A Feasibility Study using Image-based Parallel Modeling for Treatment Planning

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Abstract

Coarctation of the aorta (CoA) is one of the most common congenital heart defects in the United States, and despite treatment, patients have a decrease in life expectancy. This paper proposes an initial feasibility study for using image-based parallel modeling to optimize treatment outcomes for patients presenting CoA. Such simulations can provide the physician with a more complete view of the different treatment options under different physiological conditions. The presented tool HARVEY enables both treatment planning and assessment of patient-specific risk factors based on prospective analysis of treatment procedures. We demonstrate that in silico *treatment planning yields more than a 50% decrease in the pressure drop across the coarctation throughout systole. In both physiological states, the resulting gradient was below the clinically accepted risk cutoff. This comparison of pre- and post-virtual operative hemodynamics demonstrates the potential application of the proposed framework in optimizing patient-specific CoA treatment planning.*

1. Introduction

Coarctation of the aorta (CoA) is characterized by a severe narrowing of the aorta that can lead to congestive heart failure. It accounts for 5-8% of congenital heart defects in the United States each year [1]. Current clinical practice is to take a course of action that reduces the pressure gradient across the narrowing, or stenosis, to below 20 mmHg as a high gradient can result in an increased cardiac workload [2]. Treatment options such as surgical repair, balloon angioplasty, and stent implantation have proven successful in the short term; however, long term results reveal decrease in life expectancy and predilection for hypertension, early onset coronary disease, stroke and aneurysm formation.

The pressure gradient is strongly influenced not only by the degree of coarctation but also by the physiological condition of the patient. Even mild exercise or stress can raise the gradient significantly, but such states are difficult to replicate in the clinic. There is therefore a need for a non-invasive method to monitor risk factors under a variety of physiological conditions to enable prognostic methods and to evaluate potential treatment outcomes. Such a personalized CoA surgical planning system would have a 3-fold benefit: (1) support a more quantitative approach to treatment planning, (2) enable the assessment of a range of physiological conditions on virtual post-operative outcomes, and (3) inform design of medical devices such as stents.

Image-based computational fluid dynamics (CFD) have started to be widely used to study the localization and progression of vascular diseases, such as atherosclerosis and aneurysms [3, 4]. Recent efforts have targeted the development of models that capture the impact of stress conditions on patients presenting CoA [5]. Most research has focused on prognostic and diagnostic methods and there is little work on dynamic surgical planning. There has been limited success demonstrated for the Fontan procedure [6], stent design [7], and aneurysm treatment [8], but there is a need for prospective analysis to predict the impact of the different treatment options for CoA. Patients treated for CoA often present recurrence in adulthood and are prone premature atherosclerotic disease [1]. CFD simulations of local hemodynamic risk factors can provide physicians with a more detailed view of treatment options. The majority of previous studies either focus on the pre-operative state or provide retrospective studies of post-operative states from existing imaging data. A gap exists to enable treatment planning and assessment of patient-specific risk factors based on prospective analysis of treatment procedures.

In order to fill this gap between retrospective and prospective treatment planning there is a pressing need for the development of new geometry processing and CFD techniques that are robust, effective, and ideally usable in clinical settings. In this paper, we present an initial fea-

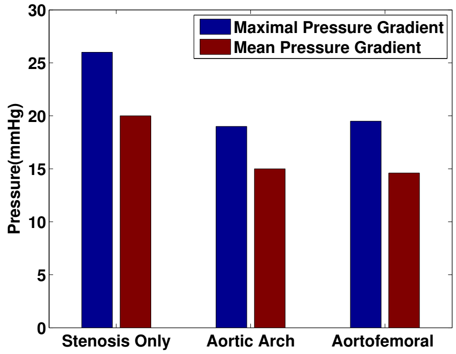

Figure 1. **Pressure Gradient.** Calculated pressure gradient for the same narrowing region with different sizes of extraneous vasculature included..

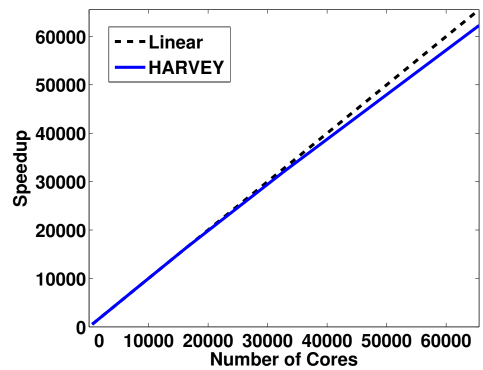

Figure 2. **Speedup.** Parallel speedup on 65,536 cores of the IBM Blue Gene/Q.

sibility study for using image-based computational modeling for treatment planning. Unlike previous studies, our approach allows the user to modify the pre-procedure CoA arterial geometry to identify preferred treatment plans. We investigate the pressure profile in pre-operative and virtual post-operative models under rest and exercise conditions at various stages in the cardiac cycle. The combination of clinical imaging data, CFD, and virtual surgery through manipulation of the image data, introduces a method evaluate treatment outcomes that is simply not possible with imaging alone.

2. Computational Model

To enable personalized simulations of blood flow in the aorta, we have developed a massively parallel computational hemodynamics application, HARVEY, based on the lattice Boltzmann method (LBM). The LBM is an alternative to the traditional Navier-Stokes equation for modeling fluid flow. The volume of a 3D mesh is filled with a regular array of lattice points on which a minimal form of the classical Boltzmann equation is simultaneously solved for a set of fictitious particles. We use an embedded boundary method to convert the triangular mesh of the vessel geometry to the regular Cartesian grid needed for the LBM simulation.

Many initial studies modeled flow through a subsection of the aorta including the stenosis and the small region of the vessel on either side. The pressure gradient across the narrowing is, however, impacted not only by the degree of narrowing but also factors like the geometry of the surrounding vasculature, inflow rate, and physiological condition. To determine the region of vasculature required to reach a convergence in pressure measurement, we conducted a preliminary study of three arterial geometries. The first included simply the stenosed region, the second the full aortic arch, and the third the entire aortofemoral region. Fig. 1 shows the mean and maximal pressure gradients for each region. The initial set containing only the coarcted portion of the vessel produced a measurement 30% larger than the other two sections. From these initial findings, it shows that at least the full aortic arch must be included to accurately assess pressure in a patient exhibiting CoA.

For the geometries in question in this paper, a 10 micron resolution simulation includes approximately 800,000 fluid grid points. The memory and computational intensity involved requires use of a large scale supercomputer such as the IBM Blue Gene/Q. Using the techniques such as deep halo ghost cells, optimized data handling, loop reordering and separation, and communication tuning, HARVEY has been optimized to scale efficient on large-scale supercomputers [9]. For bulk fluid we need to include at least a resolution of 10 microns to see convergence [4]. Fig. 2 demonstrates a 98% parallel efficiency on up to 65,536 cores.

3. Initial Case Study

The geometries used in this paper are from de-identified pre-existing imaging studies provided as part of the Vascular Model Repository [10]. The geometry of the vessels was obtained through gadolinium-enhanced MR angiography (MRA) with a 1.5-T GE Signa scanner. A segmented mesh file was created using customized SimVascular software (Simtk.org). Flow rates were measured by PC-MRI sequence encoding and provided for the duration of a cardiac cycle [6].

3.1. Virtual Treatment Planning

We propose a method to deform the vascular mesh retrieved from medical imaging to enable the creation of virtual post-operative outcomes prediction of treatment success. Such a method requires that: (1) the resulting mesh be a closed and triangular [8]; (2) pressure gradient is reduced to below 20 mmHg; (3) the vessel geometry outside the aortic coarctation remains unchanged; (4) the modified region has a smooth transition so as to not introduce any flow instability. An illustration of the virtual post-operative vessel as compared to the pre-operative state is shown in Fig. 3.

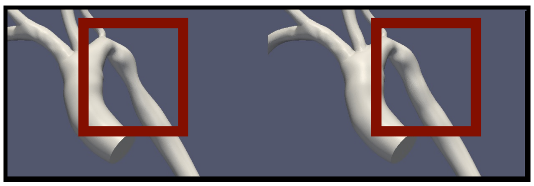

Figure 3. Pre-operative patient-specific mesh depicting a coarctation as compared to the virtual post-operative state with the stenosis removed.

A Newtonian behavior of the blood was assumed with a density of 0.001 gr/mm^3 and a dynamic viscosity of 0.004 gr/mm/sec. The Zou-He boundary conditions were implemented in which a patient-specific inflow velocity was prescribed at the inlet and a constant pressure gradient was applied out the outlets. The inflow velocity was obtained via a 2D, phase-contrast (PC) MRI sequence with through-plane velocity encoding [6].

We use Blender software (open source shareware, www.blender.org), a modeling and animation application, to modify the triangular mesh. In Fig. 3, we define a cylindrical control cage around the narrow region of the mesh and use a built-in modifier to draw the mesh vertices towards it, thereby dilating the vessel. The modifier is parameterized so that we can control the range of influence and type of falloff. This allows us to produce a variety of natural shapes including those representative of potential stent grafts. We chose Blender because it is free and compatible with our mesh representations, but we expect most mesh editing and CAD software to be sufficient for the task of anatomical editing.

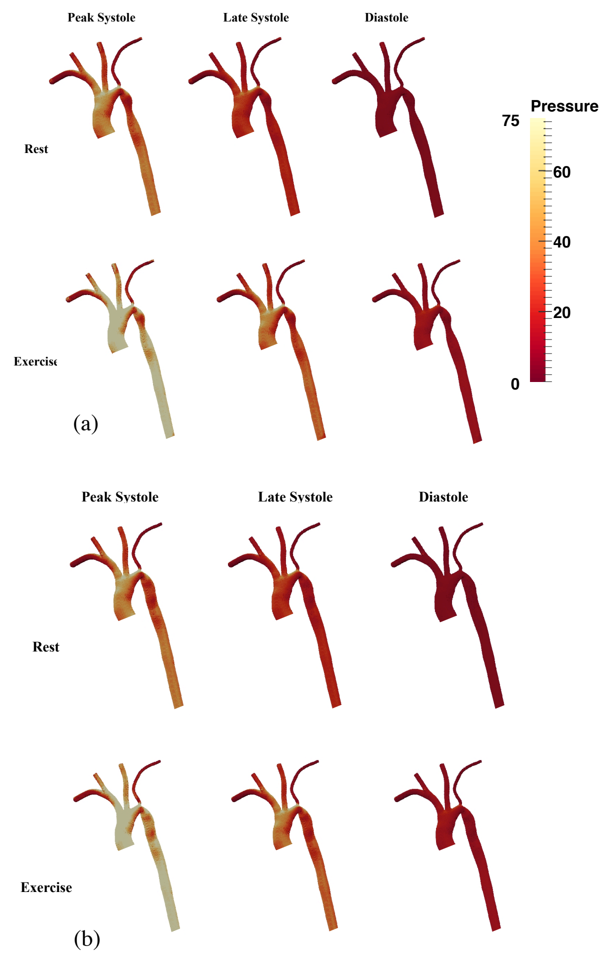

Figure 4. **Pressure map in patient-specific data set.** Hemodynamics in two different geometries was assessed: (a) Pre-operative geometry. (b) Post-virtual operative geometry. The results for both exercise and rest conditions at peak systole, late systole, and diastole demonstrate a large variance in pressure, specifically a strong correlation with the higher inflow rates associated with peak systole and exercise. The different inflow conditions cause a significantly different pressure field across the entire vessel but specifically throughout the region of coarctation.

4. Results

Detailed pressure distribution maps were generated for both the pre- and post-operative meshes configurations under two different physiological states. The results at peak systole, late systole, and diastole are shown in Figure 4. There are large differences in pressure across the cardiac cycle resulting in wide pressure gradients across the coarctation, ranging from a minimal value of 1 mmHg during diastole under rest conditions to 39 mmHg during peak systole under exercise conditions. For both cases, the magnitude of the pressure field at the wall is strongly correlated to the inflow velocity resulting in an overall higher-pressure field both during systole and under stress or exercise conditions. We also note that the stress conditions have a large impact on the pressure gradient when compounded with the greater flow rates of systole over diastole.

The effect of the virtual treatment planning is highlighted in Fig. 5, showing a greater than 50% decrease in pressure gradient for both rest and exercise conditions throughout systole. Under both rest and exercise conditions, the treatment outcome lowered the observed pressure gradient to below the clinically accepted maximum pressure gradient criterion of 20 mmHg. The pressure gradient is not only dependent on the severity of the coarctation but also the physiologic state, flow profile, and geometry of the vasculature feeding into the stenosis. It is therefore necessary to simulate the treatment outcome rather than simply increase the diameter of the vessel.

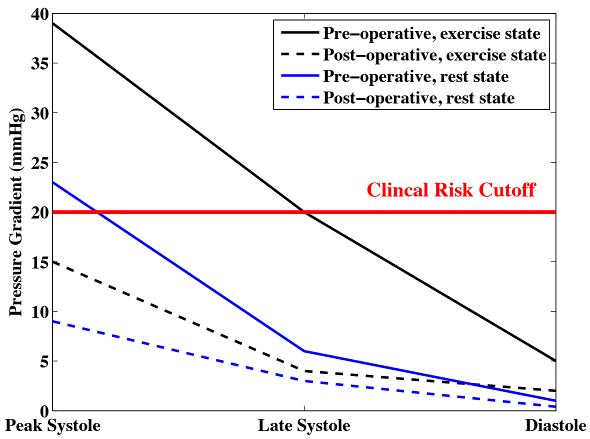

Figure 5. **Reduction in pressure gradient.** The virtual treatment planning successfully reduced the pressure gradient across the coarction to below the critical risk cutoff of 20 mmHg. Under both rest and exercise conditions, the treatment outcome was a greater than 50% decrease in pressure gradient during systole.

5. Conclusion

We have presented here a tool for patient-specific virtual treatment planning. Through a case study of one patient with a severe CoA, we investigate the impact of the treatment through comparison of the pressure gradient across the coarctation under different physiological states in the pre-operative and virtual post-operative vessels. The pressure metrics showed that under both rest and exercise conditions, the virtual post-operative geometry lowered the pressure gradient significantly, bringing it below the critical risk threshold.

The result of the CFD simulation can be analyzed to determine if the potential treatment outcomes are associated with adverse hemodynamics such as low or oscillating wall shear stress or elevated pressure gradients. These results can feed directly back to the virtual surgery component to adjust the post-operative mesh and optimize the surgical reconstruction *in silico*. In this initially feasibility study we focus on the aortic arch but in future work we will extend this research to look at medications with larger region and more patients.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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