2nd CFD Challenge

Predicting Patient-Specific Hemodynamics at Rest and Stress through an Aortic Coarctation

STACOM 2013 Website: http://www.cardiacatlas.org/web/stacom2013/challenges

CFD Challenge Website: http://www.vascularmodel.org/miccai2013/

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Background

Coarctation of the aorta (CoA), a narrowing of the aorta, accounts for approximately 10% of congenital heart defects in the western world. Due to the reduction in diameter, high pressure gradients can appear across the aortic coarctation, resulting in an increased cardiac workload. Current therapies, either surgical or minimally-invasive, aim to alleviate the blood pressure gradient through the coarctation. The pressure gradient is dependent on the severity of the aortic narrowing: the greater the percentage of area reduction, the larger the pressure gradient. The pressure gradient is also highly 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 stress conditions. For these reasons, it is critical to assess the blood pressure gradient during exercise induced stress, for an accurate diagnosis. As opposed to the routine assessment during resting conditions, , measuring the pressure gradient under exercise conditions is more challenging since these conditions are not easy to replicate in the clinic. 'Pharmacological stress-test' is sometimes performed. However, 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 extracted from patient data. The combination of these technologies offers the possibility of computing pressure gradient 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. During the first MICCAI-STACOM CFD Challenge (Nice, Oct. 5th, 2012), a representative variety of CFD codes were compared for the simulation of blood pressure gradient at rest. **The objective of the second edition is to assess the predictive power of CFD methods in computing the blood pressure gradient under exercise conditions, through a moderate aortic coarctation model, given physiological conditions and imaging at rest**. Details on the patient data are provided in the next section.

Model Geometry and Physiologic Data

Anatomic data

The subject was a 71kg, 177cm tall, 17-year old male with a mild thoracic aortic coarctation whose body surface area (BSA) was 1.9 m^2. A Dotarem (Gadolinium-based) contrast agent MR angiography (MRA) was performed with the participant in the supine position inside a 1.5-T Phillips scanner. 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 in mm. The number of faces and vertices in the .stl file is 138,532 and 69,268, respectively. The inlet and outlet faces are tagged in the .stl file with the following labels: INLET1, OUTLET1, OUTLET2, OUTLET3 and OUTLET4. The lumen is tagged as VESSELWALL.

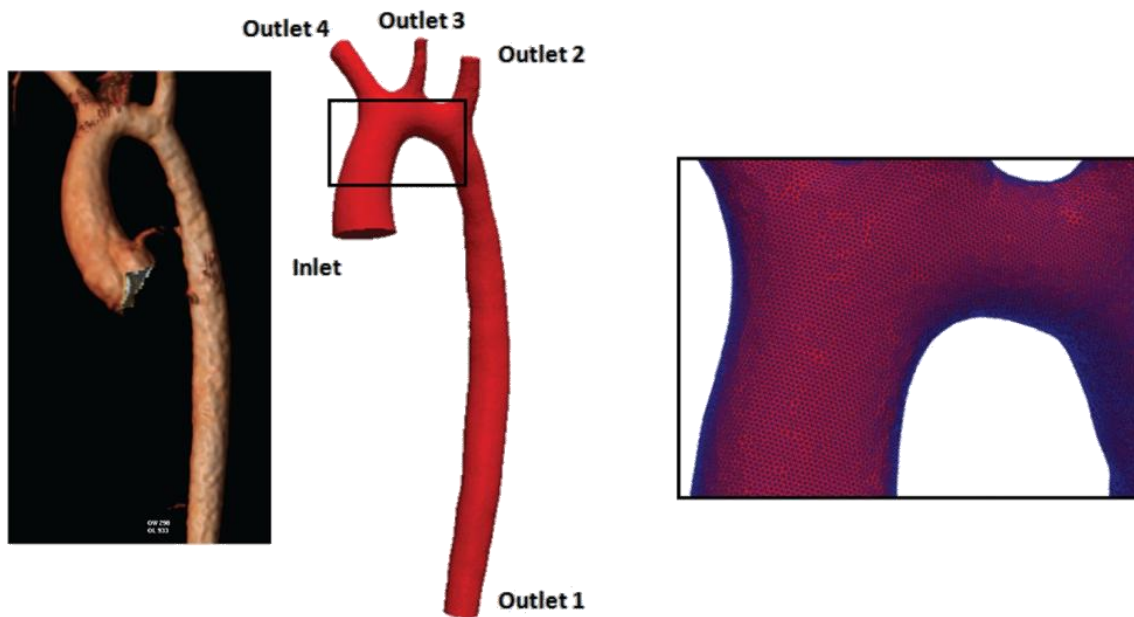The anatomic model is given in the following STL ASCII file:

- coarctation_model.stl

Figure 1: Left: Rendering of MRA and.stl file representing the thoracic aortic anatomy. **Right:** close-up view of the surface mesh.

Hemodynamic data

Rest Conditions

Flow data

Blood flow information was acquired using a cardiac-gated, 2D, respiratory compensated, phase-contrast (PC) cine sequence with through-plane velocity encoding. The cardiac output of the patient was 3.71 L/min, the heart rate 47 beats per minute (cardiac cycle T = 1.277 sec). Flow waveforms were reconstructed at the levels of the ascending aorta (AscAo) and diaphragmatic aorta (DiaphAo). These waveforms are depicted in Figure 2. We provide a 15-term Fourier reconstruction of the flow waveforms, according to the following expression:

$$Q\left(t\right) = \text{real}\left\{\sum_{n=0}^{14} Q_n e^{i\omega n t}\right\}$$

where Q_n is the Fourier mode, $\omega = 2\pi/T$, T is the cardiac cycle, and i is the imaginary unit.

The flow waveforms and corresponding Fourier reconstruction are provided in the following files:
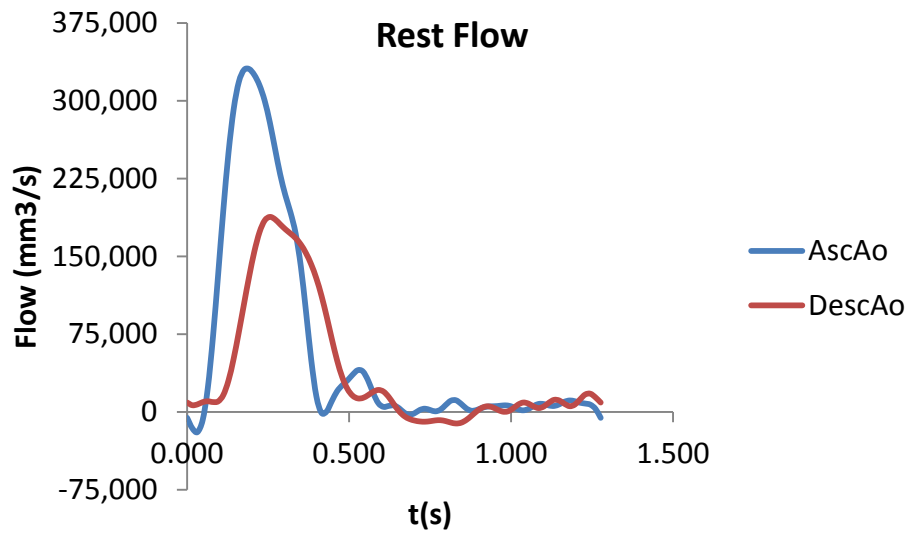
- AscAortic-Rest.csv
- DescAortic-Rest.csv

Figure 2: Ascending aortic and diaphragmatic aortic flow waveforms (in mm³/sec) as measured by the (PC)-MRI sequence

The quality of the waveforms to the supra-aortic vessels (innominate, left carotid (LC), and left subclavian (LS) arteries) was deemed too noisy to be used in the computations and therefore total flow through those branches is reported instead. Table 1 provides total flow rates through each branch given as a percentage of the ascending aortic flow.

	AscAo	Innominate	LCC	LS	DiaphAo
Total Flow (L/min)	3.71	0.624	0.312	0.364	2.41
% AscAo	100	17	8	10	65

Table 1: Total flow (in L/min) and percentage of ascending aortic flow through the various branches of the aortic model under rest conditions

Pressure data

Invasive pressure wire measurements were acquired in a catheterization laboratory-equipped XMR suite. Pressures were obtained for both the ascending aorta (proximal to the coarctation) and the diaphragmatic aorta (distal to the coarctation). The proximal systolic, diastolic, and mean pressures were 83.92, 49.68, and 63.35 mmHg, respectively. **For the purposes of this challenge, we do not disclose the pressure measurements in the diaphragmatic aorta that enable the calculation of the pressure gradient through the coarctation. This information will be released at the end of the challenge**. The participants must obtain and report the pressure gradient through the coarctation using CFD tools. The proximal pressure waveform and corresponding 15-mode Fourier reconstruction are provided for in the following file:

- P-AscAortic-Rest.csv

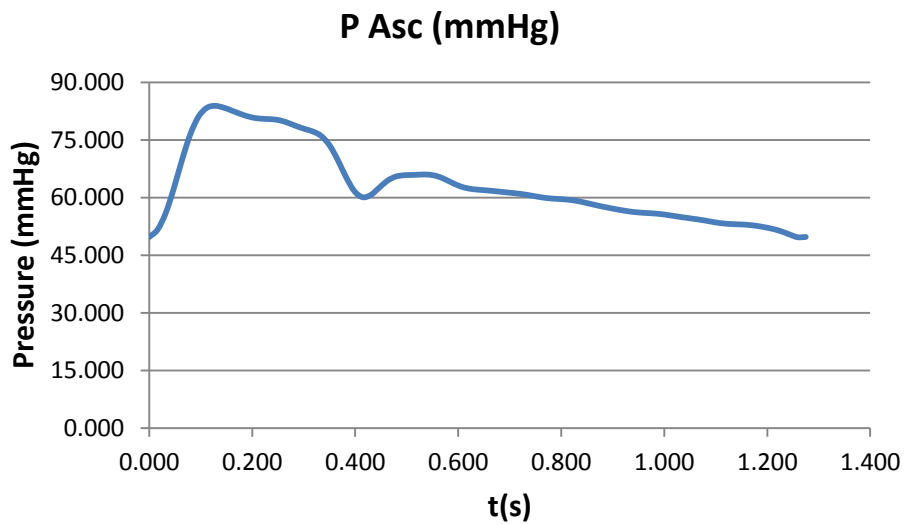Figure 3 illustrates the pressure wave acquired in the ascending aorta (proximal to the coarctation).

Figure 3: Ascending aortic pressure (in mmHg) measured with a pressure catheter under rest conditions

Stress Conditions

Stress conditions were induced by administering isoprenaline to the subject. Flow and pressure data waveforms were acquired using the same protocol as in the rest conditions.

Flow data

The cardiac output of the patient increased to 13.53 L/min, the heart rate to 141 beats per minute (cardiac cycle T = 0.425 sec). Flow waveforms were reconstructed at the levels of the ascending aorta (AscAo) and diaphragmatic aorta (DiaphAo). These waveforms are depicted in Figure 4.
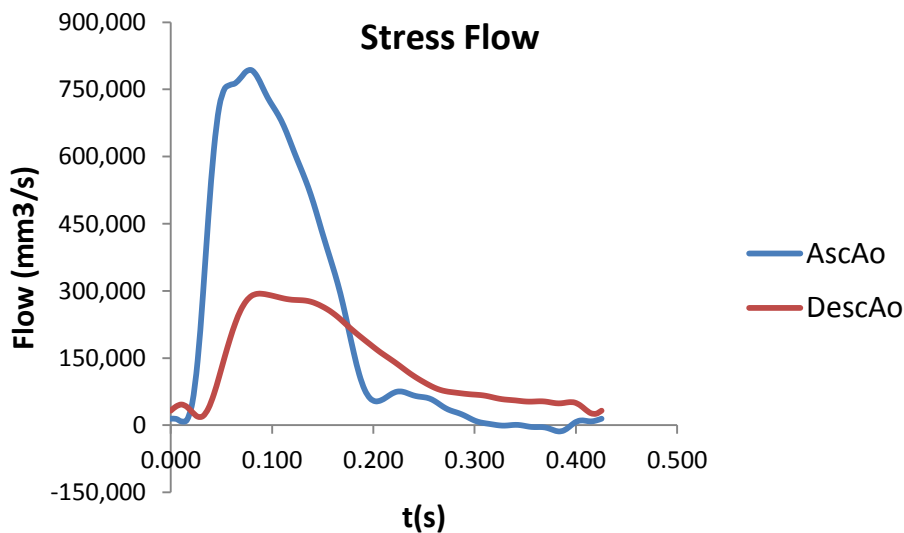

Figure 4: Ascending aortic and diaphragmatic aortic flow waveforms (in mm³/sec) under stress conditions

The flow waveforms and corresponding Fourier reconstruction are provided in the following files:

- AscAortic-Stress.csv
- DescAortic-Stress.csv

Table 2 provides the total flow rates under stress conditions through each branch given as a percentage of the ascending aortic flow.

	AscAo	Innominate	LCC	LS	DiaphAo
Total Flow (L/min)	13.53	3.355	0.6875	1.4575	8.03
% AscAo	100	25	5	11	59

Table 2: Total flow (in L/min) and percentage of ascending aortic flow through the various branches of the aortic model under stress conditions

Pressure data

Pressures were obtained for both the ascending aorta (proximal to the coarctation) and the diaphragmatic aorta (distal to the coarctation). The proximal systolic, diastolic, and mean pressures were 123.35, 36.77, and 64.30 mmHg, respectively. **For the purposes of this challenge, we do not disclose the pressure measurements in the diaphragmatic aorta that enable the calculation of the pressure gradient through the coarctation. This information will be released at the end of the challenge**. The participants must obtain and report the pressure gradient through the coarctation using CFD tools. The proximal pressure waveform and corresponding 15-mode Fourier reconstruction are provided for in the following file:

- P-AscAortic-Stress.csv

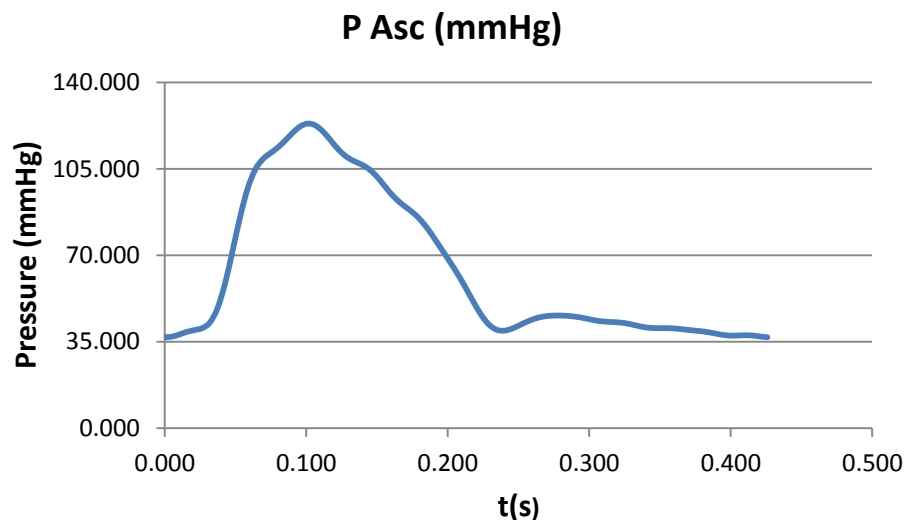Figure 5 illustrates the pressure wave acquired in the ascending aorta (proximal to the coarctation).

Figure 5: Ascending aortic pressure (in mmHg) measured with a pressure catheter under stress conditions

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 $\rho = 1000.0$ g/mm^3 and a dynamic viscosity $\mu = 0.004$ g/mm/sec.

Objective

Considering the data given above, **the goal is to produce a numerical CFD simulation that estimates the pressure gradient through the coarctation at rest and stress**. Ground truth measurements at rest and stress conditions will be disclosed during the workshop, together with a discussion of the results reported by all the participants. The use of a turbulent model is discouraged. The simulation must verify the main physics of fluid dynamics, plus the following conditions:

- 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 Tables 1 and 2.
- The pressure proximal to the coarctation must match the recorded systolic, diastolic and mean pressures for each hemodynamic state.

The manuscript should report the basics of the employed CFD framework, the detailed specifications of the boundary conditions, 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. The 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. Finally, if any model fitting is performed, the details of the method employed to estimate the parameters from the rest and stress data should be described and discussed.

The main deliverable is the mean pressure gradient through the coarctation at rest and stress, and an 8-page LNCS-style paper reporting method and experimental results. The pressure gradients will be compared with the clinically measured pressure gradients.

Paper Submission

We invite submissions through the STACOM 2013 site (http://www.cardiacatlas.org/web/stacom2013). Papers must be formatted using LNCS style, with up to 8 pages, strict limit (http://www.springer.com/computer/lncs?SGWID=0-164-6-793341-0). They will be reviewed (double-blind) by members of the program committee and assessed for technical soundness and quality. Author guidelines can be found on the MICCAI 2013 website (http://www.miccai2013.org/submission_guideline.html).

Important Dates

- **June 7th 2013**: Letter of intent of participation and paper registration (tentative title and short abstract)
- **June 14th 2013**: Paper submission deadline (introduction, methods and first results)
- **July 5th 2013**: Notification of paper acceptance
- **July 22nd 2013**: Early bird MICCAI registration deadline
- **TBD (MICCAI)**: Camera-ready submission deadline with final results
- **September 26th 2013**: Workshop

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Summary of Files

The following files for the challenge are being hosted by www.vascularmodel.org:

- flyer.pdf
- coarctation_model.stl
- AscAortic-Rest.csv
- DescAortic-Rest.csv
- P-AscAortic-Rest.csv
- AscAortic-Stress.csv
- DescAortic-Stress.csv
- P-AscAortic-Stress.csv