Modeling and Simulation Framework for Hemodynamic Assessment of Aortic Coarctation Patients

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Introduction

Coarctation of the aorta, congenital obstruction of the aortic arch, is increasingly treated by aortic stenting outside of the neonatal period. However we lack the means to determine the optimal information or anatomy for the best physiology repair either by surgical or non-surgical means. Our aim within this study is to construct a simulation pipeline enabling automatic assessment of hemodynamic conditions in stent implanted coarctation patients.

It is becoming more and more established that the combined use of non-invasive imaging and Computational Fluid Dynamics (CFD) simulation can be instrumental in the better clinical assessment of aortic coarctation. For example, previous work by [Valverde et al 2011] showed good agreement at rest and moderate agreement at stress between CFD computed pressure and invasive measurements. Such work, while on one hand underlines the value of CFD methods for recovering through simulation patient-specific hemodynamic quantities; it also indicates the need of the use of patient-specific boundary conditions, which may be hard to come by through the use of non-invasive methods. In this paper, we propose a novel framework that uses 2D PC-MRI data to supply boundary conditions for a coupled 1D and 3D CFD simulations. Our simulation method first uses an axisymmetric 1D simulation with compliant walls to compute physiological pressure gradients by taking into account both flow quantities measured by PC MRI as well as the aortic compliance and the resistance of the distal arterial network, which are in turn used as enhanced boundary conditions for a 3D CFD simulation. Thus we bypass the need for invasive pressure measurements, while at the same time we are able to accurately reproduce the flow distribution. As a first validation study, we compared the simulated and PC-MRI distal aortic flow rate in six patients. The promising initial results reiterate the potential of CFD simulations to provide assessment of post operative hemodynamics.

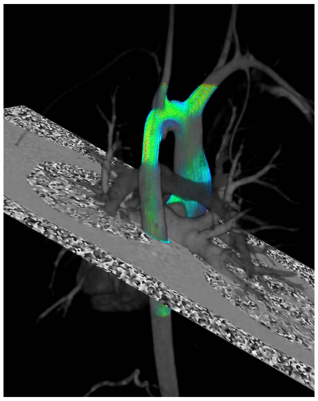

Figure 1 Simulation Results in the Thoracic Aorta

Method

In this section we provide an overview of the steps in our automated simulation pipeline. Cardiac MR images are used to estimate patient specific physiome: vessel geometry and flow profiles. Next, these parameters are represented as spatial and velocity boundary conditions for solving the Navier-Stokes fluid dynamics equations. This is followed by the validation step where the simulated results are compared to the measured phase-contrast velocity and flow rates. A brief overview of all these steps is presented below:

<u>Anatomical Model Estimation</u>: To allow reproducibility of our results, we employ automatic segmentation methods 1) to retrieve the fused geometrical representation of aortic and supra aortic lumen and 2) to delineate the vessel cross sections in the 2D PC-MR Cine sequences. This automatic processing step takes less than a minute for one study.

<u>CFD Simulations</u>: We address an important issue that arises in CFD simulation of vessel flow, namely the setup of realistic boundary conditions for a 3D incompressible Navier-Stokes simulation. As a first step computing the solution of an axisymmetric 1D simulation is carried out to estimate the patient's systemic downstream relative arterial resistance. Unsteady flow rate at the aortic inlet from the 2D PCMRI data is used as the inflow boundary condition for the 1D simulation. In order to obtain physiologically valid mean and pulse pressure values and the wave propagation effects, we use a structured tree outflow boundary condition [Olufsen 2001], wherein a morphological or fractal vessel tree is introduced to model the downstream behavior at the outlets of the vessel tree. This provides additional temporal pressure boundary conditions for predicting complete 4D hemodynamics (Fig 1) in a cardiac cycle. Such computations provide in an efficient manner the necessary patient-specific pressure information that we subsequently use as Dirichlet pressure boundary conditions for the full 3D Navier Stokes simulations.

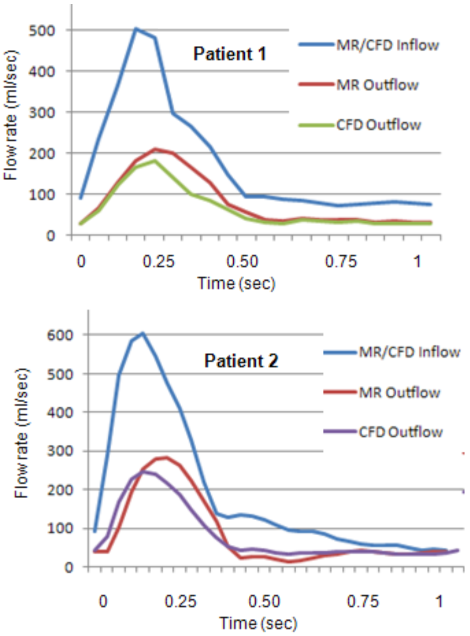

Figure 2: Flow comparison at the descending aorta site between CFD simulation and 2D PC-MRI measurements for Patient #1 and #2.

Results

We employed the proposed methodology on data from six patients (all post stent implantation). The data was acquired within established clinical protocols for coarctation patients, not specific to this study. The simulation results consist of 3D+time velocity and pressure values in the aortic lumen with a much higher temporal resolution compared to MR. We compared the CFD and the PC-MRI flow profiles at the descending aorta acquisition site. The results obtained with our proposed patient-specific boundary conditions are superior when compared to the ones from generic boundary conditions, e.g. zero pressure gradients between supra-aortic and descending aortic flow. The results are in good agreement with the MR measurements (Fig. 2), with the maximum of the simulated flow within 10% of the PC-MRI flow. We observed a slight phase mismatch between simulated and measured flow profiles, which is likely due to volumetric changes introduced by the 1D FSI simulations, which are not accounted for in the 3D CFD computations. These volumetric changes will be imposed in future versions as boundary conditions at the aortic walls in order to improve the matching in phase of the flows. The promising initial results further reiterate the potential of CFD simulations to provide assessment of post operative hemodynamics.