Non-invasive assessment of aortic coarctation severity using computational fluid dynamics: a feasibility study

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Background

- Aortic coarctation (CoA) is one of the most common forms of congenital heart disease (incidence: 5-8% of all congenital lesions).
- Complications after repair are encountered in more than one third of adult patients throughout their lives [1].
- Cardiovascular magnetic resonance (CMR) and CT imaging mainly provide anatomical information. Obtaining hemodynamic information is more challenging but very valuable to detect complications.
- The gold standard to assess CoA severity is the pressure drop across the narrowing measured with catheterization. Intervention is recommended if the pressure gradient exceeds 20 mmHg [1].
- Unfortunately, catheterization is an invasive procedure with a 1 in a 1000 risk of patient death or serious injury [2].
- Computational fluid dynamics (CFD) is a promising non-invasive method to calculate the pressure drop through the CoA, based on CMR or CT images.

Goal

To evaluate the performance of an imaging-guided CFD approach to obtain the pressure drop across the coarctation in a non-invasive way, using catheterization as reference standard.

Methodology

Step 1: Geometrical Reconstruction

- The 3D vessels geometry of 14 patients were reconstructed from magnetic resonance angiography or CT images from the institutional database of the Toronto General Hospital, using the software VMTK (*www.vmtk.org*).
- This process, illustrated in Fig. 1, resulted in a computational mesh describing the shape of the thoracic aorta.

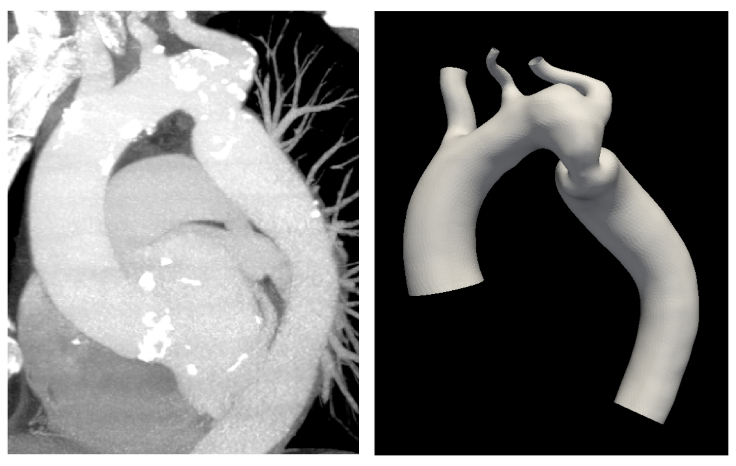

Figure 1: *Left panel: sagittal oblique MIP-CT image of thoracic aorta. Right panel: 3D reconstructed geometry.*

Step 2: Boundary Conditions

- At the inlet of the ascending aorta, an estimated blood flow rate was imposed to model the blood flow originating from the heart [3].
- At the outlets, a resistor-capacitor-resistor (RCR) boundary condition was imposed to model circulation in distal vasculature [4], as illustrated in Fig. 2.
- Resistors account for the resistance offered to blood flow by the vasculature beyond the computational domain.
- Capacitors model the compliance of the vessels due to the elasticity of their walls.

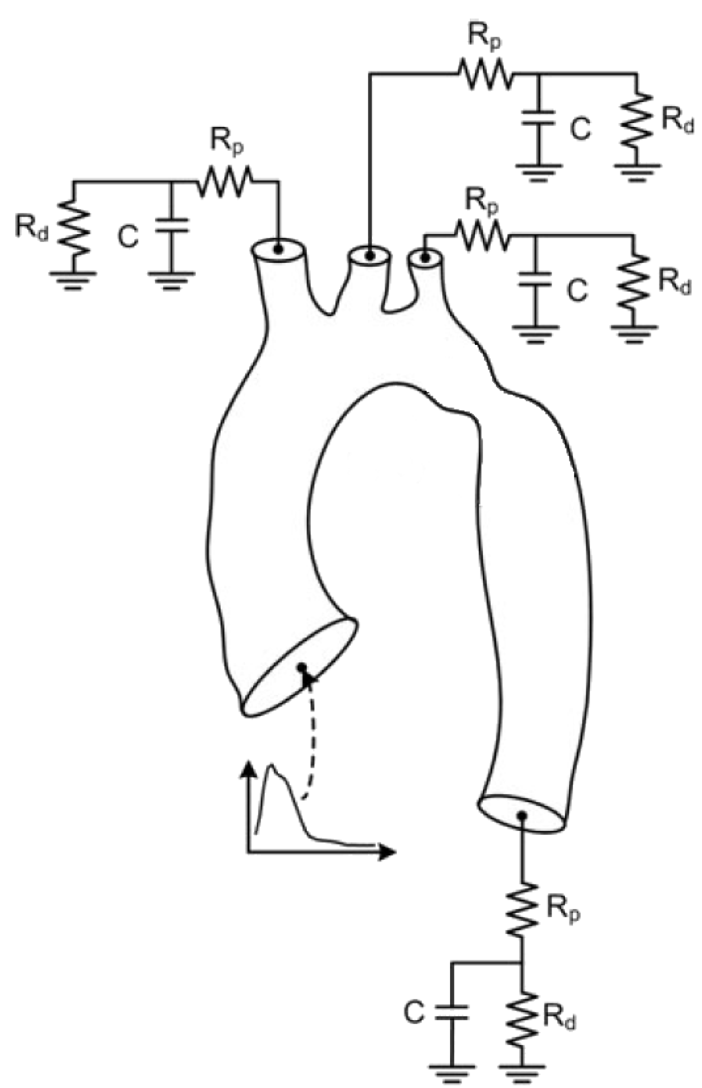

Figure 2: *Illustration of the computational model, with imposed flow rate on the ascending aorta, and the RCR boundary conditions at the outlets* [4].

Step 3: Fluid Dynamics Simulation

- Navier-Stokes equations were used to accurately describe how blood flows in the thoracic aorta, and determine pressure P and flow velocity $\boldsymbol{u}$ resolved in both space and time

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho\boldsymbol{u}\cdot\nabla\boldsymbol{u} - \mu\Delta\boldsymbol{u} + \nabla P = \boldsymbol{f}$$

$$\nabla\cdot\boldsymbol{u} = 0$$

- The Navier-Stokes equations were solved with Simvascular, an open-source CFD software from Stanford University (*simvascular.github.io*).
- The computational simulation provided the blood velocity and pressure in the aorta and surrounding vessels.
- The maximum value reached by the pressure drop over the cardiac cycle was compared to the gold standard measured with catheterization.

Results

- Fourteen CoA patients (3 female, mean age 40 ± 14 years) were included. Eight (57%) patients had native and six (43%) post repaired CoA.
- Table 1 shows the relationship between the pressure drop from catheterization and CFD.
- A significant pressure gradient (>20mmHg) was found in 9 (64%) patients by catheterization.
- In 13 (93%) patients, the CFD method was in agreement with catheterization ($p = 0.003$).
- In only 1 (7%) patient the CFD method disagreed with catheterization, underestimating the pressure drop.
- A very good agreement between the two methods ($k = 0.85$) was obtained.

Table 1: *Relationship between the pressure drop obtained with catheterization and CFD.*

	Cath $\leq$ 20mmHg	Cath $>$ 20mmHg	Total
CFD $\leq$ 20 mmHg	5 (83%)	1 (17%)	6 (43%)
CFD $>$ 20 mmHg	0 (0%)	8 (100%)	8 (57%)
Total	5 (36%)	9 (64%)	14

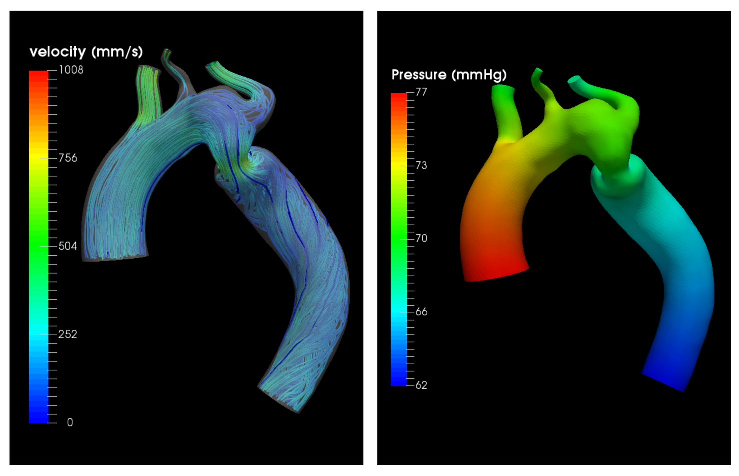

Figure 3: *Left panel: velocity stream at $t = 1.28\,\mathrm{s}$ obtained from the CFD simulation. Right panel: pressure distribution.*

Conclusions

- The results of our pilot study suggest that CFD has the potential to become a non-invasive alternative to estimate the pressure drop through the narrowing and evaluate CoA severity.
- Future work will leverage the proposed approach to devise innovative and non-invasive means for the diagnosis, treatment and follow-up of aortic coarctation.

Acknowledgements

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