



CFD Challenge: Simulation of Hemodynamics in a Patient-Specific Aortic Coarctation Model

Background

Coarctation of the aorta (CoA) accounts for 8%-11% of congenital heart defects, affecting tens of thousands of patients annually in the western world. Surgical or catheter-based treatments seek to alleviate the blood pressure gradient through the coarctation in order to reduce the workload on the heart. The pressure gradient is dependent on the anatomic severity of the coarctation: the greater the % of area reduction, the larger the pressure gradient. Furthermore, the pressure gradient is also greatly dependent on the flow rate and therefore the physiologic state of the patient: a small pressure gradient at rest can increase several-fold even in mild exercise conditions. The clinician can easily measure the pressure gradient through the coarctation under resting conditions, either by using a catheter-driven pressure transducer or a sphygmometer. However, measuring the pressure gradient under exercise conditions is more challenging since these conditions are not easy to replicate in the clinic. Toward this end, a 'pharmacological stress-test' is sometimes performed, whereby a drug –typically dobutamine, is administered to the patient to increase the heart rate and contractility, and therefore replicate some of the mechanisms of exercise while the pressure and flow measurements are recorded. Besides the limitations in replicating other mechanisms present in real exercise conditions such as alterations in peripheral vascular resistance, the stress tests are not ideal for the patient since they often present side-effects such as palpitations, chest pain, shortness of breath, headache, nausea or fatigue.

Advances in medical imaging and computational fluid dynamics (CFD) techniques make it possible to simulate blood flow and pressure in thoracic coarctation models built from patient data. The combination of these technologies offers the possibility of calculating pressure gradients through the coarctation non-invasively. This task can, in principle, be accomplished via satisfactory solution of a two-step process:

1. Reproduction of the measured pressure gradient at rest, via proper specification of inflow and outflow boundary conditions.
2. Estimation of the pressure gradient under exercise conditions, via adequate modification of the resting inflow and outflow boundary conditions.

However, the wide range of computer codes, formulations and approaches to boundary condition formulation make it difficult to assess the consistency and repeatability of computational results. As a first step for the validation of CFD in the clinic, the objective of this challenge is to assess the variability in the calculation of the pressure gradient through a moderate thoracic aortic coarctation model. Details on the patient data are provided next.

Model Geometry and Physiologic Data

The subject was 8-year old female patient with a moderate thoracic aortic coarctation (approximately 65% area reduction) whose body surface area (BSA) was 0.94 m². Gadolinium-enhanced MR angiography (MRA) was performed with the participant in the supine position inside a 1.5-T GE Signa scanner. The subject was instructed to hold her breath during the MRA acquisition period for approximately 20 sec. Figure 1 shows a rendering of a .stl file containing the segmentation from the MRA data. The model includes the ascending aorta, arch, descending aorta, and upper branch vessels. The dimensions of the .stl file are mm. The number of faces and points in the .stl file is 114,514 and 57,259, respectively.

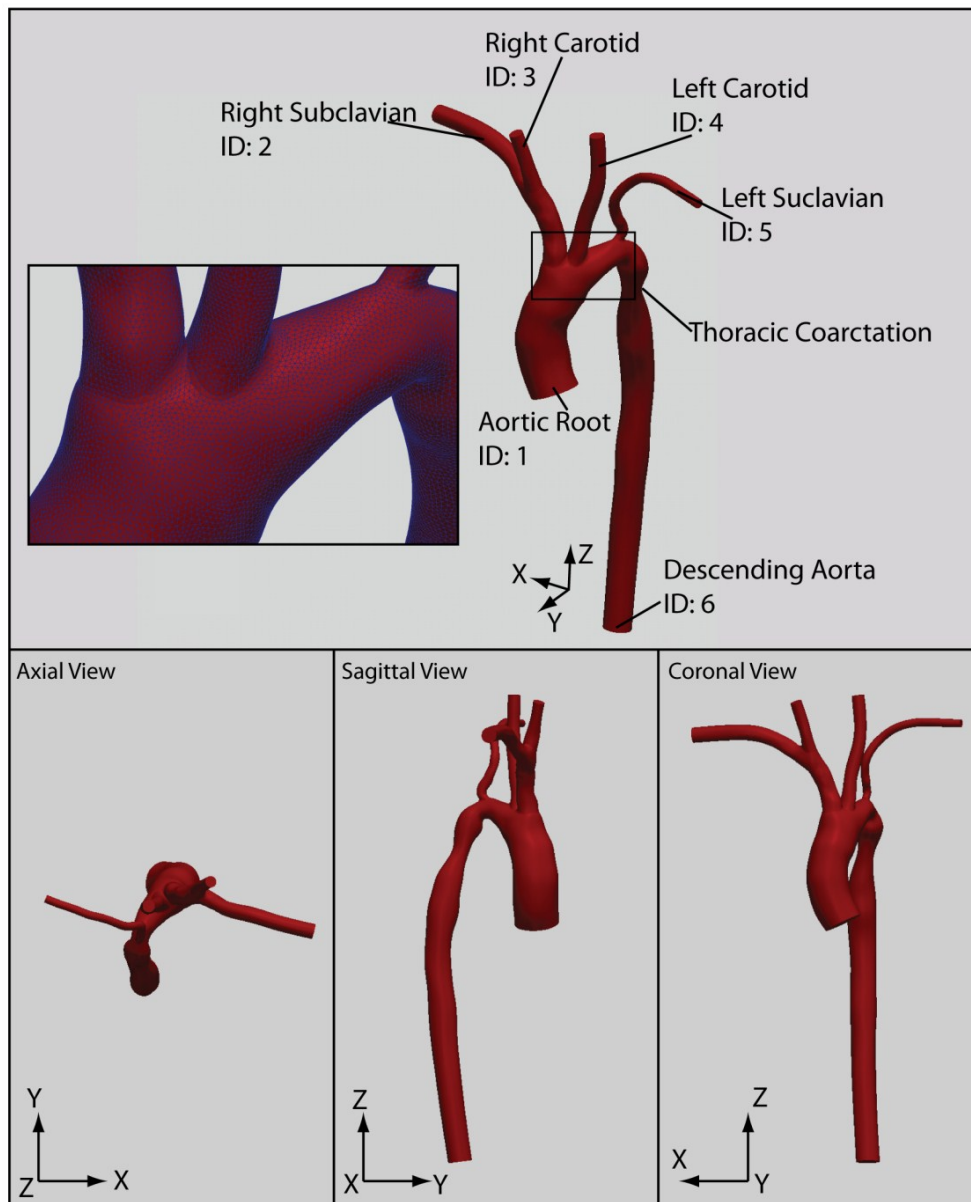


Figure 1: Rendering of the thoracic aortic coarctation anatomy. Labels of the various vessels are provided together with an arbitrary surface ID.

Flow data

Blood flow information was acquired using a cardiac-gated, 2D, respiratory compensated, phase-contrast (PC) cine sequence with through-plane velocity encoding. Each scan lasted approximately 3 min while the subject breathed freely. Figure 2 shows the ascending aortic flow (in mm³/sec) as measured by the PC-MRI sequence encoding 20 phases over the cardiac cycle. The cardiac output of the patient was 3.245 L/min, the heart rate 86 beats per minute (cardiac cycle $T = 0.7$ sec). Additional PC-MRI planes were defined to measure the flow rates through the upper branch vessels as well as the descending aorta. These flow rates are given as a percentage of the ascending aortic flow in Table 1.

Ascending Aortic Flow

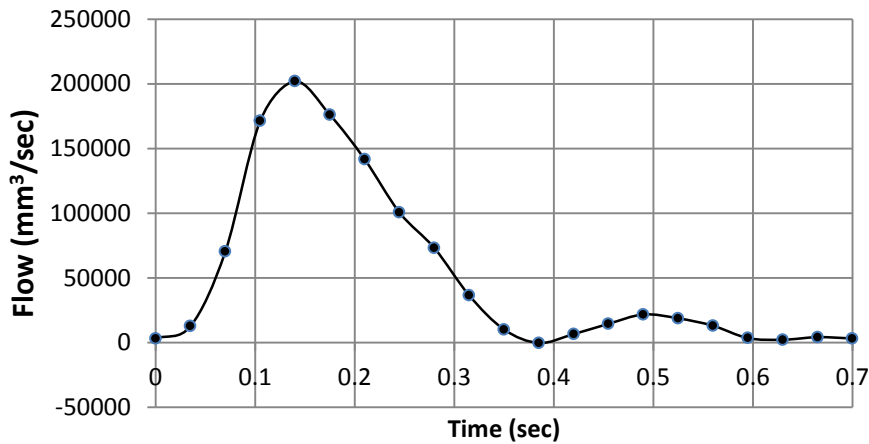


Figure 2: Ascending aortic flow (in mm³/sec) as measured by a phase-contrast (PC) MRI sequence with through-plane velocity encoding. 20 phases were reconstructed and are represented by the black dots in the curve.

Location	Q _{IA}	Q _{LCCA}	Q _{LSA}	Q _{DA0}
% Ascending Aortic Flow	25.6	11.3	4.26	58.8

Table 1: % of ascending aortic flow through various branches of the aortic model as measured via PC-MRI. Q_{IA}: flow through innominate artery; Q_{LCCA}: flow through left common carotid artery; Q_{LSA}: flow through left subclavian artery; Q_{DA0}: flow through descending aorta.

Please note that only flow through the base of innominate artery was recorded: you will have to make reasonable assumptions to estimate flow going through the right subclavian and right common carotid outlet faces.

Pressure data

The upper-body systolic and diastolic blood pressures as measured via a sphygmometer were 115 and 65 mmHg, respectively. The lower-body systolic blood pressure was also measured with a sphygmometer in order to determine the mean pressure gradient through the aortic coarctation, but for the purpose of this challenge, this data will not be disclosed at this point, since the purpose is to obtain the pressure gradient through the coarctation using CFD tools.

Constitutive properties

In this challenge, the arterial wall will be assumed to be rigid. Although this is an important limitation, it will make the simulation effort simpler and will likely reduce the variability in the result obtained by different groups. A Newtonian behaviour is assumed for the blood, with a density $\rho = 0.001 \text{ gr/mm}^3$ and a dynamic viscosity $\mu = 0.004 \text{ gr/mm/sec}$.

Objective

Considering the data given above, the goal is to produce a numerical simulation using your CFD framework to estimate the pressure gradient through the coarctation. The use of a turbulent model is discouraged. Your simulation must verify the following:

- The provided inflow waveform must be prescribed at the inflow face of the model. You can map the provided volumetric flow to either a parabolic, plug, or Womersley velocity profile. Please specify and justify your choice in the reported results.
- The flow distribution through the various branches must match the data given in Table 1.
- The pressure proximal to the coarctation must match the recorded systolic and diastolic pressures of 115 and 65 mmHg, respectively.

In your report, you should describe the basics of your CFD framework, your approach to boundary condition specification: i.e., direct flow and pressure waveform specification or Windkessel models. If 3-element Windkessel models are used at the outlet faces, please report the R_p , C , and R_d values utilized in your analysis. Your report should also include the details of the computational mesh: element type, size (number of elements and nodes), whether boundary layer meshing was utilized, etc. The main deliverable of your work will be the mean pressure gradient through the coarctation, and an 8-page LNCS-style paper reporting method and experiment results. This pressure gradient will be compared with the clinically measured pressure gradient at rest. In a future edition of the CFD challenge, the objective will be to estimate the pressure gradient under exercise conditions.

The files included in this CFD challenge are

- miccai-2012-cfd-challenge-anatomy.stl
- miccai-2012-cfd-challenge-inflow.txt
- miccai-2012-cfd-challenge-description.pdf

Paper Submission

We invite submissions through the STACOM 2012 site, see (<http://www.physense.org/stacom2012/>). Papers must be formatted using LNCS style, with up to 8 pages (strict limit). They will be reviewed (double-blind) by members of the program committee and assessed for quality.

Reporting the Pressure Gradient

In order to consistently compare the computed pressure gradients reported by the challengers, we provide the location of a proximal (π_1) and a distal (π_2) plane to the coarctation site, see Figure 3 below. The centroid of the intersection of each plane with the aorta and the unit normal vector at each location are also noted in the figure.

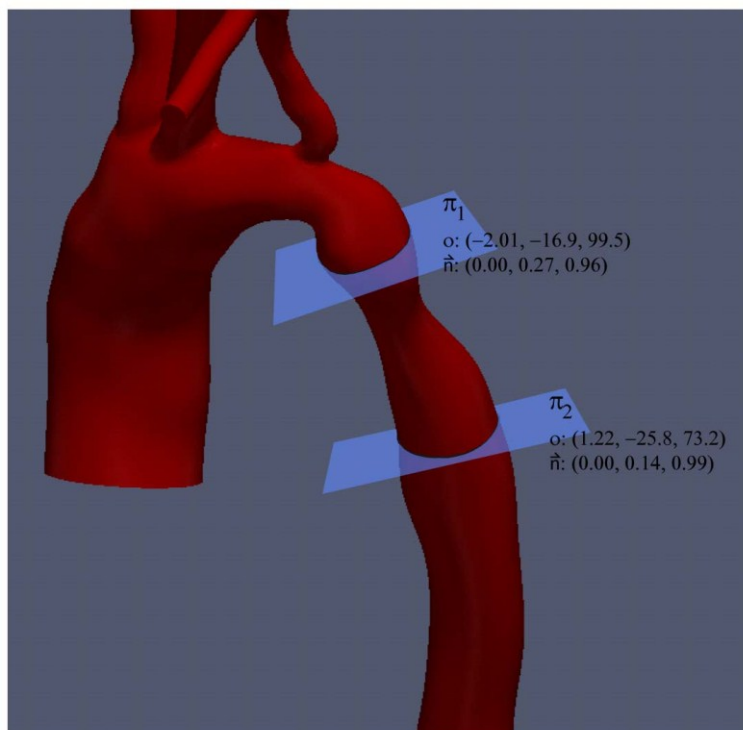


Figure 3: Location of the proximal and distal planes to the coarctation site for reporting the pressure gradients.

The challengers should calculate the spatial average of the pressure field on each plane. The pressure gradient at any given time will be given by the difference between the spatial averages of the pressure field on each of the planes. The authors should report the time-average of the pressure gradient over the cardiac cycle, as well as the maximum (i.e., systolic) pressure gradient.

Important Dates

- **May 15th 2012:** Deadline for submitting letter of intent of participation
- **June 1st 2012:** Registration on the submission system (abstract + title)
- **June 15th 2012:** Deadline for paper submission with method and preliminary results for review
- **July 6th 2012:** Notification of paper acceptance to the authors
- **July 12th 2012:** Early-bird registration deadline for MICCAI conference
- **July 23rd 2012:** Deadline for submission of the final version
- **October 5th 2012:** Workshop

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