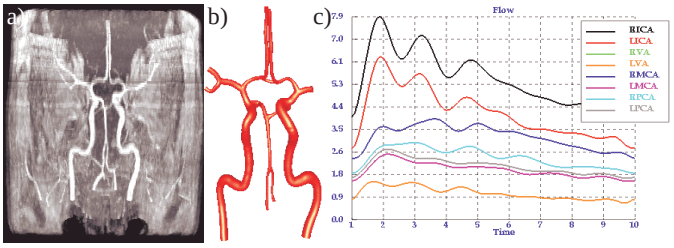

Figure 1: a) MRA images; b) reconstructed arterial model; c) flow waveforms obtained from PC-MR images.

Boundary Conditions

Physiologic flow conditions are derived from phase-contrast magnetic resonance (PC-MR) measurements of flow velocity. Flow waveforms are obtained by integration of the velocity profile over the cross-section of the vessels (figure 1c). Since in general it is not practical to measure flow rates in all the outlet boundaries of the arterial model, vascular bed models based on simplifying assumptions have been used in the past [2]. However, more realistic models can be constructed as explained below. It is the purpose of this work to develop and evaluate such models. In order to estimate the flow resistance at each outlet, measured flow rates were prescribed at the boundaries of the internal carotid arteries, vertebral arteries, middle cerebral arteries, and anterior cerebral arteries. Traction-free boundary conditions were imposed at the outlets of the posterior cerebral arteries. The finite element model then provides values for the flows and pressure drops in all these boundaries, which can then be used to estimate the flow resistances.

Arterial Tree Models

Realistic vascular trees can be constructed using the method of constructive constrained optimization (CCO) [7]. For each outlet of

the arterial model, a perfusion volume is specified from anatomical images of the brain. The model outlet serves as the feeding artery and the tree is grown such as to minimize the intravascular volume. The statistics of quantities such as bifurcation angles, symmetry and area ratios of the resulting vascular trees have been shown to be in agreement with experimental observations [8]. Figure 2 shows the reconstructed arterial model (top) and the generated arterial trees (bottom) from three perpendicular views. Colors indicate vessel radius of the vascular tree segments.

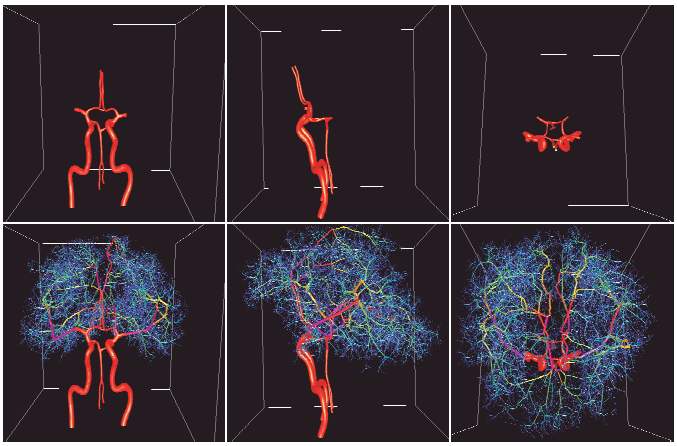

Figure 2: Reconstructed 3D arterial model and arterial tree models generated for each outflow boundary.

Boundary conditions at the model outlets can then be specified by measuring the resistance (or impedance) of the corresponding arterial tree. Alternatively, the 3D flow model can be coupled to lumped parameter or 1D flow models along the arterial tree.

RESULTS

Preliminary pulsatile blood flow solutions were obtained for a complete cardiac cycle. Boundary conditions were derived from the PC-MR flow measurements as explained before. The flow solution becomes periodic in less than two periods, i.e. at about t=1.2 T the solution is identical to that at t=0.2 T where T is the period of the cardiac cycle. This is important in cases in which one is interested in advecting either particles or a substance in order to simulate transport processes. The flow solution was then used to compute mean hemodynamics quantities such as mean wall shear stress (WSS) and oscillatory shear index. The regions of low mean WSS (<10 dyne/cm^2) are shown in figure 3a. The velocity profiles at peak systole and end diastole are shown in figures 3b and 3c, respectively. As expected, the lowest mean WSS is observed at arterial bifurcations and regions of high curvature, coincident with regions of low flow and flow recirculation.

CONCLUSIONS

A methodology for constructing realistic models of the cerebral circulation from magnetic resonance image data has been presented. Detailed hemodynamics conditions in the circle of Willis have been computed. These results will be used to test vascular bed and arterial tree models used to impose boundary conditions in 3D finite element models.

Current and future work focuses on:

- Accounting for wall compliance.
- Coupling 3D flow models to 1D or network models to obtain the hemodynamics conditions along the arterial trees.
- Improving/automating the algorithms for image-based generation of arterial trees.
- Extending the algorithms of arterial tree generation to model collateral branches between neighboring trees.
- Dynamic remodeling of arterial trees to account for auto-regulation [3].
- Predicting tissue perfusion from the arterial trees.
- Validation of the methodology using several imaging modalities.

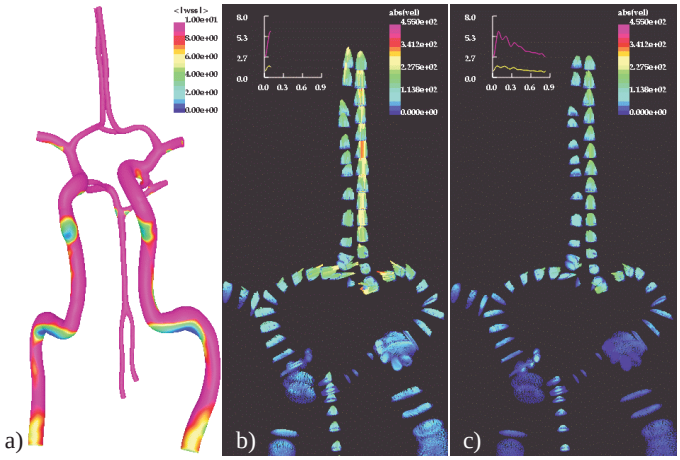

Figure 3: a) Regions of low mean wall shear stress; b) profiles at peak systole; c) profiles at end diastole.

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