Non-invasive Assessment of Aortic Coarctation through Blood Flow Computation and MRI

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Objectives

This study was designed to investigate the feasibility of novel Computational Fluid Dynamics (CFD) based methods for non-invasive assessment of hemodynamics (particularly trans-stenotic pressure drop) in coarctation of the aorta (*CoA*) patients.

1. Introduction

Coarctation of the aorta is characterized by a severe narrowing of the aorta producing obstruction to blood flow in the isthmus region. Coarctation of the aorta patients account for *5-8%* of the *8/1,000* congenital heart disease (that is *4-6/10,000*) live births in the USA [6]. The usual treatments for this abnormality are invasive surgical repair and recently stent implantation and balloon angioplasty. Standard diagnostic severity assessment of coarctation involves thoracic MR imaging and blood pressure measurements. In order to evaluate the physiological significance of the pre-operative coarctation and to review the post-intervention condition, the hemodynamic assessment is usually performed by measuring the pressure drop across the coarctation site via invasive pressure catheterization. A $\Delta P > 20\ mmHg$ systolic blood pressure difference between the ascending and descending parts of the aorta is the indication necessitating correction of coarctation.

Various non-invasive alternatives to estimate the trans-stenotic pressure drop have been proposed: difference of the cuff pressures in the upper and lower body measured in the arms and legs, or modified Bernoulli's equation based methods that approximate blood pressure from radiologic examinations of blood flow velocity (such as Doppler ultrasound and phase-contrast MRI). Both measures have been shown to be inferior in terms of accuracy compared to pressure catheterization. Cuff pressures measured at the extremities are not an accurate indicator for aortic pressures, due to their distance from the coarctation site, while a simplified relationship (represented in the Bernoulli equation) may not be able to characterize the non-laminar flow-field associated with CoA. In contrast, the Navier–Stokes equations hold in arbitrary complex geometries observed in coarctation patients. Multiple researchers [2,3,4] have investigated CFD solutions of the full Navier-Stokes equation in the context of CoA assessment. These studies were designed to work on clinical data specifically acquired for the experiment (and possibly difficult to reproduce using standard exam protocols), while we are aiming to introduce a pipeline capable of integration into existing clinical workflow.

2. Methodology

Within the following paragraphs we describe in detail each component of the proposed framework, as illustrated on Figure 1.

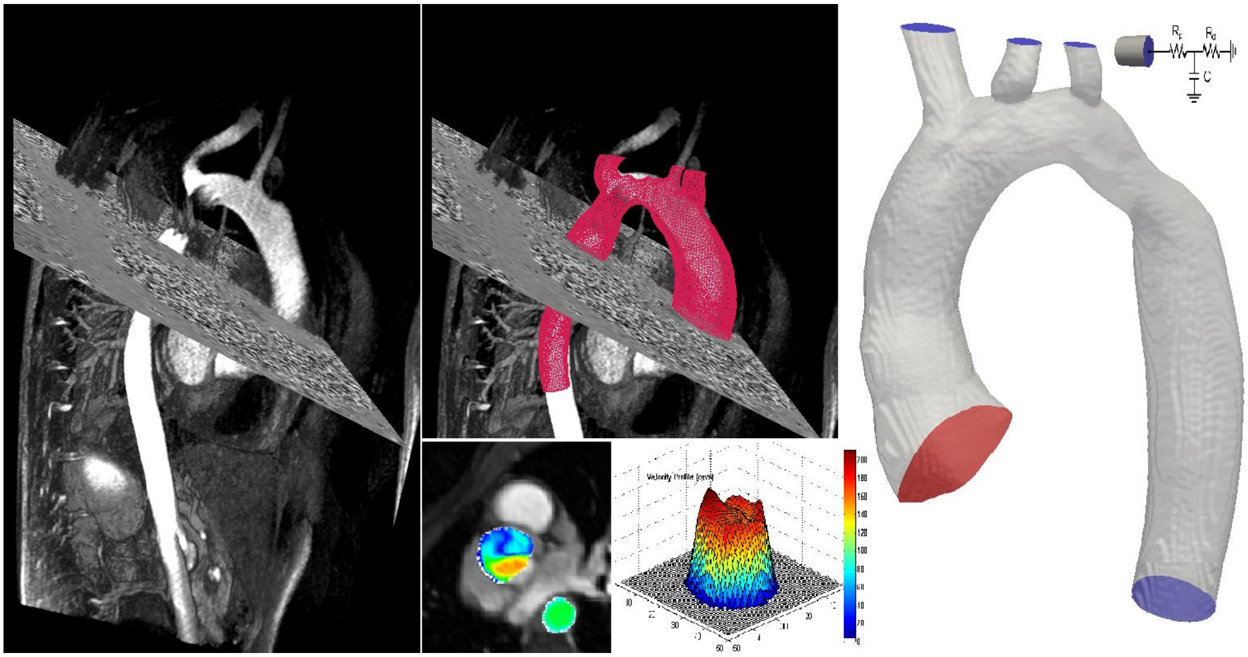

Figure 1, Proposed modeling and flow computation pipeline: Left) MR Images, Middle) Segmented vessel tree and delineated aortic flow profiles, Right) Overview of boundary conditions applied, measured flow profile at ascending aorta, Windkessel model at carotid and descending outlets

2.1 Estimation of the Patient-Specific Lumen

An accurate geometrical representation of the lumen boundaries is essential for subsequent flow computations. To facilitate reproducibility of our computation, we employ a robust learning-based method to estimate a 3D geometric model of the aorta and supra-aortic arteries from contrast enhanced MR angiograms [1].

2.2 Estimation of Patient-specific Boundary Conditions

Besides the geometric vessel wall boundaries, the flow computations are personalized by imposing the time-varying flow rate in the ascending aortic inlet obtained from the PC-MRI data. At the carotid and descending outlets, the boundary conditions are computed over the cardiac cycle according to a 3-element Windkessel model, within an axi-symmetric reduced-order model formulation[7].

2.3 Patient-specific 3D CFD Flow Computation

Aortic coarctation hemodynamics has an increased fluid dynamics complexity when compared to healthy aortic flow, manifested in large scale features like increased pressure drops, or small scale features like recirculation areas downstream from the stenotic region. While larger scale features that are quasi-invariant to rotations about the centerline (e.g. pressure) can be captured by axi-symmetric Navier-Stokes computations, smaller scale features like recirculation areas, quasi- stable vortices or wall-shear stress patterns require 3D computations of the blood dynamics. We would like to obtain comprehensive flow information in three dimensions. We solve the full 3D Navier-Stokes equations in the luminal aortic domain using an embedded boundary method. The Cartesian domain is classified as *exterior*, *interior*, *inlet*, *outlet* and *wall* cells based on the closest point transform (CPT) of the rigid vessel wall surface mesh. Exterior nodes do not incur any computation, while at the inlet, outlet and wall nodes appropriate boundary conditions are applied [5]. We use a variable-in-time flat inlet velocity profile, and outlet pressure boundary conditions provided by the axi-symmetric reduced-order computations. The blood density and dynamic viscosity are set to literature accepted values for healthy individuals, namely $\rho = 1.05\frac{g}{cm^3}$ and $\mu = 4\ mPas$.

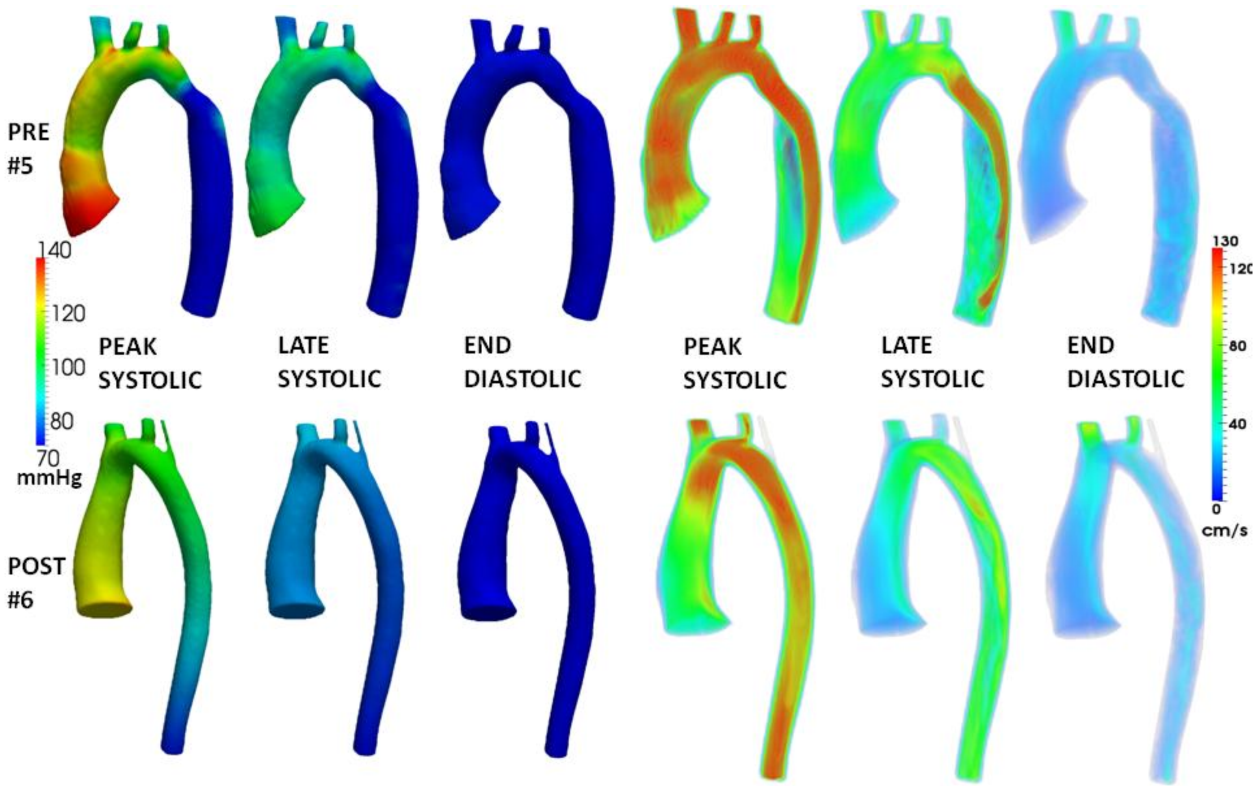

Figure 2 Pre- and post-operative pressure and velocity distribution in patients #5 and #6. Due to the stenosis there is a significant pressure difference across the coarctation at the peak systole, which gradually disappears towards the end diastole, the high velocity jet in the narrow isthmus region is clearly visible as expected.

3. Results and Validation

To demonstrate the proposed method for non-invasive assessment of aortic hemodynamics, we investigated 5 patient pre- and post-operative datasets with coarctation that involved the aortic isthmus or the first segment of the descending aorta. All examinations were part of the FDA approved COAST [6] trial, acquired employing standard clinical practice and not specifically for this study. Computed values of the trans-stenotic pressure drop for pre-operative coarctation patients have been tabulated in Table 1, together with the values measured by a pressure wire during cardiac catheterization. All patients received repair through transcatheter stent delivery. As the metal stent implant influences the material properties of the aorta, special consideration is required to model the induced change in wall-stiffness. The preliminary results for stented case #6 are shown in the bottom row of Figure 2.
Figure 3 illustrates the differences in flow turbulence before and after repair, in case #1. The repair results in restoration of a more laminar flow distal to stented region.

4. Conclusion

The focus of this study was to advance the management of patients with congenital aortic arch disease. To this end, we proposed an MR image-based pre-processing and hemodynamic computation pipeline for non-invasive estimation of key hemodynamic parameters in pre- and post-operative coarctation of aorta patients. Pressure-drops computed with the proposed method show an excellent agreement with the clinical gold standard (cardiac catheterization) for measuring trans-stenotic pressure gradients,.

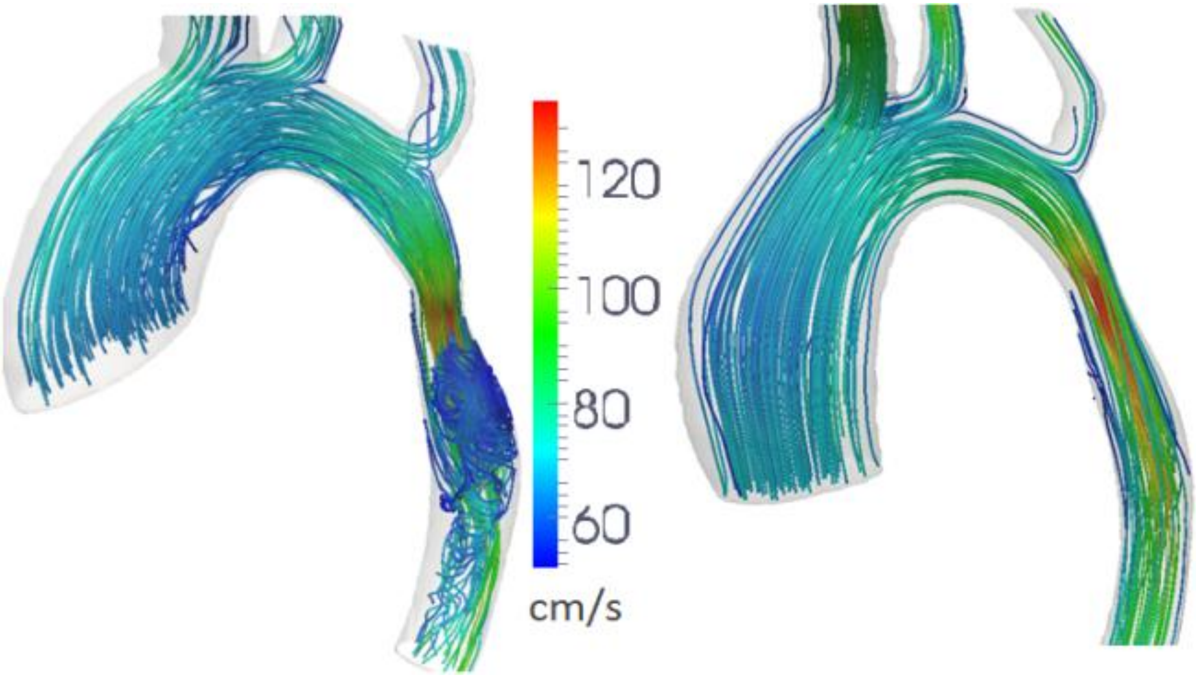

Figure 3 Streamlines of blood flow in stenotic and repaired aorta of Patient #1. Left: The pre-operative study reveals the presence of turbulent vortex formation downstream the coarctation. Right: After stent implantation turbulence disappears, characterized by lack of recirculation.

Patient	ΔP AAo-DAo Cath./CFD	ΔP TAA-DAo Cath./CFD
#1	55/53.97	53/54.18
#3	8/10.28	8/10.47
#4	30/28.11	28/28.61
#5	14/14.62	18/14.99
#6	39/6.7	43/6.1

Table 1 Comparison of non-invasive computed and invasive catheter based pre-operative blood pressure measurements. Comparison of the pressure obtained from invasive catheterization and our proposed non-invasive method: systolic blood pressure drops (*mmHg*) between ascending aorta (*AAo*)-descending aorta (*DAo*) and transverse aortic arch (*TAA*)-descending aorta.

5. Acknowledgements

This work has been funded within the European Union project Sim-e-Child (FP7 -- 248421).

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